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Revision 6

DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operations Program – Joint Research and Development Plan

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DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operations Program – Joint Research and Development Plan

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April 2017

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SUMMARY

Nuclear power has safely, reliably, and economically contributed almost 20% of the total amount of electricity generated in the United States over the past two decades. High capacity factors and low operating costs make nuclear power plants some of the most economical power generators available. Further, nuclear power remains the single largest contributor (more than 60%) of non-greenhouse-gas-emitting electric power generation in the United States. Even when major refurbishments are performed to extend operating life, these plants continue to represent cost-effective, low-carbon assets to the nation's electrical generation capability.

As of March 2017, 87[a] commercial nuclear power plants in the United States have received a renewed operating license from the U.S. Nuclear Regulatory Commission (NRC), permitting those plants to operate up to 60 years. By the end of 2017, more than one-third of the existing domestic fleet will have passed their 40th anniversary of power operations and about one-half of the fleet will reach the same 40-year mark within this decade. A regulatory process exists (10 CFR Part 54) for obtaining approval from NRC on extended nuclear power plant operations beyond 60 years. However, NRC will require nuclear power plants that choose to apply for a second renewal of their operating license (identified as "Subsequent License Renewal" by NRC; industry uses the term "Second License Renewal") to demonstrate that adequate design and operational safety margins will be maintained over the duration of the extended operations period.

While recent, overall performance has been excellent (i.e., average capacity factors exceeding 90%), the fleet continues to face a number of technical challenges related to long-term operations. If current nuclear power plants do not operate beyond 60 years, the total fraction of domestic electrical energy generated from nuclear power will begin to decline—even with the expected addition of new nuclear generating capacity. Replacing these units will require long-lead planning periods (i.e., 10 to 15 years prior to unit retirement). In addition, significant capital investments (i.e., hundreds of billions of dollars) will be needed to design, construct, and commission the replacement generation capacity. Further, if the new capacity has to meet any carbon-neutral criteria (i.e., the replacement units must not produce more greenhouse gas emissions than the units being retired), costs for replacement generation capacity will be even higher.

Recognizing the challenges associated with pursuing extended service life of commercial nuclear power plants, the U.S. Department of Energy's (DOE) Office of Nuclear Energy (NE) and the Electric Power Research Institute (EPRI) have established separate but complementary research and development (R&D) programs (DOE-NE's Light Water Reactor Sustainability [LWRS] Program and EPRI's Long Term Operations [LTO] Program) to address these challenges. Since calendar year 2010, the LWRS and LTO Programs have cooperatively pursued extensive, long-term R&D activities related to the ability (from a

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[a] Three units with renewed licenses (Kewaunee, Vermont Yankee and Fort Calhoun) have since been permanently closed.

material and economic perspective) of operating the existing fleet for periods up to 80 years and beyond. Contributions to-date have advanced the state of knowledge on the measured and predicted performance of materials (e.g., metals, concrete, and cabling) used in nuclear power plant systems, structures, and components; improved analysis methods and tools for understanding safety margins; and advanced instrumentation, information, and control technologies with no generic technical barriers identified that would make long-term plant operations infeasible. The R&D activities of both programs, including progress achieved and plans for continued work, are described herein.

To ensure that a proper linkage is maintained between the programs, DOE-NE and EPRI executed a memorandum of understanding to "establish guiding principles under which research activities (between the LWRS and LTO Programs) could be coordinated to the benefit of both parties." The memorandum of understanding calls for DOE-NE and EPRI to "provide and annually update a coordinated plan for the LWRS and LTO Programs. The plan should provide for the integration of the separate LWRS and LTO Program plans at the project level, showing project scope, schedule, budgets, and key interrelationships between the LWRS and LTO Programs, including possible cost sharing." This document represents the sixth annual revision to the initial version (March 2011) of the plan, as called for in the memorandum of understanding.

CONTENTS

TABLES

ACRONYMS

AMP	aging management program
ASR	alkali-silica reaction
ASSW	austenitic stainless steel welds
BWR	boiling water reactor
CASS	cast austenitic stainless steel
DOE	U.S. Department of Energy
EAF	environmentally assisted fatigue
EMDA	Expanded Materials Degradation Assessment
EPRI	Electric Power Research Institute
HSSL	Human Systems Simulation Laboratory
IASCC	irradiation-assisted stress corrosion cracking
I&C	instrumentation and control
II&C	instrumentation, information, and control
ILCM	integrated life-cycle management
IMT	Issues Management Table
INL	Idaho National Laboratory
ITT	Issue Tracking Table
LTO	Long-Term Operations
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
MAaD	materials aging and degradation
MDM	materials degradation matrix
MOOSE	Multi-physics Object Oriented Simulation Environment
NDE	nondestructive examination
NE	Office of Nuclear Energy

NEI	Nuclear Energy Institute
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
R&D	research and development
RAVEN	Reactor Analysis and Virtual Control ENvironment
RELAP	Reactor Excursion and Leak Analysis Program
RIMM	risk-informed margin management
RISMC	risk-informed safety margin characterization
RPV	reactor pressure vessel
RST	reactor safety technologies
SLR	Second License Renewal (Subsequent License Renewal for NRC)
SSC	systems, structures, and components

DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operations Program – Joint Research and Development Plan

1. BACKGROUND

1.1 U.S. Department of Energy Office of Nuclear Energy

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE) conducts research and development (R&D) on nuclear energy to advance nuclear power as a resource capable of meeting U.S. energy, environmental, and energy security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration activities, as appropriate. DOE-NE's Office of Light Water Reactor Deployment, NE-52, and the program Technical Integration Office, located at the Idaho National Laboratory (INL), manage R&D efforts under the Light Water Reactor Sustainability (LWRS) Program.

1.2 Electric Power Research Institute

The Electric Power Research Institute (EPRI) conducts R&D in the public's interest, mostly with funding provided by its membership and the electric utility industry, with respect to the production, transmission, distribution, and utilization of electric power, including research designed to improve the safety, reliability, and economy of nuclear power plants. R&D efforts in the Long-Term Operations (LTO) Program are managed as a separate technical program operating in the Plant Support Department of the EPRI Nuclear Power Sector, with the guidance of an industry advisory Integration Committee.

1.3 Research and Development Cooperation

DOE-NE and EPRI R&D activities directed at providing the technical foundations for licensing and managing the long-term safe and economical operation of commercial nuclear power plants are described in the following documents:

1. LWRS Program Integrated Program Plan (February 2017)

2. EPRI Long Term Operations Strategic Roadmap (January 2017).

In late 2010, DOE-NE and EPRI executed a memorandum of understanding[b] to "establish guiding principles under which research activities (between the LWRS and LTO Programs) could be coordinated to the benefit of both parties." This cooperation includes the sharing of responsibilities (leadership and financial) for conducting portions of large, multi-year R&D projects; the exchange of information on R&D work in areas of mutual interest; and participation in periodic conference calls and meetings (technical and budget reviews) for the other program.

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b. "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. This memorandum of understanding has been replaced by a new memorandum of understanding, dated December 15, 2015, between DOE-NE and EPRI on "Cooperative Nuclear Power Research." The language on cooperation between the LWRS and LTO Programs has been retained in an addendum to the new memorandum of understanding.

The work funded and managed by DOE under the LWRS Program is laid out along the following R&D pathways:

1. Materials Aging and Degradation (MAaD)
2. Risk-Informed Safety Margin Characterization (RISMC)
3. Advanced Instrumentation, Information, and Control (II&C) Systems Technologies
4. Reactor Safety Technologies (RST).

The work funded and managed by EPRI under their LTO Program is organized and managed in the following work areas:

1. Primary System Metals Aging
2. Concrete Structures, including Containment Degradation
3. Cable Aging
4. Instrumentation and Control (I&C) and Information Technology (including online monitoring of critical equipment)
5. Advanced Safety and Risk Analysis Tools
6. Aging Management Program Scope for Operation Beyond 60 Years
7. Integrated Strategy, Process Plan, and Demonstration Plants.

As acknowledged in the memorandum of understanding, “the technical areas above encompassing each participant’s work scope are roughly the same;” that is, both organizations have the same objectives to deliver technology on critical issues in a timely manner to inform decisions on life extension and license renewal. LTO Technical Area 6, Aging Management Program Scope for Operation Beyond 60 Years, currently is an exception for which there is no corresponding LWRS Program pathway. In a few cases, activities are highly collaborative and co-funded — both organizations fund the same activity with the same deliverable. However, in most cases, as stated in the memorandum of understanding, “…the planned work in each program is distinctly different as the result of planning that reduces duplication of effort and takes into account each party’s interests and strengths.”

At the center of DOE’s interest is work to develop new scientific knowledge, models, tools, and technology. DOE brings the strong expertise of national laboratory investigators, unique laboratory capabilities, and relationships with universities and other laboratories. At the center of EPRI’s interest are adaptation, validation, and implementation of technology with deliverables such as databases, guidelines, and pilot applications. EPRI brings global leadership in conducting public interest R&D with collaboration from nuclear utilities. Through joint planning and defined cooperation, the intent is to leverage diversity between the LWRS and LTO Programs to more efficiently and effectively meet the joint objectives.

2. DESCRIPTION OF RESEARCH AND DEVELOPMENT PROGRAMS

2.1 Department of Energy Office of Nuclear Energy Light Water Reactor Sustainability Program

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 hardware so the nuclear power plant lifetime can be extended and the nuclear power plants can continue to operate safely, efficiently, and economically; and (2) provide science-based solutions to industry to implement technology to exceed the performance of the current labor-intensive business model and practices.

In April 2010, DOE-NE’s R&D Roadmap was issued. The 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 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 systems, structures, and components (SSCs) as they age in environments associated with continued long-term operation of 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

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

Through the LWRS Program, DOE collaborates with industry and interfaces with the U.S. Nuclear Regulatory Commission (NRC) in appropriate ways to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, nuclear power plant license extensions, and age-related regulatory oversight decisions. The DOE role focuses on aging phenomena and issues that require long-term research and are generic to reactor type.

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

1. ***MAaD*** with R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. This work will provide data and methods to assess the performance of SSCs essential to safe and sustained nuclear power plant operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant SSCs that are subject to long-term operating conditions, providing key input to both regulators and industry.

2. ***RISMC*** with 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 margin quantification and (2) create advanced tools for safety assessment that enable more accurate representation of nuclear power plant safety margins and their associated influence on operations, reliability 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 nuclear power plant

safety and operational margins and permits cost-effective management of those margins during periods of extended operation.

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

4. ***RST*** with 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 (LWR) fleet.

Public Law 109-58 (National Energy Policy Act of 2005, EPAct 2005) and Congressional language establish a clear expectation that the DOE-NE funding for LWRS Program activities will be supported by industry to “cost share” the overall R&D effort. Cost sharing of LWRS Program R&D projects by industry ensures that federal funding is leveraged on the most important technical challenges relative to long-term operations of the current reactor fleet. Each LWRS Program pathway considers cost-share contributions from industry as part of the R&D selection process. In 2017, the value of industry cost sharing for LWRS Program R&D activities is approximately $41.04 million. This compares to 2015 and 2016 values of $30.45 million and $38.56 million, respectively. The major elements of this cost sharing include the value of in-kind contributions of services/resources (i.e., subject matter expert involvement in R&D projects, shared test data, and donated/shared materials for testing). Details are provided in Appendix A of this plan.

2.2 Electric Power Research Institute Long Term Operations Program

High capacity factors and low operating costs make nuclear power plants some of the most safe and most economical power generators available. Even when major plant components must be upgraded to extend operating life, nuclear power plants often represent a safe, cost-effective, low-carbon asset. The decision to extend nuclear power plant life involves inter-related technical, economic, regulatory, and public policy issues. Unknown or uncertain technical inputs impact the decision-making process both directly and indirectly (i.e., directly through design and operational contingencies and indirectly through impacts on regulatory actions and public policy).

Recognizing the many technical challenges confronting nuclear power plant operation, EPRI launched the LTO Project in 2009. LTO is defined as being high-performance nuclear power plant operation under extended service conditions. High performance is measured by reliability, availability, cost of operations, and safety.

The LTO Project at EPRI is justified by the potential benefits that long-term operations present to society and to member companies. In 2011, the EPRI LTO Project was elevated to program status and is funded by all EPRI Nuclear Sector members. However, success is contingent on timely and useful products. LTO products must provide a sound technical basis for decisions necessary to achieve high-performance nuclear power plant operation under extended service conditions. Specifically, LTO Program projects must address one or more of the following:

1. License renewal for long-term nuclear power plant operation
2. Aging management and life-cycle management throughout long-term operation
3. Opportunities for modernization and performance improvement.

Criteria for selecting technical areas and specific work scopes within technical areas are as follows:

1. Projects address one or more of the following needs:
   a. Identify and characterize (or dismiss) a potential life-limiting issue
   b. Support aging management and life-cycle management
   c. Provide opportunities for modernization
   d. Develop enabling technology (e.g., analysis methods) that will be needed to enhance performance or reduce cost.
2. Useful results are planned for the timeframe up to 2019 to support the expected need for decision making.
3. It is unlikely that planned R&D would be performed within other programs at EPRI.
4. EPRI involvement is necessary to provide industry input to R&D efforts with collaborating partners such as the DOE-NE LWRS Program or NRC's Office of Nuclear Regulatory Research.

The R&D portfolio addresses the following seven technical areas and associated principal objectives:

1. For ***primary system metals***, characterize the conditions and parameters associated with aging degradation, develop data resources and predictive models for remaining useful life, and provide methods to mitigate risk and manage component aging throughout life. Importantly, research results are incorporated into EPRI Inspection and Evaluation (I&E) guidance reports that are used by utilities in their aging management programs. These guideline documents are produced by the appropriate EPRI Technical Program having oversight of the affected components. Selected individual projects addressing this objective include the following:
   a. Revisions to the Materials Degradation Matrix and Issues Management Tables to include Degradation Mechanisms to 80 Years and Beyond
   b. Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components
   c. Identifying Mechanisms and Mitigation Strategies for Irradiation-Assisted Stress Corrosion Cracking of Stainless Steel in LWR Core Components
   d. Reactor Pressure Vessel (RPV) Embrittlement from Long-Term Fluence
   e. Welding of Irradiated Materials for Reactor Internals Repair and Replacement.
   f. Development of Advanced Radiation-Resistant Materials
   g. Improved Evaluation of Environmentally Assisted Fatigue (EAF)

2. For ***concrete structures, including containment***, identify and prioritize degradation mechanisms and locations; establish methods for issue resolution, including new nondestructive examination (NDE) and forensic concrete examination methods; perform prognostic modeling to determine remaining useful life; and investigate mitigation measures for issues important to long-term operations. As for metal materials, this area will also produce guidance reports to assist utilities in robust aging management of concrete structures.

3. Develop the ***technical basis for aging management and life-cycle management of cables***, specifically, identifying cable aging management activities, classes of cables that can be life limiting, and data and methods for life-cycle management of aging cables. Enhanced testing and end-of-life predictive methods will be investigated.

4 Through support of ***advanced I&C and information technology*** to address obsolescence aging of components and systems. The EPRI LTO program coordinates with the EPRI Nuclear Sector Instrumentation and Control (I&C) Program to develop and transfer advanced I&C and information technologies. These technologies, and the underlying technical knowledge, enable existing and new nuclear plants to tap into functionality and capabilities important in maintaining safe operation, while managing I&C obsolescence and achieving higher levels of equipment reliability and plant productivity.

   The EPRI Instrumentation and Control Program is designed around three main research initiatives, some of which are coordinated with LWRS / LTO:

   (1) Use advanced I&C to improve overall plant health and productivity: Existing plant I&C equipment and functionality do not accommodate up-to-date features and techniques that can reduce costs and enhance reliability and productivity. Expanded capabilities can streamline many plant tasks and procedures to reduce operations and maintenance costs while improving reliability and extending component lifetimes. This research area pursues advanced technologies, such as remote monitoring, wireless communication, early prognosis, and data visualization that can inform maintenance tasks and intervals, on-line equipment condition assessment, self-testing and diagnostics, and access to plant data.

   (2) Develop technologies and technical approaches that reduce the risk of implementing replacement I&C systems: As the nuclear industry transitions from analog to digital technology, there are several I&C-related issues for which the available technical solutions are unclear, incomplete, or evolving. Examples include failure analysis, software common cause failure prevention, cyber security, defense-in-depth and diversity, various design considerations for control rooms, and the impact of new technologies such as field programmable gate arrays. This research area develops the technical bases to support the deployment and licensing of I&C and human system interface (HSI) replacement systems; develops guidelines for implementing new I&C, information, and HSI technologies in nuclear applications; and documents operating experience and lessons learned.

   (3) Improve reliability of existing systems and components: I&C systems such as sensors, printed circuit cards and radiation monitoring systems must be reliable to avoid unplanned plant trips and down-powers. This research area develops generic technical bases for effective maintenance and life-cycle management of I&C systems and components already installed in the plant. Such technical research is required to maintain and improve the reliability of existing I&C systems and equipment. Key research

products include maintenance templates for I&C components to reduce failures and inappropriate maintenance activities.

5. Create ***advanced safety and risk analysis tools*** to address anticipated needs during the period of long-term operation and develop an approach for best estimate safety margins assessments that can identify the contributions of design and operational changes, aging effects, and key uncertainties.

6. Investigate ***aging management program scope*** for long-term operation. Research results and operating experience might identify additional components of concern, failure mechanisms or conditions that would be part of aging management programs for long-term operation. R&D activities will be identified where risk-important gaps exist for aging management activities, including time-limited aging assessments, one-time inspections, and periodic inspections or monitoring.

7. Develop an ***integrated strategy, process plan, and demonstration plants*** to support license renewal, the decision to extend operation, and life-cycle management of assets. Demonstration plants will pilot applications of monitoring methods, inspection guidelines, testing methods, demonstrations of new technologies, and analyses. The principal projects addressing this objective are as follows:

   a. LTO Integration and Collaboration

   b. Lead plant support for second license renewal (SLR) by identifying issues and developing appropriate technical bases to support their license renewal applications to the NRC

   c. Ongoing linkage and coordination with utility and Nuclear Energy Institute (NEI) working groups to address license renewal issues

In addition, a “living” Issue Tracking Table (ITT) maintains visibility on all identified issues and assigned priorities. This table is regularly reviewed for accuracy and completeness by EPRI stakeholders, LWRS Program representatives, a working group from NEI, and EPRI advisors. The objectives and associated projects listed in this document have been selected from high-priority issues in the ITT that meet the selection criteria and have received concurrence of the LTO Program Integration Committee. A copy of the latest ITT (2016) is included as Attachment A to this plan.

Finally, it is important to emphasize that considerable supporting R&D is pursued within EPRI that is driven by current operating nuclear power plant issues rather than by a specific LTO need. For example, buried and underground piping and tank research is an area where the impact is primarily directed at resolving issues for the operating fleet with respect to identifying the extent of in-service degradation and technology to detect and/or mitigate degradation. Additional areas are summarized in Section 5 and include technical bases updates to EPRI technical reports to support SLR, buried piping and tanks, nuclear plant chemistry, and steam generator management program. If appropriate, work with an LTO focus and objective may be identified as the in-progress R&D efforts yield data and direction.

2.3 Reporting of Research and Development Projects

Consistent with the memorandum of understanding, the R&D projects described in the program plans for the LWRS and LTO Programs are presented in this joint plan using the following categories:

1. Section 3 discusses “Coordinated (but independent) Activities,” meaning “in general, work in the category will be managed by either DOE or EPRI, using standard, approved processes for R&D

management. Funding is also likely to be independent for work in this category. Coordination will be limited to joint planning and communications to limit possible overlaps and gaps that may exist in the planned activities."

2. Section 4 discusses "Collaborative Activities," meaning (subject to definitive and legally binding agreements) "DOE and EPRI intend for work in the category to be planned and executed on a collaborative basis. The collaborative efforts between DOE and EPRI may involve joint funding as deemed appropriate by the parties under their respective operational parameters, subject to applicable law and the availability of appropriated funds. DOE and EPRI intend to determine which organization will lead each effort based on which Party is positioned to most efficiently and effectively execute the work."[c]

3. Section 5 (added in 2014) discusses "Program Unique Activities," meaning R&D activities supported by DOE-NE (under the LWRS Program) or EPRI that are not considered (per the memorandum of understanding) to be coordinated or collaborative in nature, yet they add to the body of knowledge that may be consulted by nuclear power plant owners and operators as they weigh the technology, regulatory, and business factors involved with pursuing renewals of their plant's operating license from NRC.

In Sections 3 and 4, work of the lead program for the R&D activity is described first, followed by a similar description of work by the supporting program (in some cases, the lead for the activity is jointly shared by the LWRS and LTO Programs).

Table 1 represents a summary overview of the joint R&D plan. The table lists (beginning in the left column) the LWRS Program's R&D activities, the corresponding (coordinated or collaborative) LTO Program's R&D activities, and the program-unique R&D activities. For the purposes of this plan, multiple R&D activities are, in selected instances, rolled up under a single heading.

Table 1. Summary overview of the joint research and development plan.

LWRS Program R&D Activity	Related LTO Program R&D Activity	Coordinated Activity	Collaborative Activity	Program Unique Activity
Materials Aging and Degradation	Understanding, Prediction, and Mitigation of Primary System Aging Degradation			
Expanded Materials Degradation Assessment				LWRS
	Materials Degradation Matrix and Issues Management Tables			LTO
RPV – High Fluence, Materials Variability, and Attenuation Effects on RPV Steels	RPV Embrittlement from Long-Term Fluence (focus on power reactor surveillance capsules irradiation and analyses)	LWRS-LTO joint lead		

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[c] As committed to in the memorandum of understanding, "DOE and EPRI intend to plan, integrate, and prioritize nuclear R&D in Coordinated Activities and Collaborative Activities, and intend to keep each other informed of meetings, correspondence, and the status of work." Further, the LWRS and LTO Programs are committed to maintaining an inventory of the relevant technical results from these R&D projects and sharing each program's R&D results with the other organization.

LWRS Program R&D Activity	Related LTO Program R&D Activity	Coordinated Activity	Collaborative Activity	Program Unique Activity
Mechanisms of Irradiation-Assisted Stress Corrosion Cracking (IASCC)	IASCC: Identifying Mechanisms and Mitigation Strategies for IASCC of Austenitic Steels and LWR Core Components		LWRS-LTO joint lead	
Irradiation Effects (core internals – IASCC, swelling, phase transformations, and segregation)	Irradiation Effects (core internals – IASCC, swelling, and phase transformations)	LWRS-LTO joint lead		
Crack Initiation in Ni-Base Alloys	Environmental-Assisted Cracking: Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components	LWRS-LTO joint lead		
EAF	EAF – long-term focus; EPRI has a short-term focus effort (i.e., current operating plants) as well	LWRS-LTO joint lead		
Thermal Aging of Cast Austenitic Stainless Steel (CASS)	Thermal Aging of CASS and Stainless Steel Welds	LWRS-LTO joint lead		
Concrete (irradiation effects and alkali silica reaction [ASR])	Comprehensive Aging Management of Concrete Structures		LWRS-LTO joint lead	
Cabling	Technical Basis for Aging Management and Life-Cycle Management of Cables		LWRS-LTO joint lead	
Advanced Weld Repair	Advanced Welding Methods for Irradiated Materials		LWRS-LTO joint lead	
Advanced Replacement Alloys	Advanced Radiation-Resistant Materials Program		LWRS-LTO joint lead	
Thermal (Post-Irradiation) Annealing				LWRS
Integrated Research – International Activities (Halden Project)	Participation in Halden Project	LWRS-LTO joint lead		

LWRS Program R&D Activity	Related LTO Program R&D Activity	Coordinated Activity	Collaborative Activity	Program Unique Activity
Integrated Research – International Activities (Materials Ageing Institute)	Partnership in Materials Ageing Institute (EPRI Nuclear Sector)	LTO lead		
Zion Materials Management and Coordination				LWRS
Baffle Bolt Harvesting and Examination				LWRS
NDE Technologies	Opportunities to Employ NDE Technologies for Automatic, Continuous, In-Situ Monitoring	LWRS-LTO joint lead		
RISMC				
Margins Analysis Techniques and Industry Applications	Enhanced Safety Analysis Capability		LWRS-LTO joint lead	
RISMC Toolkit	Enhanced Risk Assessment and Management Capability	LWRS-LTO joint lead		
External Hazards Experimental Testing				LWRS
Advanced II&C Systems Technologies				
New Instrumentation and Control and Human System Interfaces and Capabilities (including Advanced II&C Pilot Projects)	Requirements Database and Guidelines for Advanced I&C, Human System Interface, and Information Technology	LWRS lead		
Halden Project	Halden Project	LWRS-LTO joint lead		
Centralized Online Monitoring and Information Integration	Centralized Online Monitoring Methodology, Guidelines, and Pilot Studies (Part of Advanced II&C Pilot Projects)	LWRS lead		

LWRS Program R&D Activity	Related LTO Program R&D Activity	Coordinated Activity	Collaborative Activity	Program Unique Activity
Industrial and Regulatory Engagement	Requirements Database and Guidelines for Advanced I&C, Human System Interface, and Information Technology			LWRS
RST				
Gap Analysis				LWRS
Fukushima Inspection Plan				LWRS
Severe Accident Analysis				LWRS
Accident-Tolerant Components				LWRS
Other Projects				
	Technical Bases Updates to EPRI Technical Reports to Support SLR			LTO
	Buried Piping and Tanks			EPRI (Plant Engineering and NDE)
	Nuclear Plant Chemistry			EPRI (Water Chemistry)
	Steam Generator Management			EPRI (Steam Generator Management Program)

3. LIGHT WATER REACTOR SUSTAINABILITY PROGRAM / LONG TERM OPERATIONS PROGRAM – COORDINATED RESEARCH AND DEVELOPMENT ACTIVITIES

R&D Area	MAaD (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LWRS – RPV: High Fluence, Materials Variability, and Attenuation Effects on RPV Steels	**R&D Scope and Objectives:** High-Fluence Effects – The last few decades have seen much progress in developing a mechanistic understanding of irradiation embrittlement for RPVs. 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 long-term aging under irradiation on RPV embrittlement. Acquisition of samples from past programmatic campaigns (e.g., NRC programs), specimens harvested from decommissioned reactors (e.g., Zion Unit 1), surveillance specimens from operating nuclear power plants, and materials irradiated in test reactor campaigns all have value in understanding high-fluence effects. Testing includes impact and fracture toughness evaluations, hardness, and microstructural analysis (i.e., electron microscopy, 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 2017 in a detailed report, along with all supporting research data. Materials Variability and Attenuation Effects – The subject of material variability has experienced increasing attention in recent years as additional research programs began to focus on 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 with 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 (i.e., 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.
LTO – RPV Embrittlement from Long-Term Fluence	**R&D Scope and Objectives:** Currently, RPV embrittlement is not considered to be a life-limiting factor for 60 years of operation because of the relatively low fluence level. However, for 80 or more years, refinement of analysis, testing, and validation of embrittlement models using irradiated samples will be needed. This project will design, fabricate, and irradiate two supplemental surveillance capsules that will provide high-fluence irradiated data in approximately 2027 to support future development of embrittlement trend curves applicable for LWR operation at high fluences. For boiling water reactors (BWRs), an

	integrated program covering all units was implemented to address surveillance material testing for operation through 60 years. This program will need to be extended to address 80 years of operation. Options and implementation plans have been developed, evaluated and reviewed with the NRC. Per industry and NRC feedback, a detailed project plan is being developed for implementation to resolve the BWR surveillance requirements. This project will also support mechanical property testing and then microstructurally characterize pressurized water reactor (PWR) surveillance materials that were irradiated in both PWR and Advanced Test Reactor irradiation environments to identify and quantify potential flux and dose effects. In addition, there is a need to develop new testing methods to extend the use of existing surveillance specimens to generate master curve fracture toughness data. This project will participate in a round robin test program to assess one such method that has been developed.
LWRS – RPV: High-Fluence, Materials Variability, and Attenuation Effects on RPV Steels	**Milestones:** High-fluence effects: • (2017) Provide validated model for transition temperature shifts in RPV steels. • (2019) Complete validation of miniature compact tension test specimen as technique for RPV master curve determination. Future milestones and specific subtasks will be based on the results of the previous years' testing, as well as ongoing, industry-led research. Furthermore, future research will explore attenuation effects through the RPV thickness and mitigation techniques. The experimental data and model development 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; high-quality data can be used to inform operational decisions by industry for the RPV. 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. Materials variability and attenuation effects: • (2018) Complete a detailed review of the NRC pressurized thermal shock re-evaluation project relative to the subject of material variability and identify specific remaining issues. • (2021) 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. These 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.

LTO – RPV Embrittlement from Long-Term Fluence	**Milestones**: This project involves irradiation of supplemental surveillance specimens to high fluence in a PWR. The follow-up testing and analysis must be performed in a laboratory with the capability of handling irradiated materials and reconstituting Charpy specimens. The project requires 10 or more years to complete the work. The work will be coordinated with ongoing and planned work within the PWR Materials Reliability Program and BWR Vessel and Internals Project to address RPV embrittlement after extended operation. • (2015) Continuing participation in round robin testing of a new method to extend the use of existing surveillance specimens to generate Master Curve data. Having earlier tested base metal, the 2015 effort seeks to demonstrate efficacy of the method for weld metal. • (December 2015) Design, fabricate, and insert a supplemental surveillance capsule in a host PWR. • (2016 through 2017) Post-irradiation examination of specimens from ATR-2 irradiation (joint activity with DOE). • (2016) Published an EPRI Report (3002007041) covering evaluation of BWR surveillance specimen options to address 80 years of operation. • (2016 through 2018) Address BWR vessel surveillance requirements for 80 years of operation. Plan submittal to NRC for approval in 2018. • (2016 through 2019) Develop an updated embrittlement trend correlation for prediction of the decrease in upper shelf energy with irradiation and obtain American Society of Mechanical Engineers (ASME) code and regulatory approval.
LWRS – Irradiation Effects (core internals – IASCC, swelling, phase transformations, and segregation)	**R&D Scope and Objectives:** IASCC – 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 will address two high-fluence IASCC issues. The first is to examine and confirm if hydrogenated water chemistry to control crack growth rate in a BWR remains an effective mitigation technique at high dose. This work will also determine the maximum stress intensity factor acceptable as a function of dose to maintain the effectiveness of hydrogenated water chemistry as a mitigation technique. The second goal will be to examine the effect of void swelling on IASCC. Swelling is one of the features that appear at high fluence for PWR core internals. Although the material to be used for this study was not irradiated in PWR-relevant conditions, it provides an opportunity to systematically study the effect of swelling on crack propagation rate. Swelling – 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.

	Phase Transformations – This task will provide detailed microstructural-based analysis through modeling and confirmatory experimental evaluations of phase transformations in key samples and components (both model alloys and service materials). These results will be used to develop and validate a phenomenological model of phase transformations under LWR operating conditions. This will be accomplished through use of computational thermodynamics and extension of models for radiation-induced segregation in austenitic steels and precipitation and growth kinetics of copper-rich and manganese-nickel-silicon-rich precipitates in RPV steels. 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. Segregation – Computational thermodynamic techniques are a recent development and they enable new ways of examining material compatibility and stability. This work will include development of computational tools by coupling a radiation-induced segregation model with computational thermodynamics for simulation of radiation-induced segregation and radiation-induced precipitation in LWR steels. Segregation of solute atoms due to radiation-enhanced diffusion to interfaces (such as grain boundaries) can produce changes in material susceptibility to corrosion attack. Similarly, enhanced solute diffusion to pre-existing or radiation-induced defect structures can result in precipitation of phases that will influence the mechanical properties of the material.
LTO – Irradiation Effects (core internals – IASCC, swelling, and phase transformations)	**R&D Scope and Objectives:** EPRI work on IASCC, swelling, and phase transformations is coordinated under the Materials Reliability Program for PWRs and under the BWR Vessel and Internals Program for BWRs. Significant work, including international cooperative programs, is funded under these two EPRI Programs. For example, the Gondole Project is a multi-national effort that includes EPRI funding that specifically seeks to develop data via test reactor irradiation of prototypical materials to characterize irradiation-induced swelling degradation effects in stainless steels. The current Phase 2 of the project seeks to drive irradiation to doses of 30 dpa. This phase is in progress, with completion expected in 2018. This work contributes to a broader effort on modeling IASCC crack initiation and growth that is expected to result in a mechanistic model by 2020. Additionally, EPRI is performing thermal and irradiation embrittlement studies on weld material removed from the retired Zorita PWR in Spain. This information will be used to inform both PWR and BWR fracture toughness considerations. This effort is in progress and an interim report was completed in 2015. The above research efforts will inform revisions to EPRI guidance documents on aging management of PWR internals. Interim guidance will be developed for lead plant second license renewal applications in the 2018-2019 period. A full revision of the EPRI guidance to encompass all U.S. PWRs is planned for 2020.
LWRS – Irradiation Effects (core internals – IASCC, swelling, phase	**Milestones:** IASCC: • (2018) Complete evaluation of effectiveness of hydrogen water chemistry in crack growth mitigation over normal water chemistry conditions at high fluence in stainless steel.

transformations, and segregation)	The effectiveness of hydrogenated water chemistry as a function of fluence is a collaborative effort with Nippon Nuclear Fuel Development Company to test specimens irradiated in a previous Japanese irradiation program. Results from this task can be used to investigate the potential for IASCC under extended service conditions and potential mitigation techniques and limitations. This work will also extend the mechanistic studies from other tasks in the LWRS Program and can be used to validate predictive models at high fluence. Swelling: • (2017) Deliver predictive capability for swelling and hardening in austenitic steel 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. Development and delivery of 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 because it will permit more focused component inspections, component replacements, and more detailed regulatory guidelines. Phase transformations: • (2018) Deliver an experimentally validated, physically based thermodynamic and kinetic model of precipitate phase stability and formation in austenitic stainless steel under anticipated extended lifetime operation of LWRs. • (2019) Deliver validated model of the mechanisms of high fluence precipitation in RPV alloys. • (2021) Deliver model of high fluence precipitate stability in annealed RPV alloys. The development and delivery of a validated model for phase transformations in core internal components at high fluence is an important step in estimating the useful life of the core internal components. Understanding which components are susceptible to this form of degradation is of value to industry and regulators because it will permit more focused component inspections, component replacements, and more detailed regulatory guidelines. Segregation: • (2018) Development and validation of computational tools for determining thermal segregation and radiation-induced segregation. Validation of tools using experimental radiation-induced segregation and phase stability data will be coordinated with other tasks within the program to provide comparative data from both experimental test reactor and LWR service exposed materials. Solute segregation that is driven by thermal or coupled to radiation will result in changes to materials behavior that impacts stress corrosion susceptibility and influences the overall mechanical performance of materials. The ability to accurately model these effects as a function of exposure variables will allow better prediction of long-term performance and enable more accurate decisions to be made regarding material replacement. Information from this task will provide important information toward development of advanced replacement alloys.

LTO – Irradiation Effects (core internals – IASCC, void swelling, and phase transformations)	**Milestones:** - (2014) Published a report on improved void swelling model (MRP-391, EPRI report #3002003083). - (2015) Interim results of IASCC crack growth and irradiation embrittlement studies on Zorita weld and HAZ material in BWR environments (MRP-392, EPRI report #3002003084). - (2015 through 2022) Additional irradiation of welds and HAZ from Zorita to assess crack growth and fracture toughness. - (2018) Neutron-irradiated materials IASCC testing and reporting. - (2020) Report on IASCC modeling for initiation and cracking growth rate. - (2020) Revised report on Aging Management of PWR Internals (MRP-227, Rev 2).
LWRS – Crack Initiation in Ni-Base Alloys	**R&D Scope and Objectives:** 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 600 and 690 as well as metal weldments (152/52) 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 Ageing 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.
LTO – Environmental-Assisted Cracking: Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components	**R&D Scope and Objectives:** Environmental-assisted cracking of primary system components is the most prevalent degradation mechanism that directly impacts the sustainability of reliable operation of LWRs. To achieve long-term operation, it is imperative to extend the useful life of components in LWRs through better understanding of the crack initiation and propagation processes, improved predictive models, and identify effective countermeasures against SCC. The objectives of this project include the following: - Determine the composition and impedance properties of metal surface oxides resulting from interaction with LWR environments, including the effects of Fe^{2+}, Ni^{2+}, and Zn^{2+} cations, to identify the key process leading to cracking. - Evaluate the effect of Fe^{2+}, Ni^{2+}, and Zn^{2+} cations on oxide properties. - Investigate the influence of hydrogen partial pressure on the damage processes prior to crack initiation in Alloy 600 in PWR primary water. - Understand the mechanistic reasons for the superior performance of Alloy 690 relative to Alloy 600, particularly in the context of long-term performance; such a mechanistic basis will support proposals for optimizing the inspection frequency of Alloy 690 components. - Participate in a collaborative research program in Japan to deepen the understanding of interface oxidation dynamics through the use of in-situ and ex-

	situ measurements by synchrotron x-rays at the Spring-8 synchrotron radiation facility in Japan. • Identify the mechanisms leading to decreased fracture resistance in component materials in LWR environments. • Develop improved prediction models of IASCC initiation and propagation and evaluation methodologies for assessing the reliability of LWR structural materials to support LTO and xLPR (Extremely Low Probability of Rupture) programs. • Develop strategies to mitigate the risk of environmental-assisted cracking degradation and to extend component life, based on a sound mechanistic understanding.
LWRS – Crack Initiation in Ni-Base Alloys	**Milestones:** • (2019) Deliver predictive model capability for Ni-base alloy SCC susceptibility. Completing research to identify the mechanisms and precursor states is an essential step in predicting the extent of this form of degradation under extended service conditions. Understanding the 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 also may 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.
LTO – Environmental-Assisted Cracking: Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components	**Milestones**: Activity 1: In-situ surface oxide film characterization and correlation between oxidation and crack initiation: • (2014) Summarize results of in-situ surface oxide film composition and impedance properties as functions of materials/LWR environment combinations, including the effects of cations (delayed, expected completion in 2016). • (2013 through 2014) Damage Processes Prior to Crack Initiation in Ni Alloys (Published in 2013, EPRI report: 1025119). • (2014) Summarize the results of in-situ surface oxide structure and oxidation kinetics. (Published in 2014 as part of POLIM Project performed in Japan EPRI report: 3002003049). • (2017) Summarize results of grain boundary and surface oxide structure and oxidation kinetics. • (2019) Establish correlation between intergranular oxidation and crack initiation. Activity 2: Local strain-stress behavior associated with crack: • (2019) Establish correlation between grain boundary cohesive strength and SCC initiation. Activity 3: Parametric study and development of mitigation strategy: • (2018) Summary of parametric experiments on crack initiation. • (2020) Development of understanding on overall SCC vulnerability for Alloy 600TT. Activity 4: Modeling (Collaboration with EDF-MAI CORIOLIS Project): • (2012) Program on Technology Innovation: Hybrid Models of SCC Propagation

	for Nickel Alloy Welds in Low-Electrochemical Potential PWR Primary Water Environments (Published as 1024863, February 2012). • (2018) Summary of LOCAL Model for integrated SCC evaluation. • (2020) Summary of applying integrated SCC model for primary system components. Activity 5: Consolidation of Knowledge Base for LTO: • (2017 and 2020) Environmentally-assisted cracking knowledge base updates for LTO.
LWRS – EAF	**R&D Scope and Objectives:** The objective of this task is to model environmentally assisted mechanisms through a mechanistic-based approach that is supported by experimental studies to develop a finite element-based fatigue model. This will provide a capability for extrapolating the severity of the mode of degradation under realistic reactor environment loading cycles and under multi-axial stress states. 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.
LTO – EAF (long-term focus)	**R&D Scope and Objectives:** The lack of definite design rules for EAF creates uncertainty for both new and operating nuclear power plants, where design compliance must be shown for the extended operating period (significant uncertainty for a potential 80-year life). To attain acceptable fatigue usage, design changes that increase design, construction, and operations costs without meaningful safety benefits may be required for previously certified designs, as well as designs currently under review by NRC. Affected items in the design may include materials selection, piping thickness, fitting tolerances, and number and locations of piping supports. Additionally, for license renewal, there is uncertainty as to the requirements that may be imposed by NRC because the scope of locations requiring environmental fatigue analysis is open to interpretation. Several EPRI programs will combine expertise and share final EAF results to address the current data and analysis process. Upon completion of this work, EPRI intends to work through the ASME code process to support effective code revisions that resolve the fatigue issue. These actions will include the following: • Publication of reports and related documents that form the technical basis of code modifications in order to obtain code approval and regulatory acceptance, providing appropriate levels of conservatism. • Development of EPRI guidance and code cases that provide evaluation procedures for assessing fatigue environmental factors that are accepted by regulatory authorities. • Promoting an understanding of new procedures to provide for consistency of application by nuclear power plant vendors, construction firms, and utilities (new and operating plant owners). • Supporting ASME Section III and XI code revisions that permanently include EAF procedures within the body of the code. Note that EPRI continues to perform projects that address fatigue and EAF in the current operating fleet. EPRI is also now considering the potential impacts of fatigue related to flexible operations.

LWRS – EAF	**Milestones:** • (2017) Complete experimental validation and deliver model for EAF in LWR components. • (2018) Begin environmental fatigue assessment of dissimilar metal (508 low alloy steel to 316 grade stainless steel) weldments. Completing research to identify the mechanisms of EAF to support model development is an essential step in 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 EAF will enable more focused material inspections, material replacements, and more detailed regulatory guidelines.
LTO – EAF	**Milestones:** • (2012) Roadmap published (EPRI report 1026724). • (2013) Publish guidance for EAF methodology. (Published as EPRI report 1025823, December 2012). • (2014) Feasibility study to determine code margins versus EAF impact (EPRI report # 3002003922). • (2013 through 2019) Continue international research collaboration with expert panel review and advice. Prototypical testing planned to start in 2017. • (2015 through 2017) Reduce conservatism in ASME fatigue evaluation methodology. • (2013 through 2017) Initiate specimen testing and R&D to resolve EAF knowledge gaps – address inconsistencies in test data vs. operating plants experience on crack initiation. • (2013 through 2018) Formulate and validate models of EAF enhancement and retardation in BWR and PWR environments based on fundamental understanding of EAF.
LWRS – Thermal Aging of CASS	**R&D Scope and Objectives:** In this research task, the effects of elevated temperature service in CASS will be examined. The 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 nuclear power plants during extended service life. Mechanical and microstructural data obtained through accelerated aging experiments and computational simulation will be key input for the prediction of CASS behaviors and for the integrity analyses for various CASS components. In 2015, the work was expanded to include austenitic stainless steel welds (ASSW) as part of the International Nuclear Energy Research Initiative between the U.S. and South Korea. The inclusion of aging effects in ASSW with the CASS alloys is in collaboration with research efforts at the Korea Advanced Institute of Science and Technology. While accelerated aging experiments and computational simulations will comprise most of the knowledge base for CASS/ASSW aging, the data also will be obtained from operational experience. These data are required to validate the accelerated aging methodology. Therefore, in addition to using existing data, 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 an extended lifetime.

LTO – Thermal Aging of CASS and Stainless Steel Welds	**R&D Scope and Objectives:** Review and evaluate all available data on thermal aging in ferritic-austenitic stainless welds and CASS material and at LWR temperatures, as well as effects of thermal aging on mechanical properties and corrosion resistance. Additionally, EPRI is developing probabilistic fracture mechanics evaluation and acceptance criteria for use by currently operating nuclear power plants. A technical report has been developed and shared with ASME Code for incorporation into Code Case N-838. It is currently in the review/approval process.
LWRS – Thermal Aging of CASS	**Milestones:** • (2019) Complete analysis and simulations on aging of CASS components and ASSW with the delivery of predictive capability for components under extended service conditions. • (2022) Evaluation of the combined and synergistic effects of irradiation and thermal aged CASS materials. Completing research to identify potential thermal aging issues for CASS/ASSW components is an essential step to identifying the possible synergistic effects of thermal aging (e.g., corrosion or mechanical) 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. These data also will help close gaps identified in the EPRI Materials Degradation Matrix (MDM) and the Expanded Materials Degradation Assessment (EMDA) reports.
LTO – Thermal Aging of CASS and Stainless Steel Welds	**Milestones:** • (2014) A technical report has been developed and shared with ASME Code as the basis into Code Case N-838. The Code Case has since been approved.
LWRS – Integrated Research/ International Collaborations (Halden Project and Materials Aging Institute)	**R&D Scope and Objectives:** Participate in international collaborations that offer opportunities for a broader and more detailed research program than possible in an isolated research program. Coordinated research with international institutions (such as the Materials Aging Institute of which EPRI is a member) will provide more collaboration and cost sharing. In addition, research opportunities through information exchanges with the Halden Project are a planning element of the R&D collaboration.
LTO – Integrated Research/ International Collaborations (Halden Project and Materials Aging Institute)	**R&D Scope and Objectives:** Participate in international collaborations (such as the Halden Project) that offer opportunities for a highly leveraged and more detailed research program than is possible in an isolated research program. Coordinated research with the Materials Aging Institute (of which EPRI is a member) will provide more collaboration and cost sharing.
LWRS – Integrated Research/ International Collaborations	**Milestones:** LWRS milestones related to international collaborations are identified under the specific MAaD R&D areas.

LTO – Integrated Research/ International Collaborations	**Milestones** EPRI membership is at a level above the specific LTO Program focus, such that LTO-relevant R&D is evaluated on a case-by-case basis.
LWRS – NDE	**R&D Scope and Objectives:** NDE R&D is planned for the following MAaD R&D areas: Concrete – Developing new techniques that allow for condition monitoring of concrete structures and components is the objective of this work. This effort includes performing a survey of available samples, developing techniques to perform volumetric imaging on thick reinforced concrete sections, determining physical and chemical properties as a function of depth, developing techniques to examine interfaces between concrete and other materials, developing acceptance criteria (i.e., model and validation), and developing automated scanning systems. This task is collaborative with the Advanced II&C Systems Technologies Pathway. Cabling – The objectives of this task include development and validation of new NDE technologies for the monitoring of cable insulation condition. 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 utilization of 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.
LTO – NDE	**R&D Scope and Objectives:** Identification and management of aging degradation for critical structures and components is fundamental to long-term operation. One-time inspections are specified to establish the extent of degradation; periodic inspections are specified as part of aging management programs. For quantitative and trendable results, NDE technology is used for these inspections. For some degradation mechanisms, in-situ online monitoring that employs NDE technology can provide quantitative and sometimes predictive results. These monitoring systems can have advantages over traditional periodic inspections (e.g., cost, accuracy, radiation exposure, and prognostic capability). The EPRI NDE program provides NDE technology, procedures, validation, and training for identified materials, mechanisms, components, and locations of concern. This process is ongoing and robust and is expected to be effective for the life of the nuclear power plant, including SLR periods. Additionally, the NDE program continues to investigate new technologies that may provide enhanced detection and flaw characterization performance that may be incorporated into aging management programs. The LTO Program investigates opportunities to employ NDE technologies that can be installed for automatic, continuous, in-situ monitoring for certain identified aging degradation concerns. The investigations will include identification of parameters, design of sensors and sensor configurations, data capture and analysis, validation of the NDE/monitoring system, and demonstration of the process in an operational environment.

LWRS – NDE	**Milestones:** Concrete: • (2018) Complete preliminary methodology and technique development for NDE of concrete structures. • (2020) 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 clearly valuable to both industry and regulators. Cabling: • (2017) Development of key indicators for remaining useful life. • (2019) Deliver predictive capability for end-of-useful life for cable insulation. Development of NDE techniques to permit in-situ monitoring of cable insulation performance could be revolutionary and allow for an assessment of cable insulation performance at specific locations of interest and at more frequent intervals, which is a significant difference from today's methodology. This would reduce uncertainty in safety margins and is clearly valuable to both industry and regulators.
LTO – NDE	**Milestones**: • (Ongoing) NDE-related work is reported under the topical areas as appropriate.
R&D Area	**RISMC**
LWRS – RISMC Toolkit	**R&D Scope and Objectives:** While simulation methods in risk and reliability applications have been proposed before, the availability of advanced mechanistic and probabilistic simulation tools have been limited. However, with advanced tools and modern computational resources, simulation is now a viable approach to represent complex scenarios. Consequently, the RISMC Pathway approach is to use a set of advanced simulation tools to model plant behavior and determine safety margins. Computational approaches developed and used within RISMC include both finite element and mesh-free solvers. The principal enabler of the RISMC Toolkit is the INL's Multi-physics Object Oriented Simulation Environment (MOOSE) high-performance computing framework.[d] MOOSE is the INL development and runtime environment for the solution of multi-physics systems that involves 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 described as follows: • ***RELAP-7 (Reactor Excursion and Leak Analysis Program)*** 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 nuclear power plant level with a level of fidelity that will support analysis and decision making necessary to economically and safely extend and enhance operation of the current nuclear power plant fleet. • ***RAVEN (Reactor Analysis and Virtual Control ENvironment)*** is a multi-tasking application focused on simulation control, plant control logic, system

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[d] Gaston, D., G. Hansen, and C. Newman, 2009, "MOOSE: A Parallel Computational Framework for Coupled Systems for Nonlinear Equations. International Conference on Mathematics," *Computational Methods, and Reactor Physics*. Saratoga Springs, New York: American Nuclear Society.

	analysis, uncertainty quantification, and scenario-generation for computational risk assessment for postulated events. RAVEN is a probabilistic code and has the capability to "drive" RELAP-7 (and other MOOSE- and non-MOOSE based applications) for conduct of RISMC analyses. • ***Grizzly*** is a MOOSE-based tool for simulating component aging and response of aged components. Grizzly will model degradation mechanisms experienced in reactor pressure vessels, core internals, weldments, and concrete structures, and their effects on the integrity of those components. This degradation can be due to exposure to a variety of environmental conditions including neutron flux, corrosive environments, high temperatures and pressures. Grizzly can couple with RELAP-7 and RAVEN to provide aging analysis. • ***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 probabilistic risk assessment analysis. • ***MASTODON*** is a tool that will have the capability to perform stochastic nonlinear soil-structure interaction in a risk framework. These nonlinear soil-structure interaction simulations will include structural dynamics, time integration, dynamic porous media flow, hysteretic nonlinear soil constitutive models (elasticity, yield functions, plastic flow directions, and hardening softening laws), hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (gapping and sliding). • ***Neutrino*** is a mesh-free, smooth particle hydrodynamics-based solver, which also uses advanced boundary handling and adaptive time stepping. Neutrino is an accurate fluid solver and is being used simulate coastal inundation, river flooding, and other flooding scenarios. Neutrino models friction and adhesion between solid/fluid boundaries and various adhesive hydrodynamic forces between fluid/fluid particles.
LTO – Enhanced Risk Assessment and Management Capability	**R&D Scope and Objectives:** To achieve successful long-term operations of the current fleet of operating nuclear power plants, it will be imperative that high levels of safety and economic performance are maintained. Therefore, operating nuclear power plants will have a continuing need to undergo design and operational changes and manage aging degradation, while simultaneously preventing the occurrence of safety significant events and analytically demonstrating improved nuclear safety. This portion of the EPRI LTO Program addresses the following two specific issues that are imperative to achieving these objectives: a. First, as the current fleet of operational nuclear power plants ages, new challenges to plant safety are expected to emerge. These challenges could be due to any number of causes such as a change in regulatory policy or the occurrence of an event at one or more operational nuclear power plants. b. Second, as new technologies and capabilities become available, it will be desirable to take advantage of these opportunities to enhance nuclear power plant technical and economic performance. Examples of such enhancements could include performing extended power uprates or implementation of new technologies or materials.

	In each situation, a comprehensive and integrated assessment of the impact on nuclear safety will be required to support effective and efficient decision making. This research project will develop and validate enhanced risk assessment and management capabilities and tools. A critical element of this research effort will be to integrate the results obtained from the EPRI PHOENIX software development effort, which is being conducted to develop an advanced probabilistic risk assessment and configuration risk management integrated tool suite. This research effort will support development of PHOENIX by integrating risk management analytical capabilities that are necessary for nuclear power plant long-term operations (e.g., RISMC/Risk Informed Margin Management [RIMM]) and providing for the capability of the PHOENIX software to link to the RISMC software to permit its uses as a risk simulation tool. This project also provides significant interface and coordination of research efforts being conducted in safety analysis code development and safety margin analyses being performed by INL as part of the LWRS Program.
LWRS – RISMC Toolkit	**Milestones:** • (2017) Release the reactor metals beta version 1.5 of Grizzly. This version will include capabilities for modeling selected aging mechanisms 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) Release beta version of seismic probabilistic risk assessment model. • (2017) Complete validation of pre-critical heat flux closure relations and establish function of single-phase compressible branch model in RELAP-7. • (2018) Complete validation for remaining (post- critical heat flux and horizontal) closure relations, implement robust numerical solution architecture, and establish plenum models in RELAP-7. • (2018) Flooding model is validated against an accepted set of data. • (2018) Release advanced flooding analysis tool suitable for ocean- and river-based flooding scenarios. • (2018) Flooding fragility models for mechanical components are validated against an accepted set of data. • (2018) Complete flooding fragility experiments for mechanical components. • (2018) Release beta version 2.0 of Grizzly, including capabilities for modeling reinforced concrete. • (2018) Completion of RAVEN user interface platform. • (2019) Complete flooding fragility experiments for electrical components. • (2019) Complete Grizzly (concrete) validation against an accepted set of data. • (2019) Complete seismic experiments for critical phenomena. • (2019) Flooding fragility models for electrical components are validated against an accepted set of data. • (2019) Implement balance of plant system components with compatible two-phase models (turbines, pumps, valves), special process capabilities (CCFL, thermal stratification, and critical flow), and control system architecture in RELAP-7. • (2020) Implement reactor system components with conjugate heat transfer (e.g. core sub-channel capability, steam generator components, etc.) and establish non-condensable model. Release Beta Version (developmental) of RELAP-7 for testing multi-physics coupling. • (2020) Release beta version 3.0 of Grizzly, including capabilities for modeling selected aging mechanisms in reactor internals.

	• (2020) Implement risk-informed margins management module in RAVEN RISMC Toolkit that will perform analyst-augmented evaluation of facility safety to search for vulnerabilities and potential management strategies. • (2021) Complete Grizzly (core internals) validation against an accepted set of data. • (2021) Integrate reactor system components and test for integrated and coupled systems. Release Version 0.0 of RELAP-7 for extended validation testing. • (2022) Complete select set of validation tests, integrated effects tests, and reactor systems analysis benchmarks for release of Version 1.0 of RELAP-7.
LTO – Enhanced Risk Assessment and Management Capability	**Milestones:** In previous years, this LTO research effort has supported the Phase 1 and Phase 2 portions of the PHOENIX research effort. A key milestone provided by this research was development of the PHOENIX functional requirements document and roadmap (EPRI Report 1019207). During 2013, a "beta" version of the PHOENIX software was produced that concentrates on enhanced methods for configuration risk management applications. During 2017, support of PHOENIX development, testing, and initial deployment will continue. The following activities are planned: • Provide industry analysis/input to LWRS Program for selection of RISMC methods pilot demonstration projects. Develop and demonstrate integrated RIMM approach (ongoing input into DOE LWRS planning). • Continue RISMC rollout to industry stakeholders. Rollout started during 2012 using outcomes from the LOFW pilot and provides oversight/review of the BWR EPU SBO (extended power uprate station blackout) case study. This work has transitioned to the conduct of pilot applications to address specific LTO-related issues at host plants. These applications also are focusing less on direct reactor safety figures of merit (e.g., core damage frequency) and more on other plant impact states that have more direct business implications for LTO (e.g., plant life limiting events and economic consequences). Progress in this area will be dependent on successful development and verification of advanced analytical tools and successful pilot applications. • Investigation of broader application of modeling and simulation framework to address emerging challenges to nuclear power plant long-term safety and economic viability. Initial applications are being targeted at assessing the likelihood, impacts, and consequences of various external hazards (e.g., seismic, flooding, high wind, and extreme temperature events). • (2017-2018) Investigation of the integration of RISMC software (EMRALD and RAVEN) into PHOENIX.
R&D Area	**Advanced II&C Systems Technologies**
LWRS – New Instrumentation and Control and Human System Interfaces and Capabilities (including Advanced II&C Pilot Projects)	**R&D Scope and Objectives:** 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 nuclear power 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. A Utility Working Group, composed of leading nuclear utilities across the industry and EPRI, advises the program. The Utility Working Group 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.[e] 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. Centralized online monitoring and information integration 4. Integrated operations 5. Automated nuclear power 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. 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 nuclear power plants. Through the LWRS Program, individual utilities and nuclear power 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 achieving longer-term outcomes of sustainable II&C technologies. They are designed to emphasize success in some crucial aspect of nuclear power plant technology refurbishment and sustainable modernization. They provide the opportunity to develop and demonstrate methods for 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 program 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.
LTO – Requirements	**R&D Scope and Objectives:** EPRI will participate in the LWRS Program working group for Advanced II&C

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

Database for Advanced I&C, Human System Interface, and Information Technology	Systems Technologies. This working group includes utility representatives from Exelon, Entergy, Duke, Southern, South Texas Project, Arizona Public Service, Constellation, Progress, Tennessee Valley Authority, and the STARS Alliance. Through the working group, the LWRS Program is sponsoring pilot studies of advanced applications of I&C and other information technology projects at individual utilities. The LWRS Program also has developed the Human Systems Simulation Laboratory (HSSL) to support these applications and to perform related R&D at INL. The HSSL employs 15 bench-board-style touch panels that resemble the control panels currently used in nuclear power plants. This equipment is capable of running nuclear power plant simulators to produce a high-fidelity control room environment for control room modernization R&D. EPRI will participate in these activities on behalf of the LTO project membership. EPRI will interact with the working group on the LTO requirements database activities. EPRI is making relevant EPRI technical reports available to INL for work in the LWRS Program Advanced II&C Systems Technologies area.
LWRS – New Instrumentation and Control and Human System Interfaces and Capabilities (including Advanced II&C Pilot Projects)	**Milestones:** Human performance improvement for nuclear power plant field workers: • (2017) Complete a report documenting a user study to evaluate the automated work package capabilities. • (2018) Develop a report describing advanced and intelligent automated work package capabilities and the user study to evaluate the new capabilities. • (2018) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers. • (2019) 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) Develop a report on the guidelines of implementing automated work package capabilities for the nuclear power industry and describing the path forward for the industry to adopt the evaluated capabilities. • (2020) 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. Outage safety and efficiency: • (2017) Develop and demonstrate 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 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. Integrated operations: • (2018) Develop and demonstrate (in the 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. • (2019) Develop and demonstrate (in the 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). • (2020) 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 a highly automated plant. Demonstrate representative remote activities with a host nuclear power plant. • (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 a highly 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 a highly 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. • (2023) 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. • (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.

	Automated plant: • (2017) Develop and evaluate use cases for data mining and analytics for employing information from plant sensors and database for use in developing improved business analytics. • (2018) 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. • (2019) 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. • (2020) 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. • (2021) 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. • (2022) Develop and publish a transformed nuclear power plant operating model and organizational design derived from a top down analysis of nuclear power plant operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies. • (2022) Develop concepts for advanced control automation for control room operators based on human technology function allocation developed in the pilot project for automating manually performed plant activities. Publish a technical report on candidate applications for automation reflecting design and human factors principles. • (2023) Develop and demonstrate (in the 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 the 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.

	Hybrid control room: • (2017) Develop a Human Factors Engineering Plan for the Palo Verde Control Room Modernization Project that describes a graded set of activities that will be used to ensure that the control room improvements conform to human factors principles. • (2017) Develop a business case framework for the control room end-state concept based on work efficiency gains and improved operator performance. • (2018) Complete a report describing the results of the Control Room Human Factors Engineering – Design activities for Phase 1of the Palo Verde Control Room Modernization Project. • (2018) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 1 (N-1) of the Fleet-Based Control Room Modernization Design Project • (2019) Complete a report describing the results of the Control Room Human Factors Engineering – Design activities for Phase 2 of the Palo Verde Control Room Modernization Project. • (2019) Complete a report describing the results of the Control Room Human Factors Engineering – Design activities for Phase 2 (N) of the Fleet-Based Control Room Modernization Design Project. • (2019) 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 the HSSL. • (2020) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 3 of the Palo Verde Control Room Modernization Project. • (2020) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 3 (N+1) of the Fleet-Based Control Room Modernization Design Project. • (2020) 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. • (2021) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 4 of the Palo Verde Control Room Modernization Project. • (2021) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 4 (N+2) of the Fleet-Based Control Room Modernization Design Project. • (2021) Develop an operator advisory system that provides plant transient performance monitoring with operator alerts for challenges to nuclear safety goals. • (2022) Complete a report describing the results of the Control Room Human Factors Engineering – Design activities for Phase 4 of the Palo Verde Control Room Modernization Project. • (2022) Complete a report describing the results of the Control Room Human Factors Engineering – Verification and Validation activities for Phase 3 (N+1) of the Fleet-Based Control Room Modernization Design Project. • (2022) 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) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 5 of the Palo Verde Control Room Modernization Project. • (2023) Complete a report describing the results of the Control Room Human Factors Engineering – Verification and Validation activities for Phase 4 (N+2) of the Fleet-Based Control Room Modernization Design Project. • (2024) Complete a report describing the results of the Control Room Human Factors Engineering – Design activities for Phase 5 of the Palo Verde Control Room Modernization Project. • (2024) Complete a report describing the results of the Control Room Human Factors Engineering – Planning and Analysis activities for Phase 5 (N+3) of the Fleet-Based Control Room Modernization Design Project. • (2025) Publish a summary report on the Control Room Modernization Design Project providing lessons-learned and initial operational benefits for Palo Verde. • (2025) Publish a summary report on the Fleet-Based Control Room Modernization Design Project providing lessons learned and initial operational benefits for Exelon Nuclear.
LTO – Requirements Database for Advanced I&C, Human System Interface, and Information Technology	**Milestones**: No milestones (EPRI collaboration is maintained through sharing of EPRI I&C reports and participation in the LWRS II&C Pathway UWG).
LWRS – International Collaborations (Halden Project)	**R&D Scope and Objectives:** The programs of the Halden Reactor Project (Halden) 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 Halden to evaluate their advanced II&C technologies to take advantage of the applicable developments. In addition to the technologies, the validation and human factors studies conducted during development of the technologies will be carefully evaluated to ensure similar considerations are incorporated into the pilot projects. Bilateral agreements may be employed in areas of research where collaborative efforts with Halden will accelerate development of the technologies associated with the pilot projects.
LTO – Halden Project	**R&D Scope and Objectives:** EPRI, as an associated member of the Halden Reactor Project, is providing input to Halden on their research activities in the man-machine-technology program.

LWRS – International Collaborations (Halden Project)	**Milestones:** • Activities involving contributions from Halden are discussed under the individual pilot projects.
LTO – Halden Project	**Milestones**: Activities involving contributions from Halden are discussed under the individual pilot projects.
LWRS – Centralized Online Monitoring and Information Integration	**R&D Scope and Objectives:** 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 active components based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions concerning long-term 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 nuclear power plant life. Working closely with the MAaD and RISMC Pathways and EPRI, this pathway will develop technologies to complement sensor development for online 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 NDE of materials during periodic inspections. The RISMC Pathway is developing tools that can guide sensor development and placement. The Advanced II&C Systems Technologies 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 SSCs that are monitored.
LTO – Centralized Online Monitoring	**R&D Scope and Objectives:** **(Note: This area is now under the EPRI I&C/Software Development Program and is not funded by LTO. Planned work is expected to be completed as scheduled.)** The commercial nuclear power industry is subject to a challenging economic environment due to low cost alternative power sources, such as natural gas. An area for large potential operating and maintenance (O&M) savings is through the use of plant monitoring to replace or extend the intervals of preventive maintenance and surveillance tasks. The industry needs guidance on a variety of topics on this subject, including business case development, sensor development, data transmission and analysis. This work will be coordinated with LWRS in 2017.

	The EPRI Plant Monitoring project, has two primary objectives: 1. Develop R&D products to advance monitoring to reduce maintenance tasks from a current Technology Readiness Level of 2 (concept) to TRL of 8 (full field validation) by the end of 2017. 2. Based upon lessons learned and infrastructure installed in Objective 1, update the plan and develop other R&D products that will further help nuclear plants to automate repetitive tasks, such as advanced electronic work packages and equipment reliability diagnostics / prognostics Initial focus on the following deliverables: 1. Gap Analysis (present state versus best practices) 2. Generic Business Case (cost / benefit process) 3. Technical Basis for Monitoring as Replacement for Maintenance Tasks 4. Generic Wireless Sensor Specification 5. Data Analytics Evaluation In addition, the project will coordinate with key EPRI work that supports this focus (e.g. Cyber-Security and Wireless Communication).
LWRS – Centralized Online Monitoring and Information Integration	**Milestones:** • (2017) Develop an integrated framework for multi-physics simulation, full-field imaging, data analytics and uncertainty quantification, demonstrate for large laboratory structures, and develop a validation strategy. • (2017) Develop signal processing methods and techniques to extend the range of currently available guided waves technologies. Publish a technical report on advanced signal processing de-noising techniques capable to extend the range of guided waves monitoring and to reduce spurious deflections from complex geometries. • (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) Develop online monitoring techniques, which will address the technology gaps existing in currently available guided waves techniques. • (2019) Develop an online integrated monitoring system, which will perform data processing, data fusion, and decision making to provide end users the status of the piping system, specifically evaluation of wall thickness and the remaining useful life of pipes. • (2020) Conduct utility-scale testing of an online monitoring system. Publish a report describing the system development and performance.

LTO – Centralized Online Monitoring	**Milestones**: • (2016) Gap Analysis (present state versus best practices) results will be incorporated into 2017 milestone products. • (2017) On-Line Monitoring Implementation Guide with Generic Business Case (cost / benefit process). • (2017) Technical Basis for Monitoring as Replacement for Maintenance Tasks. • (2018) Generic Wireless Sensor Specification & Industry Wireless Survey. • (2017) Data Analytics Evaluation & Data Aggregation Pilots at EPRI. • (2018) Data Aggregation & Analytics at EPRI.

4. LIGHT WATER REACTOR SUSTAINABILITY PROGRAM / LONG TERM OPERATIONS PROGRAM – COLLABORATIVE RESEARCH AND DEVELOPMENT ACTIVITIES

R&D Area	MAaD (LWRS) / Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LWRS – Mechanisms of IASCC	**R&D Scope and Objectives:** 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.[f] 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. Additionally, new in-situ characterization techniques will be developed to examine deformation mechanisms in the material and the direct influence of defects, grain boundaries, and localized twinning on the generation and propagation of cracks. 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.
LTO – IASCC: Identifying Mechanisms and Mitigation Strategies for IASCC of Austenitic Steels and LWR Core Components	**R&D Scope and Objectives:** A better fundamental understanding of key parameters that affect IASCC is required to develop improved materials. For extended operation, IASCC is potentially a major failure mechanism that could impact the reliability of reactor core internal components due to higher fluence. The metallurgical modifications caused by neutron irradiation generally increase IASCC susceptibility of austenitic stainless steels. Currently, this long-term LTO project is co-funded by EPRI and DOE. The project work is performed by the University of Michigan. The objectives of this LTO project include the following: • Full assessment of high-purity solute addition alloys and, in particular, the roles of C, Mo, Ti, Nb, Cr+Ni, and P on crack growth rate and crack initiation. • Full assessment of the roles of commercial alloy microstructure on crack growth rate and crack initiation. • Linkage between irradiated microstructure and crack growth rate or crack initiation for solute addition and commercial alloys, as well as effects of cold work and dose. • Relation between IASCC cracking susceptibility and neutron-irradiated alloys. • Determination of the predictive capability of crack initiation due to proton irradiation by assessment against crack initiation due to neutron irradiation. • Role of localized deformation on the IASCC susceptibility in neutron-irradiated materials.

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

	This LTO project on study of IASCC mechanisms has completed the Phase 1 study, and an EPRI report has been published to summarize the key results from the experiments on fast neutron irradiated alloys. In 2017, EPRI and DOE continue the follow-on study on IASCC mechanisms. The follow-on study focuses on identifying and modeling the mechanism of IASCC. The strategy for this program is to develop a model for IASCC initiation and growth based on localized deformation arising from irradiation-induced changes to the microstructure. The working hypothesis is to quantify the stress or strain at the dislocation channel-grain boundary intersection, which may induce fracture of the oxide film above the grain boundary. Determination of which process is responsible for IASCC will provide a pathway to a more physically based model for cracking. In addition to testing the neutron-irradiated stainless steels, the similar stainless steels irradiated to the similar fluence by proton irradiation will be tested by constant extension-rate tensile tests. The cracking susceptibilities associated with neutron irradiation and with proton irradiation will be cross compared. The role of localized deformation on IASCC susceptibility will be investigated. The additional EPRI-funded IASCC study includes the following: • Investigate whether small-volume mechanical testing can provide an alternate method of assessing IASCC susceptibility to enable a potential strategy of retrieval and subsequent mechanical examination of materials from the field, in support of long-term operation. • Compile crack growth rate data on irradiated stainless steels from several EPRI and international programs and convene an expert panel to screen the available crack growth rate data on irradiated materials using appropriate screening criteria and recommend crack growth disposition curves for BWRs and PWRs to support current and long-term operation. • Testing in-service materials harvested from LWR plants. The results from testing these plant materials will be important to validate the findings from the mechanistic studies currently co-funded by EPRI and DOE.
LWRS – Mechanisms of IASCC	**Milestones:** • (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.
LTO – IASCC: Identifying Mechanisms and Mitigation Strategies for IASCC of Austenitic Steels and LWR Core Components	**Milestones**: • (2015) Report on key factors in IASCC initiation and propagation of austenitic alloys in core internals and mitigation measures that could minimize IASCC in current LWR stainless steel components (actually published in 2014, EPRI report: 3002003105). • (2014) Report on improved IASCC crack growth prediction models for BWRs and PWRs (published in 2014, EPRI report: 3002003103). • (2018) Phase 1 report on IASCC-resistant materials for repair and replacement.

Concrete	
LWRS – Concrete (irradiation effects and ASR)	**R&D Scope and Objectives:** Concrete makes up the largest volume of material used in nuclear power plants and is exposed to a variety of environmental conditions. 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, primarily as a result 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. Although a number of organizations have sponsored work addressing the aging of nuclear power plant structures (e.g., NRC, Nuclear Energy Agency, 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). The EMDA, NUREG/CR-7153, provided a list of research priorities addressing second license renewal. Along with irradiated concrete, the effects of ASR in nuclear structures are the focus of the MAaD Pathway. *Irradiation effects:* The objective of this task is to provide data and information in support of continuing the service of safety-related nuclear power plant concrete structures past their initial 40-year design life. In meeting this objective, potential activities include compilation of material property data, evaluation of long-term effects of elevated temperature and irradiation, identification of improved damage models and acceptance criteria, development of improved constitutive models and analytical methods for evaluation of non-linear response, investigation of non-intrusive inspection methods for thick reinforced concrete sections, global inspection methods for containment liners and their inaccessible regions, identification of data and information on performance of repair materials and methods, and formulation of structural reliability methodology to address time-dependent changes in concrete structures and evaluate how aging affects structural reliability. *ASR:* The goal of this project is to study the development of ASR expansion and induced damage of large-scale specimens that are representative of structural concrete elements found in nuclear power plants. This will be done through experimentally validated models that explore the structural capacity of ASR-affected structures like the biological shield, the containment building, and fuel handling building. Experiments have begun in accelerated conditions, employing extensive monitoring and nondestructive techniques to evaluate structural stresses generated in the large block test specimens. Final destructive testing will address the question of shear capacity. This project will benefit from the experience and knowledge gathered from the RILEM (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures) international committee on the prognosis of ASR-affected structures.
LTO – Comprehensive Aging Management of Concrete	**R&D Scope and Objectives:** Adequate understanding and (where necessary) inspection techniques of concrete civil infrastructure in commercial nuclear power plants is an essential need for comprehensive decision making for long-term operation. There are a variety of

Structures	kinetic processes that can lead to degradation of civil structures and these may be accelerated by operating environments specific to nuclear power plants. It is important that industry understand the impact of accelerated aging of civil infrastructure, particularly for LTO, as individual utilities will be required to provide both sound technical and economic justifications for long-term operation. The interim goal of this project is to create a project that looks at various degradation phenomena being experienced in operating nuclear power plants. The initial stage of the project compiled an Aging Reference Manual, which defined the physics of kinetic degradation processes and discussed operational issues dealt with by the industry over the past 40+ years. The manual contains a framework for identifying at-risk structures and applicable degradation mechanisms. More recently, the NRC published Volume 4 of the EMDA (NUREG/CR-7153), which prioritized aging degradation issues in concrete. Building on these guiding documents, a number of individual research projects that aim to obtain further understanding of those degradation mechanisms and structures identified as “at-risk” have been and will continue to be undertaken. The results of the individual studies will be merged into an Aging Management Toolbox Platform, which will be an open-ended tool for operators to assess the severity of damage and explore repair or mitigation options. It is anticipated that these investigations will yield one or more industry examination guidelines for concrete aging assessment(s). Key areas of research will cover aging degradation due to irradiation and thermal environments, risks and impact of ASR, and assessment of nuclear power plant risks due to concrete creep effects. Related work covering spent fuel pools, including boric acid corrosion assessment, will be addressed. EPRI is also engaging with Spanish utilities in a project to evaluate concrete cores removed from the biological shield of the decommissioned Zorita nuclear power plant. Work is expected to begin in 2017.
LWRS – Concrete (irradiation effects and ASR)	**Milestones:** *Irradiation effects:* • (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. This effort will work toward the development of a methodology and documentation that provides risk-informed guidelines for evaluation of the performance of aging safety-related concrete SSCs for use in current and future condition assessments, taking into account service conditions and environmental factors that might diminish the residual life of these structures during potential future design basis events. *ASR:* • (2019) Complete experimentally validated sheer capacity model of ASR-affected concrete. Future milestones and specific tasks will be based on the results of the previous years’ testing, as well as ongoing, industry-led research. This effort will work toward development of a methodology and documentation that provides risk-informed guidelines for evaluation of the performance of ASR-affected structural concrete elements. Information obtained during this work will also benefit understanding of condition monitoring predictions through non-destructive

	techniques.
LTO – Comprehensive Aging Management of Concrete Structures	**Milestones**: • (2014) Initial report on preliminary findings of the effect of irradiation damage on reactor cavity concrete (Completed – EPRI Report 3002002676). • (2013) Containment aging pilot plant investigation Outage 2011 and Outage 2012 reports (results of destructive examination/NDE at Ginna and Nine Mile Point); industry guideline(s) for examination of structures for concrete aging (Completed – EPRI Report 3002002335). • (2014) Literature review of creep in concrete post-tensioned containment structures (Completed – EPRI Report 3002003220). • (2016) Report on experimental study of the effects of boric acid corrosion on concrete and guidance for aging management. (Completed – EPRI Report 3002007348). • (2015) Report on risk screening for ASR in concrete structures in existing plants (Completed – EPRI Report 3002005389). • (2016) Two interim reports to support aging management of concrete subject to alkali silica reaction (ASR) completed (3002007595 and 3002008117). • (2017) Final interim report on ASR and final report on aging management guidance. • (2016) Reports on radiation damage effects on concrete. Separate reports completed on neutron impact for BWRs (3002008128) and PWRs (3002007247). Third report (3002008129) completed on radiation (gamma) heating impact. • (2018) Complete concrete and civil infrastructure toolbox development with DOE and Materials Ageing Institute partners. • (2018) Report on characterization of concrete cores removed from Zorita biological shield. Work to commence in 2016.
Cabling	
LWRS – Cabling	**R&D Scope and Objectives:** Understanding cable-aging mechanisms that result in changes to cable performance and improved means for accurately assessing these property changes is an important area of study to ensure safe and efficient operation of nuclear power plants. This effort also provides plant operators the necessary information to conduct more accurate and cost-effective inspections in determining when mitigation or replacement is required. Degradation of these cables is primarily caused by long-term exposure to high temperatures; however, synergistic effects with irradiation and moisture may produce additional long-term use concerns. While wholesale replacement of cables is economically undesirable, incorporating more accurate condition monitoring techniques is a strategic investment in continuing safe and reliable operation. This task provides an understanding about 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. These experimental data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated

	aging protocols. The experimental data and mechanistic studies can be used to help identify key operational variables related to cable aging, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-range, design tolerant materials.
LTO – Advanced Cable Testing Technology for Life-Cycle Management of Cables	**R&D Scope and Objectives:** Fifty-five Westinghouse lifetime monitors were installed in a PWR in late 2015. The monitors will be removed in early 2017. An interim report was issued in 2015 (3002005517) documenting progress to-date. The 2013 collection of data did support the belief that cables see only a fraction of the dose used for environmental qualification, but the data could not be correlated to actual cable locations. The second major effort in 2015 is the harvesting of service-aged cables for accelerated cable aging research in the areas of inverse temperature, diffusion-limited oxidation, and filling gaps in the existing thermal and thermal/radiation models for the most often used cable types. A final report will be issued in late 2017 after analyzing the data collected. Associated work of interest to LTO is being funded by EPRI's Plant Engineering group to develop the technical basis for aging management and life-cycle management of cable systems.* Specifically, EPRI is performing a submergence qualification for Kerite ethylene propylene rubber insulation; pink Okonite ethylene propylene rubber qualification aging began in late 2015. An aging acceleration regime is being attempted in this project using a high frequency (i.e., 450 Hz and 900 Hz), along with 2.5 times line voltage. Forensic research evaluation of medium voltage water-related degradation was completed in 2015. Analysis of member-provided Tan δ data and EPRI-recommended acceptance criteria continues. Report 3002005321 was issued in 2015. Nearly 2,000 cable tests have been analyzed. EPRI's Plant Engineering group continues to support aging management implementation through the cable user group meetings. All of these projects support identifying cable system aging management activities, the portions of the cable system having limited life, and data and methods for life-cycle management of aging cable systems. Enhanced testing and end-of-life predictive methods will continue to be investigated. * *Cable systems include field cables, their terminations and splices, and local wiring, as well as the support and protective systems such as trays, conduits, and ducts.*
LWRS – Cabling	**Milestones:** - (2017) Complete analysis of key degradation modes of cable insulation. - (2018) 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 developing and delivering 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 also may allow for an alternative to cable replacement and would be of high value to industry by avoiding costly replacements.
LTO – Advanced Cable Testing Technology for Life-Cycle Management of	**Milestones:** - (2016) Harvesting and distribution of service aged cables from Crystal River Unit 3 to research projects on EMDA gaps was completed.

Cables	• (August 2015) Finalize research needed based on analysis of existing cable aging research data gaps for major cable types needed to be addressed to qualify condition and remaining useful life. • (2015) Tan Delta testing data evaluation and analysis summary (Completed – EPRI Report 3002005321). • (2015) Technical update for Phase II of the radiation and temperature monitoring data collection will be issued on the methods and process for data collection (Completed – EPRI Report 3002002994). • (2016) Completed report on low voltage cable wet susceptibility performance (EPRI Report 3002007991). • (2017) In-plant temperature and radiation monitoring. Monitoring initiated in late 2015 and planned for one fueling cycle. • (2017) Evaluation of dielectric spectroscopy for assessing cable aging. • (2018 through 2019) Updates to cable aging management guidelines for medium, low, and I&C cables.
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LWRS – Advanced Weld Repair	**R&D Scope and Objectives:** 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. The joint research project includes both the evaluation of advanced welding techniques (laser and friction stir welding) as well as development of a 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.
LTO – Advanced Welding Methods for Irradiated Materials	**R&D Scope and Objectives:** As the existing LWR fleet ages, the weldability of the structural material used to construct the RPVs and reactor internals may be diminished. The decrease in weldability is caused by formation of helium in the base material structure. This is caused by nuclear transmutation reactions of boron and nickel within the reactor materials and increases as neutron fluence accumulates. Helium-induced weld cracking is a complex phenomenon that is related to the concentration of helium in the material, heat input of the welding technique used, and stresses during cooling of the weld. Modest improvement in the weldability of irradiated material can be achieved by lowering the heat input using conventional laser beam welding, but once stainless steel components reach a certain fluence (typically at 20 to 30 years of exposure), some may be welded by current welding methods. As nuclear power plants age further (40 years and beyond), consideration of the embrittlement effect of helium on weld repair becomes critical. The development of advance welding processes (hybrid fusion and solid state) is needed to extend the weldability of these irradiated reactor components. There is significant justification for development of advanced welding methods to repair irradiated reactor materials. However, development of advanced welding processes for repair of irradiated reactor components is a relatively complex task

	and will take both fundamental research related to welding of irradiated materials and refinement of existing welding technologies. This is a relatively long-lead-time development process and research needs to be started now if welding repair options are to be available for reactor material and internals as they age and require repair or replacement. Expected work includes the following: • Perform review and prepare summary report on advanced welding processes and the potential application for welding of irradiated reactor components in the underwater environment. Processes being considered are – Low force friction stir welding – Low force friction stir cladding – Auxiliary beam laser welding – Low dilution laser beam welding • Prepare a detailed project plan for the multi-year project – Sample irradiation plan – Welding hot cell design/fabrication/installation – Advanced welding equipment technical requirements and procurement specification – Welding experiments to benchmark models and provide process development/refinement – Budgeting and detailed task planning • Design and procurement of a stainless steel sample set for irradiation. Project tasks are funded by the LTO Program and the DOE LWRS Program, with some tasks being co-funded. LTO-related work supported by the LWRS Program is performed at Oak Ridge National Laboratory. The Oak Ridge National Laboratory scope will focus on development of fundamental science for developing predictive models and simulations for advanced welding processes and measurement of residual stress at high temperatures. Oak Ridge National Laboratory has the following facilities to achieve the project goals: • High-Flux Isotope Reactor – Irradiation of the sample set will occur at this facility, as well as potential measurement of residual stresses at high temperature. • Material Process Hot Cell – Welding of irradiated material requires facilities that can remotely handle radioactive materials. • Advanced Microstructure Characterization Laboratory – Examination of radioactive material at the sub-grain level is a unique capability of Oak Ridge National Laboratory.
LWRS – Advanced Weld Repair	**Milestones:** • (2017) 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 also may have utility in repair or

	component replacement applications in other locations within a nuclear power plant.
LTO – Advanced Welding Methods for Irradiated Materials	**Milestones**: • (2013) Completed sample set fabrication. • (2014) Initial irradiation campaign for sample set. • (2014) Complete fabrication of welding cubicle. • (2014) Published three technical reports (3002003143, 3002003146, 3002002954). • (2016) Initiated installation of welding cubicle at Oak Ridge National Laboratory (Completed in 2017). • (2017) Initial welding experiments on irradiated material sample set. • (2016) Fabricate second set of specimens and initiate irradiation. • (2018) Start evaluations of welded samples (irradiated material) • (2019) Report on welding performance on irradiated material.
LWRS – Advanced Replacement Alloys	**R&D Scope and Objectives:** 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 2024.
LTO – Advanced Radiation-Resistant Materials Program	**R&D Scope and Objectives:** EPRI has initiated a new international collaborative project with DOE on development of radiation-resistant materials for LWR applications. EPRI and DOE have jointly prepared a comprehensive report on the state of current knowledge of radiation-induced degradation in LWRs and a roadmap to develop and qualify more radiation-resistant materials. The report was prepared by a team of world-class experts and widely reviewed by the international research community. The roadmap will be used to formulate a long-range R&D plan to develop improved materials for long-term operation of current and new nuclear power plants.
LWRS – Advanced Replacement Alloys	**Milestones:** • (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 will be determined through collaboration with EPRI's Advanced Radiation-Resistant Materials Program. A preliminary advanced radiation-resistant materials plan was initiated in 2013, which detailed the partnerships contribution to this effort. Completing the joint effort with EPRI on an alloy down-select and

	development plan is an essential first step in this alloy development task.
LTO – Advanced Radiation-Resistant Materials Program	**Milestones:** • (2015) Interim report on the results of Phase 1, documenting the results of microstructural, mechanical, and SCC studies on proton-irradiated commercial alloys to identify promising materials for further evaluation in Phase 2. • (2017) Final report on the results of Phase 1, recommending alloys for further evaluation under neutron irradiation. • (2019) Interim report on the results of Phase 2, documenting microstructural, mechanical, and SCC studies on neutron-irradiated commercial and advanced alloys. • (2022) Final report on the results of Phase 2, identifying one or two radiation-resistant commercial alloys for LWR internals.

R&D Area	RISMC
LWRS – Margins Analysis Techniques and Industry Applications	**R&D Scope and Objectives:** The purpose of the RISMC Pathway R&D is to support nuclear power plant decisions for RIMM, with the aim to improve economics and reliability and sustain the safety of current nuclear power plants over periods of extended 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. *Margin Management Strategies* 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; 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 key 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. 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 (**C – L**) (safety margin) or **C/L** (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 of the probabilistic type. In cases where deterministic margins are evaluated, the analysis is typically very conservative in order 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. 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 a nuclear power plant's 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[g] of consideration (e.g., peak fuel clad temperature), the nuclear power plant simulation will determine the time and scenario-dependent outcomes for both the load and capacity. Specifically, the safety margin approach will use the physics-based nuclear power 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.

The RISMC methods are to be described in a set of technical reports for RIMM.

Margin 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 for RISMC applications:

1. Characterize the issue to be resolved in a way that explicitly scopes the modeling and analysis to be performed, including delineating the performance metrics to be analyzed (i.e., safety and economics).
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. The scenarios will be able to capture timing considerations that may affect the safety margins and nuclear power plant physical phenomena, as described in Steps 4 and 5. As such, there will be strong interactions between the analyses in Steps 3 through 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 nuclear power plant operation probabilistically using the scenarios identified in Step 3. For example, nuclear power plant operational rules (e.g., operator procedures, technical specifications, and maintenance schedules) are used to provide realism for scenario generation. Because numerous scenarios will be generated, the nuclear power plant and operator behavior cannot be manually created similar to 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 nuclear power plant physics mechanistically. The nuclear power plant systems level code (RELAP-7) 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

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[g] Safety performance metrics may be application-specific, but, in general, they 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."

	calculated high loading (from pressure, temperature, or radiation) in an SSC may disable a component, thereby impacting an accident scenario. 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 the 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 in order 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 relaxed) safety control is justified. *Industry Applications* One of the primary avenues for collaboration with industry is through RISMC industry applications. The primary purpose of industry applications in the RISMC Pathway is to demonstrate advanced risk-informed decision making capabilities for relevant industry questions. The end goal of these activities is the full adoption of RISMC tools and methods by industry applied to their decision-making process. EPRI is a partner in carrying out these industry applications, supporting the identification of relevant problems, and analysis. From 2013 to 2014, the RISMC Pathway team performed multiple case studies, including a demonstration using INL's Advanced Test Reactor, a hypothetical PWR, and a BWR 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. Currently, the RISMC Pathway has identified high-priority industry applications to cover a range of current industry issues (in order of importance): • Industry Application 1 – Performance-Based Emergency Core Cooling System Cladding Acceptance Criteria • Industry Application 2 – Enhanced External Hazard Analyses (multi-hazard) • Industry Application-REIP – Risk-Informed Engineering Programs • Industry Application-CONTAIN – Reactor Containment Analysis These are the most relevant industry topics of today that can potentially impact plant operations in a significant way in the near future, making them interesting, relevant applications for the RISMC Toolkit. Because of their broad range of applicability, an industry application may spawn one or more demonstration problems, each depending on stakeholder interest on different aspects of a given industry application.
LTO – Enhanced Safety Analysis Capabilities	**R&D Scope and Objectives:** This research project will develop and validate an integrated framework and advanced tools for conducting risk-informed assessments that enable accurate characterization, visualization, and management of nuclear power plant safety margins. This LTO Program task is intended to develop an integrated methodology

	to assess plant safety margins and perform cost-effective, risk-informed safety analyses to meet these needs. It will achieve this objective through demonstration of effective and efficient application of the RISMC approach to issues important to the long-term operation of nuclear power plants. This project also provides significant interface and coordination of research efforts being conducted in safety analysis code development (via RELAP-7 and RAVEN) and safety margin analyses being performed by INL as part of the LWRS Program.
LWRS – Margins Analysis Techniques and Industry Applications	**Milestones:** *Margin analysis techniques* • (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. • (2019) Initial demonstration of RPV steel embrittlement using a bottoms-up, lower length scale model to capture causal mechanisms of embrittlement. • (2020) Apply margins analysis techniques to evaluation of FLEX operations for extended station blackout conditions. • (2022) Ensure development and validation to the degree that by the end of 2022, 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. *Industry applications* • (2017) Complete the Emergency Core Cooling System Cladding Acceptance Criteria Industry Application. • (2018) Demonstrate the margins analysis techniques specific to the understanding of coping time for accident tolerant fuel designs (in cooperation with the Advanced Fuels Campaign) and possible implications for economic savings using 10 CFR 50.69. • (2018) Demonstrate the margins analysis techniques, including a fully coupled RISMC toolkit, for reactor containment analysis including hardened reliable vents and shallow- and deep-water flooding and seismic events. • (2020) Complete the demonstration of the margins analysis techniques, including a fully coupled RISMC toolkit, for long term coping studies to evaluate FLEX and extended station blackout conditions.
LTO – Enhanced Safety Analysis Capabilities	**Milestones**: In previous years, this LTO research effort successfully demonstrated that the RISMC methodology could be applied in an economical and efficient manner to analyze issues important to nuclear power plant safety. Key results of this research were documented in EPRI Report 1023032 (*Technical Framework for Management of Safety Margins - Loss of Main Feedwater Pilot Application*), which applied the RISMC methodology to evaluate the safety margins associated with a loss-of–all-feedwater event at a hypothetical PWR. An initial application of the RISMC approach to evaluate the impact on safety margins in the context of LTO decision making was conducted in 2012 and documented in EPRI Report 1025291 (*Pilot Application of Risk Informed Safety Margins to Support Nuclear Plant Long Term Operation Decisions: Impacts on Safety Margins of Power Uprates for Loss*

	of Main Feedwater Events). In 2013 (and 2014), the EPRI LTO portion of the RISMC research expanded upon this research by performing additional analyses of safety-significant applications that have the potential to impact critical long-term operation decision making. The EPRI research also will engage nuclear power plant owners/operators to initiate transfer of the technology for application to relevant safety issues with impact on nuclear power plant LTO. To support these objectives: • EPRI and EPRI member utilities will provide technical advice on RISMC/ RIMM development by participation on the RISMC Pathway Advisory Committee being formed by INL as part of the LWRS Program. This committee, which consists of a broad selection of risk assessment/ management technical experts, is being formed to provide external input and advice to the planned RISMC/RIMM development and deployment efforts. • EPRI will continue engagement with NRC researchers who are involved with similar regulatory research into development and application of the RISMC methodology. This interaction will be conducted under the existing memorandum of understanding between EPRI and NRC'S Office of Nuclear Regulatory Research. • EPRI also will continue to participate in external communication of RISMC research at appropriate venues, including conduct of EPRI industry workshops, presentations at applicable conferences, and reporting results of pilot applications in peer-reviewed scientific literature. • EPRI will continue to support LWRS development of the next generation safety analysis software (RELAP-7). Previously, EPRI provided important contributions to this work via EPRI Reports 1019206 (*Framework for Risk Informed Safety Margin Characterization*), which summarized the current state-of-the-art (as of 2009) for the RISMC methodology and deterministic safety analysis and probabilistic risk assessment software tools, and 1021085 (*Desired Characteristics for Next Generation Integrated Nuclear Safety Analysis Methods and Software*), which specified desired elements for the next generation safety analysis tool suite (from the perspective of a plant owner/operator). During 2014, EPRI provided a comprehensive and prioritized catalog of test data available to support the validation of the RELAP-7 code. The results of this effort were published in EPRI 3002003110 (*Data Sources for Capability Assessments of Next Generation Safety Analysis Codes*). Since code validation is an essential element for utility use of any safety analysis code, in 2015 and beyond, EPRI will continue to support INL's development of RELAP-7 by providing input to its development, validation, and deployment and supporting the conduct of trial applications as modules become available

5. LIGHT WATER REACTOR SUSTAINABILITY PROGRAM / LONG TERM OPERATIONS PROGRAM – PROGRAM-UNIQUE RESEARCH AND DEVELOPMENT ACTIVITIES

LWRS – EMDA	**R&D Scope and Objectives:** The objectives of this research task were 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 provided an organized and updated assessment of key materials aging degradation issues and supported NRC and EPRI efforts to update the Proactive Materials Degradation Assessment or the MDM documents. Successful completion of this activity provides a valuable means of task identification and prioritization within this pathway, as well as identifying new needs for research. An EMDA of degradation mechanisms for 60 to 80 years or beyond was identified as a useful tool in further prioritizing degradation for research needs. Based on joint discussions between DOE and NRC, it was decided that the EMDA would consist of separate and focused documents covering the key SSCs. This approach yielded a series of independent assessments (i.e., core internals primary and secondary piping, RPV, concrete civil structures, and electrical power and I&C cabling and insulation) that, when combined, created a comprehensive EMDA. The LWRS Program will use this as a tool for identifying and prioritizing research in future years. NRC will use the EMDA to inform the regulatory framework. The nuclear industry will use the EMDA results as a complementary tool to their MDM. **Milestone:** • (2014) Complete and deliver a gap analysis of the key materials degradation modes via the EMDA (NUREG/CR-7153, Volumes 1-5, October 2014).
LTO –MDM and Issues Management Tables	**R&D Scope and Objectives:** EPRI's MDM, PWR Issues Management Tables (IMTs), and BWR IMTs are three key reference documents that are part of industry's materials initiative guided by NEI 03-08. The MDM and IMTs identify knowledge gaps based on likely degradation mechanisms and aging issues through an expert elicitation process. The MDM and IMTs also assess the state of industry knowledge worldwide, survey the laboratory data and field experience data, and prioritize the gaps for industry to resolve in the most effective way. MDM results are used as direct inputs into the BWR IMT and PWR IMT. Degradation mechanisms identified in MDM are used as primary input for the set of degradation mechanisms considered by the IMT process. The MDM was first published in 2004 (Rev. 0), and it has been revised three times in 2007 (Rev. 1), 2010 (Rev. 2), and 2013 (Rev. 3). Sequentially, two IMTs were first published in 2005 (Rev. 0) and then revised in 2008 (Rev. 1), 2010 (Rev. 2), and 2013 (Rev. 3). Rev. 0 and Rev. 1 of MDM and the IMTs only addressed issues related to the current license period (40 years operation) and the license renewal period (from 40 to 60 years operation). Long-term operation of nuclear power plants up to 80 years may pose additional materials degradation issues that may not be deemed to be life-limiting factors for 60-years operation. For example, the increased fluence level can be a serious

	concern to some of the reactor internal components. The increased fluence level not only can lead to changes in materials properties and cracking susceptibility, but also can be an issue in repairing the internal components. In support of the LTO Program, an LTO ‘flag’ has been added to the MDM (starting with Revision 2 in 2010), indicating ongoing work or evaluation that is needed to support 60 to 80 years of operation. The objective of this addition to the MDM is to 1. Identify applicable degradation mechanisms and assess the extent to which applicable degradation mechanisms are understood 2. Evaluate the state of industry knowledge worldwide associated with mitigation of degradation mechanisms 3. Address any concerns related to regulatory and licensing renewal considerations. MDM and IMTs are based on an expert elicitation process. A panel consisting of materials experts, industry personnel, and EPRI staff provided the key inputs for the ongoing revisions. The expert panel considered relevant operating experience, information from newly published and ongoing research projects worldwide, the consequence of failure, and the availability of mitigation strategies when developing the results. 1. Develop a fundamental understanding of the degradation phenomena/mechanisms and determine materials (and locations) that are known or can logically be assumed to be susceptible to aging/degradation phenomena when exposed to the operating environment. 2. Conduct generic operability and safety assessments for the locations of the various materials potentially susceptible to damage/degradation phenomena. 3. Develop inspection and evaluation guidelines and technology for the identified locations, starting with those for which the potential consequences of failure are most severe. 4. Evaluate available mitigation options and, if necessary, develop additional options. 5. Evaluate repair/replace options and, where necessary, encourage/support the development of additional options. 6. Monitor, evaluate, and feedback nuclear power plant operating experience. 7. Obtain regulatory acceptance of the items above and support licensees on nuclear power plant-specific applications as needed. The MDM focuses on the development of a fundamental understanding of the degradation phenomena/mechanisms, based on the materials/environment combination. Expert elicitation, laboratory studies, and field experience were used to identify potential mechanisms by which each of the materials might degrade. The PWR IMT and BWR IMT are component-based evaluations of the consequence of failure. This component-based approach also emphasizes the considerations of mitigation strategies, repair/replacement, inspection and evaluation guidelines, and regulatory requirements. All considerations will be captured in IMT gaps, which will then be prioritized. The prioritization of IMT gaps provides a basis for industry to prioritize R&D efforts to address materials’ reliability issues and LTO concerns effectively. The LTO Program will also support the current EPRI online Materials Information Portal. With built-in navigation and interlinks, the EPRI online

	Materials Information Portal integrates multiple EPRI resources (i.e., MDM, PWR IMT, BWR IMT, and the Materials Handbook). This portal provides a comprehensive, integrated view of materials issues and associated information necessary for materials aging management at nuclear power plants. **Milestones:** MDM and IMTs are living documents and they require updates and revisions periodically to reflect the knowledge gained and the evolving challenges. The MDM and IMTs are scheduled to be revised every three years, and more frequent interim updates of underlying information can be achieved through the maintenance of the Materials Information Portal. The Materials Information Portal maintenance frequency is semi-annual (twice a year). The LTO-supported work will be coordinated with the planned work within the Primary System Corrosion Research program to update and maintain the MDM and Materials Information Portal and work within the PWR Materials Reliability Project and BWR Vessel and Internals Project to update and maintain the IMTs. • (2013) Update of the MDM complete (EPRI Report 3002000628, Rev 3). • (2013) Update of the IMTs complete (EPRI Reports 3002000690 for BWRs and 3002000634 for PWRs). • (2017 and 2019) Planned MDM Updates. • (2017 and 2020) Planned IMT Updates for BWRs and PWRs.
LWRS – Thermal (Post-Irradiation) Annealing	**R&D Scope and Objectives:** 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 resolve technical issues required to implement this strategy. Successful completion of this effort will provide data and theoretical understanding to support implementation of this alternative mitigation technology. **Milestones:** • (2020) Complete post-irradiation thermal annealing experimental and modeling studies for mitigation of RPV embrittlement. • (2024) Complete re-irradiation studies on annealed and previously irradiated materials to higher fluence to evaluate long-term potential of RPV mitigation techniques. 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 allow for recovery from embrittlement in an RPV, which would be of high value to industry by avoiding costly replacements.
LWRS – Zion Materials Management and Coordination	**R&D Scope and Objectives:** 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 an RPV. Current work includes the successful procurement of two RPV wall sections in 2015/2016 that include the beltline weld. These sections have since been transferred to Zion Solutions facility for further sectioning into smaller blocks, which will then serve as the preforms for more precise test sample fabrication occurring in the early part of calendar year 2017. Research performed on the Zion RPV sections will address gaps in knowledge on attenuation effects and material variability in RPV cross-sections, provide direct comparison to surveillance and high flux reactor data, and provide material for future evaluating mitigation techniques such as warm pre-stressing or annealing and the further effects of re-irradiation to higher total fluence. **Milestones:** • (2016) Segmentation of RPV, shipping and cutting of preform blocks from RPV sections. • (2017) Fabrication of test specimens from preform blocks and the start of examinations. • (2021) Complete analysis of harvested Zion RPV sections.
LWRS – Baffle Bolt Harvesting and Examination	**R&D Scope and Objectives:** The Constellation Pilot Project was a joint venture between the LWRS Program, EPRI, and the Constellation Energy Nuclear Group. The project utilized two of Constellation's nuclear stations, R. E. Ginna and Nine Mile Point 1 (both units now owned by Exelon), for research opportunities to support extended operation of nuclear power plants. Specific areas of joint research have included baffle former bolt harvesting (an activity that was completed in 2016 with the removal of bolts from the spent fuel pool), 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. **Milestones:** • (2018) Complete microstructural and mechanical property evaluation of bolt material.
LWRS – External Hazards Experimental Testing	**R&D Scope and Objectives:** One of the technical gaps that have been identified related to the external events analysis is the lack of fragility models, especially in the area of flooding analysis. Historically, rudimentary conservative methods for conducting flooding risk assessment fall short because they fail to sufficiently characterize both the fragility of components and the risk from the hazards. In short, current risk analysis methodology assumes that many components simply fail if contacted by water. The RISMC Pathway proposes to test representative nuclear power plant components and structures to failure (and, potentially, to the point of recovering after failure) and develop a science-based approach to flooding risk analysis. Wave impact, rising water, and top-down water spray testing will be conducted as part of this experimentation for both mechanical and electrical components. The experimental data obtained on flooding and seismic tests will ultimately be used in conjunction with simulations to create a more accurate risk assessment. **Milestones:** • Milestones are addressed under the "RISMC Toolkit" project.

LWRS – Industrial and Regulatory Engagement	**R&D Scope and Objectives:** 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 Systems Technologies Pathway will support this effort by providing relevant information and participating in development activities. **Milestones:** Human performance improvement for nuclear power plant field workers: • (2020) Publish guidelines to implement technologies for human performance improvement for nuclear power plant field workers field workers. Outage safety and efficiency: • (2020) Publish guidelines to implement technologies for improved outage safety and efficiency. Centralized online monitoring and information integration: • (2020) Publish guidelines to implement technologies for centralized online monitoring and information integration. Integrated operations: • (2022) Publish guidelines to implement technologies for integrated operations. Automated plant: • (2025) Publish guidelines to implement technologies for an automated plant. Hybrid control room: • (2025) Publish guidelines to implement technologies for a hybrid control room.
LWRS – RST (Gap Analysis)	**R&D Scope and Objectives:** Many of the activities associated with the RST Pathway represent DOE initiatives that had commenced shortly after the Fukushima accident. Thus, there was a need to perform a comprehensive review on areas of engagement by industry for beyond design basis events, as well as what R&D activities NRC is supporting in this area. In 2015, a gap analysis[h] was completed using a team of reactor safety experts from industry (i.e., EPRI, BWR and PWR Owners Groups, and U.S. vendors), DOE and its national laboratories, and academe. This gap analysis provided the technical foundation for identifying the activities in this pathway. The gap analysis will be periodically reviewed in collaboration with industry to ensure that the results remain current and that R&D efforts are focused on the knowledge gaps that have the highest impact on reactor safety.

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[h] R. Bunt, et al., "Reactor Safety Gap Evaluation of Accident Tolerant Components and Severe Accident Analysis," ANL/NE-15/4, March 31, 2015.

LWRS – RST (Fukushima Forensics and Inspection Plan) [i]	**R&D Scope and Objectives:** 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 and 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 early in cleanup and decommissioning plans in order to minimize the impact on decommissioning cost and schedule. Japan has already begun planning decommissioning of the damaged Fukushima reactors; therefore, this is an appropriate time to identify inspection and sampling needs, prioritize them, and sequence them most efficiently into the planning process. 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 Owners Groups, and EPRI), and informed by interactions with representatives from NRC and TEPCO. These insights are also contributing to synergistic international efforts, such as the CSNI (Committee on the Safety of Nuclear Installations, under the Office for Economic Cooperation and Development's Nuclear Energy Agency) 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. To ensure that the maximum benefit is obtained from information available in the affected units at Fukushima during the TEPCO decontamination and decommissioning, an initial plan[j] was developed in 2015 that documents consensus input from U.S. experts for prioritized time-sequenced examination information and supporting R&D activities that could be completed with minimal disruption of planned TEPCO decontamination and decommissioning activities. This plan was developed with input from a broad spectrum of U.S. experts from

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[i] The forensics task within the RST Pathway will be moving to the Office of International Nuclear Safety (NE-6) in FY18. However, the severe accident analysis tasks currently underway within RST will continue to coordinate with the forensics work after this move occurs. Coordination is vital to ensure that the findings from the forensics work are factored into severe accident analysis and inform model improvement activities.

[j] J. L. Rempe (editor), R. Bunt, M. Corradini, P. Ellison, M. Farmer, M. Francis, J. Gabor, R. Gauntt, C. Henry, R. Linthicum, W. Luangdilok, R. Lutz, C. Paik, M. Plys, C. Rabiti, K. Robb, R. Wachowiak, "US Efforts in Support of Examinations at Fukushima Daiichi, Draft," ANL/LWRS-15/2, August 2015.

	industry, universities, and national laboratories. Experts from U.S. government organizations (i.e., NRC and DOE) also attended and informed participants during the meetings on topics, such as ongoing regulatory activities and other relevant international research. As part of this effort, TEPCO engineers discussed their decontamination and decommissioning efforts. **Milestones:** • (Annually to 2020) Review new data from Fukushima forensics and update plans as required. • (Annually to 2020) Review severe accident/dose assessment codes, incorporate new information into code models; provide feedback on forensics plans. • (Annually) Support forensics inspections or technology deployment as required.
LWRS – RST (Severe Accident Analysis)	**R&D Scope and Objectives:** 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 accident progression, these activities also highlighted where the existing computer system models being used did not always produce consistent results. There was recognition that if such tools were to be used in developing effective severe accident management guidelines and associated training, further work was needed to identify the sources of uncertainties and inconsistencies in the models. This information would, in turn, provide greater confidence in the use of these tools as well as to inform the need for updated/new tools. The objective of this R&D activity is to improve the understanding of (and reduce uncertainties in) severe accident progression, phenomenology, and outcomes using existing analytical codes. Insights from this improved understanding of accident progression support improvements to 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 can also 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. A further benefit of the analysis efforts can be to aid in preparations and planning for the examination of the damaged Fukushima units. **Milestones:** In-vessel behavior: • (2017) Complete MAAP-MELCOR crosswalk Phase 2 using an accident scenario that is similar to the TMI-2 severe accident. • (2019) Complete water management severe accident analysis in collaboration with BWR ex-vessel mitigating strategies. • (2020) Confirm severe accident management guideline (SAMG) actions with severe accident analysis, including uncertainties. • (2020) Upgrade BWR Owners Group technical support guidelines using severe accident analysis. Ex-vessel behavior: • (2017) Deliver melt spreading and debris coolability models for industry use. • (2018) Complete debris coolability experiments to validate debris

	coolability model. - (2019) Complete water management severe accident analysis in collaboration with in-vessel behavior. - (2020) Incorporate spreading and debris coolability model into advanced system analysis model.
LWRS – RST (Accident-Tolerant Components)	**R&D Scope and Objectives:** 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 and 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. 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. Finally, analyses and experiments in support of industry initiatives may reveal additional margin in reactor safety systems and components. The reactor core isolation cooling (RCIC) for BWRs and turbine auxiliary feed water for PWRs are key safety systems that are used to remove decay heat from the reactor under a wide-range of conditions, ranging from operational pressures down to lower pressures approaching cold shutdown conditions. Both systems use steam produced from the reactor core decay heat to drive a steam turbine, which in turn powers a pump to inject water back into the core (BWR) and into the steam generators (PWR) to maintain the needed water inventory for long-term core cooling. Based on events at Fukushima and associated analyses[k], it is known that RCIC operation was critical in delaying core damage for days (almost 3 days for Fukushima Unit 2), even though the turbine-pump system ran without direct current power for valve control and with high water temperatures from the BWR wetwell. The RCIC system apparently operated in a self-regulating mode, supplying water to the core and maintaining core cooling until it eventually failed at about 72 hours. The principal objective of R&D in this area is to reduce knowledge gaps on emergency response equipment performance under beyond design basis event conditions for both BWRs and PWRs; specifically, RCIC and auxiliary feed water systems. In effect, there is a need to better determine the actual operating envelope of these components under beyond design basis event conditions. **Milestones:** - (2016) Complete development of a turbine-pump (RCIC) model. - (2017) Finalize plans for possible testing of single-stage turbine-pump system

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[k] R.O. Gauntt et al., Fukushima Daiichi Accident Study, SAND2013-6173, December 2012.

	under beyond design basis conditions. The decision has been made to move forward with these experiments as part of a collaborative effort between U.S. industry, Japan, and DOE. Work is expected to begin in the second half of 2017.
LTO – Technical Bases Updates to EPRI Technical Reports to Support SLR	**R&D Scope and Objectives:** Technical bases are the data and associated implementation tools (e.g., guidelines, analytical models, evaluation bases, etc.) that provide reasonable assurance that the current condition of the subject SSC is assessed to allow safe, continued operation as is through a defined period prior to reassessment or to allow remedial actions prior to risk of failure. In December 2015, NRC issued draft versions of the generic aging lessons learned report for SLR and the corresponding standard review plan for SLR. The final versions, after comment resolution, of these documents are expected to be issued in 2017. They provide the basis for NRC review of SLR applications that are expected to occur starting in 2018. The LTO Program will lead and coordinate EPRI efforts to development technical data to inform stakeholders about establishing reasonable assurance for safe operation during the SLR period. A follow-on effort is focused on the review of EPRI technical documents that form the foundation for Aging Management Program (AMP) actions to assess their applicability through the extended operating period. Where appropriate, the need for technical updates will be identified and then incorporated into a schedule for such updates to be completed. Consideration will be given in the process to supporting potential utility licensing decision making as expected to occur in the 2015 through 2019 timeframe.
Buried Piping and Tanks (work not directly in LTO scope due to near-term, nuclear power plant operational impact)	**R&D Scope and Objectives:** This research area is under the NEI 09-14 initiative. EPRI buried pipe research is focused on furthering state-of-the-art technologies for inspection, analysis, repair, and mitigation of ongoing corrosion in buried infrastructure. This includes the following: • Development and delivery of appropriate reference documents and training to support broad knowledge awareness for buried and underground piping. • Development and transfer of new buried pipe inspection technologies, such as remote field NDE inspection robotics. • Identification and evaluation of existing technologies that may be directly applied or easily adapted for nuclear power plant buried piping inspection. • Improved understanding regarding the usefulness of guided wave acoustic NDE technologies for buried piping inspections. • Availability of repair and replacement alternatives for buried pipe applications, including high-density polyethylene. • Enhanced buried pipe risk-ranking technologies through updates to existing software. Research activities are coordinated across EPRI's Plant Engineering and NDE Programs.

	The Plant Engineering Program provides buried pipe program owner guidance documents, reference materials, and upgraded risk ranking software (BPWORKS^{TM}) and also supports the development of various ASME Code Cases for repair/replacement activities. Training courses are offered for newly assigned Buried Pipe Program owners to help ensure buried pipe management guidance is appropriately deployed in the field. Reference materials on cathodic protection and coatings have been developed to address buried and underground pipe program needs. Through the Buried Pipe Integrity Group, EPRI provides a forum for information exchange among nuclear power plant personnel, vendors, and other stakeholders to identify and transfer best practices for buried pipe inspection and assessment. The NDE Program is pursuing the identification and assessment of existing robotic and inspection technologies, as well as the development of new robotic inspection technologies using remote field detection technology. Efforts continue to identify, demonstrate, evaluate, and qualify inspection technologies suitable for buried pipe applications, with special emphasis on guided wave ultrasonic technologies.
Nuclear Plant Chemistry (work not directly in LTO scope due to near-term, nuclear power plant operational impact)	**R&D Scope and Objectives:** No specific water chemistry program LTO-related R&D gaps were identified. The benefit of water chemistry technologies is generally time independent. Although mitigation through chemical means is vital to long-term aging management, any changes to program implementation over time are not likely to be related to time-dependent factors. Importantly, implementation of the water chemistry program is specifically within the scope of NEI 03-08. A robust industry program exists to ensure that water chemistry guidelines are periodically reviewed and updated and that related R&D gaps are proactively addressed. Opportunities for AMP implementation improvements may be realized from these ongoing research efforts. Key existing EPRI reports include the following: • BWRVIP-190: BWR Vessel and Internals Project, BWR Water Chemistry Guidelines – Revision 1. EPRI, Palo Alto, CA: 2014, 3002002623. • Pressurized Water Reactor Primary Water Chemistry Guidelines – Revision 7. EPRI, Palo Alto, CA: 2014, 3002000505. • Pressurized Water Reactor Secondary Water Chemistry Guidelines, Revision 7. EPRI, Palo Alto, CA: February 2009, 1016555.
Steam Generator Management Program (work not directly in LTO scope due to near-term, nuclear power plant operational impact)	The EPRI Steam Generator Management Program provides guidelines for inspection, repair, monitoring, and flaw evaluation of steam generator components and tubing materials. The Steam Generator Management Program includes aging management activities for the steam generator tubes, plugs, sleeves, and secondary side components that are contained within the steam generator. Program implementation is consistent with nuclear power plant technical specifications and includes commitments to NEI 97-06. The NDE techniques used to inspect tubes, plugs, sleeves, and secondary side internals are intended to identify components (e.g., tubes and plugs) with degradation that may need to be removed from service or repaired. The program additionally provides for degradation assessments, condition monitoring (assessment of past performance), and operational assessments (forward-looking assessment of anticipated performance until the next inspection). The Steam Generator Management Program is based on these six EPRI guidelines:

	• PWR Steam Generator Examination Guidelines • PWR Primary-to-Secondary Leak Guidelines • PWR Secondary Water Chemistry Guidelines • PWR Primary Water Chemistry Guidelines • Steam Generator Integrity Assessment Guidelines • Steam Generator In-Situ Pressure Test Guidelines. These guideline documents are supported by both evaluation handbooks (e.g., flaw evaluation and foreign object evaluation) and by technical reports that document the results of EPRI research. Reports are periodically updated using the latest R&D results.

Attachment A
Long Term Operations Issue Tracking Table

Long Term Operations (LTO) Issue Tracking Table (ITT) – 2016 Revision

LEGEND
🟩 Active on-going work
🟨 Planned work
🟥 No planned work; potential scope

The purpose of the LTO ITT is to identify and prioritize the R&D projects needed to support safe, reliable and economic long-term operations of nuclear plants. The ITT is the result of an expert solicitation process and is maintained as a living document. It is reviewed on an annual basis by stakeholders from EPRI, NEI, DOE, national laboratories and EPRI utility advisors to ensure accuracy and completeness.
The R&D projects are colored coded to indicate their status and assigned to one of the following categories:

- A – An industry developed program or R&D results are needed for a utility to submit an application for Second License Renewal (SLR) to the NRC.
- B – Sufficient information exists to submit a SLR application, but continued R&D projects are needed to provide informed insights for aging management, inspection intervals and repair/replacement decisions.
- C – R&D projects are not needed for SLR, but the projects support long-term sustainability based on addressing obsolescence and economic improvements for extended operations.

In December 2015, the NRC issued draft documents for comment covering the Generic Aging Lessons Learned (GALL) and Standard Review Plan (SRP) documents that are intended to be used in the review of applications for Second License renewal (SLR). The accompanying ITT was revised for 2016 to indicate objectives for SLR that are expected in key technical areas previously identified per industry and stakeholder reviews. It is noted that those key areas are generally consistent with the changes made in the draft NRC documents.

The EPRI-LTO and the DOE-LWRS Program use the ITT to ensure the necessary R&D projects being performed at the right time to support long-term operations of nuclear power plants by plant owners and operators. It is noted that the variability in plant designs and operation produce similar variability is aging management performance of SSCs. This situation is addressed in the NRC GALL-SLR and SRP-SLR by referencing licensee further evaluations in select areas. The expansion of data to support such further evaluation needs is an on-going element of the EPRI and DOE research efforts.

EPRI Long-Term Operation (LTO) Program
2016 Issue Tracking Table (ITT)

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
Research Focus Area #1: Aging Management for RPVs, Reactor Internals, RCS Piping, and Welding							
A	BWR – revision to the existing Integrated Surveillance Program (ISP) for SLR	Long-Term Operations (LTO) Program BWR Vessel and Internals Program (BWRVIP)	🟩	🟥	XI.M31/AMP118	Yes - BWR only.	N/A
A/B	PWR Surveillance capsules with fluence representative of 80 years of operation	Materials Reliability Program (MRP)	🟩	🟩	XI.M31/AMP118	Vendor dependent	N/A
A	PWR reactor internals management program for 80 years of operation	MRP	🟩	🟩	XI.M16A/AMP113	Yes	Yes, development of gap analysis for lead plant and response. Final results to support revisions to EPRI generic guidance report.
B	Environmentally assisted cracking (EAC) of nickel alloy base and weld materials - extend data and corresponding aging management efforts to encompass SLR.	BWRVIP and MRP	🟩	🟥	XI.M11B and 16A / AMP111 and 113 (Lesser impact on additional AMPs)	Yes	Yes. Interim results to support lead plant. Final results to support revisions to EPRI generic guidance reports.
B	Environmentally assisted cracking (EAC) of stainless steel base and weld materials - extend data and corresponding aging management efforts to encompass SLR.	BWRVIP	🟩	🟥	XI.M9 / AMP 109	BWR Only	Yes. Interim results to support lead plant. Final results to support revisions to EPRI generic guidance reports.

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
B	Irradiation assisted stress corrosion cracking (IASCC) of austenitic and cast stainless steel - extend data and corresponding aging management efforts to encompass SLR.	MRP and BWRVIP	🟩	🟥	XI.M9 and 16A / AMP 109 and 113	TBD / Likely	Yes. Interim results on fluence vs degradation to support lead plant. Final results to support revisions to EPRI generic guidance reports.
B	Thermal aging of cast austenitic stainless steel (CASS) and stainless steel welds - extend data to support SLR, as necessary.	BWRVIP	🟩	🟥	XI.M12 / AMP112	TBD / Possible depending on final consensus threshold levels with NRC staff	Possible if threshold results require additional data for lead plants and revisions for application to 80 years.
C	Flaw detection methods for cast austenitic stainless steels	NDE.	🟥	🟥	XI.M12 / AMP112	TBD / Possible depending on results from previous item and/or flaw tolerance evaluations.	N/A
B	Environmental effects on fatigue life for nickel alloys and stainless steel. Extend data to support SLR period.	MRP and BWRVIP	🟩	🟨	Time Limited Aging Analysis (TLAA) impact.	No	On-going research in progress to refine potential impact. May be needed/used to support lead plants and revise generic guidance.
B	Welding of highly irradiated reactor internals	Joint project with LWRS	Joint project with EPRI	🟥	Application of advanced technologies may impact multiple AMPs.	No	N/A. Research is on-going to establish repair option in lieu of replacement.

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
B	Analysis of potential thermal embrittlement effects on PWR vessel nozzles	MRP	🟩	🟥	XI.M31 / AMP118	Yes for PWR	On-going research in progress. Interim results may support lead plant. As appropriate, final results to support revisions to EPRI generic guidance reports.
C	Advanced alloys and fabrication methods for reactor internals replacement	Joint project with LWRS	Joint project with EPRI	🟥	Multiple Potential Applications	No.	N/A
B	Develop methods for stress improvement and repair options	MRP	🟥	🟥	Multiple AMPs depending on specific component application.	No	Yes, as applied for specific plants and components.
C	Analytical framework for extremely low probability of rupture (xLPR).	MRP	🟩	🟩	Potential impact on multiple AMPs	No.	Yes, as applied to specific plants.
C	Post-irradiation annealing of reactor pressure vessels to allow extended life.	🟥	🟩	🟥	XI.M31 / AMP118	No	N/A
Research Focus Area #2: Aging Management for Electric Cables and Components							
B	Understand the potential synergistic effects of radiation and temperature on cable insulation for long-term operations	Plant Engineering	🟩	🟩	XI.E1, E2, E3 / AMP 201, 202, 203	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
B	Testing and aging management of cables (sub-merged/wetted, EQ/non-EQ, medium and low volt-age)	Plant Engineering	🟩	🟩	XI.E1, E2, E3 / AMP 201, 202, 203	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
B	Understand factors impacting qualified life of cables.	Plant Engineering	🟩	🟩	XI.E1, E2, E3 / AMP 201, 202, 203	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
B	Condition Monitoring for Cables	Plant Engineering	🟩	🟩	XI.E1, E2, E3 / AMP 201, 202, 203	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
Research Focus Area #3: Aging Management for Concrete and Civil Structures							
B	Guidelines and analysis tools for managing alkali silica reaction (ASR), including testing and inspection techniques.	NDE (Concrete)	🟩	🟩	XI.S6 / AMP306	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
B	Guidelines and analysis tools for managing boric acid degradation on the spent fuel pool (SFP) concrete and rebar.	NDE (Concrete)	🟩	🟥	XI.S6 / AMP306	Yes	Yes, generic guidance in development.
B	Guidelines and analysis tools for managing degradation to due to radiation and temperature exposure.	NDE (Concrete)	🟩	🟥	XI.S6 / AMP306	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
B	Guidelines and analysis tools for managing creep degradation over time that impacts structural integrity and performance	NDE (Concrete)	🟥	🟥	XI.S6 / AMP306	Yes	In-progress research to inform industry. Final results to support EPRI generic guidance reports.
C	Detection method for corrosion on backside of containment liner	NDE (Concrete)	🟥	🟥	XI.S6 / AMP306	No	N/A

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
C	Detection of degradation in inaccessible concrete.	NDE (Concrete)			XI.S6 / AMP306	TBD	General NDE developed technology may be used per specific application.
Research Focus Area #4: Opportunities for Modernization and Economic Efficiencies							
B	Nondestructive evaluation methods for irregular welds, cast austenitic stainless steels, J-grooves, etc…	NDE			Potential impact to multiple AMPs	No	On-going R&D that can be used per specific applications.
B	Neutron Absorber materials for long-term operations	Used Fuel			XI.M40 / AMP137	No	On-going R&D that can be used per specific applications.
B	Testing and inspection methods for buried piping	NDE			XI.M41 / AMP125	No	On-going R&D that can be used per specific applications.
B	Mitigation of corrosion via cathodic protection	BOP Corrosion			XI.M41 / AMP125	No	On-going R&D that can be used per specific applications.
B	New materials and methods for BOP system replacement or refurbishment	BOP Corrosion			XI.M41 / AMP125	No	On-going R&D that can be used per specific applications.
B	Aging management of coatings for SLR.	Plant Engineering			XI.M36 M41 / AMP134 125	No	On-going R&D that can be used per specific applications.
B	Monitoring, assessment of degradation, and estimation of RUL using the EPRI BP Works methodology.	BOP Corrosion			XI.M41 / AMP125	No	On-going R&D that can be used per specific applications.
B	Aging management of selective leaching of elements from metal piping.	NDE and BOP Corrosion			XI.M41 / AMP125	No	On-going R&D (NDE and assessment) that can be used per specific applications.

Priority	ISSUE	EPRI	DOE	NRC	AMP IMPACT (GALL/IGALL)	Lead Plant Impact?	Research Supports Further Evaluations defined in SRP-SLR?
C	Development of enhanced safety analysis codes to address technical uncertainties in analysis codes and capabilities.	Joint Program with LWRS.	Joint Program with EPRI.	🟥	Application of advanced technologies may impact multiple AMPs.	No	On-going R&D that can be used per specific applications.
C	Development of next-generation I&C, human/system interface, and information technology architecture and capability.	Non-LTO work by Technical Programs supporting nuclear I&C performance.	Related work on advanced I&C technology.	🟥	Application of advanced technologies may impact multiple AMPs.	No	On-going R&D that can be used per specific applications.
C	Development of on-line monitoring, diagnostics and prognostics for passive components	Joint Program with LWRS.	Joint Program with EPRI.	🟥	Application of advanced technologies may impact multiple AMPs.	No	On-going R&D that can be used per specific applications.
C	Investigate techniques for NDE that can provide new technologies to monitor material and component performance.	NDE	DOE-LWRS program has developed roadmaps for future sensor and NDE enhancements	🟥	Potential application to multiple AMPs	No	On-going R&D that can be used per specific applications.
C	Fuel pool internals aging and repair.	NDE and Welding and Repair Technology Center	🟥	🟥	XI.S6 / AMP306	No	On-going R&D that can be used per specific applications.
C	Risk-informed sampling for in-service inspection	NDE	🟥	🟥	Potential impact on multiple AMPs	No	On-going R&D that can be used per specific applications.

N/A = Not Applicable
TBD = To Be Determined

Appendix A

Industry Cost Sharing

(This appendix is proprietary and has special access requirements.)