INL/EXT-11-23452
Revision 3

Light Water Reactor Sustainability Program

Integrated Program Plan

April 2015

U.S. Department of Energy

Office of Nuclear Energy

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EXECUTIVE SUMMARY

Nuclear power has safely, reliably, and economically contributed almost 20% of electrical generation in the United States over the past two decades. It remains the single largest contributor (more than 60%) of non-greenhouse-gas-emitting electric power generation in the United States.

Domestic demand for electrical energy is expected to grow by about 29% from 2012 to 2040[a]. At the same time, most of the currently operating nuclear power plants will begin reaching the end of their initial 20-year extension to their original 40-year operating license, for a total of 60 years of operation (the oldest commercial plants in the United States reached their 40th anniversary in 2009). Figure E-1 shows projected nuclear energy contribution to the domestic generating capacity for 40- and 60-year license periods. If current operating nuclear power plants do not operate beyond 60 years (and new nuclear plants are not built quickly enough to replace them), the total fraction of generated electrical energy from nuclear power will rapidly decline. That decline will be accelerated if plants are shut down before 60 years of operation. Decisions on extended operation ultimately rely on economic factors; however, economics can often be improved through technical advancements.

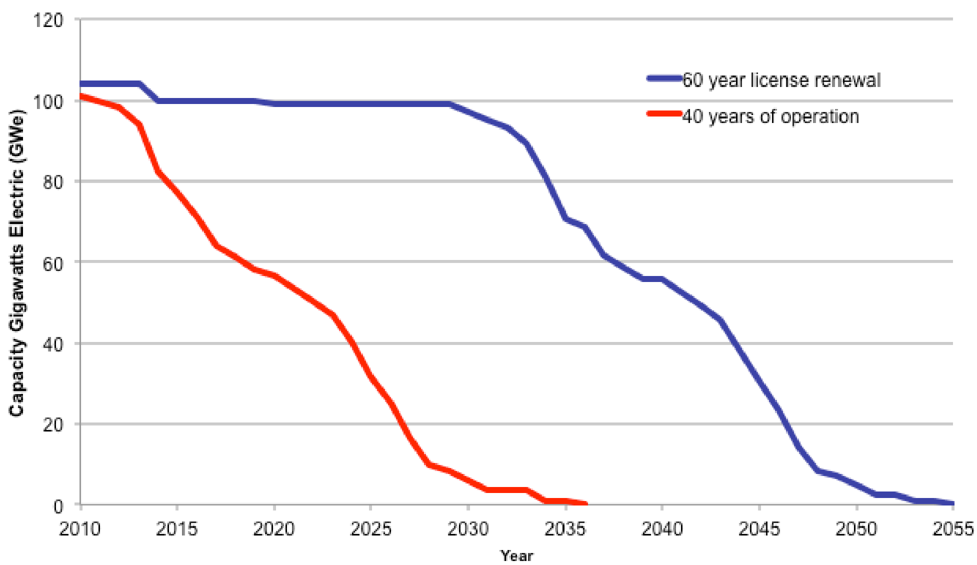

Figure E-1. Projected nuclear power generation for 40- and 60-year license periods.

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

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

a. Annual Energy Outlook 2014, page MT-16.

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

3. Develop sustainable nuclear fuel cycles.

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

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

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

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

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

- ***Materials Aging and Degradation.*** Research and Development (R&D) to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. This work will provide data and methods to assess the performance of systems, structures, and components essential to safe and sustained nuclear power plant operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant systems, structures, and components subject to long-term operating conditions, providing key input to both regulators and industry.

b. The Reactor Safety Technologies Pathway was added to the LWRS Program on October 1, 2014.

- ***Risk-Informed Safety Margin Characterization.*** R&D to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants. This pathway will (1) develop and demonstrate a risk-assessment method tied to safety margins quantification and (2) create advanced tools for safety assessment that enable more accurate representation of nuclear power plant safety margins and their associated impacts on operations and economics. The R&D products will be used to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety margins and permits cost effective management of these margins during periods of extended operation.

- ***Advanced Instrumentation, Information, and Control Systems Technologies.*** R&D to address long-term aging and modernization of current instrumentation and control technologies through development and testing of new instrumentation and control technologies and advanced condition monitoring technologies for more automated and reliable plant operation. The R&D products will be used to design and deploy new instrumentation, information, and control technologies and systems in existing nuclear power plants that provide an enhanced understanding of plant operating conditions, available margins, improved response strategies, and capabilities for operational events.

- ***Reactor Safety Technologies***. R&D to improve understanding of beyond design basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents, in particular the Fukushima Daiichi events. This information will be used to aid in developing mitigating strategies and improving severe accident management guidelines for the current light water reactor fleet.

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

- Provide mechanistic understanding of key materials degradation processes, predictive capabilities, and high-quality data to inform decisions and processes by both industry and regulators including:
    - Containment Inspection Guidelines for extended-service conditions
    - Predictive models for swelling in light water reactor components, aging of cast austenitic stainless steel components, cable degradation, and nickel-base alloy stress corrosion cracking susceptibility. Model for transition temperature shifts in reactor pressure vessel steels, precipitate phase stability and formation in Alloy 316, and environmentally-assisted fatigue in light water reactor components
    - Prototype proof-of-concept system for nondestructive examination of concrete sections, fatigue damage, and cable insulation
    - Development and transfer of weld repair technique for welding irradiated materials to industry

- Margins analysis techniques and associated models and tools to enable industry to conduct margins quantification exercises for their plants including:
  - Demonstration of the margins analysis techniques on industry-important topics
  - A modern, validated safety analysis tool (RELAP-7)
  - Component aging and damage evolution analysis tool (Grizzly), capable of modeling aging of select steel (embrittlement) and concrete failure mechanisms
  - An advanced probabilistic and data mining analysis tool (RAVEN)
- Technical reports to implement digital technologies including:
  - Hybrid integrated control room incorporating digital upgrades in an analog control room, advanced alarm systems, and control room computer-based procedures
  - Digital architecture for an automated plant
  - Human performance improvement for nuclear power plant field workers including mobile technologies for nuclear power plant field workers, and automated work packages
  - Advanced online monitoring facility for integrated operations
  - Outage safety and efficiency including advanced outage coordination, advanced outage control center, and outage risk management improvement
  - Online monitoring of active components
- Improved understanding of and reduced uncertainty in severe accident progression, phenomenology, and outcomes, including
  - Gap analysis of accident tolerant components and severe accident analysis
  - Forensics examination plan for Fukushima-Daiichi reactors
  - Reactor core isolation cooling pump model

Sections 1 through 4 in this document provide a comprehensive overview of the LWRS Program and how it functions, including detailed descriptions of the four pathways and the near-term and longer-term milestones. Appendix A is a summary of previous years' LWRS Program accomplishments, and Appendix B is a chronological listing (by pathway) of planned LWRS Program milestones.

CONTENTS

FIGURES

ACRONYMS

BWR	Boiling Water Reactor
CASL	Consortium on Advanced Simulation of LWRs
CASS	Cast Austenitic Stainless Steel
CFR	Code of Federal Regulations
CSNI	Committee on the Safety of Nuclear Installations
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy
EMDA	Expanded Materials Degradation Assessment
EPRI	Electric Power Research Institute
HSSL	Human Systems Simulation Laboratory
IAEA	International Atomic Energy Agency
IASCC	Irradiation-Assisted Stress Corrosion Cracking
II&C	Instrumentation, Information, and Control
INL	Idaho National Laboratory
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MAaD	Materials Aging and Degradation
MAI	Materials Aging Institute
MDM	Materials Degradation Matrix
MOOSE	Multi-physics Object Oriented Simulation Environment
NDE	Nondestructive Examination
NE	Office of Nuclear Energy
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEA	Nuclear Energy Agency
NEA-OECD	Nuclear Energy Agency – Organization for Economic Cooperation and Development
NEET	Nuclear Energy Enabling Technologies
NEUP	Nuclear Energy University Program
NRC	U.S. Nuclear Regulatory Commission
NUGENIA	Nuclear GENeration II & III Association

NULIFE	European Nuclear Plant Life Prediction
NUREG	NRC Technical Report
ORNL	Oak Ridge National Laboratory
PLiM	Plant Life Management
PMDA	Proactive Materials Degradation Assessment
PRA	Probabilistic Risk Assessments
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
R&D	Research and Development
RAVEN	Risk Analysis and Virtual Control Environment (simulation controller for RISMC)
RELAP-7	Reactor Excursion and Leak Analysis Program Version 7
RIMM	Risk-Informed Margins Management
RISMC	Risk-Informed Safety Margin Characterization
RPV	Reactor Pressure Vessel
RST	Reactor Safety Technologies (RST)
SCC	Stress Corrosion Cracking
SSC	Systems, Structures, and Components
U.S.	United States
UWG	Utility Working Group

Light Water Reactor Sustainability Program Integrated Program Plan

1. BACKGROUND

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

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

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

Nuclear energy is the nation's largest contributor of non-greenhouse-gas-emitting electric power generation, comprising over 60% of the non-emitting sources (Figure 1). Energy efficiency, renewable energy, and carbon capture and storage technologies are playing increasing roles in providing clean and reliable energy. Nevertheless, our nation and others will depend on nuclear energy for large-scale supply of economical, dependable, and clean electricity.

The other forms of low carbon dioxide-emitting and renewable energy production methods (e.g., hydroelectric, wind, geothermal, and solar) have the potential to produce substantial energy; however, intermittent sources are of limited use for baseload power until energy storage becomes economical. Hydroelectric power is the most widely used renewable energy source in the United States; however, there is limited opportunity for expansion. While wind, geothermal, and solar power have demonstrated promise in meeting the nation's growing demand, these sources currently contribute only a small fraction of the nation's growing energy demands. In addition, wind and solar power are inherently dilute with low power density and are intermittent, resulting in low capacity factors. Geothermal is not intermittent, but is limited to locations or regions, such as the Geysers in California, where very hot water is easily accessible. Figure 2 provides a graph of the current capacity factors by energy source. The very high capacity factor for nuclear power makes it the only reliable, non-carbon dioxide-emitting source of baseload power available.

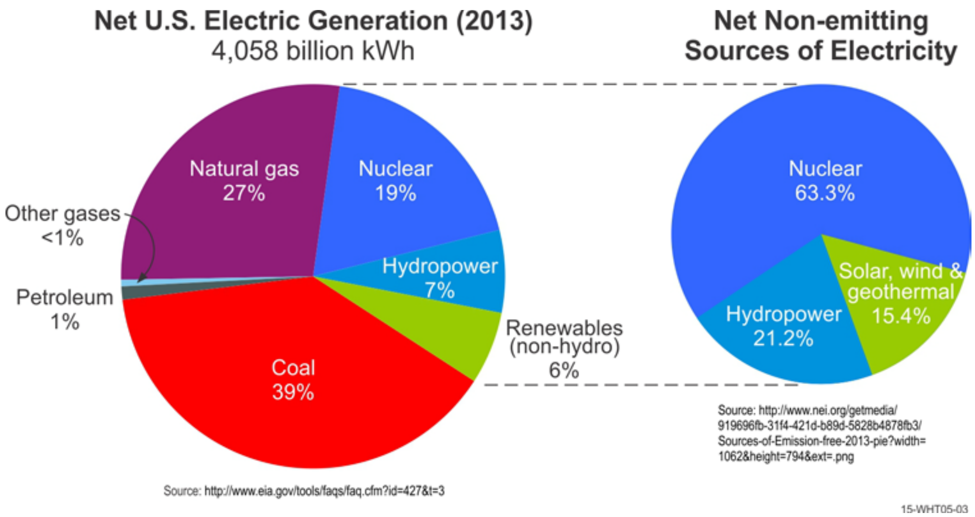

Figure 1. Current U.S. electric generating portfolio showing dominance of nuclear as a low carbon emission power source.

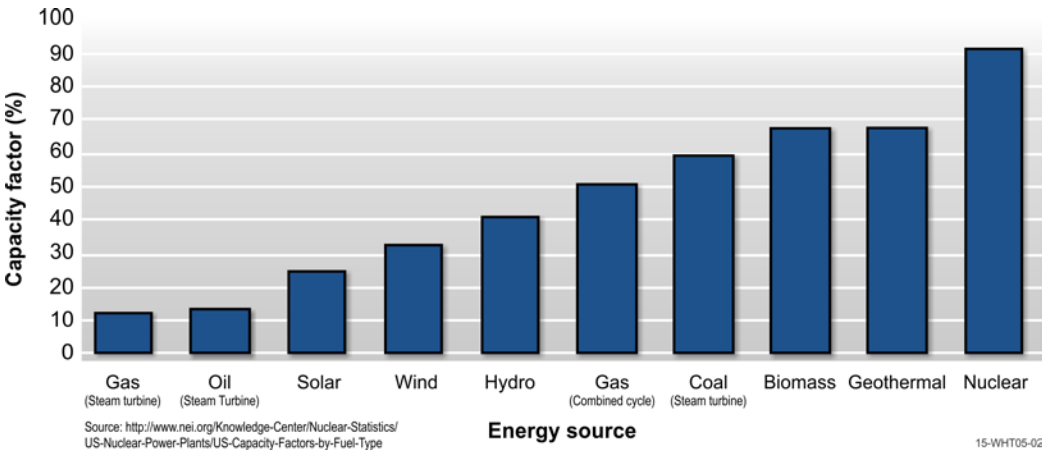

Figure 2. U.S. electrical generation capacity factors by energy source, showing high operating performance.

Construction of new nuclear power plants is a clear option for new, emission-free, electrical generating capacity. However, bringing new nuclear power plants online is facing substantial challenges and uncertainties, including high upfront capital cost, high financing cost, long construction time, and competition from low natural gas prices. A modest pace of new nuclear power plant construction is anticipated. Currently, five nuclear power plants are under construction in the United States: Vogtle Units 3 and 4, Summer Units 2 and 3, and Watts Bar Unit 2.

In January 2013, 104 nuclear power plants operated in 31 states. However, since that time, five plants have been shut down (several due to economic reasons), with additional shutdowns under consideration. That brings the number of operating nuclear plants to 99 (Figure 3). Still, the existing, operating fleet of U.S. nuclear power plants continues to maintain outstanding levels of nuclear safety, reliability, and operational performance over the last two decades and operates with an average capacity factor over 90%. Nuclear power plant capacity factors improved from around 50% in the early 1970s to over 90% in 2010. Over the same period of time, the safety of the nuclear power plants has improved substantially, as measured by predicted core damage frequency in postulated accident scenarios, and as seen by the reductions in the rates of initiating events and system failures. The significant improvements in performance, reliability, and safety have made nuclear power plants considerably more economical to operate. Major improvements were made in all areas of plant operation, including operations, training, equipment maintenance and reliability, technological improvements, and improved understanding of component degradation. More broadly, these improvements reflect effective management practices, advances in technology, and the sharing of safety and operational experience among utilities. Today, nuclear production costs are the lowest among the major U.S. power-generating options.

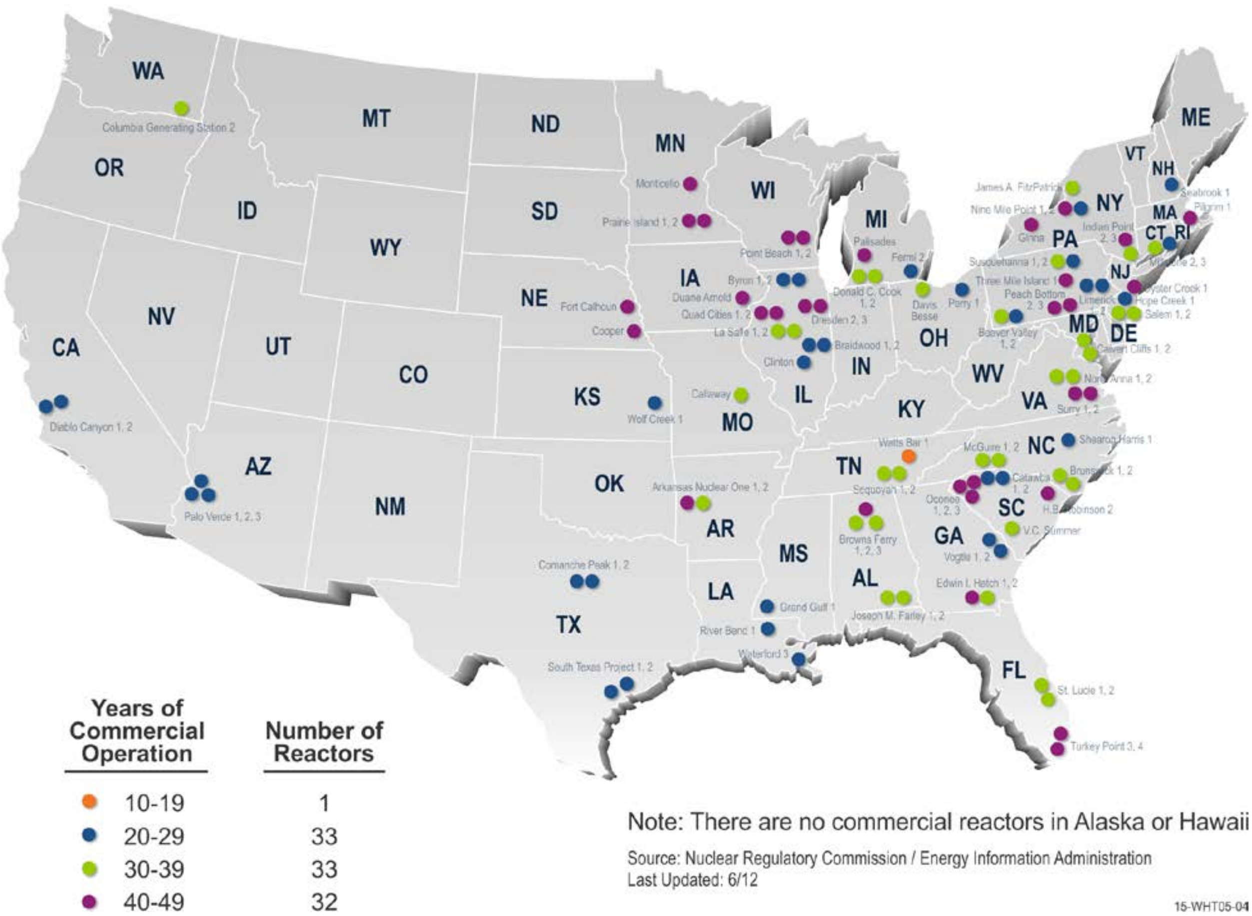

Figure 3. National distribution of the 99 operating nuclear power plants.

Figure 4 shows the following: (1) the oldest operating nuclear power plant started operation in 1969 and the newest plant started operation in 1996, (2) the first group of nuclear power plants were brought online between 1969 and 1979 and the second group between 1980 and 1996, and (3) almost all operating nuclear power plants have been issued, are applying for, or plan to apply for a 20-year license extension. This license extension will result in a licensed operating period of 60 years. Note however, that receiving a license extension doesn’t necessarily mean that the plant will continue to operate, as evidenced by the decisions of Dominion to shut down their Kewaunee plant and Entergy to shut down their Vermont Yankee plant prior to entering their license extension periods. Business decisions on extended operation ultimately rely on economic factors; however economics can often be improved through technical advancements.

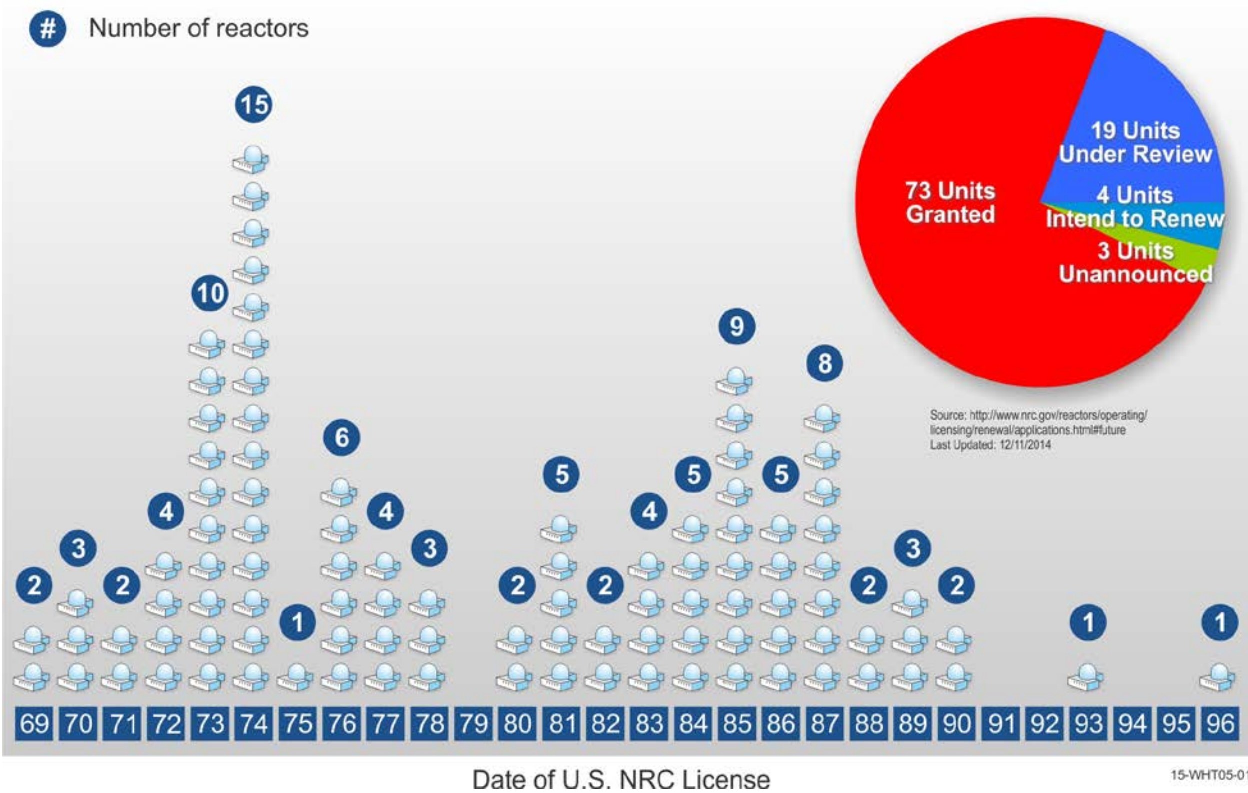

Figure 4. Nuclear power plant initial license date and license extension plans (as of December 2014).

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

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

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

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

In early 2007, DOE, with the Idaho National Laboratory (INL) engaging the Electric Power Research Institute (EPRI) and other industry stakeholders, initiated planning that led to the LWRS Program. The aim was to develop an R&D strategy that addresses nuclear energy issues within the framework of the National Energy Policy and the National Energy Policy Act of 2005. Based on considerable analysis and information gathering, the "Strategic Plan for Light Water Reactor Research and Development,"[d] was developed and reviewed by an independent committee of experts. The plan, which recommended ten top priority areas for a government-industry, cost-shared R&D program, was issued in November 2007.

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

In developing the strategic plan and the more specific program plans, it became apparent that a government/industry collaborative cost-sharing arrangement for R&D was needed to address the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry. The national strategic interests in the long-term operation of existing nuclear power plants included meeting climate change objectives, providing energy security, and minimizing cost impacts (due to plant replacements) to rate payers. The nuclear industry also had an incentive to ensure the continued safe and reliable operation of their operating nuclear power plants.

Therefore, at the nexus of these mutual interests, "cost-sharing" is being employed through cooperative R&D activities. DOE and industry are independently funding specific, related projects and sharing information to achieve goals of mutual interest. DOE-funded R&D addresses fundamental scientific questions, where private investment or capabilities are insufficient to make progress on broadly applicable technology issues for public benefit. The U.S. government (i.e., DOE and its national laboratories) holds large theoretical, computational, and experimental expertise in nuclear R&D that is not available within the industry. As such, the benefits will extend to the next generation of reactor technologies being deployed and those still under development.

Nuclear power can involve rare but high consequence events like those at Three Mile Island, Chernobyl, and Fukushima. When these events happen, the government invests substantial quantities of resources (financial and personnel) to deal with the consequences. Therefore, the government has an incentive to mitigate its risk by developing advanced materials, technologies, and analytical tools to better predict plant response and prevent/mitigate such accidents.

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

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

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

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

Decisions on subsequent license renewal and required investments to support long-term operation will be made by plant owners. The science-based technical results from the LWRS Program will provide data that translates into cost/benefit information, for owners to make informed decisions on long-term operation and subsequent license renewal, reducing the uncertainty, and therefore the risk, associated with those decisions. The LWRS Program creates an environment (by reducing uncertainty and risk) that provides incentives for industry to make the investments required for nuclear power plant operation periods to and beyond 60 years.

1.1 Program Overview

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

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

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

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

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

The LWRS Program consists of the following primary technical areas[f] of R&D:

1. ***Materials Aging and Degradation (MAaD)***: R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. This work will provide data and methods to assess the performance of SSCs essential to safe and

f. The Reactor Safety Technologies Pathway is a new R&D pathway as of October 1, 2014.

sustained nuclear power plant operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant SSCs subject to long-term operating conditions, providing key input to both regulators and industry.

2. ***Risk-Informed Safety Margin Characterization (RISMC)***: R&D to develop and demonstrate approaches to support the management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants. This pathway will (1) develop and demonstrate a risk-assessment method tied to safety margins quantification and (2) create advanced tools for safety assessment that enable more accurate representation of nuclear power plant safety margins and their associated impacts on operations and economics. The R&D products will be used to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety/operational margins and permits cost effective management of these margins during periods of extended operation.

3. ***Advanced Instrumentation, Information, and Control (II&C) Systems Technologies***: R&D to address long-term aging and modernization of current instrumentation and control technologies through development/testing of new I&C technologies and advanced condition monitoring technologies for more automated and reliable nuclear power plant operation. The R&D products will be used to design and deploy new II&C technologies and systems in existing nuclear power plants that provide an enhanced understanding of plant operating conditions and available margins and improved response strategies and capabilities for operational events.

4. ***Reactor Safety Technologies (RST)***: R&D to improve understanding of beyond design basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents, in particular the Fukushima Daiichi events. This information will be used to aid in developing mitigating strategies and improving severe accident management guidelines for the current light water reactor fleet.

The technical plans for each of the pathways are discussed in Sections 2 through 5. Measurable milestones have been developed for each of the pathways, including both near-term (i.e., 1 to 5 years) and longer-term (i.e., beyond 5 years) milestones. This Integrated Program Plan is updated yearly; a listing of major accomplishments from previous fiscal years can be found in Appendix A, and Appendix B includes a chronological listing (by pathway) of planned LWRS Program milestones.

1.2 Program Management

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

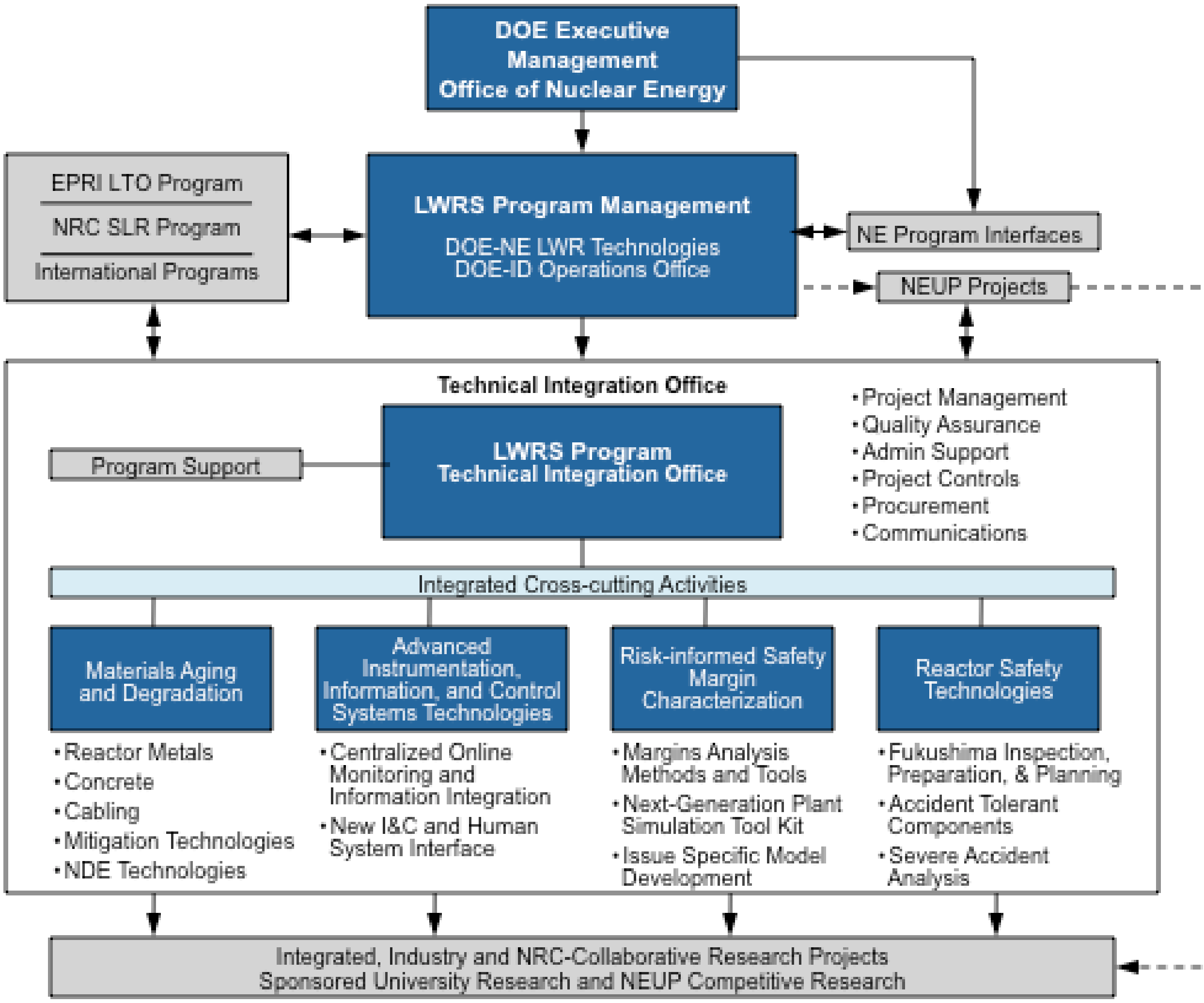

Figure 5. Light Water Reactor Sustainability Program organization.

External program review is realized both at the overall program level, as well as at the Pathway level. This has been done in a variety of ways over the lifetime of the program, including via an external review committee that provides feedback to the Technical Integration Office Director, as well as periodic reviews by the Nuclear Energy Advisory Committee (NEAC) Reactor Technologies Subcommittee that provides advice to DOE-NE. Each Pathway has informal advisory groups that provide feedback to the Pathway Lead. In 2015, the LWRS Program Technical Integration Office will implement a tiered approach to external review, beginning with a set of three to ten experts (the exact number will depend on the size of the particular pathway under review) for each pathway that will review pathway plans and progress. One to three experts from each of the pathway review teams will then participate in a review at the Technical Integration Office (Program) level. This process will be repeated approximately every 18 months, and the feedback will be used to make change to the program as agreed upon by the Federal Program Manager.

1.3 Program Research and Development Interfaces

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

The development of the scientific basis to support service operation extensions beyond 60 years and facilitate high-performance, economic operations of the existing LWR operating fleet over the extended operating period is the central focus of the LWRS Program. Therefore, coordination with industry and NRC is needed to ensure a uniform approach, shared objectives, and efficient integration of collaborative work for the LWRS Program. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that are executed among these groups.

1.3.1 Industry

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

EPRI has established the Long-Term Operations Program, which is complementary to the DOE LWRS Program. EPRI and industry's interests include applications of the scientific understanding and the tools to achieve the safe and economical long-term operation of the current LWR fleet. Therefore, the government and private sector interests are similar and interdependent, leading to strong mutual support for technical collaboration and cost sharing. The interface between DOE-NE and EPRI for R&D work supporting long-term operations of the existing fleet is defined in a memorandum of understanding[g]. A joint R&D plan defining the collaborative and cooperative R&D activities between the LWRS Program and the Long-Term Operations Program was issued in 2011 and is updated annually.[h] Also, contracts with EPRI or other industrial organizations are used as appropriate for some work.

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g. "Memorandum of Understanding Between United States Department of Energy (DOE) and The Electric Power Research Institute (EPRI) on Light Water Reactor Research Programs," dated November 1, 2010, and signed by John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, Office of Nuclear Energy, DOE and Neil Wilmshurst, Vice President Nuclear, EPRI.

h. INL/EXT-12-24562 Rev. 4, *DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operation Program – Joint Research and Development Plan*, Idaho National Laboratory, April 2015.

1.3.2 Nuclear Regulatory Commission

NRC has a memorandum of understanding[i] in place with DOE, which specifically allows for collaboration on research supporting long-term operation of nuclear power plants. Although the goals of the NRC and DOE research programs may differ, fundamental data and technical information obtained through joint research activities are recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and to avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost sharing may be done in a mutually beneficial fashion.

1.3.3 International

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

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

  INL is an associate member of the Halden Reactor Project on behalf of DOE. Membership in the Halden Reactor Project will be maintained over the course of this research program to leverage the wide spectrum of advanced capabilities developed for nuclear operations and support. Halden has been on the cutting edge of new nuclear power plant technologies for several decades and their research is directly applicable to the capabilities being pursued under the MAaD and Advanced II&C Systems Technologies Pathways.

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

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

- ***Nuclear GENeration II & III Association* (*NUGENIA):*** NUGENIA is an international collaborative R&D network of major stakeholders in nuclear power generation from industry, the utilities, research institutions and technical safety organizations. It was launched in Brussels (Belgium) in 2012, hosted by the EC's Joint Research Centre. NUGENIA aims to provide a single framework for collaborative R&D on nuclear fission technologies, with a focus on the current fleet of nuclear reactors (known as Generation II and III). It brings together existing nuclear power generation R&D under a single umbrella, including several European Networks of Excellence, such as NULIFE (see item below), SARNET (Severe Accident Research NETwork) and ENIQ (the European Network on Inspection and Qualification).

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i. "Memorandum of Understanding Between U.S. Nuclear Regulatory Commission and U.S. Department of Energy on Cooperative Nuclear Safety Research," dated May 01, 2014, and signed by Brian W. Sheron, Director, Office of Nuclear Regulatory Research, NRC, and John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, DOE-NE.

- ***European Nuclear Plant Life Prediction* (*NULIFE)*:** The European network of excellence Nuclear Plant Life Prediction has been launched under the Euratom Framework Programme with a clear focus on integrating safety-oriented research on materials, structures, and systems and using the results of this integration through the production of consistent lifetime assessment methods.
- ***Nuclear Energy Agency* (*NEA) Committee on the Safety of Nuclear Installations* (*CSNI)***: The mission of the Nuclear Energy Agency Committee on the Safety of Nuclear Installations is to assist member countries in maintaining and further developing the scientific and technical knowledge base required to assess the safety of nuclear reactors and fuel-cycle facilities.
- ***Bilateral Activities***: There are several U.S. bilateral activities either underway (e.g., U.S.-Argentina, U.S.-Japan) or under discussion (e.g., U.S.-Canada) that include activities specific to the LWRS Program. These bilateral activities provide an opportunity to leverage work ongoing in other countries.

1.3.4 Universities

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

1.3.5 Advanced Modeling and Simulation Tools

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

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

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

2. Development of more detailed computer modeling tools capable of encoding more complex behaviors (such as predictive component aging models).

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

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

1.3.5.1 Nuclear Energy Advanced Modeling and Simulation

A critical interaction of the LWRS Program is with the DOE’s Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program. The LWRS Program is leveraging the detailed, multiscale, science-based models developed by the NEAMS Program. These advanced computational tools under development in NEAMS are being used to create a new set of modeling and simulation capabilities that will be used to better understand the safety performance of the aging reactor fleet. These capabilities are information sources and tools for advancing the LWRS Program's goals.

1.3.5.2 Department of Energy's Energy Innovation Modeling and Simulation Hub

The LWRS Program is coordinating with the DOE Energy Innovation Modeling and Simulation Hub managed by the Consortium for Advanced Simulation of Light Water Reactors (CASL). The hub is addressing long-term operational challenges faced by U.S. nuclear utilities and is leveraging existing models (including models developed by national laboratories and industry), as well as developing new models.

A primary initial product of the hub is a sophisticated integrated model of a LWR (i.e., a virtual reactor with focus on modeling the reactor core). The virtual reactor will be used to address issues for existing LWRs (e.g., long-term operation and power uprates). The hub has a series of "challenge problems" selected principally to demonstrate the capability of the virtual reactor to enable long-term operation and power uprates. Some of these challenge problems may utilize models under development in the LWRS Program (e.g., systems analysis and component aging models) because the legacy tools have computational limitations that make them unsuited for some of the challenge problems. The LWRS Program will link with CASL models when detailed core modeling is needed for LWRS Program activities.

1.4 Summary

The DOE-NE Office of LWR Technologies directs the LWRS Program and closely coordinates with other agencies, the nuclear industry, and international partners to achieve LWRS Program goals. The LWRS Program Technical Integration Office supports DOE-NE in accomplishing these goals. Technical integration and program execution is accomplished by using facilities and staff from multiple national laboratories, universities, industry, consulting organizations, and research groups from cooperating foreign countries.

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

2. MATERIALS AGING AND DEGRADATION

2.1 Background

Nuclear reactors present a very challenging service environment. Components within the containment of an operating reactor must tolerate high-temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to reduced performance and, if unmitigated, can lead to failure. Materials degradation in a nuclear power plant is very complex due to the variety of materials, environmental conditions, and stress states. Over 25 different metal alloys can be found within the primary and secondary systems; additional materials exist in concrete, the containment vessel, instrumentation and control equipment, cabling, buried piping, and other support facilities. Dominant forms of degradation may vary greatly between the different SSCs and can have an important role in the safe and efficient operation of a nuclear power plant.

Extending reactor service lifetimes to and beyond 60 years increases the operational demands on materials and components. Therefore, an early evaluation of the possible effects of extended lifetime is critical. NUREG/CR-7153[j] gives a detailed assessment of many of the key issues in today's reactor fleet and provides a starting point for evaluating those degradation forms particularly important for consideration in extended lifetimes. While extending operation will add additional time and neutron fluence, the primary impact will be increased susceptibility to degradation mechanisms. In the area of crack-growth mechanisms for nickel-based alloys alone, there are up to 40 variables known to have a measurable effect. Further, many variables have complex interactions (see Figure 6). In this same instance (i.e., crack-growth mechanisms for nickel-based alloys), a purely experimental approach would require greater than a trillion experiments to address all variables and interactions. Therefore, the application of modern materials science to mechanistic studies and careful inclusion of field service conditions is required to resolve these issues in a timely manner.

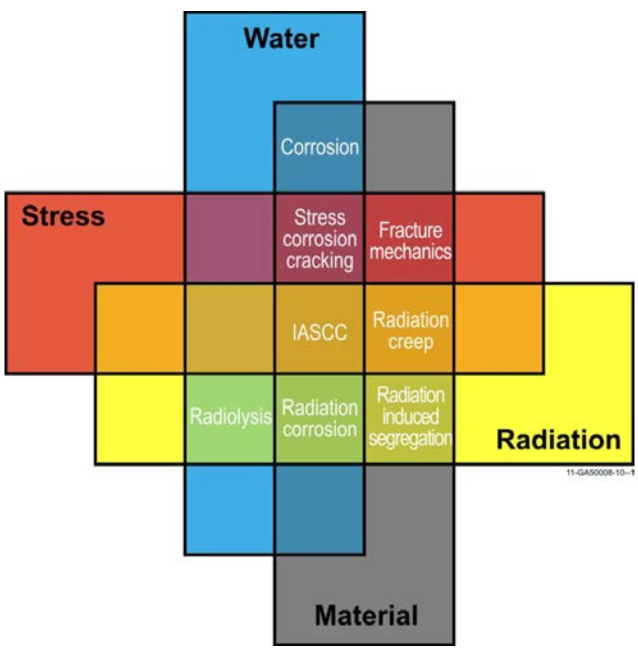

Figure 6. Complexity of interactions between materials, environments, and stresses in an operating nuclear power plant (source: A. Jennsen).

j. Expanded Materials Degradation Assessment (EMDA), NUREG/CR-7153 (Volumes 1-5), October 2014.

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

- ***Measurements of degradation:*** High-resolution measurements of degradation in all components and materials are essential to assess the extent of degradation under extended service conditions, support development of mechanistic understanding, and validate models. High quality data are of value to regulatory and industry interests in addition to academia.
- ***Mechanisms of degradation*:** Basic research to understand the underlying mechanisms of selected degradation modes can lead to better prediction and mitigation. For example, research on irradiation assisted stress corrosion cracking (IASCC) and primary water stress corrosion cracking (PWSCC) would be very beneficial for extended lifetimes and could build on existing programs within EPRI and NRC. Other forms of degradation such as swelling and embrittlement are better understood and mechanistic studies are not needed.
- ***Modeling and simulation*:** Improved modeling and simulation efforts have great potential in reducing the experimental burden for long-term operation studies. These methods can help interpolate and extrapolate data trends for extended life. Simulations predicting phase transformations, radiation embrittlement, and swelling over component lifetimes would be extremely beneficial to licensing and regulation in extended service.
- ***Monitoring*:** While understanding and predicting failures are extremely valuable tools for the management of reactor components, these tools must be supplements to active monitoring. Improved monitoring techniques will help characterize degradation of core components. For example, improved crack detection techniques will be invaluable. New nondestructive examination (NDE) techniques may also permit new means of monitoring reactor pressure vessel (RPV) embrittlement or swelling of core internals.
- ***Mitigation strategies*:** While some forms of degradation have been well researched, there are few options in mitigating their effects. Techniques such as post-irradiation annealing have been demonstrated to be very effective in reducing hardening of entire pressure vessels. Annealing may be effective in mitigating IASCC, based on initial studies. Water chemistry techniques such as NobelChem™[k] have been very effective in reducing some corrosion problems. Additional research in these areas may provide other alternatives to component replacement.

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

2.2 Research and Development Purpose and Goals

Materials research provides an important foundation for licensing and managing the long-term, safe, and economical operation of nuclear power plants. Aging mechanisms and their influence on nuclear power plant SSCs are predictable with sufficient confidence to support planning, investment, and licensing for necessary component repair, replacement, and license extension. Understanding, controlling, and mitigating materials degradation processes are key priorities. Proactive management is essential to

k. International Conference of Water Chemistry of Nuclear Reactor Systems 8: Proceedings of Volumes 1-2, Page 116, “NobleChem™ Technology for Life Extension of BWRs – Field Experiences, GE Nuclear Energy, S. Hettiarachchi, R. L. Cowan, R. J. Law, T. P Diaz, Published 2000 help ensure that any degradation from long-term operation of nuclear power plants does not affect the public's confidence in the safety and reliability of those nuclear power plants. The strategic goals of the pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations.

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

1. MAaD Pathway tasks provide fundamental understanding and mechanistic knowledge via science-based research. Mechanistic studies provide better foundations for prediction tool development and focused mitigation solutions. These studies also are complementary to industry efforts to gain relevant, operational data. The U.S. national laboratory and university systems are uniquely suited to provide this information given their extensive facilities, research experience, and specific expertise.

2. Selected MAaD Pathway tasks are focused on development of high-risk, high-reward technologies to understand, mitigate, or overcome materials degradation. This type of alternative technology research is uniquely suited for government roles and facilities. These pursuits also are outside the area of normal interest for industry sponsors due to the risk of failure.

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

Combined, these thrusts provide high quality measurements of degradation modes, improved mechanistic understanding of key degradation modes, and predictive modeling capability with sufficient experimental data to validate these tools; new methods of monitoring degradation, and development of advanced mitigation techniques to provide improved performance, reliability, and economics.

This information must be provided in a timely manner to support long-term operation generally, and subsequent license renewal decisions (with the first wave of decisions expected in the 2015 to 2020 time frame). Near-term research is focused primarily on providing mechanistic understanding, predictive capabilities, and high-quality data to inform decisions and processes by both industry and regulators. Longer-term research will focus on alternative technologies to overcome or mitigate degradation. Task outputs and products are designed to inform license extension decisions and regulatory processes. Specific products and impacts will be discussed in the following sections.

2.3 Pathway Research and Development Areas

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

Identifying, formulating, and prioritizing all of these competing needs has been done in a collaborative manner with industrial and regulatory partners. The primary objective of a workshop and follow-on activities focusing on materials aging and degradation held at the EPRI offices in Charlotte, North Carolina on August 5 and 6, 2008 was to identify an initial list of the most pressing research tasks. Twenty technical experts, providing broad institutional representation, attended the MAaD Pathway workshop. Points of discussion included organization and structure of the MAaD Pathway, need and benefits of an advisory group, and identification and prioritization of research tasks to support the LWRS

Program. Tasks were identified and prioritized, and formed the basis for the priorities in the MAaD Pathway. Research since that workshop has identified additional needs and these research topics have also been considered. Continued dialogue with EPRI, NRC, vendors, utilities and other institutions around the world has helped prioritize these emerging needs into the MAaD Pathway research portfolio.

2.3.1 Assessment and Integration

The objectives of this research task are to provide comprehensive assessment of materials degradation, relate to consequences of SSCs and economically important components, incorporate results, guide future testing, and integrate with other pathways and programs. This task provides an organized and updated assessment of key materials aging degradation issues and support NRC and EPRI efforts to update the Proactive Materials Degradation Assessment (PMDA) or the Materials Degradation Matrix (MDM) documents. Successful completion provides a valuable means of task identification and prioritization within this pathway, as well as identify new needs for research. The Expanded Materials Degradation Assessment (EMDA), an assessment of degradation mechanisms for 60 to 80 years or beyond, completed in 2014, is also used for identifying and prioritizing research.

2.3.2 Reactor Metals

Numerous types of metal alloys can be found throughout the primary and secondary systems of nuclear power plants. Some of these materials (in particular, the reactor internals) are exposed to high temperatures, water, and neutron flux, creating degradation mechanisms in the materials that are unique to reactor service. Research projects in this area will provide a technical foundation to establish the ability of those metals to support extended operations.

2.3.2.1 High Fluence Effects on Reactor Pressure Vessel Steels

The last few decades have seen much progress in developing a mechanistic understanding of irradiation embrittlement for the RPV. However, there are still significant technical issues that need to be addressed to reduce the uncertainties in regulatory application.

The objective of this research task is to examine and understand the influence of irradiation at high fluences on RPV embrittlement. Both industrial capsules and single variable experiments may be required to evaluate potential for embrittlement and to provide a better mechanistic understanding of this form of degradation. Acquisition of samples from past programmatic campaigns (such as NRC programs), specimens harvested from decommissioned reactors (e.g., Zion 1 and 2), surveillance specimens from operating nuclear power plants, and materials irradiated in new test campaigns all have value in understanding high fluence effects. Testing will include impact and fracture toughness evaluations, hardness, and microstructural analysis (atom probe tomography, small angle neutron scattering, and/or positron-annihilation spectroscopy). These research tasks all support development of a predictive model for transition-temperature shifts for RPV steels under a variety of conditions. This tool can be used to predict RPV embrittlement over a variety of conditions key to irradiation-induced changes (e.g., time, temperature, composition, flux, and fluence) and extends the current tools for RPV management and regulation to extended-service conditions. This model will be delivered in 2016 in a detailed report, along with all supporting research data. In addition, the library of assembled materials will be available for examination and testing by other stakeholders.

The major milestone associated with this task is:

- (2016) Provide validated model for transition temperature shifts in RPV steels.

Future milestones and specific subtasks will be based on the results of the previous years testing as well as ongoing, industry-led research. The experimental data and model are of value to both industry and regulators. Completion of data acquisition to permit prediction of embrittlement in RPV steels at high fluence is a major step in informing long-term operation decisions, and high quality data can be used to inform operational decisions for the RPV by industry. For example, data and trends will be essential in determining operating limits. The data will also allow for extension of regulatory limits and guidelines to extended service conditions. The delivery of a validated model for prediction of transition temperature shifts in RPV steels will allow for estimation of RPV performance over a wide range of conditions. This will enable extension of current tools for RPV embrittlement (e.g. Fracture Analysis of Vessels: Oak Ridge [FAVOR[l]]) to extended service conditions.

2.3.2.2 Material Variability and Attenuation Effects of Reactor Pressure Vessel Steels

The subject of material variability has experienced increasing attention in recent years as additional research programs began to focus on the development of statistically viable databases. The objective of this task is to develop new methods to generate meaningful data out of previously tested specimens. Embrittlement margins for a vessel can be accurately calculated using supplementary alloys and experiments using higher flux test reactors. The potential for non-conservative estimates resulting from these methodologies must be evaluated to fully understand the potential influence on safety margins. Critical assessments and benchmark experiments will be conducted. Harvesting of through-thickness RPV specimens may be used to evaluate attenuation effects in a detailed and meaningful manner. Testing will include impact and fracture toughness evaluations, hardness, and microstructural analysis (atom probe tomography, small angle neutron scattering, and/or positron-annihilation spectroscopy). The results of these examinations can be used to assess the operational implications of high-fluence effects on the RPV. Furthermore, the predictive capability developed in earlier tasks will be modified to address these effects.

The major milestones associated with this task are:

- (2016) Complete a detailed review of the NRC Pressurized Thermal Shock (PTS) re-evaluation project relative to the subject of material variability and identify specific remaining issues
- (2019) Complete analysis of hardening and embrittlement through the RPV thickness for the Zion RPV sections.

Future milestones and specific subtasks will be based on the results of the previous years testing as well as ongoing, industry-led research. The analysis of hardening and variability through the thickness of an actual RPV section from service has considerable value to all stakeholders. This data will provide a first-look at embrittlement trends through the thickness of the RPV wall and inform operating limits, fracture mechanics models, and safety margins.

2.3.2.3 Mechanisms of Irradiation-Assisted Stress Corrosion Cracking

The objective of this work is to evaluate the response and mechanisms of IASCC in austenitic stainless steels with single-variable experiments. Crack growth rate tests and complementary microstructure analysis will provide a more complete understanding of IASCC by building on past EPRI-led work for the Cooperative IASCC Research Group[m]. Experimental research will include crack-growth testing on high-fluence specimens of single-variable alloys in simulated LWR environments, tensile testing, hardness testing, microstructural and microchemical analysis, and detailed efforts to characterize localized deformation. Combined, these single-variable experiments will provide mechanistic understanding that can be used to identify key operational variables to mitigate or control IASCC, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-term, design IASCC-resistant materials.

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l. NUREG/CR-6854, ORNL/TM-2004/244, Fracture Analysis of Vessels – Oak Ridge FAVOR, v04.1, Computer Code: Theory and Implementation of Algorithms, Methods, and Correlations, P.T. Williams, T.L. Dickson, and S. Yin, Oak Ridge National Laboratory, October 2004

m. EPRI, "Final Review of the Cooperative Irradiation-Assisted Stress Corrosion Cracking Research Program, Product ID. 1020986, June 3, 2010

The major milestone associated with this task is:

- (2019) Deliver predictive model capability for IASCC susceptibility

Detailed testing and specific subtasks will be based on the results of the previous years testing, as well as ongoing, industry-led research. Understanding the mechanism of IASCC will enable more focused material inspections, material replacements, and more detailed regulatory guidelines. In the long-term, mechanistic understanding also enables development of a predictive model, which has been sought for IASCC for decades.

2.3.2.4 High Fluence Irradiation-Assisted Stress Corrosion Cracking

The objective of this task is to assess high fluence effects on IASCC for core internals. Crack growth-rate testing is especially limited for high fluence specimens. Intergranular fracture observed in recent experiments suggests more work is needed. Also of interest is identification of high fluence materials available for research and testing in all tasks.

Research includes a detailed plan to obtain high fluence specimens for IASCC testing from irradiation of as-received material to high fluence in a test reactor, obtaining high fluence materials for sample manufacturing, or a combination of those two factors. In addition, both tests (i.e., crack growth and tensile tests) will be performed in simulated water environments in addition to complementary post-irradiation examination of irradiation effects. Results from this task can be used to investigate the potential for IASCC under extended service conditions, extend the mechanistic studies from other tasks in the LWRS Program, and be used to validate predictive models at high fluence.

The major milestone associated with this task is:

- (2015) Complete revised joint plan with EPRI for very high fluence testing of core internals

Future milestones and specific subtasks will be based on the plan developed in 2013 and partnerships developed in early 2014. Completing a detailed experimental plan for high fluence IASCC testing is an essential first step in estimating the impact of IASCC at high fluence. This plan is also critical for building support and partnerships with industry and regulators.

2.3.2.5 High Fluence Phase Transformations of Core Internal Materials

This task will provide detailed microstructural analysis of phase transformation in key samples and components (both model alloys and service materials), including transmission electron microscopy, magnetic measurements, and hardness examinations. Mechanical testing to quantify any impacts on embrittlement also may be performed. These results will be used to develop and validate a phenomenological model of phase transformation under LWR operating conditions. This will be accomplished by use of computational thermodynamics and extension of models for radiation-induced segregation. The generated data and mechanistic studies will be used to identify key operational limits (if any) to minimize phase transformation concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations and, if necessary, qualify radiation-tolerant materials for LWR service.

The major milestones associated with this task are:

- (2017) Deliver experimentally validated, physically-based thermodynamic and kinetic model of precipitate phase stability and formation in Alloy 316 under anticipated extended lifetime operation of LWRs

Future milestones and specific tasks will be based on the results of the previous years testing as well as ongoing, industry-led research. The development and delivery for a validated model for phase transformations in core internal components at high fluence is an important step in estimating the useful life of core internal components. Understanding which components are susceptible to this form of degradation is of value to industry and regulators, as it will permit more focused component inspections, component replacements, and more detailed regulatory guidelines.

2.3.2.6 High Fluence Swelling of Core Internal Materials

This task will provide detailed microstructural analysis of swelling in key samples and components (both model alloys and service materials), including transmission electron microscopy and volumetric measurements. These results will be used to develop and validate a phenomenological model of swelling under LWR conditions. This will be accomplished by extension of past models developed for fast reactor conditions. The data generated and mechanistic studies will be used to identify key operational limits (if any) to minimize swelling concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, if necessary, qualify swelling-resistant materials for LWR service.

The major milestones associated with this task are:

- (2016) Complete postirradiation testing and examinations of swelling in LWR components and materials
- (2016) Deliver predictive capability for swelling in LWR components

Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research. The development and delivery for a validated model for swelling in core internal components at high fluence is an important step in estimating the useful life of core internal components. Understanding which components are susceptible to this form of degradation is of value to industry and regulators, as it will permit more focused component inspections, component replacements, and more detailed regulatory guidelines.

2.3.2.7 Cracking-Initiation in Nickel-Base Alloys

The objective of this task is the identification of underlying mechanisms of stress corrosion cracking (SCC) in Ni-base alloys. Understanding and modeling the mechanisms of crack initiation is a key step in predicting and mitigating SCC in the primary and secondary water systems. An examination into the influence of surface conditions on precursor states and crack initiation also is a key need for Ni-base alloys and austenitic stainless steels. This effort focuses on SCC crack-initiation testing of Ni-base alloys and stainless steels in simulated LWR water chemistries, but includes direct linkages to SCC crack-growth behavior. Carefully controlled microstructure and surface states will be used to generate single-variable experiments. The experimental effort in this task will be highly complementary to efforts being initiated at the Materials Aging Institute, which are focused primarily on modeling of crack initiation. This mechanistic information could provide key operational variables to mitigate or control SCC in these materials, optimize inspection and maintenance schedules to the most susceptible materials/locations, and potentially define SCC-resistant materials.

The major milestones associated with this task are:

- (2015) Complete Phase 1 mechanistic testing for SCC research
- (2019) Deliver predictive model capability for Ni-base alloy SCC susceptibility.

Completing research to identify the mechanisms and precursor states is an essential step to predicting the extent of this form of degradation under extended service conditions. Understanding underlying causes for crack-initiation may allow for more focused material inspections and maintenance, new SCC-resistant alloys, and development of new mitigation strategies, all of which are of high interest to the nuclear industry. This mechanistic understanding may also drive more informed regulatory guidelines and aging-management programs. In the long-term, mechanistic understanding also enables development of a predictive model, which has been sought by industry and regulators for many years.

2.3.2.8 Environmentally Assisted Fatigue

The objective of this task is to develop a model of environmentally assisted fatigue mechanisms. This will be supported by experimental studies to provide data for identification of mechanisms and key variables and provide data for model validation. The experimental data will inform regulatory and operational decisions, while the model will provide a capability to extrapolate the severity of this mode of degradation to extended-life conditions.

The major milestones associated with this task are:

- (2015) Complete base model development for environmentally assisted fatigue in LWR components
- (2017) Complete experimental validation and deliver model for environmentally assisted fatigue in LWR components.

Completing research to identify the mechanisms of environmentally assisted fatigue to support model development is an essential step to predicting the extent of this form of degradation under extended service conditions. This knowledge has been identified as a key need by regulators and industry. Delivering a model for environmentally assisted fatigue will enable more focused material inspections, material replacements, and more detailed regulatory guidelines.

2.3.2.9 Thermal Aging of Cast Austenitic Stainless Steels

In this research task, the effects of elevated temperature service in cast austenitic stainless steel (CASS) will be examined. Possible effects include phase transformations that can adversely impact mechanical properties. This task will provide conclusive predictions for the integrity of the CASS components of LWR nuclear power plants during extended service life. Mechanical and microstructural data obtained through accelerated aging experiments and computational simulation will be the key input for the prediction of CASS behaviors and for the integrity analyses for various CASS components. While accelerated aging experiments and computational simulations will comprise most of the knowledge base for CASS aging, the data will also be obtained from operational experience. This data is required to validate the accelerated aging methodology. In addition to using existing data, therefore, a systematic campaign to obtain mechanical data from used materials or components will be pursued. Further, the detailed studies on aging and embrittlement mechanisms as well as on deformation and fracture mechanisms are performed to understand and predict the aging behavior over extended lifetime.

The major milestones associated with this task are:

- (2017) Complete analysis of cast austenitic stainless steel specimens harvested from service conditions
- (2018) Complete analysis and simulations of aging of cast austenitic stainless steel components and deliver predictive capability for cast austenitic stainless steel components under extended service conditions.

Completing research to identify potential thermal aging issues for CASS components is an essential step to identifying possibly synergistic effects of thermal aging (corrosion, mechanical, etc.) and predicting the extent of this form of degradation under extended service conditions. Understanding the mechanisms of thermal aging will enable more focused material inspections, material replacements, and more detailed regulatory guidelines. This data will also help close gaps identified in the EPRI MDM and EMDA reports.

2.3.3 Concrete

Figure 7 serves as a reminder that large areas of most nuclear power plants have been constructed using concrete. There are some data on performance through the first 40 years of service 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 that there will be isolated examples where as a result primarily of environmental effects, the structures may not exhibit the desired durability (e.g., water-intake structures and freezing/thawing damage of containments) without some form of intervention.

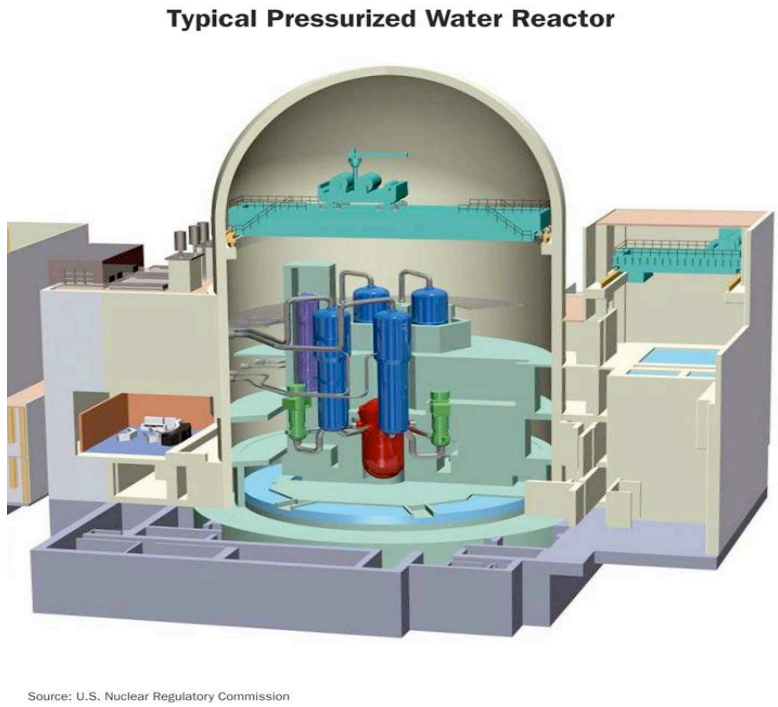

Figure 7. Cut-away of a typical pressurized water reactor, illustrating large volumes of concrete and the key role of concrete performance (source: NRC).

2.3.3.1 Concrete and Civil Structure Degradation

Although a number of organizations have sponsored work addressing the aging of nuclear power plant structures (e.g., NRC, NEA, and International Atomic Energy Agency), there are still several areas where additional research is needed to demonstrate that the structures will continue to meet functional and performance requirements (e.g., maintain structural margins). Activities under the MAaD Pathway are focused on compilation of material property data for long-term performance and trending, evaluation of environmental effects, and assessment and validation of NDE methods; evaluation of long-term effects of elevated temperature and radiation; non-intrusive methods for inspection of thick, heavily-reinforced concrete structures and basemats; and data on application and performance (e.g., durability) of repair materials and techniques. Complementary activities are being conducted under an NRC program at Oak Ridge National Laboratory (ORNL), by EPRI, and by the Nuclear Energy Standards Coordination Collaborative headed by the National Institute for Standards and Technology.

Plans for research at EPRI and NRC will continue to be evaluated to confirm the complementary and cooperative nature of concrete research under the MAaD Pathway. In addition, the formation of an Extended Service Materials Working Group for concrete issues will provide a valuable resource for additional and diverse input.

The major milestones associated with this task are:

- (2015) Deliver unified parameter to assess irradiation-induced damage in concrete structures
- (2018) Complete model tool to assess the impact of irradiation on structural performance for concrete components
- (2020) Complete model tool to assess the combined effects of irradiation and alkali-silica reactions on structural performance for concrete components

Future milestones and specific tasks will be based on the results of the previous years testing as well as ongoing, industry-led research. The database of concrete performance completed in 2013 is a high-value tool accessible to all stakeholders, and is being used to focus research on remaining knowledge gaps and will enable more focused material inspections. In the long-term, completion of a concrete and civil structures toolkit may allow for more robust prediction of concrete performance over extended service conditions. These tools are of high value to industry, a partner in their development.

2.3.3.2 Nondestructive Evaluation of Concrete and Civil Structures

Techniques for NDE of concrete provide new technologies to monitor material and component performance. This task will build on an R&D plan developed in 2012[n]. Key issues for consideration can include new or adapted techniques for concrete surveillance. Specific areas of interest may include reinforcing steel condition, chemical composition, strength, or stress-state.

The major milestones associated with this task are:

- (2016) Complete prototype proof-of-concept system for NDE of concrete sections
- (2018) Complete prototype of concrete NDE system.

The development of NDE techniques to permit monitoring of the concrete and civil structures could be revolutionary and allow for an assessment of performance that is not currently available via core drilling in operating plants. This would reduce uncertainty in safety margins and is valuable to both industry and regulators.

2.3.4 Cabling

Cable aging mechanisms and degradation is an important area of study. The plant operators carry out periodic cable inspections using NDE techniques to measure degradation and determine when replacement is needed. Degradation of these cables is primarily caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater. Wholesale replacement of cables is likely economically undesirable for plant operation beyond 60 years.

2.3.4.1 Mechanisms of Cable Insulation Aging and Degradation

This task provides an understanding of the role of material type, history, and the environment on cable insulation degradation; understanding of accelerated testing limitations; and support to partners in modeling activities, surveillance, and testing criteria. This task will provide experimental characterization of key forms of cable and cable insulation in a cooperative effort with NRC and EPRI. Tests will include evaluations of cable integrity following exposure to elevated temperature, humidity, and/or ionizing irradiation. This experimental data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated aging protocols. The experimental data and mechanistic studies can be used to help identify key operational variables related to cable aging, optimize inspection and

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n. Roadmap for Nondestructive Evaluation of Reactor Pressure Vessel Research and Development by the Light Water Reactor Sustainability Program, ORNL/TM-2012/380, September 2012.

maintenance schedules to the most susceptible materials/locations, and, in the long-range, design tolerant materials.

The major milestones associated with this task are:

- (2016) Complete analysis of key degradation modes of cable insulation
- (2017) Complete assessment of cable degradation mitigation strategies
- (2019) Deliver predictive model for cable degradation

Future milestones and specific tasks will be based on the results of the previous years testing as well as ongoing, industry-led research. Completing research to identify and understand the degradation modes of cable insulation is an essential step to predicting the performance of cable insulation under extended service conditions. These data are critical to develop and deliver a predictive model for cable insulation degradation. Both will enable more focused inspections, material replacements, and better-informed regulations. The development of in-situ mitigation strategies may also allow for an alternative to cable replacement and would be of high value to industry by avoiding costly replacements.

2.3.4.2 Nondestructive Evaluation of Cable Insulation

The objectives of this task include the development and validation of new NDE technologies for the monitoring of the condition of cable insulation. This task will build on an R&D plan developed in 2012 for sensor development to monitor reactor metal performance. In future years, this research will include an assessment of key aging indicators; development of new and transformational NDE methods for cable insulation; and utilize the NDE signals and mechanistic knowledge from other areas of the LWRS Program to provide predictions of remaining useful life. A key element underpinning these three thrusts will be harvesting of aged materials for validation.

The major milestones associated with this task are:

- (2015) Complete assessment of cable insulation degradation precursors to correlate with performance and NDE signals
- (2017) Demonstrate field testing of prototype system for NDE of cable insulation.
- (2019) Deliver predictive capability for end-of-useful life for cable insulation

The development of NDE techniques to permit in-situ monitoring of the cable insulation performance could be revolutionary and allow for an assessment of cable insulation performance at specific locations of interest and more frequent intervals, a significant difference from today’s methodology. This would reduce uncertainty in safety margins and is valuable to both industry and regulators.

2.3.5 Buried Piping

Maintaining the many miles of buried piping at a reactor is an area of concern when evaluating the feasibility of extended plant operations. While much of the buried piping is associated with either the secondary side of the plant or other non-safety-related cooling systems, some buried piping serves a direct safety function. Maintaining the integrity of the buried piping in these systems is necessary to ensure the systems can continue to perform their intended functions under extended plant service periods. Industry and regulators are already performing considerable work in this area The LWRS Program continues to evaluate this area for gaps and needs relative to extended service.

2.3.6 Mitigation Technologies

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

2.3.6.1 Advanced Weld Repair

The objective of this task is to develop advanced welding technologies that can be used to repair highly irradiated reactor internals without helium-induced cracking. This is being performed collaboratively with EPRI (highlighted in Figure 8). Research includes mechanistic understanding of helium effects in weldments. This modeling task is supported by characterization of model alloys before and after irradiation and welding. Stakeholders can use this model to further improve best practices for repair welding for both existing technology and advanced technology. In addition, this task will provide validation of residual stress models under development using advanced characterization techniques such as neutron scattering. Residual stress models also will improve best practices for weldments of reactors today and under extended service conditions. These tools could be expanded to include other industry practices such as peening. Finally, advanced welding techniques (such as friction-stir welding, laser welding, and hybrid techniques) will be developed and demonstrated on relevant materials (model and service alloys). Characterization of the weldments and qualification testing will be an essential step.

The major milestones associated with this task are:

- (2015) Demonstrate initial solid-state welding on irradiated materials
- (2018) Complete transfer of weld-repair technique to industry

Future milestones and specific tasks will be based on the results of the previous years testing as well as ongoing, industry-led research. Demonstration of advanced weldment techniques for irradiated materials is a key step in validating this mitigation strategy. Successful deployment may also allow for an alternative to core internal replacement and would be of high value to industry by avoiding costly replacements. Further, these technologies may also have utility in repair or component replacement applications in other locations within a nuclear power plant).

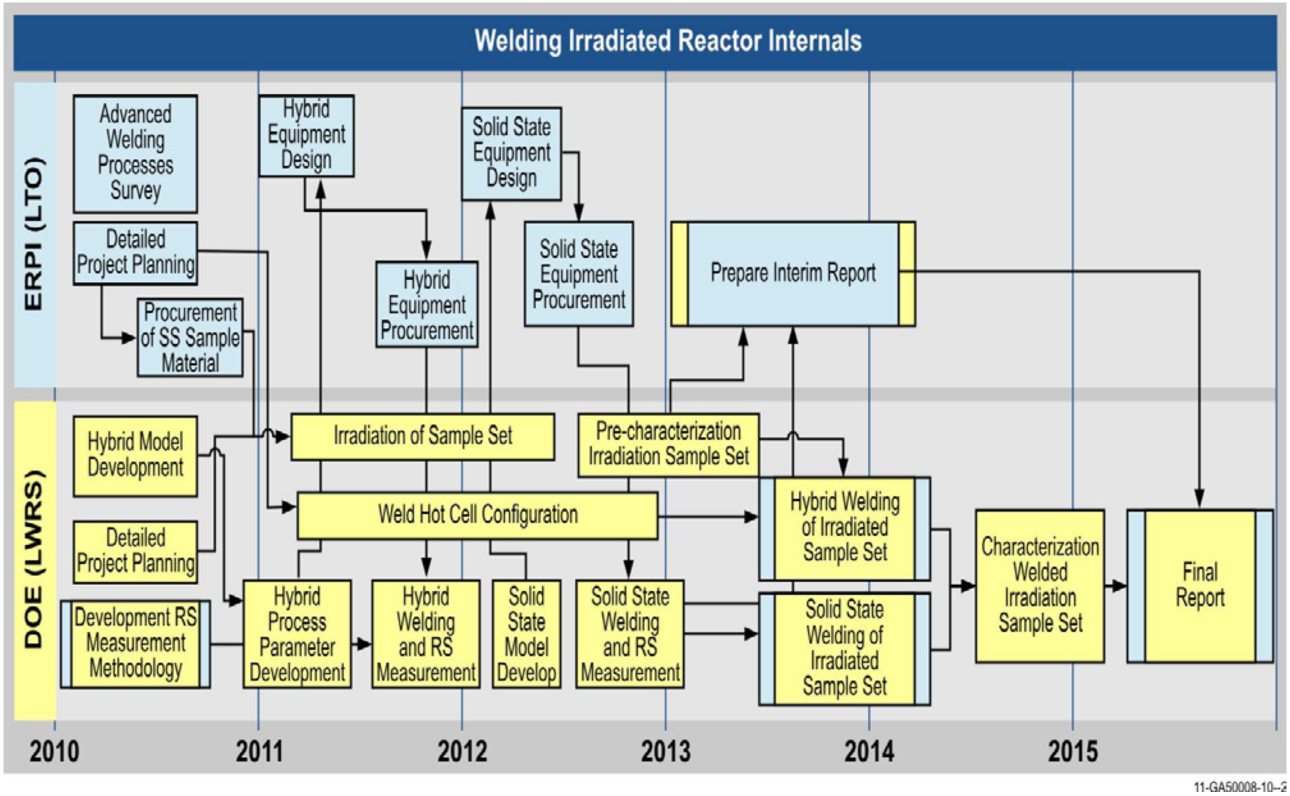

Figure 8. Process flow outline of cooperative research and development efforts on repair welding between the Department of Energy and the Electric Power Research Institute.

2.3.6.2 Advanced Replacement Alloys

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

The major milestones associated with this task are:

- (2017) Complete down-select of candidate advanced alloys following ion irradiation campaign
- (2024) Complete development and testing of new advanced alloy with superior degradation resistance with Advanced Radiation Resistant Materials partners

Future milestones and specific tasks will be assigned informed by EPRI’s Advanced Radiation Resistant Materials plan that was released in 2013 and joint assessment of partnerships and available funding. Completing the joint effort with EPRI on alloy down-select and development plan is an essential first step in this alloy development task. This plan will help identify future roles and responsibilities in this partnership with EPRI.

2.3.6.3 Thermal Annealing

This task provides critical assessment of thermal annealing as a mitigation technology for RPV and core internal embrittlement and research to support deployment of thermal annealing technology. This task will build on other RPV tasks and extend the mechanistic understanding of irradiation effects on RPV steels to provide an alternative mitigation strategy. This task will provide experimental and theoretical support to resolving technical issues required to implement this strategy. Successful completion of this effort will provide the data and theoretical understanding to support implementation of this alternative mitigation technology.

The major milestones associated with this task are:

- (2021) Complete reirradiation on RPV sections following thermal annealing
- (2025) Complete characterization of RPV sections (harvested from a reactor) that have been irradiated, annealed (post-harvesting), and then reirradiated in a test reactor

While a long-term effort, demonstration of annealing techniques and subsequent irradiation for RPV sections is a key step in validating this mitigation strategy. Successful deployment may also allow for recovery from embrittlement in the RPV, which would be of high value to industry by avoiding costly replacements.

2.3.7 Integrated Industry Activities

Access to service materials from active or decommissioned nuclear power plants provides an invaluable access to materials for which there is limited operational data or experience to inform license extension decisions and, in coordination with other materials tasks, an assessment of current degradation models to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior. LWRS Program is currently engaged in two key activities that support multiple research tasks in the previous sections: Constellation Pilot Project and Zion Harvesting Project.

The Constellation Pilot Project is a joint venture between the LWRS Program, EPRI, and the Constellation Energy Nuclear Group. The project utilizes two of Constellation’s nuclear stations, R. E. Ginna and Nine Mile Point 1, for research opportunities to support extended operation of nuclear power plants. Specific areas of joint research have included development of a concrete inspection guideline, installation of equipment for monitoring containment rebar and concrete strain, and additional analysis of RPV surveillance coupons. Opportunities for additional and continued collaboration will be explored in coming years.

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

The major milestone associated with this task is:

- (2015) Document the Status of the Service Harvested Materials Database.

Discussions regarding continued harvesting of material (including cables, concrete and RPV samples) are underway. Additional milestones will be identified once a revised decommissioning schedule is available.

2.4 Research and Development Partnerships

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

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

- **EPRI:** Considerable research efforts on a broad spectrum of nuclear reactor materials issues that are under way to provide a solid foundation of data, experiences, and knowledge. R&D cooperation on selected material's R&D activities is reflected in the LWRS Program and EPRI's Long-Term Operation Program Joint R&D Plan.[p]
- **NRC:** Broad research efforts of NRC are considered carefully during task selection and implementation. In addition, cooperative efforts through conduct of the EMDA and formation of an Extended Service Materials Working Group will provide a valuable resource for additional and diverse input.
- **Boiling Water Reactor and Pressurized Water Reactor Owners Groups:** These groups provide a forum for understanding key materials degradation issues for each type of reactor.
- **Materials Aging Institute:** The Materials Aging Institute is dedicated to understanding and modeling materials degradation; a specific example is the issue of environmental-assisted cracking. The collaborative interface with the Materials Aging Institute is coordinated through EPRI, which is a member of the Materials Aging Institute.
- **Programs in other industries and sectors:** Research in other fields may be applicable in the LWRS Program. For example, the Advanced Cement-Based Materials Program[q] may provide a valuable starting point for developing a database on concrete performance for structures.
- **Nuclear facilities:** Examination of materials from nuclear facilities provides a unique opportunity to evaluate degradation modes in relevant service materials. For example, the primary focus of the Constellation Pilot Project centers on material aging effects (Figure 9). This is a significant project commitment. However, degradation of concrete, buried piping, and cabling are not unique to nuclear reactors; other nuclear facilities (e.g., hot cells and reprocessing facilities) may be a key resource for understanding long-term aging of these materials and systems.
- **Other nuclear materials programs:** In addition, research within fast reactor and fusion reactor programs may provide key insights into high-fluence effects on materials because the mechanisms and models of degradation for fast reactor applications can be modified and provide a starting and proven framework for degradation issues in this effort. This research element includes (1) international collaboration to conduct coordinated research with international institutions (e.g., the Materials Aging Institute) to provide more collaboration and cost sharing, (2) coordinated irradiation

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o. This document is an internal EPRI document and is not publicly available

p. DOE-NE Light Water Reactor Sustainability Program and EPRI Long-Term Operations Program – Joint Research and Development Plan, INL-EXT-12-24562 Rev. 3, April 2014

q. Northwestern University McCormick School of Engineering &Applied Science, Center for Advanced cement-Based Materials, Last updated 03/02/2010,Accessed on 2/27/2013 http://acbm.northwestern.edu/

experiments to provide a single integrated effort for irradiation experiments, (3) advanced characterization tools to increase materials testing capability, improve quality, and develop new methods for materials testing, and (4) additional research tasks based on the results and assessments of current research activities.

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

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

11-GA50008-10-3

Figure 9. Constellation pilot project activities and related research and development tasks in the Materials Aging and Degradation Pathway.

2.5 Summary of Research and Development Products and Schedule

The strategic goals of the MAaD Pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations. Near-term research is focused primarily on providing mechanistic understanding, predictive capabilities, and high-quality data to inform decisions and processes by both industry and regulators. Longer-term research is focused on alternative technologies to overcome or mitigate degradation. A chronological listing of the major milestones in the pathway can be found in Appendix B.

3. RISK-INFORMED SAFETY MARGIN CHARACTERIZATION

3.1 Background

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

The RISMC methodology can be used to optimize plant safety and performance by incorporating plant impacts, physical aging, and degradation processes into the safety analysis. A systematic approach to the characterization of safety margins and the subsequent margins management options represent a vital input to the licensee and regulatory analysis and decision-making that will be involved. In addition, as R&D in the LWRS Program and other collaborative efforts yield new data and improved scientific understanding of physical processes that govern the aging and degradation of plant SSCs (and concurrently support technological advances in nuclear reactor fuels and plant instrumentation and control systems) needs and opportunities to better optimize plant safety and performance will become known. To support decision-making related to economics, reliability, and safety, the RISMC Pathway will provide methods and tools that enable mitigation options for margins management strategies.

3.2 Research and Development Purpose and Goals

The RISMC Pathway provides an enhanced understanding of LWR safety by developing methods, tools, and data in support of risk-informed margins management (RIMM). The purpose of the RISMC Pathway R&D is to support plant decisions for RIMM with the aim to improve the economics and reliability and sustain the safety of current nuclear power plants over periods of extended plant operations. The goals of the RISMC Pathway are twofold:

1. Develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by nuclear power plant decision makers as part of RIMM strategies.

2. Create an advanced RISMC Toolkit that enables more accurate representation of nuclear power plant safety margins and their associated influence on operations and economics.

One of the primary items inherent in the goals of the RISMC Pathway is the ability to propose and evaluate margin management strategies. For example, a situation could exist that causes margins associated with one or more key safety functions to become degraded (e.g., after a power uprate); the methods and tools developed in this pathway can be used to model and measure those margins. These evaluations support development and evaluation of appropriate alternative strategies for consideration by decision makers to maintain and enhance the impacted margins as necessary. When alternatives are proposed that mitigate reductions in the safety margin, these changes are referred to as margin *recovery* strategies. Moving beyond current limitations in safety analysis, the RISMC Pathway will develop techniques to conduct margins analysis using simulation-based studies of safety margins. The 2013

RISMC analysis of response to station blackout in a boiling water reactor (BWR)[r] was an initial demonstration of margins analysis.

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

- A *deterministic* margin, defined by the ratio (or, alternatively, the difference) of an applied capacity (i.e., strength) to the load. For example, a pressure tank is tested to failure where the tank design is rated for a pressure **C**, and it is known to fail at pressure **L**, thus the margin is (**L – C)** (safety margin) or **L/C** (safety factor).
- A *probabilistic* margin, defined by the probability that the load exceeds the capacity. For example, if failure of a pressure tank is modeled where the tank design capacity is a distribution f(**C**), its loading condition is a second distribution f(**L**), the probabilistic margin would be represented by the expression Pr[f(**L**) > f(**C**)].

In practice, actual loads (**L**) and capacities (**C**) are uncertain and, as a consequence, most engineering margin evaluations are, in fact, of the probabilistic type. In cases where deterministic margins are evaluated, the analysis is typically very conservative to account for uncertainties. The RISMC Pathway uses the probability margin approach to quantify impacts to economics, reliability, and safety to avoid excessive conservatisms (where possible) and treat uncertainties directly. Further, this approach is used in RIMM to present results to decision makers as it relates to margin evaluation, management, and recovery strategies.

The hypothetical example in Figure 10 is a simplified illustration of the type of approach taken by the RISMC method and tools. In this example, a nuclear power plant has two alternatives to consider: Alternative #1 – retain the existing, but aging, component as-is or Alternative #2 – replace the component with a new one. Using risk analysis methods and tools (described in Section 3.3), 30 simulations are run where this component plays a role in plant response under accident conditions. For each of the 30 simulations, the outcome of a selected safety metric is calculated – in this example peak fuel clad temperature – and compared against a capacity limit (assumed to be 2,200ºF). However, these simulations must be run for both alternative cases (resulting in a total of 60 simulations in this simplified example). The results of these simulations are then used to determine the probabilistic margin:

Alternative #1: Pr(Load exceeds Capacity) = 0.17

Alternative #2: Pr(Load exceeds Capacity) = 0.033.

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r. Diego Mandelli, et al., Risk Informed Safety Margin Characterization (RISMC) BWR Station Blackout Demonstration Case Study, INL-EXT-13-30203, September 2013.

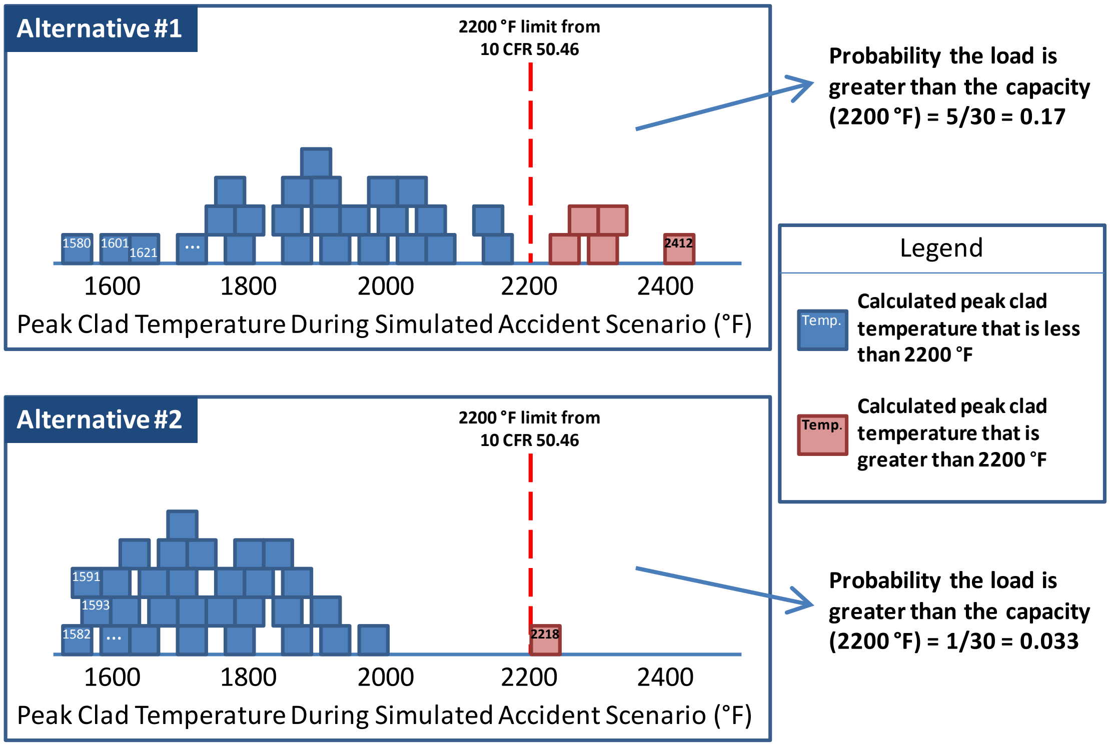

Figure 10. Risk-Informed Safety Margin Characterization example when evaluating alternatives for risk-informed margins management.

In an actual application of the risk-informed safety margin approach a much larger number of simulations would need to be performed to more accurately quantify these results and obtain a more complete characterization of the relevant statistical distributions of the key decision variables. If the safety margin characterization were the only decision factor, then Alternative #2 would be preferred (its safety characteristics are better). But, these insights are only part of the information that would be needed by the decision maker, for example the costs and schedules related to the alternatives would also need to be considered. In many cases, multiple alternatives will be available to the decision maker due to level of redundancy and several barriers for safety present in current nuclear power plants.

Because one LWRS Program objective is to develop new technologies that enhance plant performance, economics, and safety, more accurate safety margin analysis should include more realistic load and capacity implications for operating nuclear power plants. Safety, as represented by a load distribution, is a complex function that varies from one type of accident scenario to the next. However, the capacity part of the evaluation may not vary as much from one accident to the next because the safety capacity is determined by physical design elements such as fuel and material properties (which are common across a spectrum of accidents) or regulatory safety limits.

To successfully accomplish the pathway goals, the RISMC approach must be defined and demonstrated. The determination of the degree of a safety margin requires an understanding of risk-based scenarios. Within a scenario, an understanding of plant behavior (i.e., operational rules such as technical specifications, operator behavior, and SSC status) and associated uncertainties will be required to interface with a systems code. Then, to characterize safety margin for a specific safety performance metric[s] of consideration (e.g., peak fuel clad temperature), the plant simulation will determine time and scenario-dependent outcomes for both the load and capacity. Specifically, the safety margin approach will use the physics-based plant results (the "load") and contrast these to the capacity (for the associated performance metric) to determine if safety margins have been exceeded (or not) for a family of accident scenarios. Engineering insights will be derived based on the scenarios and associated outcomes.

Application of the RISMC methodology to a BWR station blackout case study shows how the methodology supports decision-making associated with a power uprates. This type of assessment cannot be easily performed in a classical PRA-based environment since the thermal-hydraulics is not integrated with the probabilistic modeling. This analysis shows the possible impact of a power uprate on the safety margin of a BWR. The case study considered is a loss of off-site power followed by the possible loss of all diesel generators, i.e., a station blackout event. The results give a detailed overview of the issues (for example the timing sequence of important events) associated with a power uprate under a station blackout accident scenario. Figure 11 shows the limit surface – the boundary in the input space between failure and success – for this particular example, specifically the limit surface for two different core power levels where variations in either off-site (i.e., AC power) recovery time or the time at which the diesel generators fail (i.e., DG failure time) can affect the outcome of core damage (failure) or not (success). As can be seen in the Figure, as the core power level is increased, core damage is more likely. In the nominal case, if off-site power is recovered in less than 7 hours (approximately 25,000 seconds) then core damage is always averted. However, in the 120% power uprate case, in scenarios where the diesel generators fail early (in less than 2 hours) and off-site power is recovered in less than 7 hours, some of those cases result in core damage.

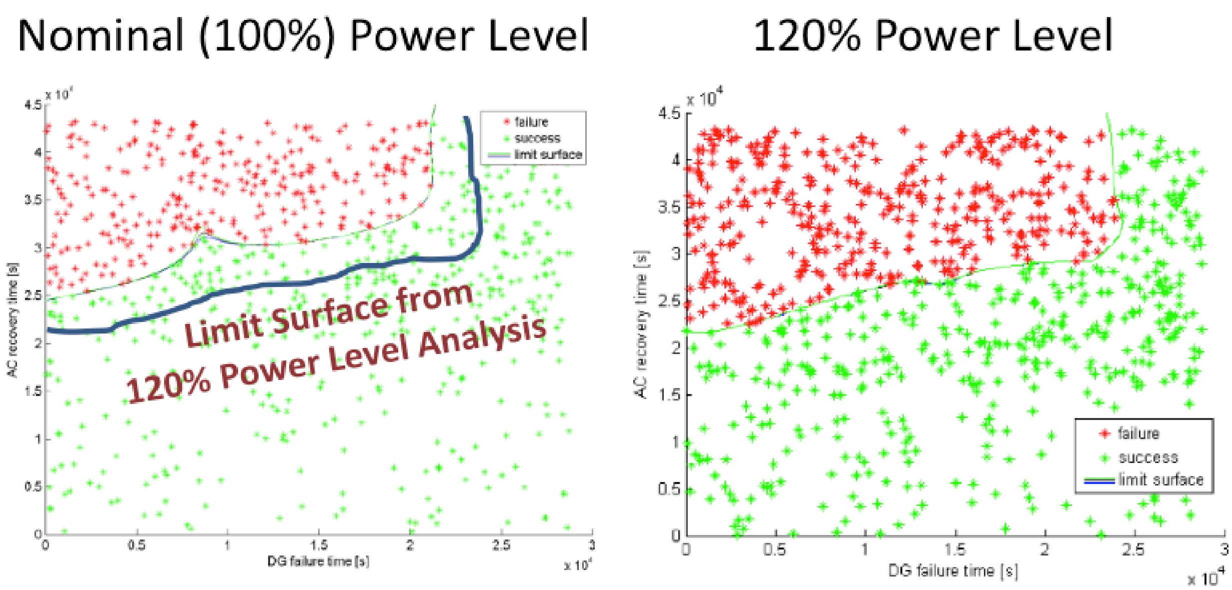

Figure 11. Examples of the limit surfaces associated with a boiling water reactor station blackout scenario.

s. Safety performance metrics may be application-specific, but in general are engineering characteristics of the nuclear power plant, for example as defined in 10 CFR 50.36, "safety limits for nuclear reactors are limits upon important process variables that are found to be necessary to reasonably protect the integrity of certain of the physical barriers that guard against the uncontrolled release of radioactivity."

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

- The development of the advanced models is high-risk, requiring multiphysics modeling capabilities developed in the DOE national laboratory system.
- The DOE national laboratory system has broad experience in validation, verification, and uncertainty quantification, which are essential components for successful development of the RISMC Toolkit.
- The RISMC Toolkit will be a very significant component of the U.S. industry capability that will promote investment in the U.S. nuclear power industry by reducing technical and, potentially, regulatory uncertainty.
- The RISMC Toolkit will significantly benefit the entire operating fleet and important classes of new facilities (e.g., small modular reactors).
- Government and industry are sharing work on methods and tools for characterizing safety margin.
  - The DOE role is to lead the development of advanced techniques, including building on uncertainty analysis methodology that has been under development for years at government laboratories and internationally.
  - Industry, under EPRI's Long-Term Operations Program, is carrying out case studies to better understand the issues and to provide feedback and comparative results to DOE on the RISMC Toolkit development and the methods and tools for analysis of safety margins.

One result of a risk-informed approach in the RISMC Pathway is the use of "performance-based" margins management strategies. These strategies will be informed by the risk assessment and will focus on desired, measurable outcomes, rather than prescriptive processes, techniques, or procedures, with the aim of identifying performance measures that ensure an adequate safety margin is maintained over the lifecycle of a nuclear power plant.

3.3 Pathway Research and Development Areas

To better understand the approach to determine safety margins, two types of analysis used in this pathway are described (see Figure 12). Note that in actual applications, a blended approach is used where both types of analysis are used to support any one particular decision. For example, the approach could be either mostly probabilistic, mostly mechanistic, or both in nature.

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

Figure 12. Types of analysis that are used in the Risk-Informed Safety Margin Characterization Pathway.

The RISMC Pathway has two primary focus areas to guide the R&D activities. First, the pathway is developing the methods that will be used to obtain the technical basis for safety margins and their use in the support of the risk-informed decision-making process. These methods are to be described in a set of technical reports for RIMM. Second, this pathway is producing an advanced set of software tools used to quantify safety margins. This set of tools, collectively known as the RISMC Toolkit, will enable a risk analysis capability that currently does not exist.

The major milestone associated with this task is:

- (2017) Complete the technical basis reports for Risk-Informed Margins Management.

3.3.1 The Safety Case

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

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

A safety case will be the output from RISMC applications when applying the method shown notionally in Figure 13. The safety-margin claims will do the following:

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

2. Produce evidence that supports the claims from #1

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

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

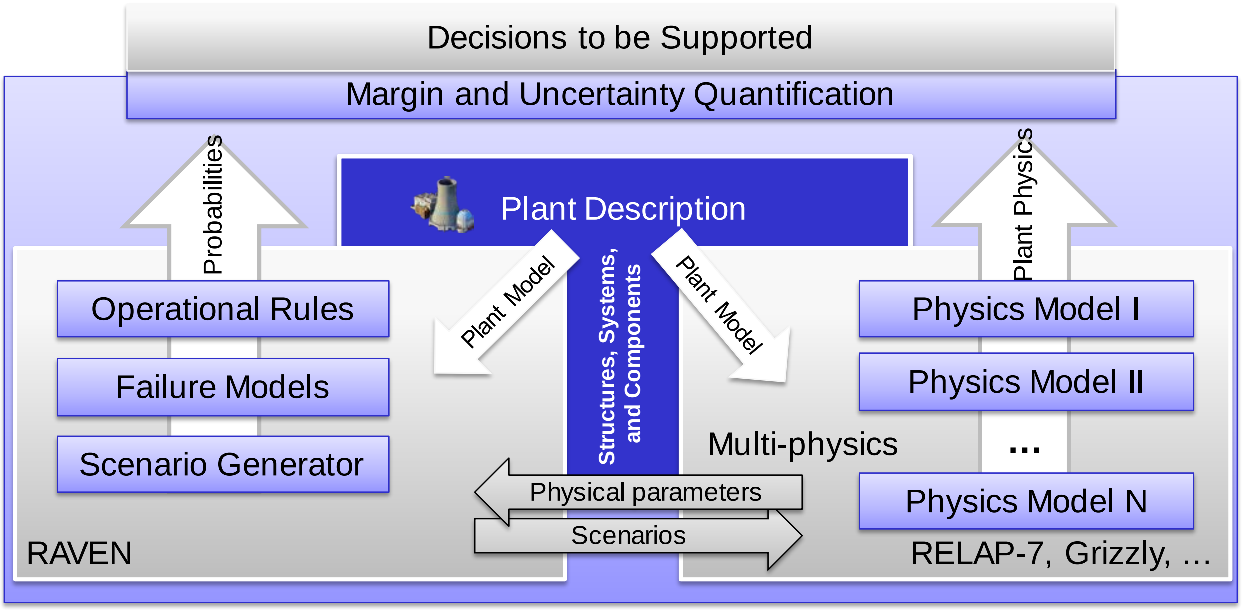

Figure 13. Attributes of the Risk-Informed Safety Margin Characterization approach for supporting decision-making.

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

5. Allow different viewpoints and levels of detail in a graded fashion to support decision-making.

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

Since safety margins are inferred (not directly observable) unlike how power output, pipe thickness, water temperature, radiation level, etc., are observed, a combination of models (probabilistic and mechanistic) are used to make safety margin predictions. These models also rely on unobserved elements such as failure rates and probabilities. Consequently, the characterization of a safety margin requires the treatment and understanding of uncertainty to effectively manage margins in a risk-informed decision-making approach. The decision of what is adequate margin resides with the nuclear power plant decision makers and can be informed by these models sensitivity cases using these models, and other information in an integrated approach.

3.3.2 Margins Analysis Techniques

This research area develops techniques to conduct margins analysis, including the methodology for carrying out simulation-based studies of safety margin, using the following generic process steps (as shown in Figure 14) for RISMC applications.

1. Characterize the issue to be resolved in a way that explicitly scopes the modeling and analysis to be performed. Formulate an “issue space” that describes the safety Figures of merit to be analyzed and proposed decision criteria to be employed.

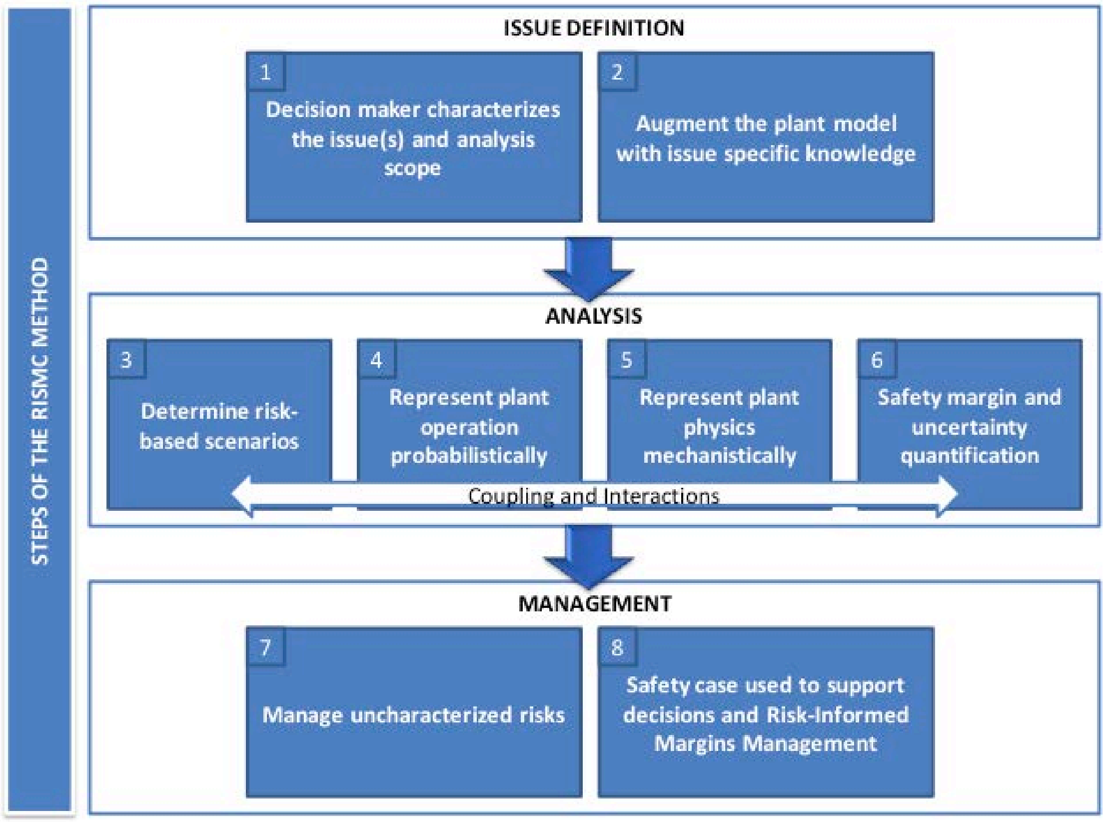

Figure 14. Depiction of the high-level steps required in the Risk-Informed Safety Margin Characterization method.

2. Quantify the decision-maker and analyst's state-of-knowledge (uncertainty) of the key variables and models relevant to the issue. For example, if long-term operation is a facet of the analysis, then potential aging mechanisms that may degrade components should be included in the quantification.

3. Determine issue-specific, risk-based scenarios and accident timelines (as shown in Figure 15). The scenarios will be able to capture timing considerations that may affect the safety margins and plant physical phenomena, as described in Steps 4 and 5. As such, there will be strong interactions between the analyses performed in Steps 3-5. Also, to "build up" the load and capacity distributions representing the safety margins (as part of Step 6), a large number of scenarios will be needed for evaluation.

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

5. Represent plant physics mechanistically. The plant systems level code will be used to develop distributions for the key plant process variables (i.e., loads) and the capacity to withstand those loads for the scenarios identified in Step 4. Because there is a coupling between Steps 4 and 5, they each can impact the other. For example, a calculated high loading (from pressure, temperature, or radiation) in an SSC may disable a component, thereby impacting an accident scenario.

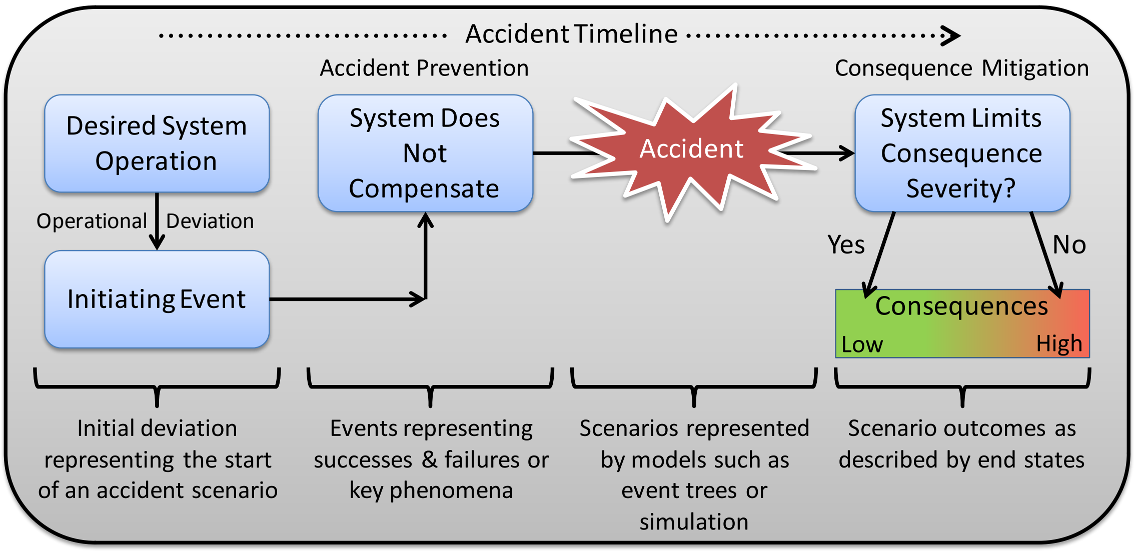

Figure 15. Accident scenario representation.

6. Construct and quantify probabilistic load and capacity distributions relating to the Figures of merit that will be analyzed to determine the probabilistic safety margins.

7. Determine how to manage uncharacterized risk. Because there is no way to guarantee that all scenarios, hazards, failures, or physics are addressed, the decision maker should be aware of limitations in the analysis and adhere to protocols of "good engineering practices" to augment the analysis. This step relies on effective communication from the analysis steps to understand the risks that *were* characterized.

8. Identify and characterize the factors and controls that determine the relevant safety margins within the issue being evaluated to develop appropriate RIMM strategies. Determine whether additional work to reduce uncertainty would be worthwhile or if additional (or reduced) safety control is justified.

The major milestones associated with this task are:

- (2016) Demonstrate margins analysis techniques by applying to performance-based Emergency Core Cooling System ECCS) Cladding Acceptance Criteria
- (2016) Demonstrate margins analysis techniques by applying to enhanced external hazard analysis (seismic and flooding)
- (2017) Apply margins analysis techniques to reactor containment analysis including hardened reliable vents and shallow and deep-water flooding and seismic events.
- (2017) Complete a full-scope margins analysis of a commercial reactor power uprate scenario. Use margins analysis techniques, including a fully coupled RISMC Toolkit, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of long-term operation or assessment of the safety benefit of advanced fuel forms). Test cases will be chosen in consultation with external stakeholders.
- (2017) Demonstrate margins analysis techniques, including a fully coupled RISMC toolkit, for long-term coping studies to evaluate FLEX for extended station blackout conditions.

- (2019) Apply margins analysis techniques to evaluation of spent fuel pool issues.
- (2020) Ensure development and validation to the degree that by the end of 2020, the margins analysis techniques and associated tools are an accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal and external events probabilistic risk assessment.

3.3.3 Case Study Collaborations

Jointly with EPRI, the LWRS RISMC Pathway is working on specific case studies of interest to the nuclear power plant industry. During FY2013 and FY2014, the team performed multiple case studies including a demonstration using the INL's Advanced Test Reactor, a hypothetical pressurized water reactor, and a boiling water reactor extended power uprate case study. Safety margin recovery strategies will be determined that will mitigate the potential safety impacts due to the postulated increase in nominal reactor power that would result from the extended power uprate. An additional task was to develop a technical report that describes how to perform safety margin-based configuration risk management. Configuration risk management currently involves activities such as the Significance Determination Process which traditionally uses core damage frequency as the primary safety metric – the research will focus on how the safety-margin approach may be used to determine risk levels as different plant configurations are considered.

3.3.4 The RISMC Toolkit

The RISMC Toolkit is being built using the INL's Multi-physics Object Oriented Simulation Environment (MOOSE) High Performance Computing framework.[u] MOOSE is the INL development and runtime environment for the solution of multi-physics systems that involve multiple physical models or multiple simultaneous physical phenomena. Models built on the MOOSE framework can be coupled as needed for solving a particular problem. The RISMC Toolkit and roles are shown in Figure 16.

Verification, validation, and uncertainty quantification is essential to producing tools that can (and will) be used by industry. Evaluation of existing data for validation is done in parallel with RISMC toolkit development; verification is done as part of the MOOSE development process. If additional data are needed, experiments will be designed and carried out to meet the validation needs. Tools for uncertainty quantification that can be used with MOOSE-based tools are under development in DOE Programs such as NEAMS and internally at INL, and will be used with the RISMC toolkit. As the development and capabilities of the RISMC Toolkit progress, the LWRS Program will work with industry to determine how to transition the tools to a user-supported community of practice, including planning for lifecycle software management issues such as training, software quality assurance, and development support. The general approach to toolkit development is that the tools will be validated to the extent that industry can then take the tools and use data specific to their particular design to create a validated model for their specific application.

3.3.4.1 RELAP-7

Reactor Excursion and Leak Analysis Program Version 7 (RELAP-7) will be the main reactor systems simulation tool for RISMC and the next generation tool in the RELAP reactor safety/systems analysis application series. RELAP-7 development will leverage 30 years of advancements in software design, numerical integration methods, and physical models. RELAP-7 will simulate behavior at the plant level with a level of fidelity that will support the analysis and decision-making necessary to economically and safely extend and enhance the operation of the current nuclear power plant fleet. A software

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u. Gaston, D., Hansen, G., & Newman, C. (2009). MOOSE: A Parallel Computational Framework for Coupled Systems for Nonlinear Equations. International Conference on Mathematics, *Computational Methods, and Reactor Physics*. Saratoga Springs, NY: American Nuclear Society.

development plan for RELAP-7 was issued in 2012,[v] and a verification and validation plan in 2014.[w] Development of RELAP-7 was initially funded by the DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program, and then transitioned to the LWRS Program in 2013.

3.3.4.2 RAVEN

Risk Analysis and Virtual Control ENvironment (RAVEN) is a multi-tasking application used for RELAP-7 simulation control, reactor plant control logic, reactor system analysis, uncertainty quantification, and performing probabilistic risk assessments (PRA) for postulated events. RAVEN will drive RELAP-7 (and other MOOSE-based reactor applications) for conduct of RISMC analyses. Development of RAVEN has been a collaborative effort between the DOE NEAMS and LWRS Programs.

3.3.4.3 Grizzly

Grizzly will simulate component aging and damage evolution events for LWRS Program applications. Grizzly will be able to simulate component damage evolution for the RPV, core internals, and concrete support and containment structures subjected to a neutron flux, corrosion, and high temperatures and pressures. Grizzly will be able couple with RELAP-7 and RAVEN to provide aging analysis in support of the RISMC methodology.

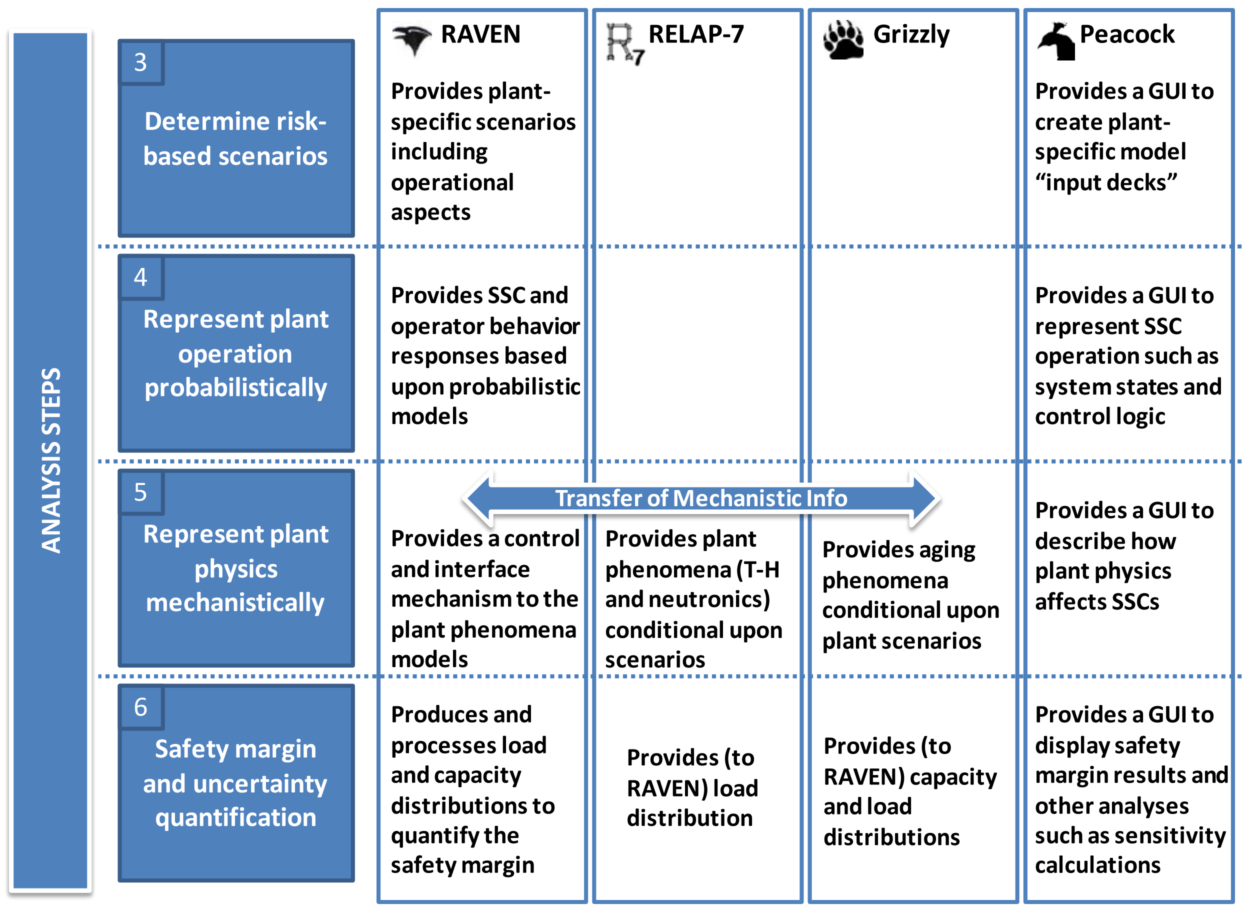

Figure 16. The Risk-Informed Safety Margin Characterization Toolkit and roles in the analysis steps.

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v. INL/MIS-13-28183, *RELAP-7 Development Plan*, Idaho National Laboratory, January 2013.

w. INL/EXT-14-33201, *RELAP-7 Software Verification and Validation Plan*, Idaho National Laboratory, September 2014.

3.3.4.4 Peacock

Peacock is a general graphical user interface for MOOSE based applications. Peacock has been built in a very general fashion to allow specialization of the graphical user interface for different applications. The specialization of Peacock for RELAP-7/RAVEN allows both a graphical input of the RELAP-7 input file and online data visualization, and is moving forward to provide direct user control of the simulation and data mining capabilities in support of PRA analysis.

3.3.4.5 External Events Tools

In 2014, the RISMC Pathway extended its analysis capabilities into additional initiating events including external events (primarily focusing on seismic and flooding events). The approach used to treat an event such as flooding is illustrated in Figure 17 and follows:

1. *Initiating event modeling*: modeling characteristic parameters and associated probabilistic distributions of the event considered
2. *Plant response modeling*: modeling of the plant system dynamics
3. *Components failure modeling*: modeling of specific components/systems that may stochastically change status (e.g., fail to performs specific actions) due to the initiating event or other external/internal causes
4. *Scenario simulation*: when all modeling aspects are complete, (see previous steps) a set of simulations can be run by stochastically sampling the set of uncertain parameters.
5. Given the simulation runs generated in Step 4, a set of statistical information (e.g., core damage probability) is generated. Determining the limit surface is also of interest: the boundaries in the input space between failure and success.

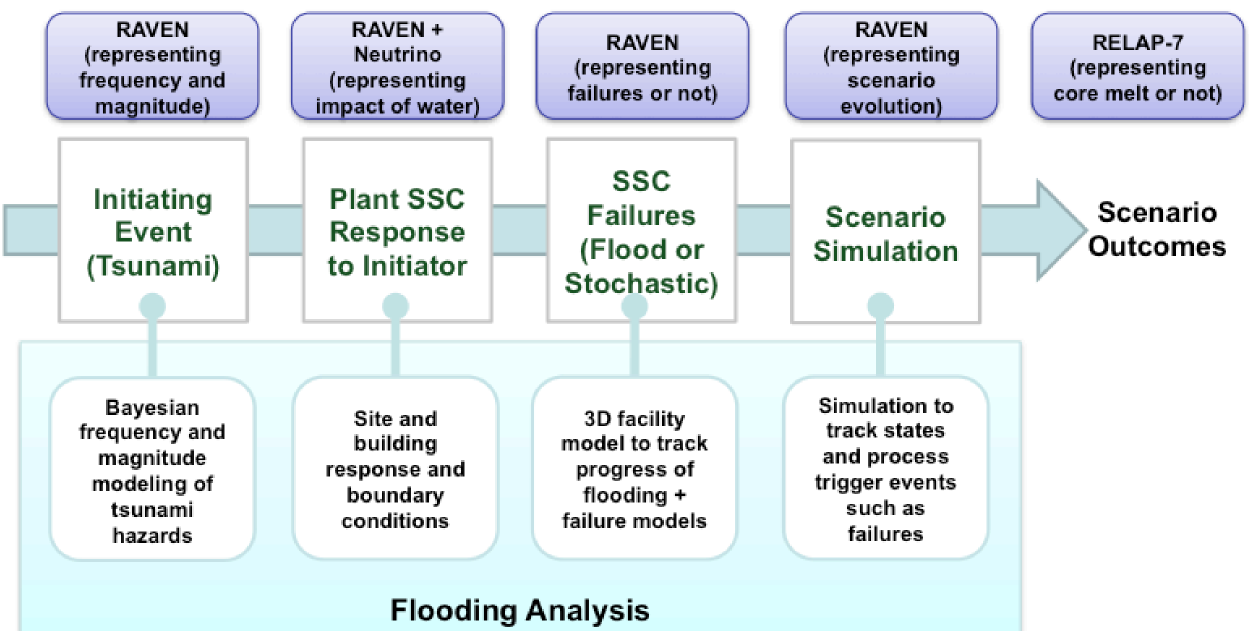

Figure 17. Overview of the plan to simulate initiating event and plant response using the Risk-Informed Safety Margin Characterization toolkit.

External events such as flooding and seismic events are being explored by leveraging existing tools (such as NEUTRINO for flooding), and by developing new tools (such as for seismic event evaluations). . Tools that are not MOOSE-based can be coupled to MOOSE-based tools (such as RAVEN) via applications developed by the MOOSE team.

The major milestones associated with the RISMC Toolkit are:

- (2015) Release the beta version of RELAP-7, including limited benchmarking
- (2015) Complete report on advanced seismic soil structure modeling
- (2016) Release the beta version 1.0 of Grizzly. This will include engineering fracture analysis capability for RPVs, with an engineering model for embrittlement, and a modular architecture to enable modeling of aging mechanisms.
- (2016) Complete the optimized and validated version of RELAP-7 that couples to RAVEN and to other applications (e.g., aging and fuels modules), for use as a balance-of-plant capability for multi-dimensional core simulators
- (2016) Grizzly (RPV) is validated against an accepted set of data.
- (2016) RELAP-7 is validated against an accepted set of data.
- (2016) Release the beta version of initial flooding model.
- (2016) Beta 1.5 release of RELAP-7 with improved closure relationships and steam/water properties, completed LWR 0D components (such as jet pump and accumulator), improved LWR components (1D-2D downcomer, 1D pressurizer, optional steam generator designs such as helical), tightly coupled multi-physics fuels performance (NEAMS code BISON), and single-phase 3D subchannel flow capability
- (2017) Release the beta version 2.0 of Grizzly. This version will include capabilities for modeling selected aging mechanisms in reinforced concrete and for engineering probabilistic RPV fracture analysis..
- (2017) Completed software that couples RAVEN to other applications (e.g., aging and fuels modules), for use as a balance-of-plant capability for multi-dimensional core simulators
- (2017) Compete flooding fragility experiments for mechanical components
- (2017) Release beta version of seismic probabilistic risk assessment model.
- (2017) Flooding model is validated against an accepted set of data.
- (2017) Beta 2.0 release of RELAP-7 with selected separate effects tests for validation data sets, validation of 3D single-phase subchannel, preliminary 3D two-phase (7-equation) subchannel, multi-physics coupling to reactor physics (NEAMS codes Rattlesnake and MAMMOTH).
- (2018) Grizzly (concrete) is validated against an accepted set of data.
- (2018) Release advanced flooding analysis tool suitable for ocean- and river-based flooding scenarios.
- (2018) Compete flooding fragility experiments for electrical components
- (2018) Initial demonstration RPV steel embrittlement using a bottoms-up, lower length scale model to capture causal mechanisms of embrittlement.
- (2018) Flooding fragility models for mechanical components are validated against an accepted set of data.

- (2018) Beta 3.0 release of RELAP-7 with additional validation and full multi-physics coupling, validated 3D two-phase subchannel capability, and implementation of droplet model for BWR SBO scenario, reflood phenomena under loss-of-coolant accident, and PWR feed and bleed process.
- (2018) Version 1.0 release of RELAP-7 with validation with selected integral effect tests, demonstration of large break loss-of-coolant accident, and three-field flow model, water, steam, droplets.
- (2019) Compete seismic experiments for critical phenomena.
- (2019) Release beta version 3.0 of Grizzly. This version includes capabilities for modeling selected aging mechanisms in reactor internals.
- (2019) Flooding fragility models for electrical components are validated against an accepted set of data.
- (2020) Implement risk-informed margins management module in RISMC Toolkit that will perform analyst-augmented evaluation of facility safety to search for vulnerabilities and potential management strategies.
- (2020) Grizzly (core internals) is validated against an accepted set of data.

3.4 Research and Development Partnerships

The RISMC Pathway relies on a strong partnership with industry to ensure that the tools under development will be useful and are targeting the right problems. Coordination with other DOE programs is also important, and international activities are pursued as warranted.

- **EPRI:** EPRI is the RISMC Pathway's primary interface with industry. EPRI plays an important role in high-level technical steering and in detailed planning of RISMC case studies. EPRI also will play a critical role in engaging industry stakeholders (i.e., personnel from operational nuclear power plants) to support pathway development, contribute technical expertise to use case development, and evaluate technical results from case study applications.
- **Nuclear Energy Advanced Modeling and Simulation (NEAMS)**: The RISMC Pathway will leverage models developed (and under development) by NEAMS. Development of RELAP-7 and RAVEN has been a joint effort between the NEAMS and LWRS Programs.
- **Consortium on Advanced Simulation of LWRs (CASL)**: CASL is developing a detailed model of the LWR core; if investigations in the LWRS Program warrant it, the LWRS Program-developed models can couple with the CASL-developed models. CASL has an interest in using RELAP-7 for one or more of their challenge problems.
- **Owners Groups:** Interactions will continue with groups such as the BWR and pressurized water reactor (PWR) Owners Groups through information exchange and evaluations of specific topics via case studies.
- **Multilateral International Collaboration**: A variety of international researcher interactions are of potential interest to the RISMC Pathway, including the NEA-OECD Committee on the Safety of Nuclear Installations (CSNI), and the European Nuclear Plant Life Prediction (NULIFE) – A virtual organization funded by over 50 organizations and the European Union under the Euratom Framework Program. This organization is working on advancing safety and economics of existing nuclear power plants.

3.5 Research and Development Products and Schedule

The purpose of the RISMC Pathway R&D is to support plant decisions for RIMM with the aim to improve economics, reliability, and sustain safety of current nuclear power plants over periods of extended plant operations. The goals of the RISMC Pathway are to develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by nuclear power plant decision makers as part of RIMM strategies, and create an advanced RISMC Toolkit that enables more accurate representation of nuclear power plant safety margins and their associated influence on operations and economics. A chronological listing of the major milestones in the RISMC Pathway can be found in Appendix B.

4. ADVANCED INSTRUMENTATION, INFORMATION, AND CONTROL SYSTEMS TECHNOLOGIES

4.1 Background

Reliable instrumentation, information, and control (II&C) systems technologies are essential to ensuring safe and efficient operation of the U.S. LWR fleet. These technologies affect every aspect of nuclear power plant and balance-of-plant operations. They are varied and dispersed, encompassing systems from the main control room to primary systems and throughout the balance of the plant. They interact with every active component in the plant and serve as a kind of central nervous system.

Figure 18. Typical nuclear power plant control room with analog technology.

Current instrumentation and human-machine interfaces in the nuclear power sector employ analog technologies such as those shown in Figure 18. In other power generation sectors, analog technologies have largely been replaced with digital technologies. This is in part due to the manufacturing and product support base transitioning to these newer technologies. It also accompanies the transition of education curricula for II&C engineers to digital technologies. Consequently, product manufacturers refer to analog II&C as having reached the end of its useful service life. Although considered obsolete by other industries, analog instrumentation and control continues to function reliably, though spare and replacement parts are becoming increasingly scarce as is the workforce that is familiar with and able to maintain it. In 1997, the National Research Council conducted a study concerning the challenges involved in modernizing existing analog-based instrumentation and controls with digital instrumentation and control systems in nuclear power plants. Their findings identified the need for new II&C technology integration.

Replacing existing analog with digital technologies has not been undertaken to a large extent within the nuclear power industry worldwide. Those efforts that have been carried out are broadly perceived as involving significant technical and regulatory uncertainty. This translates into delays and substantially higher costs for these types of refurbishments. Such experiences have slowed the pace of analog II&C replacement and further contribute to a lack of experience with such initiatives. In the longer-term, this may delay progress on the numerous II&C refurbishment activities needed to establish plants that are cost competitive in future energy markets. Such delays could lead to an additional dilemma: delays in reinvestment needed to replace existing II&C systems could create a ‘bow wave’ of needed future reinvestments. Because the return period on such reinvestments becomes shorter the longer they are delayed, they become less viable. This adds to the risk that II&C may become a limiting or contributing factor that weighs against the decision to operate nuclear power plants for longer periods. II&C replacement represents potential high-cost or high-risk activities if they are undertaken without the needed technical bases and experience to facilitate their design and implementation.

Most digital II&C implementation projects today result in islands of automation distributed throughout the plant. They are physically and functionally isolated from one another in much the same way as their analog predecessors. Digital technologies are largely implemented as point solutions to performance concerns with individual II&C components such as aging. This approach is characterized by planning horizons that are short and typically only allow for ‘like-for-like’ replacements. It is reactive to incipient failures of analog devices and uses replacement digital devices to perform the same functions as analog devices. Consequently, many features of the replacement digital devices are not used. This results in a fragmented approach to refurbishment that is driven by immediate needs. This approach to II&C aging management minimizes technical and regulatory uncertainty though, ironically, it reinforces the current technology base.

To displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability is needed that leverages the benefits of digital technologies. This includes considering goals for nuclear power plant staff numbers and types of specialized resources; targeting operation and management costs and the plant capacity factor to ensure commercial viability of proposed long-term operations; improved methods for achieving plant safety margins and reductions in unnecessary conservatisms; and leveraging expertise from across the nuclear enterprise.

The path to long-term operability and sustainability of plant II&C systems will likely be accomplished by measured, stepwise modernization through refurbishments. Through successive refurbishments, the resulting collection of II&C systems will reflect a hybrid mixture of analog and digital technologies. Operators and maintainers of II&C systems will, for an extended duration, require competencies with both types of technologies. This represents a least-risk and most realistic approach to refurbishment that allows plant personnel to become familiar with newer digital systems as they gradually replace analog devices.

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

4.2 Research and Development Purpose and Goals

The Advanced II&C Systems Technologies Pathway conducts targeted R&D to address aging and reliability concerns with the legacy instrumentation and control and related information systems of the U.S. operating LWR fleet. This work involves two major goals: (1) to ensure that legacy analog II&C systems are not life-limiting issues for the LWR fleet, and (2) to implement digital II&C technology in a manner that enables broad innovation and business improvement in the nuclear power plant operating model. Resolving long-term operational concerns with the II&C systems contributes to the long-term sustainability of the LWR fleet, which is vital to the nation's energy and environmental security. The Advanced II&C Systems Technologies Pathway R&D efforts address critical gaps in technology development and deployment to reduce risk and cost. The objective of these efforts is to develop, demonstrate, and support deployment of new digital II&C technologies for nuclear process control, enhance worker performance, and provide enhanced monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's nuclear power plants.

Figure 19. The Advanced Instrumentation, Information, and Control Systems Technologies Pathway is developing an architecture that encompasses all aspects of plant operations and support, integrating plant systems, and immersing plant workers in a seamless information architecture.

New value from II&C technologies is possible if they are integrated with work processes, directly support plant staff, and are used to create new efficiencies and ways of achieving safety enhancements. For example, data from digital II&C in plant systems can be provided directly to work process applications and then, in turn, to plant workers carrying out their work using mobile technologies. This saves time, creates significant work efficiencies, and reduces errors. A goal of these efforts is to motivate development of a seamless digital environment (Figure 19) for plant operations and support by integrating information from plant systems with plant processes for plant workers through an array of interconnected technologies:

- Plant systems – beyond centralized monitoring and awareness of plant conditions, deliver plant information to digitally based systems that support plant work and directly to workers performing these work activities.
- Plant processes – integrate plant information into digital field work devices, automate many manually performed surveillance tasks, and manage risk through real-time centralized oversight and awareness of field work.
- Plant workers – 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.

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

- Instrumentation and control modernization is critical to the sustainability of the operating nuclear fleet.
- Because of its short-term operational focus, the U.S. commercial nuclear industry could modernize its legacy instrumentation and control systems and still miss the opportunity to transform its operating model, thereby missing out on efficiencies available through advanced technologies that could reduce the costs of plant operations and outages.
- A coordinated national research program is needed to develop transformative technologies and an implementation roadmap for an outcome-based instrumentation and control replacement strategy.
- DOE's national laboratories maintain unique capabilities to develop and deliver a strategy for modernization that can be successfully deployed by the private sector:
  - A federally funded and industry cost-shared program is technologically and organizationally neutral.
  - Utilities must own the solution to successfully producing a plant-specific licensing case for modernized instrumentation and control and monitoring technologies.
  - National laboratories will collaborate with utilities to overcome barriers to technology deployment.

An overriding objective of this pathway is to ensure that legacy instrumentation and control equipment does not become a limiting factor in the decisions on long-term operation of these nuclear power plants. One way to do this is to motivate gradual introduction of newer digital technologies over a longer period of time, in smaller more affordable modernization projects, thereby avoiding lengthy and high cost high-risk investment projects. Goals for technology introduction are to enhance efficiency, safety, and reliability; improve characterizations of the performance and capabilities of passive and active components during periods of extended operation; and facilitate introduction of new advanced II&C systems technologies by demonstrating performance and reducing regulatory uncertainties. The R&D activities are intended to set the agenda for a long-term vision of future operations, including fleet-wide integration of new technologies.

4.3 Pathway Research and Development Areas

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

- Reduces the technical, financial, and regulatory risk of upgrading the aging II&C systems to support extended plant life to and beyond 60 years.
- Provides the technological foundation for a transformed nuclear power plant operating model that improves plant performance and addresses the challenges of the future business environment.

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

The program is advised by a Utility Working Group (UWG) composed of leading nuclear utilities across the industry (representing 70% of the existing LWR fleet) and EPRI. The UWG developed a consensus vision of how more integrated modernized plant II&C systems could address a number of challenges to the long-term sustainability of the LWR fleet.[x] A strategy was developed to transform the nuclear power plant operating model by first defining a future state of plant operations and support based on advanced technologies and then developing and demonstrating the needed technologies to individually transform the plant work activities. The collective work activities are grouped into the following major areas of enabling capabilities:

1. Human performance improvement for nuclear power plant field workers
2. Outage safety and efficiency
3. Online monitoring
4. Integrated operations
5. Automated plant
6. Hybrid control room

In each of these areas, a series of pilot projects are planned that enable the development and deployment of new II&C technologies in existing nuclear power plants (see Figure 20). A pilot project is an individual R&D project that is part of a larger strategy needed to achieve modernization according to a plan. Note that pilot projects have value on their own, as well as collectively. A pilot project is small enough to be undertaken by a single utility, it demonstrates a key technology or outcome required to achieve success in the higher strategy, and it supports scaling that can be replicated and used by other plants. Through the LWRS Program, individual utilities and plants are able to participate in these projects or otherwise leverage the results of projects conducted at demonstration plants

The pilot projects conducted through this pathway serve as stepping-stones to achieve longer-term outcomes of sustainable II&C technologies. They are designed to emphasize success in some crucial aspect of plant technology refurbishment and sustainable modernization. They provide the opportunity to develop and demonstrate methods to technology development and deployment that can be broadly standardized and leveraged by the commercial nuclear power fleet. Each of the R&D activities in this pathway achieves a part of the longer-term goals of safe and cost-effective sustainability. They are limited in scope so they can be undertaken and implemented in a manner that minimizes technical and regulatory risk. In keeping with best industry practices, prudent change management dictates that new technologies are introduced slowly so that they can be validated within the nuclear safety culture model.

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

- It assures that a significant portion of the LWR fleet decision-makers shares the end-state vision for plant modernization.
- It assures the near-term technologies are immediately beneficial while they comprise the long-term building blocks of a more comprehensive hybrid environment.
- It greatly reduces the risk of implementation for any one utility, and the oversight of the UWG provides a competent peer review.

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x. Long-Term Instrumentation, Information, and Control Systems (II&C) Modernization Future Vision and Strategy, INL/EXT-11-24154, Revision 3, November 2013.

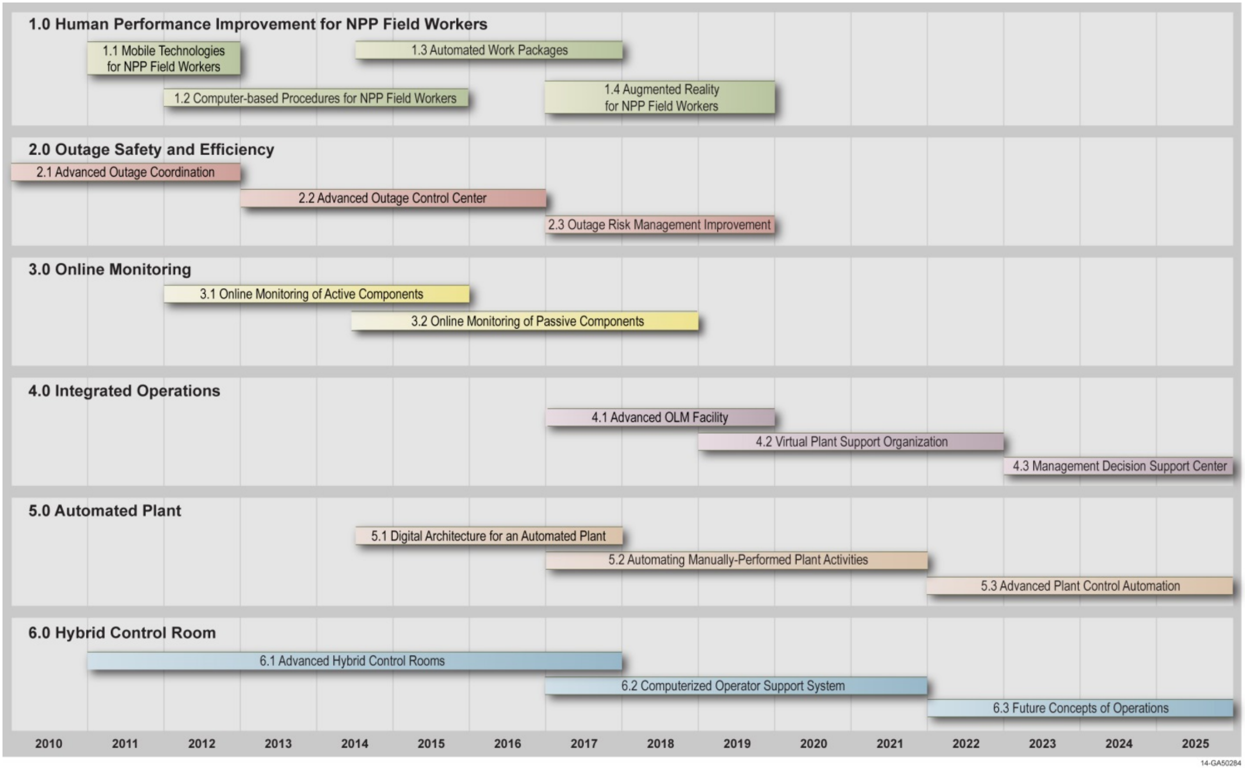

Figure 20. Pilot projects for the Advanced Instrumentation, Information, and Control Systems Technologies Pathway.

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

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

The transformation of the nuclear power plant operating model to that which is described as the future vision will take more than a decade to fully assimilate the pilot project technologies into the plant operations and business processes. The rate of transformation is a function of how the pilot projects are defined and sequenced, such that later combinations of these technologies create new capabilities that address the requirements of more complex nuclear power plant work activities. The stages of transformation are depicted in Figure 21.

The first stage involves the development of enabling capabilities that are needed to motivate the first movers in the industry to adopt new digital technologies. The pilot projects serve to introduce new technologies to the nuclear power plant work activities and validate them as meeting the special requirements of the nuclear operating environment. They must be verified to not only perform the intended functions with the required quality and productivity improvements, but they must also fit

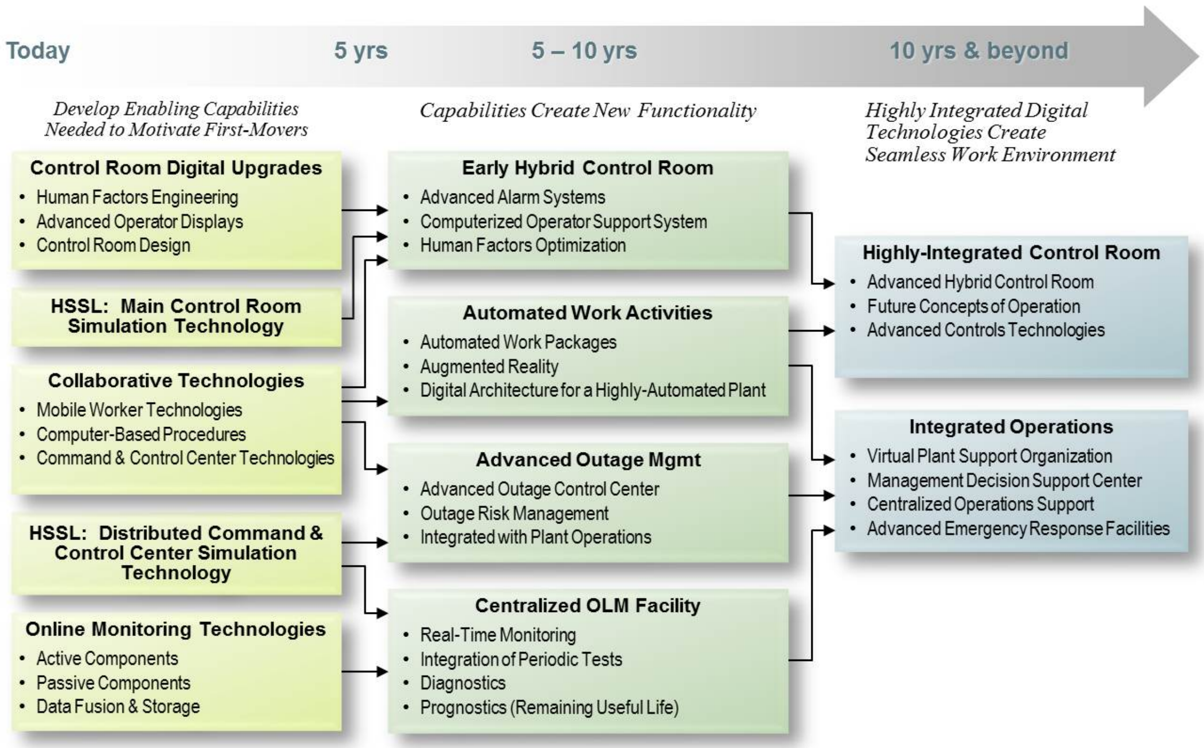

Figure 21. Stages of transformation in the Advanced Instrumentation, Information, and Controls Systems Technologies Pathway.

seamlessly into the established cultural norms and practices that define the safety culture of the nuclear power industry. This stage is characterized as new digital technologies improving the quality and productivity of work functions as they are now defined.

The outcomes of the first stage are control room upgrades employing new digital technologies, that afford improved plant communication and coordination of critical activities, and on-line monitoring technologies to improve awareness of plant component performance and aging phenomena. The Human Systems Simulation Laboratory (HSSL) is a key development focus of this stage to enable studies and validations of main control room simulation as well as distributed command and control center (e.g. outage control center) simulation (see Section 4.3.1).

The second stage begins when the enabling capabilities are combined and integrated to create new functionality. This is something of an aggregation stage: individual capabilities are combined to create new functions in the plant such as visualization and communication for outage management or predictive capabilities with online monitoring to better estimate the remaining useful life of a major plant component, thereby improving spare parts management and improving plant capacity. It includes the introduction of more enabling capabilities as further digital technology advancements are introduced and integrated. The pilot project technologies are being formulated in anticipation of this integration stage so they work in cooperation with one other to support future integrated functions that will leverage capabilities across the nuclear enterprise. This stage is characterized as the reformulation of major organizational functions based on an array of integrated technologies.

The outcomes of the second stage are the early hybrid control room, automated work activities, advanced outage management, and centralized online monitoring facilities.

The third stage occurs when there is substantial transformation of how the nuclear power plant is operated and supported based on embedding of major plant functions in a seamless digital environment. This is enabled by adopting newly developed technologies to achieve process efficiencies and the continued creation of new capabilities through technology integration. This stage is characterized as a transformation of the nuclear power plant organization and plant operating model based on advanced digital technologies that redefines and focuses the roles of plant workers and support organizations on value-added tasks rather than organizational and informational interfaces.

The outcomes of the third stage are the hybrid control room and integrated operations with their attendant functions and capabilities.

4.3.1 Human Systems Simulation Laboratory (HSSL)

The HSSL at the INL is used to conduct research in the design and evaluation of hybrid control rooms, integration of control room systems, development and piloting of human-centered design activities with operating crews, and visualizations of different end state operational concepts. This advanced facility consists of a reconfigurable simulator that supports human factors research, including human-in-the-loop performance, human-system interfaces, and can incorporate mixtures of analog and digital hybrid displays and controls. It is applicable to the development and evaluation of control systems and displays of nuclear power plant control rooms, and other command and control systems.

The HSSL consists of a full-scope, full-scale reconfigurable control room simulator that provides a high-fidelity representation of a LWR analog-based control room (Figure 22) with 15 bench board-style touch panels that respond to touch gestures similar to the control devices in an actual control room. The simulator is able to run actual LWR plant simulation software used for operator training and other purposes. It is reconfigurable in the sense that the simulator can be easily switched to the software and control board images of different LWR plants, thus making it a universal test bed for the LWR fleet.

Figure 22. Human Systems Simulation Laboratory - Reconfigurable Hybrid Control Room Simulator

For this research program, the HSSL will be mostly used to study human performance in a near-realistic operational context for hybrid control room designs. New digital systems and operator interfaces will be developed in software and depicted in the context of the current state control room, enabling comparative studies of the effects of proposed upgrade systems on operator performance (Figure 23). Prior to full-scale deployment of technologies (such as control room upgrades), it is essential to test and evaluate the performance of the system and the human operators' use of the system in a realistic setting. In control room research simulators, upgraded systems can be integrated into a realistic representation of the actual system and validated against defined performance criteria.

The key advantage of mimicking current control rooms comes from the ability to implement prototypes of new digital function displays into the existing analog control environment.

Figure 23. An operator workshop with a nuclear utility being conducted in the Human Systems Simulation Laboratory using the bench-board-style touch panel control bays.

4.3.2 II&C Pilot Project Descriptions and Deliverables

As previously mentioned, six areas of enabling capabilities have been identified, together with a series of pilot projects to collectively integrate new technologies into nuclear power plant work activities. The enabling capabilities and major milestones associated with the pilot projects are discussed in the following subsections.

4.3.2.1 Human Performance Improvement for Nuclear Power Plant Field Workers

To improve human performance for nuclear power plant field workers, a fundamental shift in approach is needed. Digital technology can be applied in a manner to perform the tedious error-prone tasks in nuclear power plant field activities, leaving the worker in more of a cognitive role. This has the potential to eliminate human variability in performing routine actions such as identifying the correct components to be worked on. In short, the technology can perform tasks at much higher reliability rates, while maintaining the desired worker roles of task direction, decision-making, and work quality oversight.

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

The major milestones associated with the pilot projects supporting human performance improvement for nuclear power plant field workers are:

- (2015) Conclude the field evaluation of the added functionality and new design concepts of the prototype computer-based procedure system, evaluating at a host utility the revisions made to the system to ensure it encompasses a broad variety of procedures, instructions, and usage scenarios
- (2015) Develop an automated work package prototype that supports paperless work flow and improved human performance.
- (2017) Integrate the automated work package with a wireless plant surveillance system and demonstrate self-documenting work packages for nuclear power plant surveillances.
- (2017) Publish a report on automated work package implementation requirements for both nuclear power plant field worker usage and self-documenting surveillances
- (2017) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers.
- (2018) Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, and restricted boundaries) for mobile plant workers.
- (2019) Publish a technical report on augmented reality technologies developed for nuclear power plant field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.

4.3.2.2 Outage Safety and Efficiency

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

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

The major milestones associated with the pilot projects supporting outage safety and efficiency are:

- (2015) Develop of improved graphical displays for an Advanced Outage Control Center, employing human factors principles for effective real-time collaboration and collective situational awareness.
- (2016) Develop technology for real-time plant configuration status during outages to improve work coordination, efficiency, and safety margin.
- (2017) Develop and demonstrate (in the HSSL) technologies for detecting interactions between plant status (configuration) states and concurrent component manipulations directed by in-use procedures, in consideration of regulatory requirements, technical specifications, and risk management requirements (defense-in-depth).
- (2018) Develop and demonstrate (in the HSSL) technologies to detect undesired system configurations based on concurrent work activities (e.g., inadvertent drain paths and interaction of clearance boundaries).
- (2019) Develop a real-time outage risk management strategy and publish a technical report to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.

4.3.2.3 Centralized Online Monitoring

As nuclear power plant systems begin to be operated during periods longer than originally licensed, the need arises for more and better types of 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 components based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions concerning long-term plant asset management. Of particular importance will be the capability to determine the remaining useful life of a component to justify its continued operation over an extended plant life.

Working closely with the MAaD and RISMC Pathways and EPRI, this pathway will develop technologies to complement sensor development for on-line monitoring of materials. This will allow for continuous assessment of the performance of critical plant components and materials during long-term operation for purposes of decision-making and asset management. The MAaD Pathway is developing the scientific basis for understanding the modes of degradation and the physical phenomena that give rise to indications of damage and degradation. In addition, the MAaD Pathway is developing models of the degradation and degradation mechanisms, and sensors and techniques for non-destructive evaluation of materials during periodic inspections. The RISMC Pathway is developing tools that can guide sensor development and placement. The Advanced II&C Pathway is developing in-situ methods to interrogate materials for indications of degradation, for monitoring components and materials in place, and for developing the tools to integrate indices that may be used to make assessments of structural and other aspects of material health in structures, systems, and components that are monitored.

The major milestones associated with the pilot projects supporting centralized online monitoring and information integration are:

- (2015) Develop select prognostic models for active components in nuclear power plants.
- (2015) Develop a passive component monitoring framework for aging effects in nuclear plant materials
- (2016) Develop a passive component monitoring framework for aging effects of piping and primary and secondary system components in nuclear plant materials
- (2017) Develop diagnostic and prognostic models for second large passive plant component based on the information integration framework.
- (2018) Develop and validate a health risk management framework for concrete structures in nuclear power plants, demonstrate for illustrative concrete structures in the nuclear power plant environment, and develop an implementation strategy for nuclear power plants.
- (2018) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for second large passive plant component, involving nondestructive examination-related online monitoring technology development, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.
- (2020) Publish a technical report tests of fiber optic systems and correlation of strain measurements with piping wall thickness, piping performance, and relationship with existing plant technical specifications for risk informed technical specification implementation.
- (2021) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for flow assisted corrosion, and integrate these with industry standards and guidance (e.g., EPRI CheckWorks, etc.).

4.3.2.4 Integrated Operations

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

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

The major milestones associated with the pilot projects supporting integrated operations are:

- (2017) Develop and demonstrate (in HSSL) concepts for an advanced online monitoring facility that can collect and organize data from all types of monitoring systems and activities and can provide visualization of degradation where applicable.

- (2018) Develop and demonstrate (in HSSL) concepts for real-time information integration and collaboration on degrading component issues with remote parties (e.g., control room, outage control center, systems and component engineering staff, internal and external consultants, and suppliers).
- (2019) Develop a digital architecture and publish a technical report for an advanced online monitoring facility, providing long-term asset management and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.
- (2019) For chemistry activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2019) Develop and demonstrate (in HSSL) concepts for a management decision support center that incorporates advanced communication, collaboration, and display technologies to provide enhanced situational awareness and contingency analysis.
- (2020) For maintenance activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2021) For radiation protection activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2022) Publish human and organizational factors studies and a technical report for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically dispersed nuclear power plant support organization.
- (2024) Develop and demonstrate (in HSSL) concepts for advanced emergency response facilities that incorporate advanced communication, collaboration, and display technologies to provide enhanced situational awareness and real-time coordination with the control room, other emergency response facilities, field teams, the Nuclear Regulatory Commission, and other emergency response agencies.
- (2025) Publish human and organizational factors studies and a technical report for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.

4.3.2.5 Automated Plant

The concept of an automated plant is one where 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 the 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.

The Advanced II&C Systems Technologies Pathway will develop an advanced digital architecture that integrates plant systems, plant processes, and plant workers in a manner that maximizes efficiency and shared-use of plant information. Opportunities for plant activity automation will be identified through a top-down analysis of nuclear power plant activities and define a transformed nuclear power plant operating model based on an automated plant. Further, to increase nuclear safety margins and plant capacity factors, the Advanced II&C Systems Technologies Pathway will develop strategies and guidance for specific automation improvements in plant control functions.

The major milestones associated with the pilot projects supporting the automated plant are:

- (2015) Complete a Digital Architecture Requirements Report documenting the information technology requirements for advanced digital technology envisioned to be applied to nuclear power plant work activities.
- (2015) Complete a Digital Architecture Gap Analysis Report documenting the gap between current typical instrumentation and control and information technologies capabilities in nuclear power plants vs. those documented in the Digital Architecture Requirements Report.
- (2017) Complete a Digital Architecture Implementation Guideline, documenting a graded approach in applying the conceptual model to selected digital technologies and in determining the incremental information technologies requirements based on a current state gap analysis.
- (2017) For nuclear power plant operations activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2018) For nuclear power plant chemistry activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2019) For nuclear power plant maintenance activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2020) For nuclear power plant radiation protection activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2021) Develop and demonstrate (in HSSL) prototype plant control automation strategies for representative normal operations evolutions (e.g., plant start-ups and shut-downs, equipment rotation alignments, and test alignments).
- (2024) Develop and demonstrate (in HSSL) prototype plant control automation strategies for representative plant transients (e.g., loss of primary letdown flow or loss of condensate pump).
- (2025) Develop the strategy and priorities and publish a technical report for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.

4.3.2.6 Hybrid Control Room

Hybrid control rooms have a mixture of traditional analog II&C technology and newer digital technology. Virtually all U.S. nuclear power plants have undertaken some amount of digital upgrades over the lifetime of the plants. In some cases, digital systems were the only practical replacement option 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 for the LWR fleet has been an ever-increasing presence of digital systems in the LWR control rooms.

Despite the significant number of digital systems that are now implemented, there have been no large-scale changes to the layout or function of LWR control rooms. Nuclear utilities have understandably been reluctant to undertake significant control room upgrades or modernization projects in consideration of cost, regulatory risk, and impact on the large investment in procedures, training programs, and other support functions that may accompany large upgrades. Also, there is a general desire to retain the high degree of operator familiarity with the current control room arrangements, and thereby avoid potential human performance issues associated with control board configuration changes.

Introducing digital systems into the control room creates opportunities for improvements in control room functions that are not possible with analog technology. These can be undertaken in measured ways such that the proven features of the control room configuration and functions are preserved, while addressing gaps in human performance that have been difficult to eliminate. By applying human-centered design principles in these enhancements, recognized human error traps can be eliminated and the introduction of new human error traps can be avoided.

Pilot projects have been defined to develop the needed technologies and methodologies to achieve performance improvement through incremental control room enhancements as nuclear plant II&C systems are replaced with digital upgrades. These pilot projects are targeted at realistic opportunities to improve control room performance with the types of digital technologies most commonly being implemented, notably distributed control systems and plant computer upgrades.

This work employs the HSSL as a test bed providing a realistic hybrid control room simulation for development and validation studies as part of the pilot projects. In addition, the Advanced II&C Systems Technologies Pathway research program has an agreement in place for access to control room upgrade technologies developed by the Halden Reactor Project, which has played a key role in several of the European control room upgrades. The Advanced II&C Systems Technologies Pathway research program is well-positioned to provide the enabling science for control room enhancements for U.S. hybrid control rooms.

The Advanced II&C Systems Technologies Pathway will conduct R&D activities to determine the optimum layout and concepts for a nuclear power plant hybrid control room based on engineering and human factors principles. The control room upgrades will be implemented and studied in INL’s HSSL to ensure that new concepts are sound and will uphold all nuclear safety requirements. The Advanced II&C Systems Technologies Pathway will assist a host utility in implementing the concepts in an actual nuclear power plant control room, conducting further studies on actual control room performance.

The major milestones associated with the pilot projects supporting the hybrid control room are:

- (2015) Develop a Distributed Control System Prototype - Using a participating utility's simulator plant model installed at the HSSL, develop a functional prototype for the turbine control system upgrade. Document the design, development, and functionality of the prototype replacement system.
- (2015) Develop prognostic software for control indicators. Provide demonstration and software for prognostic system and display interface for installation at the HSSL.
- (2015) Develop Operator Performance Metrics for Verification and Validation - Document the process how simulator studies should be performed including the various operator performance metrics that can be collected in support of control room upgrades.
- (2015) Develop a prototype of an advanced hybrid control room in the HSS that includes advanced operator interface technologies such as alarm management systems, computerized procedures, soft controls, large displays, and operator support systems.

- (2015) Test HSSL Systems in Preparation for Conducting Benefits Study with Operators - Test HSSL systems in representative configurations to verify that systems are able to function reliably in operational sequences and scenarios, test data logging and collection systems, and verify the stability of different combinations of digital systems with human interactions in preparation for data collection with actual operating crews.
- (2017) Publish a report documenting the Control Room Upgrades Benefit Study that presents the data, findings, and conclusions on performance improvements that can be obtained through the technologies of an advanced hybrid control room.
- (2017) Develop concepts for using nuclear power plant full-scope simulators as operator advisory systems in hybrid control rooms and complete a technical report on prototype demonstrations in HSSL.
- (2018) Develop concepts for a real-time plant operational diagnostic and trend advisory system with the ability to detect system and component degradation and complete a technical report on prototype demonstrations in HSSL.
- (2019) Develop an operator advisory system fully integrated into a control room simulator (HSSL) that provides plant steady-state performance monitoring, diagnostics and trending of performance degradation, operator alerts for intervention, and recommended actions for problem mitigation, with application of control room design and human factors principles.
- (2020) Complete a technical report on operator attention demands and limitations on operator activities based on the current conduct of operations protocols. This report will identify opportunities to maximize operator efficiency and effectiveness with advanced digital technologies.
- (2021) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, based on an operator advisory system that provides real-time situational awareness, prediction of the future plant state based on current conditions and trends, and recommended operator interventions to achieve nuclear safety goals.
- (2023) Develop and demonstrate (in HSSL) prototype mobile technologies for operator situational awareness and limited plant control capabilities for nuclear power plant support systems (e.g., plant auxiliary systems operations and remote panel operations).
- (2024) Develop and demonstrate (in HSSL) new concepts for remote operator assistance in high activity periods (e.g., refueling outages) and accident/security events, allowing offsite operators to remotely perform low safety-significant operational activities, freeing the control room operators to concentrate on safety functions.
- (2025) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities and the ability to interact with other control centers (e.g., emergency response facilities for severe accident management guidelines implementation).

4.3.3 Cyber Security

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

To this end, a project task has been completed to address cyber security issues arising from the technology developments in the pilot projects. A cyber security plan assessment has been conducted to identify possible threat vectors introduced by the new technologies. Individual assessments will be periodically conducted for pilot projects to identify threats specific to new technologies, characterize the degree of cyber security risk, and recommend effective mitigation measures. The assessments will be discussed with the host utility for the pilot projects and the information will be provided to the UWG.

Responsibility for cyber security ultimately lies with the utilities that implement technologies from this research program. They must ensure their own policies and regulatory commitments are adequately addressed.

4.3.4 Contribution to Industry Consensus Guidelines

To ensure appropriate transfer of technology to the nuclear power industry, guidelines documents will be published for each of the areas of enabling capabilities, incorporating the specific technologies and technical reports produced under each of the pilot projects for the respective areas. EPRI has agreed to assume responsibility for development and publication of these guidelines, using their standard methods and utility interfaces to develop the documents and validate them with industry. The Advanced II&C Pathway will support this effort by providing the relevant information and participating in the development activities.

The following milestones have been established to produce the guidelines for each area of the enabling capability:

Human Performance Improvement for Nuclear Power Plant Field Workers

- (2016) Publish interim guidelines to implement technologies for human performance improvement for nuclear power plant field workers.
- (2019) Publish final guidelines to implement technologies for human performance improvement for nuclear power plant field workers.

Outage Safety and Efficiency

- (2016) Publish interim guidelines to implement technologies for improved outage safety and efficiency.
- (2018) Publish final guidelines to implement technologies for improved outage safety and efficiency.

Centralized Online Monitoring

- (2016) Publish interim guidelines to implement technologies for centralized online monitoring and information integration.
- (2018) Publish final guidelines to implement technologies for centralized online monitoring and information integration.

Integrated Operations

- (2020) Publish revised interim guidelines to implement technologies for integrated operations.
- (2022) Publish final guidelines to implement technologies for integrated operations.

Automated Plant

- (2021) Publish interim guidelines to implement technologies for an automated plant.
- (2025) Publish final guidelines to implement technologies for an automated plant.

Hybrid Control Room

- (2018) Publish interim guidelines to implement technologies for a hybrid control room.
- (2021) Publish revised interim guidelines to implement technologies for a hybrid control room.
- (2025) Publish final guidelines to implement technologies for a hybrid control room.

4.4 Research and Development Partnerships

A systematic activity is underway to engage nuclear power plant owner-operators, suppliers, industry support organizations, EPRI, and NRC. These engagement activities ensure that R&D activities focus on issues of greatest long-term challenge and uncertainty for nuclear power plant owners and regulators alike, the products of research can be commercialized, and roadblocks to deployment are systematically addressed. Key partnerships include:

- **Utility Working Group - UWG:** The Advanced II&C Systems Technologies Pathway utilizes a UWG to define and host a series of pilot projects that, together, will enable significant plant performance gains and minimize operating costs in support of the long-term sustainability of the LWR fleet. At this time, the UWG consists of 13 leading U.S. nuclear utilities. Additional membership will be pursued for the UWG with the intent to involve every U.S. nuclear operating fleet in the program. The UWG is directly involved in defining the objectives and research projects of this pathway. The UWG meets regularly several times annually. Pilot project partners make the results of the R&D available and accessible to other commercial nuclear utilities and participate in efforts to support deployment of systems, technologies, and lessons learned by other nuclear power plant owners.
- **Electric Power Research Institute:** EPRI is both a member of the UWG and serves in a direct role in collaborative research with the Advanced II&C Systems Technologies Pathway. EPRI technical experts directly participate in the formulation of the project technical plans and in the review of the pilot project results, bringing to bear the accumulated knowledge from their own research projects and collaborations with nuclear utilities. EPRI will assist in the transfer of technology to the nuclear utilities by publishing formal guidelines documents for each of the major areas of development.
- **Halden Reactor Project:** The Halden Reactor Project's programs extend to many aspects of nuclear power plant operations; however, the area of interest to this R&D program is the human-machine interface technology research program in the areas of computerized surveillance systems, human factors, and man-machine interaction in support of control room modernization. Halden has assisted a number of European nuclear power plants in implementing II&C modernization projects, including control room upgrades. The Advanced II&C Systems Technologies Pathway will work closely with the Halden Reactor Project to evaluate their advanced II&C technologies to take advantage of the applicable developments. In addition to the technologies, the validation and human factors studies conducted during development of the technologies will be carefully evaluated to ensure similar considerations are incorporated into the pilot projects. Bilateral agreements may be employed in areas of research where collaborative efforts with Halden Reactor Project will accelerate development of the technologies associated with the pilot projects.
- **Major Industry Support Organizations:** The LWR fleet is actively supported by major industry support groups; namely EPRI, the Nuclear Energy Institute, and the Institute of Nuclear Power Operations. All of these organizations have active efforts in the instrumentation and control area, including technical developments, regulatory issues, and standards of excellence in conducting related activities. It is important that these organizations be informed of the purpose and scope of this research program, and that activities be coordinated to the degree possible. It is a task of this research program to engage these organizations to enable a shared vision of the future operating model based on an integrated digital environment and to cooperate in complementary activities to achieve this

vision across the industry with the maximum efficiency and effectiveness. There are additional industry support groups (such as the PWR and BWR Owners Groups) that need similar engagement for more focused purposes.

- **Nuclear Regulatory Commission:** Periodic informational meetings are held between DOE and members of NRC to communicate the aims and activities of individual LWRS Program pathways. Briefings and informal meetings will continue to be provided to inform staff from NRC's Office of Nuclear Regulatory Research about technical scope and objectives of the LWRS Program.
- **Suppliers:** Ultimately, it will be the role of nuclear industry II&C suppliers to provide commercial products based on technologies developed under this research program. Engagement activities with nuclear industry II&C suppliers are being conducted to facilitate communication and to make the technologies that are produced through research, the reports of research, insights and lessons learned available to suppliers so that advancements made through this program benefit the LWR fleet through available commercial products based on best practices.

4.5 Summary of Research and Development Products and Schedule

The strategic goal of this pathway is to develop an II&C architecture that encompasses all aspects of nuclear power plant operations and support, integrating plant systems, plant work processes, and plant workers in a seamless digital environment enabling enhanced nuclear safety, increased productivity, and improved overall plant performance. A chronological listing of the major milestones in Advanced II&C Systems Technologies Pathway can be found in Appendix B.

5. REACTOR SAFETY TECHNOLOGIES

5.1 Background

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

The DOE has also played a major role in the U.S. response to the Fukushima accident. Initially, DOE worked with the Japanese and the international community to help develop a more complete understanding of the Fukushima accident progression and its consequences, and to respond to various safety concerns emerging from uncertainties about the nature of and the effects from the accident. DOE R&D activities are focused on providing scientific and technical insights, data, analyses methods that ultimately support industry efforts to enhance safety. These activities are expected to further enhance the safety performance of currently operating as well as better characterize the safety performance of future U.S. nuclear power plants. In pursuing this area of R&D, DOE recognizes that the commercial nuclear industry is ultimately responsible for the safe operation of licensed nuclear facilities. As such, industry is considered the primary "end user" of the results from this DOE-sponsored work.

The response to the Fukushima accident has been global, and there is a continuing multinational interest in collaborations to better quantify accident consequences and to incorporate lessons learned from the accident. DOE will continue to seek opportunities to facilitate collaborations that are of value to the

U.S. industry, particularly where the collaboration provides access to vital data from the accident or otherwise supports or leverages other important R&D work.

5.2 Research and Development Purpose and Goals

The purpose of the Reactor Safety Technology R&D is to improve understanding of beyond design basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents, in particular the Fukushima Daiichi events. This information will be used to aid in developing mitigating strategies and improving severe accident management guidelines for the current light water reactor fleet. The RST Pathway's activities have evolved from an initial coordinated international effort to assist in the analysis of the Fukushima accident progression and accident response into the following three areas of current work:

1. Accident Tolerant Components: This R&D work is focused on analysis or experimental efforts for hardware-related issues, including systems, structures and components with the potential to prevent core degradation or mitigate the effects of beyond-design basis events.

2. Severe Accident Analyses: This R&D is focused on analyses using existing computer models and their ability to provide information and insights into severe accident progression that aid in the development of severe accident management guidelines (SAMG) and/or training operators on these SAMGs; an auxiliary benefit can be informing improvements in these models.

3. Fukushima Forensics and Examination Plans: This R&D is focused on providing insights into the actual severe accident progression at Fukushima through planning and interpretation of visual examinations and data collection of in-situ conditions of the damaged units as well as collection and analysis of samples within the reactor systems and structural components from the damaged reactors. This effort could provide substantial lessons-learned on severe accident progression, similar to those from Three Mile Island accident examinations.

In each of these topical areas, the RST Pathway focus is on beyond design basis events (e.g., extended loss of AC power) and corresponding mitigation strategies (e.g., containment venting). Given the finite resources of the LWRS Program and the need to maintain robust R&D efforts in the other technology pathways, the RST Pathway is expected to engage in reactor safety technology R&D only for beyond design basis events circumstances and only when one or more of the following principles are satisfied:

- DOE and its contractors have unique expertise with the R&D subject matter;
- DOE and its contractors have unique facilities that can support experiments needed for a topic;
- DOE and its contractors have unique ideas/concepts that employ their expertise and/or facilities;
- Meaningful contributions to the R&D effort will come from industry (e.g., EPRI, light water reactor Owners' Groups; etc.).

5.3 Research and Development Purpose and Goals

5.3.1 Gap Analysis

As previously discussed, many of the activities associated with the RST Pathway represent DOE initiatives that had commenced shortly after the Fukushima accident. Thus, there remains a need for a more comprehensive review on what the industry has engaged for beyond design basis events subjects as well as what R&D activities NRC is supporting for this area. In 2015, a "gap" analysis will be completed using a team of reactor safety experts from industry (EPRI, BWR and PWR Owners Groups, U.S. vendors), DOE and its national laboratories as well as academe. The gap analysis report will help to inform an updated RST Pathway R&D plan to be issued in the summer of 2015.

The major milestone associated with this task is

- (2015) Complete gap analysis on accident tolerant components and severe accident analysis

The results of the gap analysis will be available in mid-FY 2015 and will inform activities beyond 2015.

5.3.2 Accident Tolerant Components

The accidents at Three Mile Island Unit 2 and Fukushima demonstrate the importance of accurate, relevant, and timely information on the status of reactor systems during such an accident to help manage the event. While significant progress in these areas has been made since Three Mile Island Unit 2, the accident at Fukushima suggests that there may still be some potential for further improvement. Recognizing the significant technical and economic challenges associated with plant modifications, it is important to deploy a systematic approach, which uses state-of-the-art accident analysis tools and plant-specific information to identify critical data needs as well as equipment capable of mitigating the effects of any risk significant accident.

The objective of this R&D activity is to identify opportunities to improve nuclear power plant capability to monitor, analyze, and manage conditions leading to and during a beyond design basis event. Availability of appropriate data and the operator's ability to interpret and apply that data to respond and manage the accident was an issue during the Fukushima accident. The damage associated with the earthquake and flooding inhibited or disabled the proper functioning of the needed safety systems or components.

There are compelling reasons for pursuing this area of R&D both for our domestic reactor fleet as well as for international collaborations. Results could provide useful information to industry regarding possible post-Fukushima regulatory actions related to sensor and equipment reliability and/or operability.[y] Additionally, results and processes developed from this research could benefit Design Certification and Combined Operating License applicants as they are challenged to meet new requirements related to equipment survivability during severe accidents.[z] Finally, analyses and experiments in support of industry initiatives may reveal additional margin in reactor safety systems and components.

The major milestones associated with this task are

- (2015) Develop recommendations for accident tolerant sensor development based on evaluation of a PWR severe accident scenario.
- (2015) Develop recommendations for accident tolerant sensor development based on evaluation of a BWR severe accident scenario
- (2015) Complete reactor core isolation cooling analytical model and a draft testing program

The recommendations for accident tolerant sensor development will be provided to the Nuclear Energy Enabling Technologies (NEET) Program for their consideration. Development of accident tolerant sensor is not currently planned under the LWRS Program. Exploration in 2015 into possible testing of a reactor core isolation cooling turbine-pump system under beyond design basis conditions will inform a future decision as to whether such a test will be carried out under the LWRS Program.

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y. U.S. NRC, "Fifth 6-month Status Update on Response to Lessons Learned from Japan's March 11, 2011, Great Tohoku Earthquake and Subsequent Tsunami," SECY-14-0046, April 17, 2014.

z. U.S. NRC Standard Review Plan, Section 19.0 Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors, NUREG-0800, Draft Rev. 3, Issued September 2012.

5.3.3 Severe Accident Analysis

After Fukushima, DOE and other domestic and international groups initiated severe accident analysis efforts aimed at reconstruction and analysis of the Fukushima reactor units. While useful insights were gained as to the accident progression, these activities also highlighted where the existing computer system models being used did not always produce consistent results. If such tools were to be used to aid in effective severe accident management guidelines and associated training, further work was needed on identifying the sources of uncertainties and inconsistencies, in order to have greater confidence in the use of these tools.

The objective of this R&D activity is to improve understanding of and reduce uncertainty in severe accident progression, phenomenology, and outcomes using existing analytical codes; and to use the insights from this improved understanding of the accident to aid in improving severe accident management guidelines for the current light water reactor fleet. The information gathered from the application of existing codes to the scenario at Fukushima Daiichi could be used to inform improvements to those codes. However at this time, the LWRS Program does not plan to fund the improvement of legacy codes. The analysis efforts can also aid in preparations and planning for the examination of the damaged Fukushima units (see Section 5.3.4).

The major milestones associated with this task are

- (2015) Complete a MELCOR/MAAP comparison of analyses of the events at Fukushima Daiichi.
- (2015) Complete analysis of uncertainties in MELCOR calculations as applied to the events at Fukushima Daiichi.
- (2017) Complete MAAP-MELCOR crosswalk Phase2 with collaboration between EPRI, DOE laboratories, NRC and possibly French and Japanese partners.
- (2019) Complete water management severe accident analysis in support of BWR ex-vessel mitigating strategies

Future milestones will be informed by activities in 2015.

5.3.4 Fukushima Forensics and Examination Plan

The Fukushima accident provides the nuclear industry with opportunities to incorporate lessons learned into the operation of current plants and the design of future plants. Forensic examination of post-accident conditions at Fukushima will provide valuable insights into severe accident phenomena progression as well as an opportunity to improve severe accident analysis tools and accident management guidance and training for plant staff.

Experience from the Three Mile Island Unit 2 accident in the United States suggests that critical information can be lost if not obtained as soon as feasible during the cleanup and decommissioning process. Experience also suggests that R&D needs must be fully incorporated in cleanup and decommissioning plans early in order to minimize the impact on decommissioning cost and schedule. Japan has already begun planning the decommissioning of the damaged Fukushima reactors; therefore, this is an appropriate time to provide input to Japan on inspection and sampling needs, prioritization, and time sequencing.

The objective of this R&D activity is to provide U.S. insights into severe accident progression and the status of reactor systems through early data collection, visual examination of in-situ conditions of the damaged Fukushima units, and collection and analysis of material samples and radionuclide surveys (e.g., within the reactor building, the drywell, and the vessel). U.S. consensus insights will be obtained from severe accident experts and plant operations experts from national laboratories, academia, and industry (including plant staff, PWR and BWR owner groups, and EPRI), and informed by interactions with representatives from the NRC and TEPCO. These insights will also contribute to synergistic international efforts, such as the CSNI SAfety REsearch opportunities post-Fukushima (SAREF). SAREF is establishing a process for identifying and following up on research opportunities to address safety research gaps and advance safety knowledge related to Fukushima. The ultimate goal of this activity is to use knowledge gained from Fukushima to inform model enhancements to safety analysis codes, and to apply lessons learned based on these insights to plant systems and procedures. Lessons learned may also help improve the design of future reactor safety systems.

The major milestone associated with this task is

- (2015) Complete U.S. input towards a forensics examination plan for Fukushima Daiichi.

This plan will be updated periodically. Future milestones will be informed by activities in 2015.

5.4 Research and Development Partnerships

The RST Pathway interfaces with a number of domestic and international organizations to ensure that the R&D products of the pathway will be useful to the nuclear community.

- **Nuclear Industry:** Regarding specific RST Pathway R&D activities, EPRI will continue to serve as the primary industry interface. In addition to collaboration with EPRI, the pathway will interface as appropriate with the Nuclear Energy Institute on policy and regulatory matters, and support requests for information on program goals and results. Other industry interfaces might include the Institute for Nuclear Power Operations for details on Fukushima events analysis and/or operational, management and training matters, the reactor vendors (e.g., GE-Hitachi on design issues specific to boiling water reactors and Westinghouse for pressurized water reactors), individual plant owner/operators participating in plant evaluations, and the Pressurized Water Reactor Owners Group and Boiling Water Reactor Owners Group regarding licensing and severe accident management issues.
- **Nuclear Regulatory Commission (NRC)**: The interface with NRC is important to the success of this pathway, since NRC regulatory actions and safety priorities can influence DOE's R&D priorities. NRC's Near-Term Task Force report proposed a number of actions for consideration by the Staff and Commission. While its primary R&D role is to support research needs that facilitate the deployment and utilization of nuclear energy technologies, DOE has co-sponsored data collection, test programs, code development, and other research topic important to NRC's regulatory oversight role. DOE has a productive working relationship with NRC, based on an effective memorandum of understanding, and a history of successful collaboration on R&D. Hence, DOE intends to seek NRC input on R&D objectives and priorities and will seek to include NRC staff in monitoring of test programs, data sharing, oversight functions, etc.
- **International Organizations**: The response to the Fukushima accident has been global, resulting in multiple activities by numerous national and international stakeholders. Post Fukushima-related topics, such as accident mitigation strategies, accident monitoring systems, and reactor safety, have already been the focus of international working groups and meetings sponsored by agencies such as the International Atomic Energy Agency and the OECD-NEA. For example, the latter organization is sponsoring a multinational "Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station Project." Through the RST Pathway, DOE-NE is one of the participants in this multinational project. This is but one example of where the broader experience base and participation can be leveraged to result in more effective, timely and economical responses to enhance the state of safety knowledge. As such, the RST Pathway will seek opportunities for bilateral and multinational collaboration with several international organizations with similar interests and R&D programs.

- **Bilateral U.S. – Japan Cooperation**: A Civil Nuclear Energy Research and Development Working Group (CNWG) has been established to enhance coordination of joint civil nuclear R&D efforts between the DOE and Japan's Ministry of Economy, Trade and Industry and Ministry of Education, Culture, Sports, Science and Technology. This Civil Nuclear Energy Research and Development Working Group R&D scope is broader than just reactor safety, but a number of activities, particularly within the LWR R&D sub-working group, are closely coupled to the RST Pathway. Finally, The European Atomic Energy Community recently released a call for proposals for development of tools for the fast and reliable prediction of severe accident progression and anticipation of the source term of a nuclear accident. The call specifically suggests partnering with the United States and others, and Japanese organizations have expressed strong interest in cooperative research on the response of critical components such as reactor core isolation cooling systems and safety relief valves under severe accident conditions.
- **Universities**: University research programs sponsored by DOE represent a potentially important resource for this pathway. The NEUP was established in 2009 to consolidate DOE's university support under one initiative and to better integrate university research with DOE-NE technical programs. The NEUP provides DOE access to a broad array of innovative, cutting edge research and technology within the university system. The RST Pathway will seek opportunities for innovative solutions to reactor safety issues within NEUP.

5.5 Research and Development Products and Schedule

The purpose of the RST Pathway R&D is to provide scientific and technical insights, data, analyses and methods that can support industry efforts to enhance nuclear reactor safety during beyond design basis events as we take lessons learned from the Fukushima accident. A chronological listing of the major milestones in the RST Pathway can be found in Appendix B.

Appendix A

LWRS Program Accomplishments

Appendix A
LWRS Program Accomplishments

Appendix A includes a summary of the Light Water Reactor Sustainability Program's previous years' major accomplishments. More detail on accomplishments is provided for recent years, with higher-level summaries of the preceding years. Reports on these topics can be found on the LWRS website, www.inl.doe.gov/lwrs.

Fiscal Year 2014

Materials Aging and Degradation

- Completed post-irradiation examination plan for ORNL and University California Santa Barbara assessment of ATR-2 capsules
- Completed comprehensive and comparative analysis of atom probe tomography and small-angle neutron scattering experiments on available high fluence reactor pressure vessel (RPV) steel specimens
- Completed assessment of embrittlement effects in an RPV nozzle
- Completed examination of the microstructural and mechanical properties to determine possible root cause of failures in Alloy 718 material
- Completed development of refined microstructural model for radiation-induced swelling in high-fluence core internals
- Measured stress corrosion cracking initiation response in Alloy 690 including effects of cold work, surface damage and dynamic strain
- Completed phase transformation studies in solute addition alloys
- Completed crack growth rate studies of solute addition alloys and comprehensive analysis of crack growth rate as a function of solute addition and commercial microstructure-controlled alloys
- Developed test matrix and irradiation test plan to address the potential loss of efficiency of hydrogen water chemistry to mitigate irradiation assisted stress corrosion cracking (IASCC) in a boiling water reactor (BWR) at high fluence
- Developed initial correlation between localized deformation and IASCC response using bend tests
- Completed mechanical testing and microstructural analysis for pristine cast stainless steel materials
- Completed integration plan for joint cable research with EPRI and other stakeholders
- Completed assessment of experimental work for determining key indicators in aged cables for correlation to nondestructive examination (NDE) techniques
- Completed design of large-scale concrete mockup to study the effects of alkali-silica reaction on shear fracture propagation in stress-confined safety related structures
- Completed assessment of radiation induced aggregate swelling as a degradation mode in irradiated concrete structures
- Completed preliminary conceptual design of a thick concrete NDE specimen
- Developed a unified parameter for characterization of ionizing radiation intended for evaluation of radiation-induced degradation of concrete

- Completed initial investigation of improved volumetric imaging of concrete using an advanced processing technique
- Completed construction of the enclosure for the dedicated welding hot cell
- Completed the first batch of irradiation experiments to produce helium-containing SS304 samples for use in development of weld repair techniques
- Completed analysis of microstructure and basic properties of the procured advanced alloys for the advanced radiation resistant materials program
- Completed Final Expanded Materials Degradation Assessment
- Identified concrete cores for acquisition from Zion Unit 2

Risk-Informed Safety Margin Characterization

- Completed RELAP-7 Theory Manual
- Tested RISMC methodology using an LWR case study for enhanced accident tolerance design changes
- Completed detailed demonstration case study for an emergent issue using RAVEN and RELAP-7
- Completed report of demonstration of nonlinear seismic soil structure interaction and applicability to new system fragility curves
- Completed the preliminary design plan covering requirements, development, and important physics for severe accident analysis
- Documented the approach and results obtained from the modeling and simulation for accident tolerant fuel under accident conditions
- Completed RISMC case study for external event tolerant design changes
- Completed RELAP-7 subchannel flow capability development.
- Completed the RELAP-7 verification and validation plan
- Completed report on more detailed BWR station blackout simulations
- Developed approach for models that will be used to represent concrete degradation in Grizzly

Advanced Instrumentation, Information, and Control System Technologies

- Developed diagnostic and prognostic models for generator step-up transformers
- Developed probabilistic health monitoring framework and demonstrated problem of aging concrete structures
- Completed interim report on the results of the concrete degradation mechanisms and online monitoring techniques survey
- Completed computer based procedures validation study with nuclear power plant personnel
- Developed requirements for control room computer based procedures
- Developed operator performance metrics for use in control room modernization projects
- Completed human factors engineering design phase report for control room mode
- Developed a methodology for conducting baseline human factors and ergonomics review using a host nuclear power plant control room

- Complete Control Room Upgrades Benefit Study Plan describing the study methodologies, industry partners, cost, schedule, facilities, and resources
- Identified advanced outage functions, including the results of the real-time support task involving coordination and automated work status updating
- Developed the requirements for automated work package technologies for a sample of nuclear power plant work processes
- Implemented software tools in the Human Systems Simulation Laboratory that enable fully functional hybrid control room systems
- Completed cyber security program evaluation exercise for the pilot project technologies

Fiscal Year 2013

Materials Aging and Degradation

- Examined reactor surveillance materials from Ringhals and Ginna nuclear power plants
- Executed small-angle neutron scattering experiments of irradiated reactor pressure vessel materials
- Obtained high-strength Ni-base alloys from service and began post irradiation examination
- Completed first stage of stress corrosion cracking initiation testing on Alloy 600
- Measured stress corrosion cracking initiation response in alloy 690 including effects of cold work
- Analyzed recent characterization of irradiated specimens and irradiation-induced phase transformations
- Assessed thermodynamic and kinetic properties for model development of phase transformations
- Developed plans for acquisition and testing of baffle bolts from the Ginna nuclear power plant
- Completed tensile tests of 316 SS base metal specimens and 316 SS - 316 SS similar metal weld specimens under room and elevated temperature and fatigue testing of 316 SS base metal specimens under room temperature and continued activities on mechanistic modeling
- Completed study on mechanisms and mitigation strategies for irradiation assisted stress corrosion cracking of austenitic steels
- Executed constant extension rate tests in 320°C water to determine effect of dose, effect of alloy, and environment on stress corrosion cracking susceptibility
- Analyzed deformation mode changes in irradiated materials using bend tests and finite element modeling
- Completed preliminary listing of aging conditions and measurement methods for physical properties to be examined for key indicators of cable aging
- Completed aging assessment of field returned cables from the High Flux Isotope Reactor, Zion Nuclear Power Station, and Comision National Energia Atomica (Argentina)
- Completed measurements of physical properties on cables subjected to range of accelerated aging conditions, and assessed results for key early indicators of cable aging
- Completed initial rejuvenation and tensile tests on cable specimens
- Completed risk-informed guidelines for evaluating performance of aging safety-related concrete systems, structures, and components

- Completed validation of data contained in the concrete performance database and placed database in public domain
- Identified the state-of-the-art on non-destructive testing methods for assessment of nuclear power plant concrete materials and structures and available concrete samples for nondestructive examination testing, and evaluated ultrasonic techniques
- Defined the envelope of the radiation at the biological shield wall for U.S. commercial nuclear power plants through 80 years
- After tests on base alloy, initiated fatigue tests on welded specimens in air
- Completed proactive welding stress control model development

Risk-Informed Safety Margin Characterization

- Completed technical basis report describing how to perform safety margin configuration risk management
- Upgraded RELAP-7 capabilities through implementation of seven-equation two-phase flow model, including selected major physical components for boiling water reactor primary and safety systems
- Performed a RELAP-7 and RAVEN simulation of a station blackout scenario on a simplified geometry of a boiling water reactor
- Demonstrated proof of concept of the Grizzly component aging model applied to the reactor pressure vessel
- Demonstrated the modeling of late blooming phases and precipitation kinetics in aging reactor pressure vessel steels

Advanced Instrumentation, Information, and Control System Technologies

- Completed technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for large power transformers and emergency diesel generators
- Developed a system for generic implementation of wireless technologies for equipment condition monitoring and its application in a commercial nuclear power plant
- Completed evaluation of final computer-based procedure prototype for field workers
- Developed a Digital Control Room Upgrades reference human factors engineering plan for an optimized, human-factored control board layout
- Developed technologies for an advanced Outage Control Center that improves outage coordination, problem resolution, and outage risk management
- Completed the assembly of the Human Systems Simulation Laboratory and demonstrated its capability to model a hybrid (analog and digital) nuclear power plant control room

Advanced Light Water Reactor Nuclear Fuels

- Documented the SiC joining and irradiation studies and irradiation test preparation activities
- Completed SiC ceramic matrix composite failure mode analysis
- Completed fabrication of SiC ceramic matrix composite – zirconium alloy hybrid cladding prototype samples
- Completed the LWRS Program Fuel Development Material Inventory Database

- Completed plan for transitioning LWRS Program Fuels activities to the Fuel Cycle Technologies Program Advanced Fuels Campaign and established a path forward for communication/coordination between the RISMC Pathway and the Advanced Fuels Campaign

Fiscal Year 2012

Materials Aging and Degradation

- Completed Expanded Proactive Materials Degradation Assessment Report
- Completed planning document on concrete measurements to be performed at the Barsebäck nuclear power plant
- Completed a report on metallurgical examination of the high-fluence reactor pressure vessel (RPV) specimens from the Ringhals nuclear power plants in Sweden
- Completed examination of reactor surveillance specimens from the Ginna, Ringhals, and Palisades nuclear power plants
- Completed initial assessment of feasibility of obtaining concrete core samples from identified candidate sites
- Completed plan for collection of materials from the Nine Mile Point 1 nuclear power plant during their 2013 outage
- Documented results of examinations of the surveillance specimens from the Ginna and Palisades nuclear power plant reactors
- Developed guidelines for risk-informed condition assessment and evaluation of aging concrete
- Completed nondestructive examination (NDE) roadmaps
    - Concrete research and development (R&D)
    - Cables R&D
    - Fatigue damage R&D
    - Reactor pressure vessel R&D
- Completed upgrades to test equipment for evaluation of advanced weldments on irradiated materials
- Completed plan for modeling of high-fluence phase transformations in core internals
- Completed a report on high-fluence effects on microstructural evolution of irradiated materials
- Completed plan for modeling of high-fluence swelling effects in core internals
- Completed a report on evaluating the influence of bulk and surface microstructures on alloy 600 stress corrosion cracking initiation behavior
- Completed a report on high-fluence effects on irradiation-assisted stress corrosion cracking of stainless steels
- Completed research plan for surrogate materials and attenuation studies, building on RPV results and findings in Fiscal Years 2009 to 2012
- Completed review of potential replacement alloys for light water reactors.

Risk-Informed Safety Margin Characterization

- Completed a verification and validation strategy for LWRS Program modeling and simulation activities
- Demonstrated the Risk-Informed Safety Margin Characterization methodology using a test case based on the Idaho National Laboratory's (INL's) Advanced Test Reactor (ATR)
- Completed the RELAP-7 development plan (funded by the Department of Energy [DOE] Nuclear Energy Advanced Modeling and Simulation Program)
- Demonstrated a single-phase, steady-state version of RELAP-7 (funded by the DOE Nuclear Energy Advanced Modeling and Simulation Program)
- Completed the RELAP-7 quality assurance plan (funded by the DOE Nuclear Energy Advanced Modeling and Simulation Program)
- Completed an initial demonstration of the Grizzly model for pressurized thermal shock effects on an aged section of a pressurized water reactor RPV and assess through-wall attenuation effects of embrittlement
- Completed the plan for RELAP-7 support of a boiling water reactor major plant uprate analysis using Risk- Informed Safety Margin Characterization

Advanced Instrumentation, Information, and Control System Technologies

- Completed the Advanced Instrumentation, Information, and Control Systems Technologies Pathway vision document
- Developed prototype technologies for nuclear power plant status control and field work processes, with associated study of field trials at a nuclear power plant
- Developed outage work status capabilities, providing a means for communicating work progress and completion status directly from the field activities to the nuclear power plant outage control centers
- Completed a digital full-scale mockup of a conventional nuclear power plant control room
- Developed guidelines and demonstration technologies for nuclear power plant operations and maintenance work processes
- Completed a report on outage emergent issue resolution capabilities
- Completed a report on strategy and technical plans for online monitoring technologies in support of nondestructive examination deployment
- Completed a report on the online monitoring technical basis and analysis framework for large power transformers
- Completed a report on demonstration and data collection for prototype computer-based procedures

Advanced Light Water Reactor Nuclear Fuels

- Completed the development plan for silicon carbide ceramic matrix composite (SiC CMC) nuclear fuel cladding
- Completed failure mode and performance analysis for SiC CMC
- Documented a plan to codify American Society for Testing and Materials standards for ceramic composites for nuclear applications
- Documented the required analyses to support irradiation readiness for SiC CMC rodlets in the INL's ATR

- Completed fuel clad trade-off study
- Documented the status of irradiation test preparation activities for the joining and irradiation studies
- Completed the design and installation of a nuclear fuel cladding test system that simulates nuclear fuel heating and provides a steam atmosphere
- Selected two industry proposals for SiC CMC joining technology development.

Fiscal Year 2011

- Completed a report documenting information gaps on concrete performance and cable aging degradation from an examination of the R. E. Ginna nuclear power plant during the calendar year 2011 refueling outage
- Published an implementation plan for the development of a nuclear concrete materials database
- Developed a baseline computational model for proactive welding stress management to suppress helium induced cracking during weld repair
- Completed an initial assessment of thermal annealing needs and challenges, assessment of needs for environmental fatigue under extended service conditions, assessment of alloy options and performed alloy downselect, evaluation of in-situ cable repair, and assessment of further irradiation experiment needs
- Published the II&C industry working group vision document for II&C technologies
- Began pilot projects on real-time configuration management and control to overcome limitations with existing permanent instrumentation and real-time awareness of plant configurations
- Completed fueled irradiation safety case documentation to support irradiations in the Idaho National Laboratory Advanced Test Reactor
- Completed initial evaluations of prototype fuel rodlets
- Completed a report documenting the results of collaborations with EPRI/industry to identify, define and prioritize power uprate challenges and develop power uprate R&D strategies.

Fiscal Year 2010

- Completed literature review on concrete durability and aging
- Completed the planning document for harvesting material from the R. E. Ginna and Nine Mile Point nuclear power plants
- Completed report on architectural and algorithmic requirements for a next-generation system analysis code for that can be used to support the safety case of the LWR life extension.

Fiscal Year 2009

Fiscal year 2009 was primarily a planning year. The LWRS Program Plan was issued, a workshop on advanced fuel design was held, and a report on testing and analysis of reactor degradation was completed.

Appendix B

Chronological Listing of Planned LWRS Program Milestones

Appendix B
Chronological Listing of Planned LWRS Program Milestones

This appendix has a chronological listing of the milestones discussed in the pathway plan descriptions in Sections 2 through 5.

Materials Aging and Degradation Pathway

- (2015) Complete revised joint plan with EPRI for very high fluence testing of core internals
- (2015) Complete Phase 1 mechanistic testing for SCC research
- (2015) Complete base model development for environmentally assisted fatigue in LWR components
- (2015) Deliver unified parameter to assess irradiation-induced damage in concrete structures
- (2015) Complete assessment of cable insulation degradation precursors to correlate with performance and NDE signals
- (2015) Demonstrate initial solid-state welding on irradiated materials
- (2015) Document the Status of the Service Harvested Materials Database
- (2016) Provide validated model for transition temperature shifts in RPV steels.
- (2016) Complete a detailed review of the NRC Pressurized Thermal Shock (PTS) re-evaluation project relative to the subject of material variability and identify specific remaining issues
- (2016) Complete postirradiation testing and examinations of swelling in LWR components and materials
- (2016) Deliver predictive capability for swelling in LWR components
- (2016) Complete prototype proof-of-concept system for NDE of concrete sections
- (2016) Complete analysis of key degradation modes of cable insulation
- (2017) Deliver experimentally validated, physically-based thermodynamic and kinetic model of precipitate phase stability and formation in Alloy 316 under anticipated extended lifetime operation of LWRs
- (2017) Complete experimental validation and deliver model for environmentally assisted fatigue in LWR components
- (2017) Complete analysis of cast austenitic stainless steel specimens harvested from service conditions
- (2017) Complete assessment of cable degradation mitigation strategies
- (2017) Demonstrate field testing of prototype system for NDE of cable insulation
- (2017) Complete down-select of candidate advanced alloys following ion irradiation campaign
- (2018) Complete analysis and simulations of aging of cast austenitic stainless steel components and deliver predictive capability for cast austenitic stainless steel components under extended service conditions.
- (2018) Complete model tool to assess the impact of irradiation on structural performance for concrete components

- (2018) Complete prototype of concrete NDE system
- (2018) Complete transfer of weld-repair technique to industry
- (2019) Complete analysis of hardening and embrittlement through the RPV thickness for the Zion RPV sections.
- (2019) Deliver predictive model capability for IASCC susceptibility
- (2019) Deliver predictive model capability for Ni-base alloy SCC susceptibility
- (2019) Deliver predictive model for cable degradation
- (2019) Deliver predictive capability for end-of-useful life for cable insulation
- (2020) Complete model tool to assess the combined effects of irradiation and alkali-silica reactions on structural performance for concrete components
- (2021) Complete reirradiation on RPV sections following thermal annealing
- (2024) Complete development and testing of new advanced alloy with superior degradation resistance with Advanced Radiation Resistant Materials partners
- (2025) Complete characterization of RPV sections (harvested from a reactor) that have been irradiated, annealed (post-harvesting), and then reirradiated in a test reactor.

Risk-Informed Safety Margin Characterization Pathway

- (2015) Release the beta version of RELAP-7, including limited benchmarking
- (2015) Complete report on advanced seismic soil structure modeling
- (2016) Demonstrate margins analysis techniques by applying to performance-based Emergency Core Cooling System (ECCS) Cladding Acceptance Criteria
- (2016) Demonstrate margins analysis techniques by applying to enhanced external hazard analysis (seismic and flooding)
- (2016) Release the beta version 1.0 of Grizzly. This will include engineering fracture analysis capability for RPVs, with an engineering model for embrittlement, and a modular architecture to enable modeling of aging mechanisms.
- (2016) Complete the optimized and validated version of RELAP-7 that couples to RAVEN and to other applications (e.g., aging and fuels modules), for use as a balance-of-plant capability for multi-dimensional core simulators
- (2016) Grizzly (RPV) is validated against an accepted set of data.
- (2016) RELAP-7 is validated against an accepted set of data.
- (2016) Release the beta version of initial flooding model.
- (2016) Beta 1.5 release of RELAP-7 with improved closure relationships and steam/water properties, completed LWR 0D components (such as jet pump and accumulator), improved LWR components (1D-2D downcomer, 1D pressurizer, optional steam generator designs such as helical), tightly coupled multi-physics fuels performance (NEAMS code BISON), and single-phase 3D subchannel flow capability
- (2017) Complete the technical basis reports for Risk-Informed Margins Management.
- (2017) Apply margins analysis techniques to reactor containment analysis including hardened reliable vents, and shallow and deep-water flooding and seismic events.

- (2017) Complete a full-scope margins analysis of a commercial reactor power uprate scenario. Use margins analysis techniques, including a fully coupled RISMC Toolkit, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of long-term operation or assessment of the safety benefit of advanced fuel forms). Test cases will be chosen in consultation with external stakeholders.
- (2017) Demonstrate margins analysis techniques, including a fully coupled RISMC toolkit, for long-term coping studies to evaluate FLEX for extended station blackout conditions.
- (2017) Release the beta version 2.0 of Grizzly. This version will include capabilities for modeling selected aging mechanisms in reinforced concrete and for engineering probabilistic RPV fracture analysis
- (2017) Completed software that couples RAVEN to other applications (e.g., aging and fuels modules), for use as a balance-of-plant capability for multi-dimensional core simulators
- (2017) Compete flooding fragility experiments for mechanical components
- (2017) Release beta version of seismic probabilistic risk assessment model.
- (2017) Flooding model is validated against an accepted set of data.
- (2017) Beta 2.0 release of RELAP-7 with selected separate effects tests for validation data sets, validation of 3D single-phase subchannel, preliminary 3D two-phase (7-equation) subchannel, multi-physics coupling to reactor physics (NEAMS codes Rattlesnake and MAMMOTH).
- (2018) Grizzly (concrete) is validated against an accepted set of data.
- (2018) Release advanced flooding analysis tool suitable for ocean- and river-based flooding scenarios.
- (2018) Compete flooding fragility experiments for electrical components
- (2018) Initial demonstration RPV steel embrittlement using a bottoms-up, lower length scale model to capture causal mechanisms of embrittlement.
- (2018) Flooding fragility models for mechanical components are validated against an accepted set of data.
- (2018) Beta 3.0 release of RELAP-7 with additional validation and full multi-physics coupling, validated 3D two-phase subchannel capability, and implementation of droplet model for BWR SBO scenario, reflood phenomena under loss-of-coolant accident, and PWR feed and bleed process.
- (2018) Version 1.0 release of RELAP-7 with validation with selected integral effect tests, demonstration of large break loss-of-coolant accident, and three-field flow model, water, steam, droplets.
- (2019) Apply margins analysis techniques to evaluation of spent fuel pool issues.
- (2019) Compete seismic experiments for critical phenomena.
- (2019) Release beta version 3.0 of Grizzly. This version includes capabilities for modeling selected aging mechanisms in reactor internals.
- (2019) Flooding fragility models for electrical components are validated against an accepted set of data.
- (2020) Ensure development and validation to the degree that by the end of 2020, the margins analysis techniques and associated tools are an accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment.

- (2020) Implement risk-informed margins management module in RISMC Toolkit that will perform analyst-augmented evaluation of facility safety to search for vulnerabilities and potential management strategies.
- (2020) Grizzly (core internals) is validated against an accepted set of data.

Advanced Instrumentation, Information, and Control Systems Technologies Pathway

- (2015) Conclude the field evaluation of the added functionality and new design concepts of the prototype computer-based procedure system, evaluating at a host utility the revisions made to the system to ensure it encompasses a broad variety of procedures, instructions, and usage scenarios.
- (2015) Develop an automated work package prototype that supports paperless work flow and improved human performance.
- (2015) Develop of improved graphical displays for an Advanced Outage Control Center, employing human factors principles for effective real-time collaboration and collective situational awareness.
- (2015) Develop select prognostic models for active components in nuclear power plants.
- (2015) Develop a passive component monitoring framework for aging effects in nuclear plant materials
- (2015) Complete a Digital Architecture Requirements Report documenting the information technology requirements for advanced digital technology envisioned to be applied to nuclear power plant work activities.
- (2015) Complete a Digital Architecture Gap Analysis Report documenting the gap between current typical instrumentation and control and information technologies capabilities in nuclear power plants vs. those documented in the Digital Architecture Requirements Report.
- (2015) Develop a Distributed Control System Prototype - Using a participating utility's simulator plant model installed at the HSSL, develop a functional prototype for the turbine control system upgrade. Document the design, development, and functionality of the prototype replacement system.
- (2015) Develop prognostic software for control indicators. Provide demonstration and software for prognostic system and display interface for installation at the HSSL.
- (2015) Develop Operator Performance Metrics for Verification and Validation - Document the process how simulator studies should be performed including the various operator performance metrics that can be collected in support of control room upgrades.
- (2015) Develop a prototype of an advanced hybrid control room in the HSS that includes advanced operator interface technologies such as alarm management systems, computerized procedures, soft controls, large displays, and operator support systems.
- (2015) Test HSSL Systems in Preparation for Conducting Benefits Study with Operators - Test HSSL systems in representative configurations to verify that systems are able to function reliably in operational sequences and scenarios, test data logging and collection systems, and verify the stability of different combinations of digital systems with human interactions in preparation for data collection with actual operating crews.
- (2016) Develop technology for real-time plant configuration status during outages to improve work coordination, efficiency, and safety margin.

- (2016) Develop a passive component monitoring framework for aging effects of piping and primary and secondary system components in nuclear plant materials
- (2016) Publish interim guidelines to implement technologies for human performance improvement for nuclear power plant field workers.
- (2016) Publish interim guidelines to implement technologies for improved outage safety and efficiency.
- (2016) Publish interim guidelines to implement technologies for centralized online monitoring and information integration.
- (2017) Integrate the automated work package with a wireless plant surveillance system and demonstrate self-documenting work packages for nuclear power plant surveillances.
- (2017) Publish a report on automated work package implementation requirements for both nuclear power plant field worker usage and self-documenting surveillances
- (2017) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers.
- (2017) Develop and demonstrate (in the HSSL) technologies for detecting interactions between plant status (configuration) states and concurrent component manipulations directed by in-use procedures, in consideration of regulatory requirements, technical specifications, and risk management requirements (defense-in-depth).
- (2017) Develop diagnostic and prognostic models for second large passive plant component based on the information integration framework.
- (2017) Develop and demonstrate (in HSSL) concepts for an advanced online monitoring facility that can collect and organize data from all types of monitoring systems and activities and can provide visualization of degradation where applicable.
- (2017) Complete a Digital Architecture Implementation Guideline, documenting a graded approach in applying the conceptual model to selected digital technologies and in determining the incremental information technologies requirements based on a current state gap analysis.
- (2017) For nuclear power plant operations activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2017) Publish a report documenting the Control Room Upgrades Benefit Study that presents the data, findings, and conclusions on performance improvements that can be obtained through the technologies of an advanced hybrid control room.
- (2017) Develop concepts for using nuclear power plant full-scope simulators as operator advisory systems in hybrid control rooms and complete a technical report on prototype demonstrations in HSSL.
- (2018) Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, and restricted boundaries) for mobile plant workers.
- (2018) Develop and demonstrate (in the HSSL) technologies to detect undesired system configurations based on concurrent work activities (e.g., inadvertent drain paths and interaction of clearance boundaries).

- (2018) Develop and validate a health risk management framework for concrete structures in nuclear power plant, demonstrate for illustrative concrete structures in the nuclear power plant environment, and develop an implementation strategy for nuclear power plants.
- (2018) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for second large passive plant component, involving nondestructive examination-related online monitoring technology development, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.
- (2018) Develop and demonstrate (in HSSL) concepts for real-time information integration and collaboration on degrading component issues with remote parties (e.g., control room, outage control center, systems and component engineering staff, internal and external consultants, and suppliers).
- (2018) For nuclear power plant chemistry activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2018) Develop concepts for a real-time plant operational diagnostic and trend advisory system with the ability to detect system and component degradation and complete a technical report on prototype demonstrations in HSSL.
- (2018) Publish final guidelines to implement technologies for improved outage safety and efficiency.
- (2018) Publish final guidelines to implement technologies for centralized online monitoring and information integration.
- (2018) Publish interim guidelines to implement technologies for a hybrid control room.
- (2019) Publish a technical report on augmented reality technologies developed for nuclear power plant field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.
- (2019) Develop a real-time outage risk management strategy and publish a technical report to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.
- (2019) Develop a digital architecture and publish a technical report for an advanced online monitoring facility, providing long-term asset management and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.
- (2019) For chemistry activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2019) Develop and demonstrate (in HSSL) concepts for a management decision support center that incorporates advanced communication, collaboration, and display technologies to provide enhanced situational awareness and contingency analysis.
- (2019) For nuclear power plant maintenance activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.

- (2019) Develop an operator advisory system fully integrated into a control room simulator (HSSL) that provides plant steady-state performance monitoring, diagnostics and trending of performance degradation, operator alerts for intervention, and recommended actions for problem mitigation, with application of control room design and human factors principles.
- (2019) Publish final guidelines to implement technologies for human performance improvement for nuclear power plant field workers.
- (2020) Publish a technical report tests of fiber optic systems and correlation of strain measurements with piping wall thickness, piping performance, and relationship with existing plant technical specifications for risk informed technical specification implementation.
- (2020) For maintenance activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2020) For nuclear power plant radiation protection activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2020) Complete a technical report on operator attention demands and limitations on operator activities based on the current conduct of operations protocols. This report will identify opportunities to maximize operator efficiency and effectiveness with advanced digital technologies.
- (2020) Publish revised interim guidelines to implement technologies for integrated operations.
- (2021) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for flow assisted corrosion, and integrate these with industry standards and guidance (e.g., EPRI CheckWorks, etc.).
- (2021) For radiation protection activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for an automated plant. Demonstrate representative remote activities with a host nuclear power plant.
- (2021) Develop and demonstrate (in HSSL) prototype plant control automation strategies for representative normal operations evolutions (e.g., plant start-ups and shut-downs, equipment rotation alignments, and test alignments).
- (2021) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, based on an operator advisory system that provides real-time situational awareness, prediction of the future plant state based on current conditions and trends, and recommended operator interventions to achieve nuclear safety goals.
- (2021) Publish interim guidelines to implement technologies for an automated plant.
- (2021) Publish revised interim guidelines to implement technologies for a hybrid control room.
- (2022) Publish human and organizational factors studies and a technical report for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically dispersed nuclear power plant support organization.

- (2022) Develop and demonstrate (in HSSL) prototype plant control automation strategies for representative plant transients (e.g., loss of primary letdown flow or loss of condensate pump).
- (2022) Publish final guidelines to implement technologies for integrated operations.
- (2023) Develop and demonstrate (in HSSL) prototype mobile technologies for operator situational awareness and limited plant control capabilities for nuclear power plant support systems (e.g., plant auxiliary systems operations and remote panel operations).
- (2024) Develop and demonstrate (in HSSL) concepts for advanced emergency response facilities that incorporate advanced communication, collaboration, and display technologies to provide enhanced situational awareness and real-time coordination with the control room, other emergency response facilities, field teams, the Nuclear Regulatory Commission, and other emergency response agencies.
- (2024) Develop and demonstrate (in HSSL) new concepts for remote operator assistance in high activity periods (e.g., refueling outages) and accident/security events, allowing offsite operators to remotely perform low safety-significant operational activities, freeing the control room operators to concentrate on safety functions.
- (2025) Publish human and organizational factors studies and a technical report for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.
- (2025) Develop the strategy and priorities and publish a technical report for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.
- (2025) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities and the ability to interact with other control centers (e.g., emergency response facilities for severe accident management guidelines implementation).
- (2025) Publish final guidelines to implement technologies for an automated plant.
- (2025) Publish final guidelines to implement technologies for a hybrid control room.

Reactor Safety Technologies Pathway

- (2015) Complete gap analysis on accident tolerant components and severe accident analysis
- (2015) Develop recommendations for accident tolerant sensor development based on evaluation of a PWR severe accident scenario.
- (2015) Develop recommendations for accident tolerant sensor development based on evaluation of a BWR severe accident scenario
- (2015) Complete reactor core isolation cooling analytical model and a draft testing program
- (2015) Complete a MELCOR/MAAP comparison of analyses of the events at Fukushima Daiichi.
- (2015) Complete analysis of uncertainties in MELCOR calculations as applied to the events at Fukushima Daiichi.

- (2015) Complete US input towards a forensics examination plan for Fukushima Daiichi
- (2017) Complete MAAP-MELCOR crosswalk Phase2 with collaboration between EPRI, DOE labs, NRC and possibly French and Japanese partners.
- (2019) Complete water management severe accident analysis in support of BWR ex-vessel mitigating strategies