2017 Status of R&D Progress on Key Technical Issues for Subsequent License Renewal (SLR)

The technical bases for aging management of nuclear plant structures, systems, and components important to safety is well-established and being implemented by aging management programs (AMPs). Over 125 EPRI technical reports are referenced in the NRC Generic Aging Lessons Learned (GALL) Report for SLR.

Continuous improvement for long-term operations is a significant part of EPRI research plans and is closely coordinated with the DOE-Light Water Reactor Sustainability (LWRS) Program. An annual Joint R&D Plan is created and made publicly available on the LWRS website: (https://inlportal.inl.gov/portal/server.pt/community/lwrs_program/442/program_documents). The 2016 revision has been posted and the 2017 revision is being developed.

The four key research topics identified for SLR are:

- Reactor pressure vessel (RPVs) neutron embrittlement
- IASCC of reactor internals and primary system components
- Concrete and containment degradation
- Electrical cable qualification and condition monitoring

Each of these research topics is summarized below.

Reactor Pressure Vessel Neutron Embrittlement at High Fluence

All US plants are required to monitor the impacts of irradiation on RPVs through compliance with Appendices G and H of 10CFR Part 50. Aging management of the reactor vessel is covered SLR GALL AMP XI.M31 'Reactor Vessel Surveillance'.

- Embrittlement trend correlations for out to 80 years of operation currently exists. Two projects are under way to supplement and improve the trend correlations using data from the existing plant surveillance capsule programs. These are:
    - The PWR Coordinated Surveillance Program: The objective of this program is to obtain as much high fluence PWR surveillance data (3-10 $x10^{19}$ n/cm^2) as practical by 2025 by deferring the scheduled withdrawals of capsules at 11 PWRs in order to test them at higher fluence.
    - The PWR Supplemental Surveillance Program: This program identified useful enhancements in the PWR surveillance database and selected 24 PWR surveillance materials to enhance the database. Previously tested surveillance specimens from those materials are being reconstituted for further irradiation for 10 years, in two supplemental capsules at two host PWRs. The goal is to obtain ~24 additional high-fluence transition temperature shift (TTS) data points by 2027-28. The first capsule was installed in the Farley Unit 2 Nuclear Plant in fall 2016. The second capsule will be installed in the Shearon Harris Nuclear Plant in spring 2018.

Supporting on-going research programs for continuous improvement are:

- Testing of several specimens irradiated at a test reactor, termed the ATR-2 experiment, is in progress. Supported by US, Japan, and UK research organizations, this research project centered on the ATR-2 capsule which contained 173 alloys irradiated at the Advanced Test Reactor of Idaho

National Laboratory (INL). The objective is to develop models to accurately predict transition temperature shifts (TTS) for high fluence power reactor conditions. The irradiation phase is complete and post-irradiation examinations and evaluations at the University of California, Santa Barbara and The Oak Ridge National Laboratory (ORNL) will be completed in the next two years.

- Extend the current Integrated Surveillance Program for all US BWR vessels to the period from 60 to 80 years of operation. Initial feasibility studies have been completed and documented (EPRI Report 3002007041) and a review meeting with NRC Staff was held in December 2016.
- The experimental analysis phase of harvested RPV sections from Zion Unit-1 will start in late 2017. The purpose is to close scientific gaps related to material variability, effects of combined long-term thermal and irradiation exposures, attenuation effects through wall thickness and validation of model to predict the TTS.
- Perform and complete the joint EPRI-CRIEPI-ORNL research program on validation of small Mini-CT specimens for fracture toughness characterization of irradiated low upper shelf Linde 80 WF-70 weld.
- Complete the EPRI-CRIEPI atom probe tomography (ATP) program: This is a joint research effort to perform APT on high-fluence PWR surveillance specimens. The objective is to identify microstructural characteristics of highly irradiated RPV specimens and to identify new embrittlement mechanisms, if any, applicable to power reactor RPVs. The irradiation phase and post-irradiation examinations have been completed. Evaluations show that high fluence materials examined in this program which have significant NiMnSi solute clusters exhibit transition temperature shifts consistent with the predictions of Regulatory Guide 1.99, Rev. 2 and EONY embrittlement trend correlations (ETCs). A final report is planned for 2017.

Irradiation Assisted Stress Corrosion Cracking of Reactor Internals and Primary System Components

EPRI materials program work is coordinated under NEI initiative 03-08 which was formally implemented in 2004. This provides an overarching industry lead management strategy for metal materials issues. Some of the key aspects of the initiative are: the requirements to perform inspections; evaluation of the results; documentation and reporting of inspection findings; sharing of operating experience; and routine updates to the NRC.

The primary metals work for SLR is based on decades of on-going research projects to understand and manage aging. The EPRI materials issue management programs are living programs and the technical reports are updated based on research results, operating experience and inspection results.

Aging management of reactor vessel materials is covered under XI.M16A for PWRs and XI.M9 for BWRs. These two AMPs are based on EPRI technical reports that have been reviewed and approved by the NRC.

Supporting research programs for continuous improvement are:

- EPRI-International Expert Panel on Irradiated SS crack growth rates:
    - This program compiled crack growth rate (CGR) data on irradiated stainless steels developed by EPRI, NRC, Halden and other international programs. An Expert Panel reviewed and screened the available CGR data on irradiated stainless steel. The result of this effort was a model for use in BWR and PWR environments. Data used had accumulated fluences as high as 47.5 displacements per atom (dpa). When compared to known field data the model is conservative.
- Harvested Materials Testing
    - BWR Core Shroud Sample: Atypical cracking was identified in a BWR shroud. The owner, supported by the BWRVIP removed a boat sample for extensive laboratory testing that confirmed the cracking mechanism to be consistent with material environment and controlled by stress state (significant branching not observed). This is more indicative of IGSCC than IASCC. No change is warranted to the current perspective that the observed atypical cracking does not represent a challenge to long-term core shroud integrity.
- Specimens removed from Zorita (NRC is a participant in the project): Tests are being conducted on baffle plate materials irradiated under PWR service conditions to increase understanding of fluence effects on mechanical and microscopic properties. To date, results are as expected for the fluence range received. Selected materials will receive additional irradiation to high fluence and be tested.
- Additionally, extensive fundamental research is in progress with joint partners to address:
    - Modeling of irradiated mechanical properties and fracture toughness
    - Small-volume mechanical property evaluation for irradiated materials
    - Model development for predicting radiation-induced swelling under LWR conditions
    - Model development for predicting fatigue behavior of LWR components
    - Effects of high fluence neutron irradiation on localized deformation and IASCC
    - Water chemistry influence on crack growth rate of irradiated stainless steel
    - Develop engineering solutions to counter IASCC
    - Validate rapid simulation of high fluence using ion irradiation of LWR materials

Concrete and Containment Degradation -

EPRI has been working on R&D in the concrete area for the past five years and supports an active Technical Advisory Group for our members to share both research results and operating experience. The results of this work are being incorporated into processes and tools for aging management programs (AMPS) for concrete structures. Such AMPs can now address structures affected by corrosion, alkali silica reaction (ASR), boric acid, delamination/cracking and irradiation for SLR operation.

The key elements of the research (joint effort with DOE-LWRS and NRC-RES) are focused as follow:

- Alkali Silica Reaction (ASR) aging management including detection and mapping, structural evaluations, and programmatic guidance
    - Initial work completed and documented an assessment of NDE and testing technologies and on impact on structures.
    - Completed risk screening and tools for early detection of ASR in 2015 (Tools for Early Detection of ASR in Concrete Structures)
    - EPRI is publishing a series of guidance reports in 2016-2017 that address ASR. These reports include: Structural Deformation as a Result Of Expansion from Alkali-Silica Reaction (2016), Cracking-Index Criteria for Alkali Silica-Reaction-Affected Structures (2016), Literature Review of Structural Implications of Alkali Silica Reaction (2017), and Developing a Monitoring Strategy for Alkali Silica Reaction Affected Structures (2017). These reports will culminate in a comprehensive report on ASR aging management guidance (Aging Management of Alkali Silica Reaction Affected Structures). This report is targeted to be completed in 2017.
    - In addition EPRI staff is working with a lead plant to use the technical reports to develop an aging management approach to fulfill the AMP that can be referenced by future SLRAs.
    - DOE LWRS is continuing research on modeling of ASR for structural assessments, embedded sensors for condition monitoring and NDE techniques.
- Irradiation and gamma heating effects on mechanical properties and assessment of potential irradiation effects on structural margin of biological shield walls
    - EPRI Report on disposition of effects of radiation on BWR vessel supports published in 2016
    - EPRI Report on gamma heating in a PWR biological shield published in 2016
    - EPRI Report on a simplified structural model of a PWR biological shield published in 2016. This report was based on extensive work completed by DOE LWRS to understand the impacts of radiation on concrete. EPRI used the DOE LWRS fundamental work and built a finite element model of a PWR biological shield wall (limiting component for irradiation degradation). The results show that at the fluence levels expected at 80 years of operating there is adequate structural margin.
    - EPRI is working with a group in Spain to harvest cores from the biological shield wall of the Zorita plant.
    - DOE- LWRS program is performing constitutive modeling to assess the combined effects of irradiation and ASR on structural performance for concrete components. This is expected to complete by 2020 (joint research with ORNL/LWRS).
- Creep impact assessment for containment

    - An EPRI 2014 report/literature survey identified creep as a design consideration and a potential aging effect. It is monitored indirectly by periodic lift off testing. The tendon tension can be forecast using historical lift off test data.
- Assessment of boric acid attack on spent fuel pool structure
    - EPRI report on experimental investigation of boric acid attack in concrete was published in 2012. Follow-on work in 2015 and 2016 confirmed a very slow rate of degradation.
    - A framework for an aging management program for leaking PWR spent fuel pools was published in 2016.

On-going Development of Enhanced NDE inspection

- Current effort on assessment, refinement, and benchmarking of NDE using concrete mock-ups (with ASR, delaminations, voids, and cracks) with partners at various research laboratories and universities

On-going Repair and Mitigation Technique Development

- Early research has been completed and recommendations for repair and mitigation of structures affected by corrosion, ASR, boric acid, delamination/cracking and irradiation are development efforts to be completed in 2018.

Electrical Cable Qualification and Condition Assessment

EPRI has been conducting research for over 25 years to better understand cables insulation material degradation and develop aging management guidance. The principle stressors for aging are radiation and temperature for low voltage (LV) cables, and submergence for medium voltage (MV) cables.

EPRI technical reports are in use for LV and MV aging management and provide reasonable assurance of safety and compliance with the existing plant licensing basis. These reports have been made available to the NRC for their review. We also have a well-established cable users group. The group includes utility cable program owners, cable vendors, and the NRC and national lab researchers are invited to attend as well. This group shares operating experience and best practices for cable monitoring and aging management.

Work continues to support cables asset management. Cable asset management is to support utilities making informed decisions regarding potential needs to replace cables during long-term operations. The goal is to ultimately use condition monitoring and a developed algorithm to determine cable remaining useful life (RUL). Having these tools are beneficially for asset management, but not needed to implement an aging management program.

Working closely with DOE-LWRS and NRC Research a detailed roadmap has been developed and research activities are well underway to collect additional data on thermal and radiation aged cables, and improved technologies for cable testing and condition monitoring. Jointly, we recently harvested cables from Crystal River unit 3 that is undergoing decommissioning. These harvested cables will be tested to determine the 'as found' condition and them subject to additional radiation and thermal aging.

EPRI Technical Reports have documented many of the research efforts such as:

- License Renewal Electrical Handbook
- Cable Aging Reports
- Medium and Low Voltage Aging Management Guidelines Reports published and in use
- Cable Testing Guidelines
- In-containment Radiation and Temperature Measurements
    - Project is continuing in 2017 with monitoring equipment installed in an operating PWR in 2015 to be removed and evaluated
- Medium Voltage Cable Failure Mechanism Research
- MV Cable Submergence Qualification
    - Accelerated aging of brown and pink ethylene propylene rubber insulations
    - Brown ethylene propylene rubber cable is competing 4 years aging, results available 3rd quarter 2017
    - Pink ethylene propylene rubber cable at end of year 1 complete in 2019
    - DOE to do confirmatory research in 2017
- Low Voltage cable wet susceptibility study completed in 2016
    - 4 energized cable types exposed to conductor rated/90˚C water for 1 year with no insulation degradation
- Cable harvesting guideline
    - Web-based guidance (http://cableharvest.epri.com/)

Ongoing and future projects, including those with collaborative partners:

- Continued collection of in-containment radiation and temperature data
- Enhanced condition monitoring technology
- Cable materials handbook
- Forensic analysis of harvested cables
- Service aged cables for determination of remaining qualified life
- Testing of field returned (harvested) cables (cables shared with DOE and NRC-RES)
- Determine Remaining Useful Life through both experimental and modeling approaches
- Modeling of expected outputs of non-destructive evaluation techniques applied to degraded cables