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Revision 2

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

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Office of Nuclear Energy

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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 (NPPs) 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.

Seventeen commercial NPPs in the Unites States have passed their 40th anniversary of power operations, and about one-half of the existing fleet will reach the same 40-year mark within the next decade. While recent, overall performance has been excellent (capacity factors approaching or exceeding 90%), the fleet is facing a number of technical challenges related to long-term operation. Those challenges include uncertainties in material safety margins and degradation rates under extended operating conditions, obsolescence of instrumentation and control systems, safety analysis methods that would benefit from updating, and others. A regulatory process exists (10 CFR Part 54) for obtaining approval from the U.S. Nuclear Regulatory Commission on extended NPP operations beyond 60 years. However, the U.S. Nuclear Regulatory Commission will require plants applying for license renewals to extend NPP service life to demonstrate that adequate design and operational safety margins will be maintained over the duration of the extended operations period.

If current NPPs do not operate beyond 60 years (due to owner decisions or regulatory restrictions), 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 (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), the costs for replacement generation capacity will be even higher.

Recognizing the challenges associated with pursuing commercial NPP operations beyond 60 years, 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 programs (DOE-NE's Light Water Reactor Sustainability [LWRS] Program and EPRI's Long-Term Operations [LTO] Program) to address these challenges. To ensure that a proper linkage is maintained between the programs, DOE-NE and EPRI executed a Memorandum of Understanding in late 2010 to "establish guiding principles under which research activities (between LWRS and LTO) 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 second annual revision to the initial version (March 2011) of the plan as called for in the Memorandum of Understanding.

CONTENTS

SUMMARY iii

ACRONYMS vii

1. BACKGROUND 1

    1.1 U.S. Department of Energy Office of Nuclear Energy 1

    1.2 Electric Power Research Institute 1

    1.3 Research and Development Cooperation 1

2. DESCRIPTION OF RESEARCH AND DEVELOPMENT PROGRAMS 3

    2.1 Department of Energy Office of Nuclear Energy Light Water Reactor Sustainability Program 3

    2.2 Electric Power Research Institute Long-Term Operations Program 4

    2.3 Reporting of Research and Development Projects 7

3. LIGHT WATER REACTOR SUSTAINABILITY/ LONG-TERM OPERATIONS COORDINATED RESEARCH AND DEVELOPMENT ACTIVITIES 11

4. LIGHT WATER REACTOR SUSTAINABILITY/LONG-TERM OPERATIONS COLLABORATIVE RESEARCH AND DEVELOPMENT ACTIVITIES 27

ACRONYMS

BWR	boiling water reactor
CASS	cast stainless steel
DOE	U.S. Department of Energy
EAF	environmentally assisted fatigue
EPRI	Electric Power Research Institute
IASCC	irradiation-assisted stress corrosion cracking
I&C	instrumentation and control
II&C	instrumentation, information, and control
INL	Idaho National Laboratory
LTO	long-term operations
LWR	light water reactor
LWRS	light water reactor sustainability
MAaD	materials aging and degradation
MOOSE	Multi-physics Object Oriented Simulation Environment
NDE	nondestructive examination
NE	Office of Nuclear Energy
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
R&D	research and development
RAVEN	Reactor Analysis and Virtual Control ENvironment
RFO	refueling outage
RIMM	risk-informed margin management
RISMC	risk-informed safety margin characterization
RPV	reactor pressure vessel

SCC	stress corrosion cracking
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 the United States' energy, environmental, and energy security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration activities, as appropriate. R&D efforts under the Light Water Reactor Sustainability (LWRS) Program are managed by DOE-NE's Office of Light Water Reactor Technologies, NE-72, and the program Technical Integration Office, located at the Idaho National Laboratory (INL).

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 (NPPs). R&D efforts in the Long-Term Operations (LTO) Program are managed as a separate technical program operating in the Plant Technology Department of the EPRI Nuclear Power Sector, with the guidance of an industry advisory Integration Committee.

1.3 Research and Development Cooperation

The 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 NPPs beyond 60 years are described in the following documents:

1. The DOE-NE Light Water Reactor Sustainability Integrated Program Plan (April 2013)

2. The EPRI Long-Term Operations Program Plan (August 2012).

In late 2010, DOE-NE and EPRI executed a memorandum of understanding[a] to "establish guiding principles under which research activities (between LWRS and LTO) 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.

[a] "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.

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. Advanced Instrumentation, Control, and Information (II&C) Systems Technologies

3. Risk-Informed Safety Margin Characterization (RISMC)

4. Advanced Light Water Reactor (LWR) Nuclear Fuels.[b]

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. Instrumentation and Control (I&C) and Information Technology (including online monitoring of critical equipment)

4. Advanced Safety and Risk Analysis Tools

5. Integrated Life-Cycle Management (data, methods, and tools)

6. Cable Aging

7. Aging Management Program Scope for Operation Beyond 60 Years

8. 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 beyond 60 years. LTO Technical Area 5, Integrated Life-Cycle Management, and LTO Technical Area 7, Aging Management Program Scope, currently are exceptions for which there are no corresponding LWRS pathways. 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 the diversity between the LWRS and LTO Programs to more efficiently and effectively meet the joint objectives.

[b] This pathway will transition to the DOE Fuel Cycle R&D Program, beginning in 2013; this transition will be complete by the beginning of 2014.

2. DESCRIPTION OF RESEARCH AND DEVELOPMENT PROGRAMS

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

Sustainability in the context of LWRs is defined as the ability to maintain safe and economic operation of the existing fleet of NPPs for a longer-than-initially-licensed lifetime. It has two facets with respect to long-term operations: (1) manage the aging of hardware so the NPP lifetime can be extended and the 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.

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 NPPs. The LWRS Program is the primary programmatic activity that addresses Objective 1. The LWRS Program is focused on the following three goals:

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

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

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

Through the LWRS Program, DOE collaborates with industry and 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, 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. Cost-shared demonstration activities will be conducted when appropriate.

The LWRS Program consists of the following four 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 NPPs. The work will provide data and methods to assess the performance of SSCs essential to safe and sustained NPP operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in NPP SSCs that are subject to long-term operating conditions, providing key input to both regulators and industry.

2. ***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 NPPs that provide an enhanced understanding of plant operating conditions and available margins and improved response strategies and capabilities for operational events.

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

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

2.2 Electric Power Research Institute Long-Term Operations Program

High capacity factors and low operating costs make NPPs some of the most safe and economical power generators available. Even when major plant components must be upgraded to extend operating life, these plants often represent a safe, cost-effective, low-carbon asset. The decision to extend NPP 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: directly through design and operational contingencies and indirectly through impacts on regulatory actions and public policy.

Recognizing the many technical challenges confronting NPP operation, EPRI launched the LTO Project in 2009. LTO is defined as being high-performance NPP operation to 60 years, 80 years, or beyond. 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 NPP operation to 60 years, 80 years, or beyond. Specifically, LTO Program projects must address one or more of the following:

1. License renewal beyond 60 years

2. Aging management and life-cycle management throughout long-term operation

3. Refurbishment and uprate decisions

4. 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 and uprate

   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 of 2014 to 2019.

3. It is unlikely that the 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 LWRS Program or NRC's Office of Nuclear Regulatory Research.

The R&D portfolio addresses the following eight 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 extend component life. Individual projects addressing this objective include the following:

   a. Extension of Materials Degradation Matrix and Issues Management Tables to include Failure Mechanisms to 80 Years

   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.

2. For ***concrete structures, including containment***, identify and prioritize degradation mechanisms and locations; establish methods for issue resolution, including new nondestructive examination and forensic concrete examination methods; prognostic modeling to determine remaining useful life; and investigate mitigation measures for issues important to long-term operations.

3. Through support of structured pilot studies, demonstrate and document ***advanced I&C and information technology*** to address obsolescence aging of components and systems. Pilot studies will address highly integrated control room, highly automated plant, integrated operations, human performance improvement for field workers, outage safety and efficiency, and centralized online monitoring and information integration. EPRI will participate on a working group that oversees these studies. EPRI also will document good practices and requirements for these studies into an accessible database. For mature applications with generic applicability, EPRI will develop guidelines for future applications.

4. 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.

5. Provide industry with ***integrated life-cycle management*** data, methods, and tools for key components that will improve the cost and certainty of high-performance operation and will support optimization of integrated refurbishment and uprate plans. Individual projects addressing this objective include the following:

    a. Integrated Life-Cycle Management Data Resource and Method

    b. Pilot Application of Électricité de France (EDF) Asset Management Tools

    c. Identification and Assessment of Potential Life-Limiting Issues.

6. 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.

7. Investigate ***aging management program scope*** for operation beyond 60 years. Research results and operating experience might identify additional components of concern, failure mechanisms, or conditions that would be part of aging management programs for operation beyond 60 years. 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.

8. Develop an ***integrated strategy, process plan, and demonstration plants*** to support license renewal, the decision to extend operation beyond 60 years, 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. Nuclear Plant Life-Extension Demonstration Project.

In addition, a “living” issues tracking table maintains the status of all identified issues and their priorities. This issues tracking table is regularly reviewed for accuracy and completeness by EPRI stakeholders, LWRS representatives, a working group of the Nuclear Energy Institute, and EPRI advisors. The objectives and associated projects listed in this document have been selected from high-priority issues in the issues tracking table that meet the selection criteria and have received concurrence of the LTO Integration Committee.

Finally, it is important to emphasize that considerable supporting R&D is pursued within EPRI that is driven by current operating plant issues rather than by a specific LTO need. For example, buried and underground piping and tank research is such 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. 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 Sections 3 and 4 of this joint plan using the following categories:

1. Section 3 discusses "Coordinated (but independent) Activities," meaning that "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 that "DOE and EPRI intend work in the category to be planned and executed on a collaborative basis. The collaborative efforts between DOE and EPRI may involve, to a significant degree, joint funding as permitted by law and available appropriations. DOE and EPRI will determine which organization will lead each effort based on which party is positioned to most efficiently and effectively execute the work."[c]

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

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 and the corresponding (coordinated or collaborative) LTO Program's R&D activities. To provide more perspective on the total scope of R&D work, the table also identifies LWRS and LTO projects that do not meet the memorandum of understanding criteria for coordinated or collaborative activities. Details on those R&D projects can be found in the individual LWRS and LTO program R&D plans. 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 Project	Related LTO Project	Coordinated Activity	Collaborative Activity	Program Unique Activity
Materials Aging and Degradation	Understanding, Prediction, and Mitigation of Primary System Aging Degradation			
Expanded Materials Degradation Analysis				LWRS
	Materials Degradation Matrix and Issues Management Tables			LTO

[c] As committed to in the memorandum of understanding, "DOE and EPRI endeavor 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 in order to strengthen the partnership." 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 Project	Related LTO Project	Coordinated Activity	Collaborative Activity	Program Unique Activity
Reactor Metals				
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		
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 and phase transformations)	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		
Environmentally Assisted Fatigue (EAF)	EAF – Long-term focus; EPRI has a short-term focus (current operating plants) effort as well	LWRS-LTO joint lead		
Thermal Aging of Cast Stainless Steel (CASS)	Thermal Aging of CASS	LWRS-LTO joint lead		
Concrete	Comprehensive Aging Management of Concrete Structures (Technology Roadmap)		LWRS-LTO joint lead	
Cabling	Technical Basis for Aging Management and Life-Cycle Management of Cables	LWRS-LTO joint lead		
Mitigation Strategies				
Advanced Weld Repair	Advanced Welding Methods for Irradiated Materials		LWRS-LTO joint lead	

LWRS Project	Related LTO Project	Coordinated Activity	Collaborative Activity	Program Unique Activity
Advanced Replacement Alloys	Advanced Radiation Resistant Materials Program		LWRS-LTO joint lead	
Thermal (Post-Irradiation) Annealing				LWRS
Integrated Research – International Activities (Halden Project, International Forum on Reactor Aging Management)	Participation in both Halden Project and International Forum on Reactor Aging Management	LWRS-LTO joint lead		
Integrated Research – International Activities (Materials Aging Institute)	Partnership in Materials Aging Institute (EPRI Nuclear Sector)	LTO Lead		
Constellation Demonstration Project	Ginna and Nine Mile Point Unit 1 Demonstration Plant Activities		LWRS-LTO joint lead	
Zion Materials Management and Coordination				LWRS
Nondestructive Examination (NDE) Technologies	Opportunities to Employ NDE Technologies for Automatic, Continuous, In-situ Monitoring	LWRS-LTO joint lead		
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 lead		
Centralized Online Monitoring and Information Integration	Centralized Online Monitoring Methodology, Guidelines, and Pilot Studies (Part of Advanced II&C Pilot Projects)		LTO lead	

LWRS Project	Related LTO Project	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		LTO lead	
RISMC				
Margins Analysis Techniques Modeling and Simulation Activities	Enhanced Safety Analysis Capability		LWRS-LTO joint lead	
	Enhanced Risk Assessment and Management Capability	LTO lead		
Advanced LWR Fuels				
Safety Analysis of Advanced Fuel System Options (including use of silicon carbide cladding)				LWRS
Other Projects				
	Aging Management Program Scope for Operation Beyond 60 Years			LTO
	Alternative Cooling Strategies			EPRI work outside LTO scope
	Buried Piping			EPRI work outside LTO scope

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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
Reactor Metals	
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 RPV. However, there are still significant technical issues that need to be addressed to reduce the uncertainties in regulatory application. The objective of this research task is to examine and understand the influence of irradiation at high fluences on RPV embrittlement. Both industrial capsules and single variable experiments may be required to evaluate potential for embrittlement and to provide a better mechanistic understanding of this form of degradation. Acquisition of samples from past programmatic campaigns (e.g., NRC programs), specimens harvested from decommissioned reactors (e.g., Zion Units 1 and 2), surveillance specimens from operating NPPs, and materials irradiated in new test campaigns all have value in understanding high-fluence effects. Testing will include impact and fracture toughness evaluations, hardness, and microstructural analysis (i.e., 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 2015 in a detailed report, along with all supporting research data. In addition, the library of assembled materials will be available for examination and testing by other stakeholders. 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 the development of statistically viable databases. The objective of this task is to develop new methods to generate meaningful data out of previously tested specimens. Embrittlement margins for a vessel can be accurately calculated using supplementary alloys and experiments using higher flux test reactors. The potential for non-conservative estimates resulting from these methodologies must be evaluated to fully understand the potential influence on safety margins. Critical assessments and benchmark experiments will be conducted. Harvesting of through-thickness RPV specimens may be used to evaluate attenuation effects in a detailed and meaningful manner. Testing will include impact and fracture toughness evaluations, hardness, and microstructural analysis (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 RPVs. Furthermore, the predictive capability developed in earlier tasks will be modified to address these effects.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
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 a supplemental surveillance capsule that will provide high-fluence irradiated data to support future development of embrittlement trend curves applicable for LWR operation at high fluences. This project also will develop and refine an embrittlement trend correlation using the Master Curve approach to convert the shift in Charpy V-notch energy data at different temperatures and irradiations to a fracture toughness equivalent shift. This embrittlement trend correlation is necessary to bridge the gap between the Charpy V-notch energy evaluation approach and the fracture toughness Master Curve approach. 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: • (2013) Complete detailed analysis of RPV samples from Ringhals and R. E. Ginna NPPs. • (2014) Complete acquisition of experimental data on commercial and model RPV alloys. • (2015) Provide validated model for transition temperature shifts in RPV steels. Future milestones and specific subtasks will be based on the results of the previous years' testing, as well as ongoing, industry-led research. Both industry and regulators will use the experimental data and model. 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 for RPV by industry. For example, data and trends will be essential in determining operating limits. The data also will allow for extension of regulatory limits and guidelines to extended service conditions. The delivery of a validated model for prediction of transition temperature shifts in RPV steels will allow for estimation of RPV performance over a wide range of conditions. This will enable extension of current tools for RPV embrittlement (e.g., Fracture Analysis of Vessels: Oak Ridge [FAVOR][d]) to extended service conditions. Materials variability and attenuation effects: • (2013) 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.

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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	• (2016) Complete analysis of hardening and embrittlement through the RPV thickness for the Zion RPV sections. Future milestones and specific subtasks will be based on the results of the previous years' testing, as well as ongoing, industry-led research. The analysis of hardening and variability through the thickness of an actual RPV section from service has considerable value to all stakeholders. This data will provide a first look at embrittlement trends through the thickness of the RPV wall and inform operating limits, fracture mechanics models, and safety margins.
LTO – RPV Embrittlement from Long-Term Fluence	**Milestones**: This project involves irradiation of supplemental surveillance specimens to high fluence in a pressurized water reactor (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 Boiling Water Reactor (BWR) Vessel and Internals Project to address RPV embrittlement after extended operation. • (2013) Participate in a round robin test of a new method to extend the use of existing surveillance specimens to generate Master Curve data. • (December 2014) Design, fabricate, and insert a supplemental surveillance capsule in a host PWR. • (2014) Develop and refine an embrittlement trend correlation; report on revisions to the embrittlement trend correlation.
LWRS – Irradiation Effects (core internals – IASCC, swelling, and phase transformations)	**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 includes a detailed plan to obtain high-fluence specimens for IASCC testing from irradiation of as-received material to high fluence in a test reactor, obtaining high-fluence materials for sample manufacturing, or a combination of those two factors. In addition, both tests (i.e., crack growth and tensile tests) will be performed in simulated water environments in addition to complementary post-irradiation examination of irradiation effects. Results from this task can be used to investigate the potential for IASCC under extended service conditions, extend the mechanistic studies from other tasks in the LWRS Program, and be used to validate predictive models at high fluence. 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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	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 analysis of phase transformation in key samples and components (both model alloys and service materials), including transmission electron microscopy, magnetic measurements, and hardness examinations. Mechanical testing to quantify any impacts on embrittlement also may be performed. These results will be used to develop and validate a phenomenological model of phase transformation under LWR operating conditions. This will be accomplished by use of computational thermodynamics and extension of models for radiation-induced segregation. The generated data and mechanistic studies will be used to identify key operational limits (if any) to minimize phase transformation concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, if necessary, qualify radiation-tolerant materials for LWR service.
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. 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 planned for completion in 2014.
LWRS – Irradiation Effects (core internals – IASCC, void swelling, and phase transformations)	**Milestones:** IASCC: • (2013) Complete detailed experimental plan, timeline, and assessment of irradiation needs for high-fluence IASCC testing. Future milestones and specific subtasks will be based on the plan developed in 2013. Completing a detailed experimental plan for high-fluence IASCC testing is an essential first step in estimating the impact of IASCC at high fluence. This plan also is critical for building support and partnerships with industry and regulators. Swelling: • (2014) Complete model development for swelling in LWR components. • (2016) Deliver predictive capability for swelling in LWR components. Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research. The development and delivery for a validated model for swelling in core internal components at high fluence is an important step in estimating the useful life of core internal

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	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: • (2014) Complete basic model development for phase transformations in LWR components. • (2017) Deliver experimentally validated, physically-based thermodynamic and kinetic model of precipitate phase stability and formation in Alloy 316 under anticipated extended lifetime operation of LWRs. Future milestones and specific tasks will be based on the results of the previous years' testing, as well as ongoing, industry-led research. Development and delivery for a validated model of 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.
LTO – Irradiation Effects (core internals – IASCC, void swelling, and phase transformations)	**Milestones:** • (2011) Completed summary report on Phase 1 Gondole Void Swelling Irradiation and Testing (1022872). • 2015) Interim results of IASCC crack growth and irradiation embrittlement studies on Zorita weld and HAZ material in BWR environments. • (2018) Completion of Gondole Phase 2. • (2019) Final report on Phase 2 Gondole Void Swelling Irradiation and Testing.
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 and stainless steels in simulated LWR water chemistries, but includes direct linkages to SCC crack-growth behavior. Carefully controlled microstructure and surface states will be used to generate single-variable experiments. The experimental effort in this task will be highly complementary to efforts being initiated at the Materials Aging Institute, which are focused primarily on modeling of crack initiation. This mechanistic information could provide key operational variables to mitigate or control SCC in these materials, optimize inspection and maintenance schedules to the most susceptible materials/locations, and potentially define SCC-resistant materials.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
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 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:** • (2014) Complete Phase 1 mechanistic testing for SCC research. • (2017) 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.

<table>
<tr><th>R&D Area</th><th>Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)</th></tr>
<tr><td>LTO – Environmental-Assisted Cracking: Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components</td><td>Milestones:
Activity 1: In-situ surface oxide film characterization and correlation between oxidation and crack initiation:
• (2012) Program on Technology Innovation: Prediction and Evaluation of Environmentally Assisted Cracking in LWR Structural Materials: 2011 PEACE-E Phase II Report (1025123).
• (2013) Summarize results of in-situ surface oxide film composition and impedance properties as functions of materials/LWR environment combinations, including the effects of cations.
• (2013) Damage Processes Prior to Crack Initiation in Ni Alloys.
• (2014) Summarize the results of in-situ surface oxide structure and oxidation kinetics.
• (September 2016) Establish correlation between oxidation and crack initiation.
Activity 2: Local strain-stress behavior associated with crack:
• (2014) Results from in-situ synchrotron x-ray stress measurement.
• (2016) Establish correlation between strain rate and crack growth rate.
Activity 3: Parametric study and development of mitigation strategy:
• (2015) Summary of parametric experiments on crack growth rate.
• (2017) Develop and validate mitigation strategies.
Activity 4: Modeling:
• (2012) Program on Technology Innovation: Hybrid Models of SCC Propagation for Nickel Alloy Welds in Low-Electrochemical Potential PWR Primary Water Environments (1024863, February 2012).
• (2016) Environmental-assisted cracking crack growth prediction model.
• (September 2019) Environmental-assisted cracking crack initiation model.
Activity 5: Consolidation of knowledge base for long-term operations:
• (2013, 2015, and 2018) Environmental-assisted cracking knowledge base updates for long-term operations.</td></tr>
<tr><td>LWRS –EAF</td><td>R&D Scope and Objectives:
The objective of this task is to develop a model of EAF mechanisms. This will be supported by experimental studies to provide data for the identification of mechanisms and key variables and provide data for model validation. The experimental data will inform regulatory and operational decisions, while the model will provide a capability to extrapolate the severity of this mode of degradation to extended-life conditions. A final report will be delivered in the 2017 to 2021 timeframe, providing both the model of fatigue mechanisms and the supporting experimental data.</td></tr>
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R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LTO – EAF (long-term focus)	**R&D Scope and Objectives:** The lack of definite design rules for EAF creates uncertainty for both new plants and operating plants where design compliance must be shown for the extended operating period (significant uncertainty for 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 American Society of Mechanical Engineers 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 • 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 plant vendors, construction firms, and utilities (new and operating plant owners) • Supporting American Society of Mechanical Engineers 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.
LWRS – EAF	**Milestones:** • (2014) Complete base model development for EAF in LWR components. • (2017) Complete experimental validation and deliver model for EAF in LWR components. Completing the 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:** • (2013) Publish guidance for EAF methodology. • (2013 through 2015) Continue international research collaboration with

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	expert panel review and advice. • (2013 through 2016) 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 2015): 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. Possible effects include phase transformations that can adversely impact mechanical properties. This task will provide conclusive predictions for the integrity of the CASS components of LWR NPPs during the 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. While accelerated aging experiments and computational simulations will comprise the main components of the knowledge base for CASS 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 and 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:** Investigate fundamental mechanisms of 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.
LWRS – Thermal Aging of CASS	**Milestones:** • (2016) Complete analysis of CASS specimens harvested from service conditions. • (2017) Complete analysis and simulations on aging of CASS components and deliver predictive capability for CASS components under extended service conditions. Completing research to identify potential thermal aging issues for CASS components is an essential step to identifying possibly synergistic effects of thermal aging (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 and upcoming Expanded Materials Degradation Analysis reports.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LTO – Thermal Aging of CASS and Stainless Steel Welds	**Milestones:** (2014) White paper on R&D relating to CASS and stainless steel weld metals in PWRs.
Cabling	
LWRS – Cabling	**R&D Scope and Objectives:** Cable aging mechanisms and degradation is an important area of study. The plant operators carry out periodic cable inspections using NDE techniques to measure degradation and determine when replacement is needed. Degradation of these cables primarily is caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater. Wholesale replacement of cables is likely economically undesirable for plant operation beyond 60 years. 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.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LTO – Advanced Cable Testing Technology for Life-Cycle Management of Cables	**R&D Scope and Objectives:** In support of long-term operation, two projects will be performed in 2013. The first will gather actual radiation dose and temperature condition data at the location of the cables in containment. Accurate assessment of cable environmental conditions will help guide future cable aging research and assure that degradation modes and rates are reflective of cable conditions in NPPs. Collecting these data, analyzing it, and making it available to members and researchers will be done under this project. The second long-term operation project will evaluate the need for, scope, and associated cost of cable replacement to support operation of today's plants to 80 years. A typical mid-1970's vintage BWR and a PWR will be evaluated. This work will leverage the research work on cable risk algorithm development and cost evaluation software (IPOP) being developed by the integrated life cycle management group. Associated work of interest to LTO is being funded by EPRI's Plant Engineering (PE) 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 (EPR) insulation and plans are to add pink Okonite EPR to the project this year. An aging acceleration regime is being attempted in this project using high frequency (i.e., 450 Hz and 900 Hz) along with 2.5 times line voltage. Additionally, research on medium voltage water-related degradation is continuing in 2013 to identify causes of insulation breakdown. Analysis of member-provided Tan δ data and EPRI recommended acceptance criteria has been validated to classify the degree of wet cable insulation degradation. Further analysis will be done that may provide insight into rates of degradation and perhaps remaining life predictability. PE 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 the 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:** • (2014) Complete analysis of key degradation modes of cable insulation. • (2015) Complete assessment of cable mitigation strategies. • (2017) 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 clearly critical to develop and deliver a predictive model for cable insulation degradation. Both will enable more focused inspections, material replacements, and better informed regulations. The development of in-situ mitigation strategies also may allow for an alternative to cable replacement and would be of high value to industry by avoiding costly replacements.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LTO – Advanced Cable Testing Technology for Life-Cycle Management of Cables	**Milestones**: • (September 2013) Assessment of online continuous differential partial discharge test for medium voltage cable has been completed and a report will be issued on the results. • (2014) Determine containment cable temperature and radiation levels for representative, current NPPs for input into cable aging research. • (2014) Assess cable system vulnerability by environment and service condition to estimate replacement needs for long-term operation.
Mitigation Strategies	
LWRS – Integrated Research/ International Collaborations (Halden Project and the International Forum on Reactor Aging Management)	**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. Research opportunities also can be explored through cooperative efforts with the International Forum on Reactor Aging Management, which facilitates the appropriate exchange of information among those parties and organizations around the world that presently are planning to address or are addressing issues of NPP SSCs aging management. 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 (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 (Halden Project and the International Forum on Reactor Aging Management)	**Milestones:** LWRS milestones related to international collaborations are identified under the specific MAaD R&D areas.
LTO – Integrated Research/ International Collaborations (Materials Aging Institute)	**Milestones** • (2012) Participated in the International Forum on Reactor Aging Management meetings and activities. • (2014) Participate in the Halden IASCC Advisory Group meeting to review progress and establish future direction of the program. • (November 2012) Completed agreement for participation in the Materials Aging Institute activities coordinated with the LWRS Program.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LWRS – NDE	**R&D Scope and Objectives:** NDE R&D is planned for the following MAaD R&D areas: RPV – In the context of long-term operations, the RPV will see increased exposure to time-at-temperature, along with the effects of extended irradiation as described in previous sections. This exposure is expected to reduce the fracture toughness of the RPV. As a result of this exposure and the operational stresses experienced, issues of concern in RPV durability will include phase transformations due to irradiation and embrittlement and hardening. Preexisting flaws in the RPV also are of interest for their implications on RPV structural performance during accident scenarios. Development of one or more NDE techniques that can assist in the determination of current RPV fracture toughness and in prediction of fracture toughness with further aging of the vessel is essential. The NDE measurements and the corresponding models that can verify their applicability to the problem, sensitivity to embrittlement and microcracking, and accuracy in characterizing physical properties of RPV steels to establish correlations with RPV fracture toughness will provide important information for long-term operation. Cracking Precursors – The purpose of this task is to investigate and demonstrate the technical basis for, and feasibility of, advanced NDE methods for evaluation of cracking precursors. These activities will build on the current state-of-the-art in NDE and leverage advances occurring in non-nuclear applications. EAF – In parallel with research on long-term performance of reactor metals, techniques for NDE of key reactor metals are needed toward development of technologies to monitor material and component performance. This task follows the R&D plan developed in 2012 for sensor development to monitor reactor metal performance. In future years, sensor development will be performed with a demonstration of key prototypes by 2016. This ambitious date will require collaboration with other tasks within the LWRS Program and other programs and critical assessment and use of technologies from other industries. Validation and qualification of the sensors will be established and documented in the 2017 to 2021 timeframe. Concrete – Techniques for NDE of concrete provide new technologies to monitor material and component performance. This task will build on an R&D plan developed in 2012 for sensor development to monitor reactor concrete performance. Key issues for consideration can include new or adapted techniques for concrete surveillance. Specific areas of interest may include reinforcing steel condition, chemical composition, strength, or stress state. 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.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
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, and locations of concern. This process is assumed to be effective for the life of the plant, including subsequent license renewal periods. 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:** RPV: • (2019) Demonstrate and deploy new or improved NDE technologies for RPV components. Cracking precursors: • (2017) Complete capability demonstrations for crack precursor detection on prototypic materials. • (2019) Complete demonstration of the technical basis and feasibility for use of crack precursor detection NDE, diagnostics, and prognostics for LWR long-term operation (60 to 80 years). EAF: • (2017) Demonstrate key prototypes of fatigue damage NDE sensors in field test. • (2021) Complete validation of fatigue damage NDE sensors. Concrete: • (2016) Complete prototype proof-of-concept system for NDE of concrete sections. • (2018) Complete prototype of concrete NDE system. Cabling: • (2015) Complete assessment of cable insulation precursors to correlate with performance and NDE signals. • (2017) Demonstrate field testing of prototype system for NDE of cable insulation.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)

LTO – NDE	**Milestones**:
	• (2013) Final report on application of in-situ monitoring (tendons at Ginna Nuclear Plant) of material degradation of passive assets.
	  – Joint milestone with Online Monitoring Project.
	• (2014) Pilot application of in-situ monitoring of material degradation of passive assets.
	  – Joint milestone with Online Monitoring Project.

R&D Area	Advanced II&C Technologies
LWRS – International Collaborations (Halden Project)	**R&D Scope and Objectives:** The Halden Reactor Project's programs extend to many aspects of NPP operations; however, the area of interest to this R&D program is the man-machine-technology research program that conducts research in the areas of computerized surveillance systems, human factors, and man-machine interaction in support of control room modernization. Halden has been on the cutting edge of new NPP technologies for several decades and their research is directly applicable to the capabilities being pursued under the pilot projects. In particular, Halden has assisted a number of European NPPs in implementing II&C modernization projects, including control room upgrades. The II&C Pathway will work closely with Halden to evaluate their advanced II&C technologies to take advantage of the applicable developments. In addition to the technologies, the validation and human factors studies conducted during development of the technologies will be carefully evaluated to ensure similar considerations are incorporated into the pilot projects. Specific Halden developments of interest to the pilot projects are as follows: • Advanced control room layout • Computer-based procedures • Advanced, state-based alarm systems • Integrated operations • Plant worker mobile technologies. INL has entered into a bilateral agreement 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 has established the Productivity Improvements through Advanced Technology Advisory Group. This group is looking at II&C enabled productivity improvements in NPPs and is interacting closely with the LWRS Program's II&C Pathway, including a joint meeting held in August 2012. The Advanced Technology Advisory Group had the Halden Reactor Project give presentations in the June 2010 and April 2012 meetings. The intent is to identify opportunities to support productivity improvements in NPPs, taking advantage of activities in Halden's Man-Machine-Technology Program. 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.

R&D Area	Advanced II&C Technologies
LWRS – International Collaborations (Halden Project)	**Milestones:** (2011) Agreement between Halden and INL signed.
LTO – Halden Project	**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.

R&D Area	RISMC (see "Margins Analysis Techniques" for LWRS cooperative R&D)
LTO – Enhanced Risk Assessment and Management Capability	**R&D Scope and Objectives:** To achieve successful long-term operations of the current fleet of operating NPPs, it will be imperative that high levels of safety and economic performance are maintained. Therefore, operating NPPs 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: (1) First, as the current fleet of operational NPPs ages, it is anticipated that new challenges to NPP safety will 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 plants. (2) Second, as new technologies and capabilities become available, it will be desirable to take advantage of these opportunities to enhance 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 NPP long-term operations (e.g., RISMC/Risk Informed Margin Management [RIMM]) and providing for the capability of the Phoenix software to link to the RELAP-7 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.
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

R&D Area	RISMC (see "Margins Analysis Techniques" for LWRS cooperative R&D)
	and roadmap (EPRI Report 1019207). During 2013, the support of PHOENIX development, testing, and initial deployment will continue. The following activities are planned: • (2013) Update of PHOENIX software development plan to incorporate LTO Program and LWRS Program requirements. This will include prioritization of LTO-related applications for inclusion into PHOENIX and the integration of these modules into the PHOENIX development plan and roadmap. This update of the development plan will identify appropriate linkages to the Reactor Analysis and Virtual Control ENvironment (RAVEN) controller being developed for use in the interface with the RELAP-7 systems analysis code being developed by INL. • (Starting in 2013) Initiate a PHOENIX LTO pilot application and report results during 2014.

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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
Reactor Metals	
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[e]. Experimental research will include crack-growth testing on high-fluence specimens of single-variable alloys in simulated LWR environments, tensile testing, hardness testing, microstructural and microchemical analysis, and detailed efforts to characterize localized deformation. Combined, these single-variable experiments will provide mechanistic understanding that can be used to identify key operational variables to mitigate or control IASCC, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-term, design IASCC-resistant materials.
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.

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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	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. 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. This LTO project is a 5-year effort that started in 2009. The scope of this LTO project can be summarized as investigating the following: • Role of solutes in crack initiation • Role of solutes in crack propagation • Role of starting microstructure in crack initiation • Role of starting microstructure in crack propagation • Effectiveness of proton irradiation in forecasting relative crack growth rate behavior • Comparison of crack initiation following proton and neutron irradiation • Comparison of crack initiation and crack growth in neutron-irradiated samples as a function of solute addition or starting microstructure • Structure property relationship for neutron irradiated alloys • Effect of alloy, alloy purity, heat, and dose on crack growth and crack initiation • Investigate whether small-volume mechanical testing can provide an alternate method of assessing IASCC susceptibility to enable 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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	screening criteria and recommend crack growth disposition curves for BWRs and PWRs to support current and long-term operation.
LWRS – Mechanisms of IASCC	**Milestones:** • (2015) Complete mechanistic testing for IASCC research. • (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**: • (2012) Program on Technology Innovation: A Preliminary Hybrid Model of Irradiation-Assisted Stress Corrosion Cracking of 300-Series Stainless Steels in Low-Electrochemical Potential Light Water Reactor Environments (1024863). • (2014) 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. • (2014) Report on improved IASCC crack growth prediction models for BWRs and PWRs. • (2018) Report on IASCC-resistant materials for repair and replacement.
Concrete	
LWRS – Concrete	**R&D Scope and Objectives:** Large areas of most NPPs have been constructed using concrete and there are some data on performance through the first 40 years of service. In general, the performance of reinforced concrete structures in NPPs has been very good. Incidents of degradation initially reported generally occurred early in the life of the structures and primarily have been attributed to construction/design deficiencies or improper material selection. 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 NPP structures (e.g., NRC, Nuclear Energy Agency, and International Atomic Energy Agency), there are still several areas where additional research is desired to demonstrate that the structures will continue to meet functional and performance requirements (e.g., maintain structural margins). Activities under the MAaD Pathway are focused on compilation of material property data for long-term performance and trending, evaluation of environmental effects, and assessment and validation of NDE methods; evaluation of long-term effects of elevated temperature and radiation; non-intrusive methods for inspection of

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	thick, heavily-reinforced concrete structures and basemats; and data on application and performance (e.g., durability) of repair materials and techniques. Complementary activities are being conducted under an NRC program at Oak Ridge National Laboratory, by EPRI, and by the Nuclear Energy Standards Coordination Collaborative headed by the National Institute for Standards and Technology. To support these activities, a detailed and populated database on concrete performance, with data for performance into the first life-extension period, high-temperature effects, and irradiation effects, will be delivered by 2016. Plans for research at EPRI and NRC will continue to be evaluated to confirm the complementary and cooperative nature of concrete research under the MAaD Pathway. In addition, the formation of an Extended Service Materials Working Group for concrete issues will provide a valuable resource for additional and diverse input.
LTO – Comprehensive Aging Management of Concrete Structures	**R&D Scope and Objectives:** Without an adequate understanding and (where necessary) inspection, concrete civil infrastructure in commercial NPPs is a potential "show-stopper" in lieu for long-term operation. There are a variety of kinetic processes that can lead to degradation of civil structures, and these may be accelerated by operating environments specific to NPPs. 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 NPPs. The initial stage of the project will be to compile an Aging Reference Manual, which will clearly define the physics of kinetic degradation processes and discuss operational issues dealt with by the industry over the past 40+ years. The manual will contain a framework for identifying at-risk structures and applicable degradation mechanisms. Building upon this, a number of individual research projects, aimed at further understanding of those degradation mechanisms and structures identified as "at-risk," will be commenced. 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 this investigation will yield one or more industry examination guidelines for concrete aging assessment.
LWRS – Concrete	**Milestones:** • (2013) Complete validation of data contained in the concrete performance database and place database in the public domain. • (2018) Complete concrete and civil infrastructure toolbox development with EPRI and Materials Aging Institute partners. Future milestones and specific tasks will be based on the results of the previous years' testing, as well as ongoing, industry-led research. Completing and publishing a database of concrete performance will yield a high-value tool accessible to all stakeholders. This will allow for more focused research on remaining knowledge gaps and enable more focused material inspections. In the

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	long-term, completion of a concrete and civil structures toolkit may allow for more robust prediction of concrete performance over extended service conditions. These tools are of high value to industry, a partner in their development.
LTO – Comprehensive Aging Management of Concrete Structures	**Milestones**: • (2012) Published report on literature review of radiation damage effects in concrete. • (2013) Initial report on preliminary findings of the effect of irradiation damage on concrete mechanical properties. • (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. • (2015) Report on experimental study of the effects of boric acid corrosion on concrete. • (2016) Report on radiation damage effects on concrete.
Mitigation Strategies	
LWRS – Advanced Weld Repair	**R&D Scope and Objectives:** This task for developing and demonstrating advanced welding technology for repair applications is being performed collaboratively with EPRI. Research includes mechanistic understanding of helium effects in weldments. This modeling task is supported by characterization of model alloys before and after irradiation and welding. This model can be used by stakeholders to further improve best practices for repair welding for both existing technology and advanced technology. In addition, this task will provide validation of residual stress models under development using advanced characterization techniques such as neutron scattering. Residual stress models also will improve best practices for weldments of reactors today and under extended service conditions. These tools could be expanded to include other industry practices such as peening. Finally, advanced welding techniques (such as friction-stir welding, laser welding, and hybrid techniques) will be developed and demonstrated on relevant materials (model and service alloys). Characterization of the weldments and qualification testing will be an essential step.
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

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	welding methods. As 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. • Prepare 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 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:** • (2015) Demonstrate initial solid-state welding on irradiated materials.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	• (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 also may 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 power plant.
LTO – Advanced Welding Methods for Irradiated Materials	**Milestones**: • (2012) Project status report for 2010 and 2011 and detail project plan for the remainder of project (EPRI Technical Update Report). • (2012) Proof-of-concept for hybrid laser welding. • (2013) 50% engineering design review for welding cubicle (hot cell). • (2013) 100% engineering design review for welding cubicle (hot cell). • (2013) Completion of sample set fabrication. • (2013) EPRI technical update report on project status and results. • (2014) Completion of irradiation of sample set. • (2014) Complete fabrication of welding cubicle. • (2015) Installation of welding cubicle at Oak Ridge National Laboratory. • (2015) Welding experiments on irradiated material sample set.
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 2020.
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 NPPs.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
LWRS – Advanced Replacement Alloys	**Milestones:** • (2013) Complete down-selection and development plan on advanced replacement alloys in cooperation with EPRI. Future milestones and specific tasks will be assigned following release of EPRI's Advanced Radiation Resistant Materials plan in early 2013. Completing the joint effort with EPRI on the alloy down-select and development plan is an essential first step in this alloy development task. This plan will help identify future roles and responsibilities in this partnership with EPRI.
LTO – ARRM	**Milestones:** • (2012) Critical Issues Report and Roadmap for the Advanced Radiation-Resistant Materials Program (1026482). • (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.
LWRS – Constellation Demonstration Project	**R&D Scope and Objectives:** The Constellation Pilot Project is a joint venture between the LWRS Program, EPRI, and the Constellation Energy Nuclear Group. The project utilizes two of Constellation's nuclear stations, R. E. Ginna and Nine Mile Point 1, for research opportunities to support extended operation of NPPs. Specific areas of joint research have included development of a concrete inspection guideline, installation of equipment for monitoring containment rebar and concrete strain, and additional analysis of RPV surveillance coupons. Opportunities for additional and continued collaboration will be explored in the coming years.
LTO – Ginna and Nine Mile Point Unit 1 Demonstration Plant Activities	**R&D Scope and Objectives:** Containment Assessments at Ginna and Nine Mile Point Unit 1 – The Ginna assessment will include, pending plant site approval, application of fiber optics strain gages to tendon shims, and digital image correlation to selected external surfaces to generate baseline and transient data during the planned Integrated Leakage Rate Test. Selected containment sites also will be subject to carbonation testing, and data from site planned inspection activities will be reviewed and evaluated for use and impact on greater than 60-year life. Nine Mile Point Unit 1 activities will be limited to data evaluation from site planned inspections. After the refueling outages of 2011 and 2012, a draft Comprehensive Containment Assessment Guideline will be developed for review by LTO members and testing at future outages. Internals Assessments at Ginna and Nine Mile Point Unit 1 – For Ginna, the data from site planned inspection activities per guidance provided in EPRI MRP-227 will be reviewed and evaluated for use and impact on greater than 60-year life. A sample of stainless steel baffle bolts (of the 28 removed from service during

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	outage) will be destructively evaluated to assess damage progression at varying neutron fluence levels. For Nine Mile Point Unit 1, the data from site-planned inspection activities per guidance provided by the EPRI BWR Vessel and Internals Project will be reviewed and evaluated for use and impact on greater than 60-year life. Potential exists to perform more refined ultrasonic inspection to characterize cracking and provide a baseline for crack growth assessment on the stainless steel top guide. Cracks are believed to be examples of IASCC. After the refueling outages of 2011, draft guidance was developed for review by LTO members and considered as incremental inspection/documentation recommendations for plants considering operations to 80 years. Vessel Assessments at Ginna and Nine Mile Point Unit 1– In addition to reviewing data from site-planned inspection activities at Ginna and Nine Mile Point Unit 1, vessel-specific efforts are being developed. For Ginna, previously removed and tested (Charpy tests) vessel surveillance specimens may be reconstituted and subjected to further irradiation (DOE test reactor) to increase fluence levels per extended life operation. For Nine Mile Point Unit 1, one of two remaining surveillance capsules may be removed for specimen testing, pending a formal determination that testing the capsule will provide useful information for the BWR Integrated Surveillance Program as it applies to LTO-estimated fluence. Note that evaluation activities would occur in 2012 to 2013. The results of these investigations will be input to a determination that suitable data, samples, and testing are available to support operations to 80 years. Identification of Additional SSCs for Demonstration and License Renewal Technical Issues – Work activities and results at both Ginna and Nine Mile Point Unit 1 will be reviewed to identify and pursue additional opportunities to improve life assessment efforts for other critical SSCs (e.g., cabling, spent fuel pool, and secondary piping) expected to be considered in extended-life license applications. As appropriate, an updated workscope and plan will be jointly developed in 2013.
LWRS – Constellation Demonstration Project	**Milestones:** (2013) Document describing containment inspection guidelines for extended service will be developed and delivered collaboratively.
LTO – Ginna and Nine Mile Point Unit 1 Demonstration Plant Activities	**Milestones:** Demonstration Activities on Comprehensive Containment Examination: • Participation in 2011 and 2012 refueling outages (RFOs) at Ginna and Nine Mile Point Unit 1. • (March 2013) Draft Comprehensive Containment Guideline. • Participation in 2012 RFO at Ginna. • Participation in 2013 RFOs at Nine Mile Point Unit 1. • (December 2013) Final Comprehensive Containment Guideline. Incremental Inspection and Examination of Reactor Vessel Internals: • Participation in 2011 RFOs at Ginna and Nine Mile Point Unit 1. • (December 2011) Draft Incremental Reactor Internals Inspection Guidance.

R&D Area	Materials Aging and Degradation (LWRS)/Understanding, Prediction, and Mitigation of Primary System Aging Degradation (LTO)
	• Participation in 2012 RFO at Ginna. • Participation in 2013 RFOs at Nine Mile Point Unit 1. • (December 2013) Final Incremental Reactor Internals Inspection Guidance. Task 3: • Gap Analysis and Feasibility Study of Plan for Ginna and Nine Mile Point Unit 1. • Demonstration of Plan Elements for Ginna and Nine Mile Point Unit 1. • (December 2013) Final Reactor Embrittlement Analysis and Validation Plan to 80 Years. Task 4: • (December 2013) Report on Demonstration Plant Activities in Support of License Renewal Beyond 60 Years.

R&D Area	Advanced II&C Technologies
LWRS – New Instrumentation and Control and Human System Interfaces and Capabilities (including Advanced II&C Pilot Projects)	**R&D Scope and Objectives:** R&D activities are being proposed to develop needed capabilities through digital technologies to support long-term NPP operations and management. The supporting technologies will enable the large integrated changes that industry cannot achieve without R&D support. This includes comprehensive programs that achieve the following: • Support creation of new technologies that can be deployed to address the sustainability of today's II&C systems technologies • Improve understanding of, confidence in, and facilitate transition to these new technologies • Support development of the technical basis needed to achieve technology deployments • Create or renew infrastructure needed for research, education, and testing. This research program will address aging and long-term reliability issues of the legacy II&C systems used in the current LWR fleet by demonstrating new technologies and operational concepts in actual NPP settings. This approach drives the following two important outcomes: • Reduces the technical, financial, and regulatory risk of upgrading the aging II&C systems to support extended plant life to and beyond 60 years. • Provides the technological foundation for a transformed NPP operating model that improves plant performance and addresses the challenges of the future business environment. The research program is being conducted in close cooperation with the nuclear utility industry to ensure that it is responsive to the challenges and opportunities in the present operating environment. The scope of the research program is to develop a seamless integrated digital environment as the basis of the new operating model. The program is advised by a Utility Working Group composed of leading nuclear

R&D Area	Advanced II&C Technologies
	utilities across the industry and EPRI. The Utility Working Group developed a consensus vision of how a more integrated approach to modernizing plant II&C systems could address a number of challenges to the long-term sustainability of the LWR fleet.[f] A strategy was developed to transform the NPP operating model by first defining a future state of plant operations and support based on advanced technologies and then developing and demonstrating the needed technologies to individually transform the plant work activities. The collective work activities were grouped into the following major areas of enabling capabilities: 1. Highly integrated control room 2. Highly automated plant 3. Integrated operations 4. Human performance improvement for field workers 5. Outage safety and efficiency 6. Centralized online monitoring and information integration. Within these areas of enabling capabilities, 20 pilot projects were defined as the roadmap for industry to collectively integrate new technologies into NPP work activities. For online monitoring, two broad areas of development have been defined at the present, which will be further defined into additional pilot projects. A pilot project is an individual demonstration that is part of a larger strategy needed to achieve modernization according to a plan. Note that pilot projects have value on their own, as well as collectively. They are small enough to be undertaken by a single utility, they demonstrate a key technology or outcome required to achieve success in the higher strategy, and they support scaling that can be replicated and used by other plants. The pilot projects were defined as the appropriate points for introducing enabling technologies across the spectrum of plant work activities. These technologies serve as the stepping stones to the eventual digital environment that enables a transformed NPP operating model. In a September 2011 workshop, the Utility Working Group prioritized the pilot projects in terms of value to the utilities and validated the development order. The sequence of development is designed to achieve progressively greater benefits as the growing aggregate of integrated technologies enables higher degrees of automation and innovation. The pilot projects are scheduled over a 12-year period (i.e., 2010 to 2021).
LTO – Requirements Database for Advanced I&C, Human System Interface, and Information Technology	**R&D Scope and Objectives:** EPRI will participate in the LWRS working group for Advanced II&C. This working group includes utility representatives from Exelon, Entergy, Duke, Southern, SONGS, STP, APS, Constellation, Progress, TVA, 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 a Human Systems Simulation Laboratory to support these applications and to perform related R&D at INL. The Human Systems Simulation Laboratory employs 15

[f] Long-Term Instrumentation, Information, and Control Systems (II&C) Modernization Future Vision and Strategy, INL/EXT-11-24154, February 2012.

R&D Area	Advanced II&C Technologies
	bench-board-style touch panels that resemble the control panels currently used in NPPs. This equipment is capable of running NPP 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 Advanced II&C area.
LWRS – New Instrumentation and Control and Human System Interfaces and Capabilities (including advanced II&C pilot projects)	**Milestones:** Highly integrated control room: • (2013) Publish a reference human factors engineering plan for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators. • (2015) Publish a technical report for computer-based procedures that enhance worker productivity, human performance, plant configuration control, risk management, regulatory compliance, and nuclear safety margin. • (2016) Publish a technical report for an advanced alarm management system in a NPP control room and a methodology for integrating diverse alarms and annunciators across all systems and digital platforms. • (2016) Develop an end-state vision and strategy, based on human factors engineering principles, for the implementation of both a hybrid and a full highly integrated control room as new digital technologies and operator interface systems are introduced into traditional control rooms. • (2017) Develop an operator advisory system fully integrated into a control room simulator 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. • (2018) Complete a technical report on operator attention demands and limitations on operator activities based on the current conduct of operations protocols. This report will identify opportunities to maximize operator efficiency and effectiveness with advanced digital technologies. • (2019) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, based on an operator advisory system that provides real-time situational awareness, prediction of the future plant state based on current conditions and trends, and recommended operator interventions to achieve nuclear safety goals. • (2021) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities and the ability to interact with other control centers (e.g., emergency response facilities for severe accident management guidelines implementation). Highly automated plant: • (2014) Publish a technical report that provides a current state and gap analysis for integrating plant information residing in plant II&C systems, plant work processes, and information resources needed for mobile worker technologies. • (2016) Publish a technical report on an advanced digital architecture,

R&D Area	Advanced II&C Technologies
	integrating plant systems, plant work processes, and plant workers in a seamless digital environment, with guidance on how to apply the architecture to an NPP's established data network systems. • (2016) For NPP 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. • (2017) For NPP 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. • (2018) For NPP 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. • (2019) Develop and publish a transformed NPP operating model and organizational design derived from a top-down analysis of NPP operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies. • (2020) Develop the strategy and priorities and publish 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. • (2021) Develop the strategy and priorities and publish a technical report for improving plant control algorithms, based on greater availability of sensed and derived plant parameters through the advanced digital architecture, resulting in more anticipatory, adaptive, and resilient control functions. Integrated operations: • (2017) 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. • (2018) 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

R&D Area	Advanced II&C Technologies
	NPP. • (2019) 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 NPP. • (2020) 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 NPP. • (2021) 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 NPP support organization. • (2021) 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. Human performance improvement for field workers: • (2014) Develop automated work package prototype technologies for NPP work processes with associated study of field trials at an NPP. • (2015) Develop human factors evaluations and an implementation strategy for deploying automated field activity work packages built on mobile technologies, resulting in more efficient and accurate plant work processes, adherence to process requirements, and improved risk management. • (2016) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers. • (2017) Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, and restricted boundaries) for mobile plant workers. • (2018) Publish a technical report on augmented reality technologies developed for NPP field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities. Outage safety and efficiency: • (2013) Develop technologies for an advanced outage control center that improves outage coordination, problem resolution, and outage risk management. • (2014) Develop human factors studies and publish a technical report for an advanced outage control center that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage

R&D Area	Advanced II&C Technologies
	coordination, problem resolution, and outage risk management. • (2017) 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.
LTO – Requirements Database for Advanced I&C, Human System Interface, and Information Technology	**Milestones**: • Report on Project Plan for Framework for an Advanced I&C Requirements Database (2010). • Summary Report on Database Structure Capability Levels and Simple Prototype (2013). The following deliverables will be jointly developed by LWRS and LTO and are listed identically as milestones for each program: • (2015) Publish interim guidelines to implement technologies for improved outage safety and efficiency. • (2016) Publish revised interim guidelines to implement technologies for human performance improvement for NPP field workers. • (2016) Publish interim guidelines to implement technologies for a highly integrated control room. • (2017) Publish interim guidelines to implement technologies for a highly automated plant. • (2018) Publish final guidelines to implement technologies for improved outage safety and efficiency. • (2018) Publish interim guidelines to implement technologies for integrated operations. • (2019) Publish revised interim guidelines to implement technologies for a highly integrated control room. • (2019) Publish final guidelines to implement technologies for human performance improvement for NPP field workers. • (2020) Publish revised interim guidelines to implement technologies for integrated operations. • (2021) Publish final guidelines to implement technologies for a highly automated plant. • (2022) Publish final guidelines to implement technologies for integrated operations. • (2022) Publish final guidelines to implement technologies for a highly integrated control room.
LWRS – Centralized Online Monitoring and Information Integration	**R&D Scope and Objectives:** As NPP 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 NPPs. It enables real-time assessment and monitoring of

R&D Area	Advanced II&C Technologies
	physical systems and better management of components based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions concerning long-term plant asset management. Of particular importance will be the capability to determine the remaining useful life of a component to justify its continued operation over an extended plant life. Working closely with the MAaD Pathway and EPRI, this pathway will develop technologies to complement sensor development and monitoring of materials to assess the performance of SSC materials during long-term operation for purposes of decision making and asset management. The MAaD Pathway would be responsible for developing the scientific basis for modeling the degradation mechanisms and determining the types of sensors needed to monitor the degradation.
LTO – Centralized Online Monitoring	**R&D Scope and Objectives:** To achieve continued safe and economical long-term operation of the U.S. domestic and international NPPs, it will be imperative that NPPs maintain high levels of operational performance and efficiency. NPPs have a continuing need to undergo design and operational changes, as well as manage aging SSCs. Effective management of SSCs will require integration of advanced information monitoring and analysis capabilities into plant operations, maintenance, and engineering activities. Centralized online monitoring is a highly automated condition analysis and asset management system designed to capture and build in knowledge, experience, and intelligence from many diversified operating systems and monitoring environments. Domestic NPPs can be described as having constrained resources to support programs not required for direct plant operation or regulatory issues. These constraints dictate that a comprehensive online monitoring capability will be an evolutionary development determined by the functional capabilities needed to support current operational requirements and to provide for long-term asset management. A key functional requirement of a well-developed monitoring program is its information interface with the operating plant and associated staff. To achieve the stated strategic goals of EPRI's LTO project, industry must develop an effective monitoring program that has a well-designed data and information integration platform with advanced technologies, including anomaly detection; automated diagnostic capabilities; a repository of equipment failure signatures captured from industry events; and, ultimately, prognostics-remaining useful life capabilities designed to evaluate critical plant assets for optimized maintenance and investment decisions to support LTO. EPRI's research will build on previously developed monitoring technologies and leverage the LTO resources with our strategic partners. The EPRI LTO project completed an in-depth industry analysis of monitoring capabilities and identified the needed analytical and programmatic capabilities (gap analysis). These results provide the foundation to define project priorities, identify needed technologies, project the costs and schedule, obtain required funding to execute the research, and manage all the implementation phases through successful implementation. In support of implementation of plant monitoring programs, EPRI has published comprehensive centralized online monitoring implementation guidelines, based on the current state-of-the-art diagnostics and prognostics technology developed by EPRI, with

R&D Area	Advanced II&C Technologies
	guidance based on early adopter and generations experience from the power industry's operational monitoring centers. The development and execution of the required research must include broad and frequent interfacing with all of EPRI's strategic partners, including member advisors and technical specialists and their commercial support organizations. Other partners include qualified vendors, universities, government laboratories, and utility research programs.
LWRS – Centralized Online Monitoring and Information Integration	**Milestones:** • (2015) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large passive plant component/structure, involving NDE-related online monitoring technology development and including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type. • (2017) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for second large passive plant component structure, involving NDE-related online monitoring technology development and including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.
LTO – Centralized OLM	**Milestones**: • (2013) Report on the results of cooperative research with industry partners to expand research on (1) diagnostics R&D, 2) industry database research to support Asset Fault Signature Database signature capture, (3) develop design-derived fault signatures to support Asset Fault Signature Database selected components, and (4) develop prognostics remaining-useful-life application and database. • (2013) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for the station emergency diesel generator as an important active component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type. • (2013) Complete EPRI prognostics and health management software installation at the pilot plant utilities. • (2013) Pilot applications of in-situ monitoring of material degradation of passive assets. • (2014) Production release of EPRI's prognostics and health management software and access to the associated databases. • (2014) Complete joint research on diagnostics and prognostics (remaining useful life) application to critical plant assets. • (2015) Publish interim guidelines to implement technologies for centralized online monitoring and information integration. • (2017) Complete transient analysis R&D. • (2018) Publish final guidelines to implement technologies for centralized online monitoring and information integration.

R&D Area	Advanced II&C Technologies
LWRS – Industrial and Regulatory Engagement	**R&D Scope and Objectives:** Nuclear asset owner engagement is a necessary and enabling activity to obtain data and accurate characterization of long-term operational challenges, assess the suitability of proposed research for addressing long-term needs, and gain access to data and representative infrastructure and expertise needed to ensure success of the proposed R&D activities. Engagement with vendors and suppliers will ensure that vendor expectations and needs can be translated into requirements that can be met through technology commercialization.
LTO – Requirements Database for Advanced I&C, Human System Interface, and Information Technology	**R&D Scope and Objectives:** EPRI will develop a repository of advanced I&C, human system interface, and other information technology requirements and good practices from the pilot studies and from other industry activities. The purpose of this repository is to have a living resource for utilities to review the state-of-the-art and good practices in the industry related to I&C enhancement projects.
LWRS – Industrial and Regulatory Engagement	**Milestones:** Included in discussion on "New Instrumentation and Control and Human System Interfaces and Capabilities" (including advanced II&C pilot projects).
LTO – Requirements Database for Advanced I&C, Human System Interface, and Information Technology	**Milestones**: (2016, 2018, and 2020) Releases of repository of advanced I&C requirements based on pilot studies within the advanced I&C working group, other industry pilot studies, and LWRS user facility results.

R&D Area	RISMC
LWRS – Margins Analysis Techniques and Modeling and Simulation Activities in Support of RISMC	**R&D Scope and Objectives:** The purpose of the RISMC Pathway is to support plant decisions for risk-informed margins management with aim to improve the economics and reliability and sustain the safety of current NPPs over periods of extended plant operations. The RISMC Pathway has two primary focus areas to guide R&D activities. First, the pathway is developing the methods that will be used to obtain the technical basis for safety margins and their use in support of the risk-informed decision making process. These methods are to be described in a set of technical reports for RIMM. Second, the pathway is producing an advanced set of software tools used to quantify safety margins. This set of tools, collectively known as the RISMC Toolkit, will enable a risk analysis capability that currently does not exist. 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 will then 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

R&D Area	RISMC
	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 (**L** – **C)** (safety margin) or **L/C** (safety factor). • A *probabilistic* margin, defined by the probability that the load exceeds the capacity. For example, if failure of a pressure tank is modeled where the tank design capacity is a distribution f(**C**), its loading condition is a second distribution f(**L**), the probabilistic margin would be represented by the expression Pr[f(**L**) > f(**C**)]. In practice, actual loads (**L**) and capacities (**C**) are uncertain and, as a consequence, most engineering margin evaluations are, in fact, of the probabilistic type. However, due to a number of reasons (e.g., insufficient data, complexity in analysis, or resource constraints), the more simplistic deterministic approach is often applied in practice. In these cases where deterministic margins are evaluated, the analysis is typically very conservative in order to account for uncertainties; this approach, while historically quite effective in ensuring appropriate levels of safety are maintained, results in significant economic and operational constraints. Additionally, because uncertainties are not explicitly characterized and evaluated, the potential exists for margins to be exceeded during periods of abnormal operation, resulting in unanticipated consequences. 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 risk-informed margins management to present results to decision makers as it relates to margin evaluation, management, and recovery strategies. Margin Management 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. Formulate an "issue space" that describes the safety figures of merit to be analyzed and the proposed decision criteria to be employed. 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

R&D Area	RISMC
	safety margins and plant physical phenomena, as described in Steps 4 and 5. As such, there will be strong interactions between the analysis 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 plant operation probabilistically using the scenarios identified in Step 3. For example, 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 plant and operator behavior cannot be manually created like for current risk assessment using event and fault trees. In addition to the *expected* operator behavior (plant procedures), the probabilistic plant representation will account for the possibility of failures. 5. Represent plant physics mechanistically. The plant systems level code will be used to develop distributions for the key plant process variables (i.e., loads) and the capacity to withstand those loads for the scenarios identified in Step 4. Because there is a coupling between Steps 4 and 5, they each can impact the other. For example, a calculated high loading (from pressure, temperature, or radiation) in an SSC may disable a component, thereby impacting an accident scenario. 6. Construct and quantify a probabilistic load and capacity distributions relating to the figures of merit that will be analyzed to determine the probabilistic safety margins. 7. Determine how to manage uncharacterized risk. Because there is no way to guarantee that all scenarios, hazards, failures, or physics are addressed, the decision maker should be aware of limitations in the analysis and adhere to protocols of "good engineering practices" to augment the analysis. This step relies on effective communication from the analysis steps in order to understand the risks that *were* characterized. As part of this step, it also is appropriate to evaluate the decision criteria proposed in Step 1 and modify (the criteria, the analysis, or both) as appropriate. 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. Case Study Collaborations: Jointly with EPRI, the LWRS Program's RISMC Pathway is working on specific case studies of interest to the commercial NPP industry. In Fiscal Year 2013, the team will be collaborating on 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 postulated extended power uprate. A second case study of interest to industry is the task to develop a technical report that will describe how to perform safety margin-based configuration risk management. Configuration risk management currently involves activities such as the significance determination process, which traditionally uses core damage frequency as the primary safety

R&D Area	RISMC
	metric; the research for the second case study will focus on how the safety-margin approach may be used to determine risk levels as different plant configurations are considered. RISMC Toolkit: The RISMC Toolkit is being built using the Multi-physics Object Oriented Simulation Environment (MOOSE) high-performance computing framework.[g] MOOSE is the INL development and runtime environment for the solution of multi-physics systems that involve multiple physical models or multiple simultaneous physical phenomena. Models built on the MOOSE framework can be coupled as needed for solving a particular problem. The RISMC Toolkit and roles are described as follows: • RELAP-7: RELAP-7 will be the main reactor systems simulation tool for RISMC and the next generation tool in the RELAP reactor safety/systems analysis application series (the replacement for RELAP5). RELAP-7 development will leverage 30 years of advancements in software design, numerical integration methods, and physical models. RELAP-7 will simulate behavior at the plant level with a level of fidelity that will support the analysis and decision-making necessary to economically and safely extend and enhance the operation of the current NPP fleet. • RAVEN: RAVEN is a multi-tasking application focused on RELAP-7 simulation control, reactor plant control logic, reactor system analysis, uncertainty quantification, and performing probabilistic risk assessments for postulated events. RAVEN will drive RELAP-7 (and other MOOSE-based reactor applications) for conduct of RISMC analyses. • Grizzly: Grizzly will simulate component aging and damage evolution events for LWRS Program-specific applications. Grizzly will be able to simulate component damage evolution for the RPV, core internals, and concrete support and containment structures subjected to a neutron flux, corrosion, and high temperatures and pressures. Grizzly will be able to couple with RELAP-7 and RAVEN to provide aging analysis in support of the RISMC methodology. • Peacock: Peacock is a general graphical user interface for MOOSE-based applications. Peacock has been built in a very general fashion to allow specialization of the graphical user interface for different applications. The specialization of Peacock for RELAP-7/RAVEN allows both a graphical input of the RELAP-7 input file and online data visualization and is moving forward to provide direct user control of the simulation and data mining capabilities in support of probabilistic risk assessment analysis.

[g] 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, NY: American Nuclear Society.

R&D Area	RISMC
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 NPP plant safety margins. This LTO 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 NPPs. 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 – Margins Analysis Techniques and Modeling and Simulation Activities in Support of RISMC	**Milestones:** Margin Management Strategies: • (2013) Produce technical report that outlines the RIMM process and its relation to RISMC characterization. • (2016) Final technical report for RIMM process, including description of pilot application of RISMC/RIMM to an issue of interest at a host plant. Margin Management Techniques: • (2014) Assess leading accident-resistant fuel technologies to understand potential changes in safety margins that could be achieved by adoption of the technology using the RISMC methodology. • (2014) Demonstrate RISMC approach using LWR Case Study for Enhanced Accident Tolerance design changes using risk-informed margins management approaches. • (2014) Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the RISMC approach. • (2015) The margins analysis techniques will be sufficiently mature to enable initial industry margins quantification exercises, including using the RISMC Toolkit. • (2016) Complete a full-scope margins analysis of a commercial reactor. 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. • (2020) Ensure development and validation to the degree that by the end of 2020, the margins analysis techniques and associated tools are an accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment. Case Study Collaborations: • (2013) The RISMC team will be collaborating with EPRI on 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

R&D Area	RISMC
	nominal reactor power that would result from the postulated extended power uprate. RISMC Toolkit: • (2013) Upgrade the RELAP-7 capabilities through implementation of a seven-equation, two-phase flow model, including selected major physical components for BWR primary and safety systems. • (2013) Perform the RELAP-7 simulation resolving a station blackout (SBO) scenario on a simplified geometry of a BWR. • (2014) Complete the software structure of the coupled RAVEN/RELAP-7 portion of the RISMC Toolkit. At this time, RELAP-7 can be fully controlled by RAVEN for complete systems analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuels modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other DOE programs. • (2014) Deliver the RELAP-7 verification and validation plan. • (2014) Version 1.0 of Grizzly will be released. This version will include aging of steel (embrittlement) and a modular architecture to enable inclusion of additional mechanisms. • (2015) RELAP-7 will be validated against an accepted set of data. • (2016) Version 2.0 of Grizzly will be released. This version will include the capabilities of Version 1.0, as well as aging of selected concrete. • (2018) Validation and benchmarking of Grizzly will be completed.
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 NPP 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 NPP. 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 will expand 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 NPP owners/operators to initiate transfer of the technology for application to relevant NPP safety issues with impact on NPP LTO. To support these objectives, the following activities will be conducted during 2013 and 2014: Project 1: RISMC Pilot Projects • Conduct RISMC analysis of safety margins associated with an extended station blackout event at a large BWR that desires to implement an extended power uprate. This project was initiated in 2012, with final results provided in an EPRI technical report to be published in 2013.

R&D Area	RISMC
	• Assess the potential for the RISMC approach to be used to support utility and regulatory evaluations of the safety impact on NPP events by application of the RISMC approach to one or more previous events that resulted in a regulatory significance determination process analysis. Project 2: Socialize RISMC Approach Among External Stakeholders • An EPRI Technical Advisory Group will be formed of industry experts to review and guide the application of RISMC to issues of importance to NPP safety management and long-term operation. This group also will provide input to EPRI's continuing interaction with RISMC research activities being conducted by INL for the LWRS Program. This Technical Advisory Group will include participation from both U.S. and international members of EPRI's nuclear sector. • 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. One notable outcome of this engagement in 2012 was conduct of a loss-of-feedwater analysis similar to that described in EPRI 1023032 by NRC research personnel, using standard NRC tools, in which similar results were obtained and similar conclusions were reached. • 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. In addition to application of the RISMC methodology, EPRI will continue to support INL development of the next generation safety analysis software (RELAP-7). Prior to this year, EPRI has 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 an NPP owner/operator). During 2012 and 2013, EPRI will continue to support INL's development of RELAP-7 by providing input to its development and conducting trial applications as modules become available. Project 3: RISMC Safety Margin Method and Tool Development (LWRS) • Support development of RELAP-7 by closely working with the INL RELAP-7 development team to provide input to software development and by conducting testing on trial safety analysis applications as modules become available. In particular, it is intended that the RELAP-7 software will be applied to support/confirm results from RISMC analysis of the station blackout event for a BWR, with an extended power uprate being conducted by EPRI during 2013. EPRI also will work closely with INL to develop appropriate benchmarking and validation plans and identify relevant data sources for code verification and validation activities.