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EPRI'S RESEARCH FOR EFFECTIVE AGING MANAGEMENT PROGRAMS

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Safe and reliable long-term operations (LTO) embody a management philosophy centered around the implementation of aging management programs (AMP).

Aging management includes identification of material degradation, inspection techniques, evaluation methodology, and repair or replacement criteria. The AMPs are built on decades of material-science research, engineering innovation, and operating experience. The Electric Power Research Institute (EPRI), in collaboration with research entities around the world, has played a crucial role in developing the technical basis to inform decisions related to LTO and AMPs.

The programs, based on global lessons learned, and best practices, are included in the International Generic Aging Lessons Learned (IGALL) report, developed by the International Atomic Energy Agency (IAEA). The IGALL, now in its third revision, serves as the framework in many countries for nuclear power plant extended operations. More than 125 EPRI research reports are references for the IGALL report.

INTRODUCTION

This article outlines the importance of AMPs for LTO; provides a summary of EPRI's aging management research; and makes the case for broad international collaboration for safe, reliable, and economic long-term operations.

Because nuclear plants in the United States are, on average, 5-10 years older than nuclear plants in Europe and Asia, their operating experience and management philosophy informed the development of the first set of AMPs required for license renewal by the U.S. Nuclear Regulatory Commission (NRC). Those AMPs helped create the U.S. GALL report, which became a starting point and forerunner for the IAEA IGALL report.

More than 60% of the world's 446 nuclear reactors are more than 30 years of age and are currently facing the critical decision of life extension. In the United States, the NRC may issue licenses for up to a 40-year operating life with a 20-year renewal period, and today, more than 80% of the U.S. plants have had their licenses extended from 40 to 60 years (Figure 1).

Several utilities in the U.S. are in the process of submitting applications to the NRC for "subsequent" or second license renewal for 60 to 80 years.

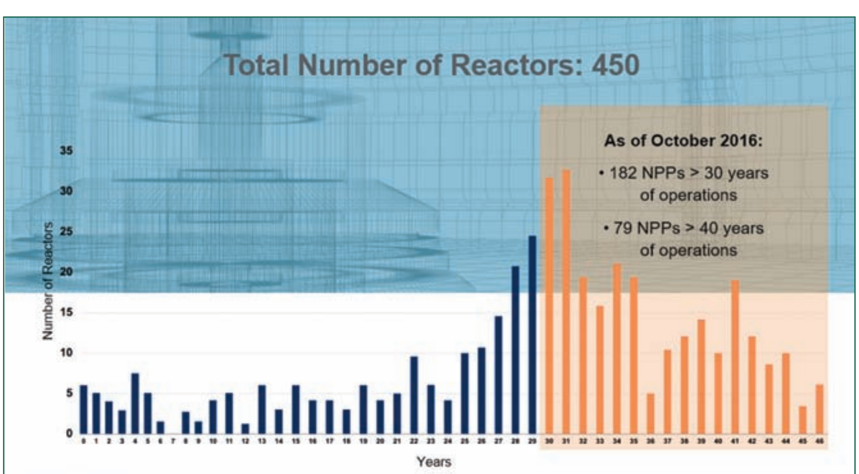

Figure 1. Long-Term Operations Global Perspective.

EPRI'S RESEARCH PROGRAMS

EPRI, established in 1973, is an independent, nonprofit, collaborative organization that conducts research and development (R&D) relating to generation, delivery, and use of electricity for the benefit of the public. Today, more than 320 reactors worldwide, representing 75% of the world's commercial nuclear units, participate in EPRI's nuclear sector programs. Research efforts are enhanced through collaboration with various global entities, including the IAEA, Nuclear Energy Agency, Électricité de France and its Material Aging Institute, World Association of Nuclear Operators, Central Research Institute of Electric Power Industry in Japan, and the U.S. Department of Energy.

Research findings to date indicate that life extension of nuclear plants beyond 60 years, and out to 80 years is technically feasible. The caveat is that plant owners and operators need to implement robust AMPs. The AMPs in the IGALL are regularly reviewed and updated, based on operating experience, research results, and sharing of global best practices.

EPRI's research in this area, which began in 2010, draws on a broad range of technical expertise and decades of data, observation, and experiences collected by EPRI and others in materials, engineering, and plant operations.

The research has two has primary purposes:

- To provide technical information to nuclear power plant owners so they can make informed decisions on plant life extension and refurbishments.
- To provide a scientific and technical foundation for AMPs that address safety, performance, and cost.

The focus is on those components that are the most critical to safety and the hardest to replace. These include the reactor pressure vessel, reactor internals, large concrete civil structures, and the electrical cable system. Replacing any of these components would most likely be cost prohibitive and may lead to plant closure.

This article discusses EPRI's research in four major areas:

- Neutron embrittlement of the reactor pressure vessel and stress corrosion cracking of reactor vessel internals.
- Concrete degradation from alkali-silica reactions and radiation.
- Degradation of electrical cables and tools to monitor them.
- Advances in online condition monitoring and diagnostics, as well as advances in water chemistry automation.

REACTOR PRESSURE VESSELS AND REACTOR INTERNALS

Reactor pressure vessels (RPV) and reactor internals operate in an environment that combines high temperatures, neutron irradiation, and reactive water chemistries. The potential impact of this environment has prompted decades of international research on the causes and mechanisms of material degradation and the development of AMPs to inspect, evaluate, and mitigate the damage.

BWRs

Utilities have been safely managing impacts to the internals for decades. The boiling water reactor (BWR) design experienced degradation of reactor internals earlier in life than some other reactor designs.

Intergranular stress corrosion cracking (IGSCC) in austenitic piping was a major issue for BWRs in the 1980s. In the 1993-1994 timeframe, cracking was found in the welds used to hold the BWR shroud assembly together.

EPRI began researching degradation issues in BWR vessel internals in 1994. The goal was to identify, develop, and evaluate generic, cost-effective aging management strategies. "Utility operators across the globe now have a well-documented inspection program based on 20 years of experience to confirm that components are safe," said EPRI Principal Technical Executive Robin Dyle.

PWRs

In pressurized water reactors (PWR), a comparable assembly to the BWR shroud surrounds the core and directs coolant past the fuel bundles. The assembly is held together by baffle bolts that are highly irradiated and susceptible to cracking. Under stress they can shear off, causing alignment problems.

"EPRI started to research material reliability in the late 1990s, anticipating that there would be problems with the bolts, but visual and ultrasonic inspections found that a few plants had more degraded bolts than expected. In response, we issued interim guidance making inspection criteria more comprehensive and rigorous," said Dyle.

Over the years, EPRI has made significant contributions to the specific materials issues of PWRs, including neutron embrittlement of the RPV and irradiated-assisted stress corrosion cracking of reactor internals.

In 2003, EPRI began to proactively identify and prioritize research needs to manage materials degradation. This led to the development of two foundational documents—the materials degradation matrix (MDM) and the issues management table (IMT). The MDM compiles the latest scientific knowledge of material degradation, material by material, and component by component. Along with the IMT, it identifies gaps in knowledge that direct future R&D. The MDM establishes the technical basis for the AMPs. The AMPs direct inspection procedures and maintenance of various components and systems. These documents are maintained as living documents to reflect the latest operating experience and research results available.

Neutron Embrittlement

Of greatest concern for the RPV is the possible reduction of its fracture toughness due to neutron fluence and high temperatures. For monitoring, irradiation surveillance capsules are placed inside the reactor, then periodically removed and tested. Extensive knowledge of embrittlement trends is available and can be used to predict material properties in RPVs for out to 80 years of operation, informing decisions regarding continued operation to 80 years or longer.

Research has been aided significantly by the material harvested from decommissioned plants. The Jose Cabrera Nuclear Power Station in Spain, known as Zorita, has been an invaluable source. Zorita baffle plate material tests are now being run to improve understanding of the irradiation effects on tensile strength, fracture toughness, and crack initiation and growth. Zorita core barrel weld materials are also being tested to understand the embrittlement of stainless steel welds.

Advanced Welding

Advanced welding techniques such as laser welding and friction stir welding (Figure 2) are being developed to repair highly irradiated materials. With friction stir, a specially designed tool is pressed against the surfaces to be joined. The tool rotates as it moves along the joint line, softening the underlying column of material. The softened material flows around the tool and recrystallizes. "There's a lot of promise for these advanced techniques that could potentially improve performance of weld repairs on the internals, but they are not quite ready for deployment in the field," said Dyle.

CONCRETE

EPRI has been conducting research on concrete structures for several years and has made significant progress understanding and providing technical guidance for the aging management of a number of degradation mechanisms. The two main areas of study are alkali-silica reactions (ASR) and the effects of neutron irradiation and gamma heating. In both of these areas, EPRI has published a number of technical reports and comprehensive guidance to inform AMPs.

ASR

Alkali-silica reactivity occurs because silica in the concrete aggregates can be highly reactive with the alkali in the cement, especially at high temperatures and humidity. "Alkali-silica reactions form a gel around the aggregate that expands as it absorbs moisture. The expansion exerts tensile forces on the concrete that can cause microcracking," said EPRI Technical Leader Sam Johnson. "This cracking typically forms in patterns that resemble spider webs, but is not generally seen on the surface. It takes a substantial amount of expansion before you start to see visual symptoms."

The expansion can also lead to misalignment of equipment attached to the structure, such as piping, piping penetrations, and support structures. "The key is to assess alignments periodically, initially with a visual walkaround, perhaps augmented with photos, and to continuously monitor serviceability. The primary issue is to ensure serviceability is sustained," said Johnson.

Most utilities already have visual monitoring techniques for concrete. They may have to enhance them for license renewal as a part of their structures monitoring program. More detailed techniques for inspection include nondestructive evaluation (NDE) and removing core samples. "Ultrasonic methods are good for detecting delamination or voids inside

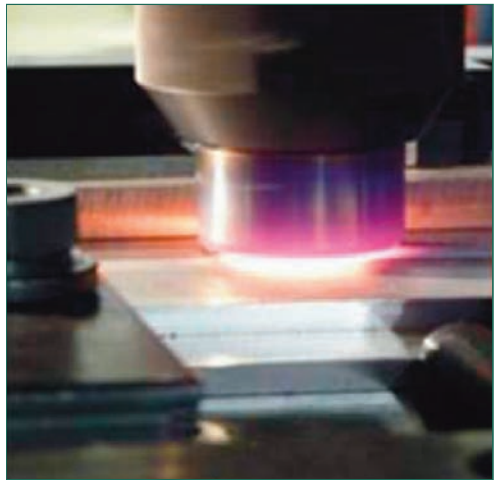

Figure 2. Friction stir welding.

the concrete. For a more detailed analysis, utilities can bore out a concrete core—usually four inches in diameter with an eight-inch-long cylinder," said Johnson.

EPRI published a series of white papers in 2017, with a comprehensive aging management guideline released in late 2017.

Irradiation impacts

The limiting concrete structure for irradiation impacts in a PWR is the biological shield. The shield wall is a four-foot-thick structure of concrete and rebar surrounding the reactor vessel, which is subjected to neutron fluence, gamma radiation, and elevated temperature.

"The metal of the reactor vessel acts as the first line of defense, absorbing energy from neutrons generated in the core. Then the concrete shield cuts down the radiation further by an order of magnitude in the first few inches," said Emma Wong, EPRI senior technical leader. "Neutrons are a lot bigger than gamma rays and cause some of the bonds in the concrete to break up, whereas the gamma rays heat the water molecules in the concrete, creating another source of stress. A lot of the research we've done over the last few years has found damage is limited to only the first six inches of concrete closest to the reactor."

Through models, the neutron fluence impacting the biological shield was projected out over an 80-year period. "For BWRs, the neutron fluence is not expected to rise above the threshold of 1.0E+19 neutrons/cm^2 (the limit established by the NRC in the GALL for Subsequent License Renewal). For many of the PWRs studied, the greatest neutron fluence that the concrete biological shield would experience is expected to be around 6.1E+19 neutrons/cm^2," said Wong.

EPRI has recently put together a step-by-step methodology for utili-

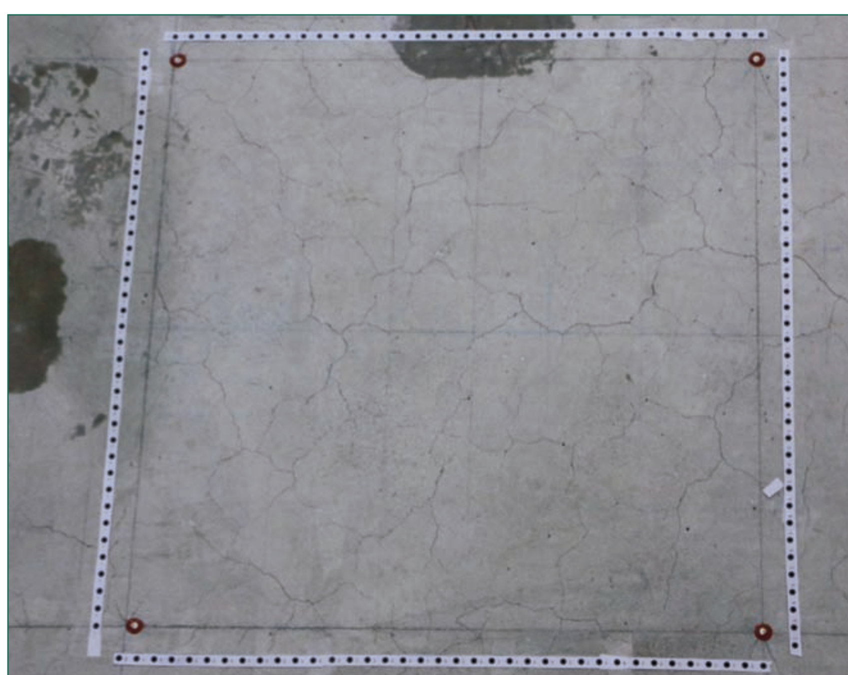

Figure 3. ARS visual symptoms of pattern cracking.

ties to use in evaluating the structural capability of its concrete biological shield. "It's an integration of three separate models," said Wong. "The first is a fluence damage model, which shows how much of the concrete is expected to be degraded. The second is a global model that shows how the influences of different loads will impact the degraded concrete biological shield. The third looks at how the remaining concrete biological shield structural capacity would support the RPV. Proceeding step-by-step, the integrated model will characterize the reduction in the structural capacity of the biological shield."

ELECTRICAL CABLES

Electrical cables are routed through every part of a nuclear power plant and can be thought of as the plant's central nervous system. Each nuclear plant, depending on design, contains an estimated 30,000-40,000 low-voltage and medium-voltage cables.

Heat, radiation, and water can accelerate aging of cable insulation. Degradation is typically localized because cables often run through many different environments from beginning to end. "Some run between buildings—for example, from the control room into the various locations in the turbine building like the heater bay," said EPRI Principal Technical Leader Drew Mantey. "Others run underground to auxiliary buildings, through conduits or embedded in concrete, which may be susceptible to moisture. Other cables go through the reactor building penetrations into containment. Some even run side-by-side with steam lines. Exposure and degradation vary greatly based on cable type (low or medium voltage) and operating environment."

Based on 30-plus years of collecting operating experience and research, EPRI has published aging management guidelines for the three categories of cables:

- Low-voltage cables for instrumentation and controls.
- Low-voltage power cables for motors and equipment.
- Medium-voltage power cables, particularly those susceptible to wetting or submergence.

"Research has focused on understanding the stressors and mechanisms of degradation, identifying those cables that are the leading indicators of degradation, and improving condition monitoring tools to manage cable aging," said Mantey.

Results to date indicate a need for continued research for cable condition monitoring tools. "For low-voltage we have a good test for identifying where anomalies exist on a cable, but we are not yet able to identify if they represent degradation or simply a change in cable geometry unrelated to degradation. There is no global test for low-voltage cables to tell us if the insulation is degraded. For medium-voltage cable we have a good test—very low frequency tan delta—for global degradation assessment, but not a very good tool for localizing the problem," said Mantey. "Our research in new conditioning monitoring tools is striving to give utilities the tools that reveal both global and local indications of cable degradation for low- and medium-voltage cables."

Figure 4. EPRI research being done to evaluate the effects of high-potential testing on commonly used cables.

Two tools being explored show promise. The first, low-voltage dielectric spectroscopy "may fill the global evaluation gap for low-voltage cables," said Mantey. The second, spread spectrum time domain reflectometry (SSTDR), is a continuous cable monitoring system now used in aerospace. "If we can add this to our toolbox as a monitoring or troubleshooting tool, it could be a game changer," said Mantey. EPRI will begin evaluating the online potential of SSTDR this year. The goal of the research is to provide enhanced tools for cable condition monitoring and, through the use of data analytics and prognostics, to determine the remaining useful life of cables.

ONLINE MONITORING AND AUTOMATION

Centralized online monitoring involves integrating multiple advanced technologies, including anomaly detection, automated diagnostics, equipment failure signature analysis, and prognostic capabilities.

Automated diagnostics can provide an early indication of the onset key component failure. The intelligence for effective diagnostics depends on a well-developed library of fault signatures that characterize possible failure modes of a monitored component. EPRI is enhancing the component failure locations in its Preventive Maintenance Basis Database by adding monitoring and diagnostic tasks. This information is already available for several components via EPRI's Continuous On-Line Monitoring (COLM) quick guides, short reports of the key information needed to start monitoring a component and reducing the maintenance work load.

Prognostic and advanced data analytics will provide nuclear plant owners with the ability to determine the remaining useful life of a component. Advances in machine learning will be necessary to effectively integrate behavioral data, historical maintenance records, and operational information to detect trends.

Field demonstration of advanced monitoring methods will be critical to acceptance and deployment. EPRI intends to demonstrate monitoring programs for assets such as main transformers, steam generators, large motors/pumps, steam turbines, generators, and condensers.

"We're trying to get away from calendar date inspection regimes and move more toward condition-based monitoring regimes," said Rob Austin, EPRI senior program manager, Plant Modernization.

One important example is water chemistry. Much of the chemistry work is still done manually, with technicians bringing separate water samples back to the laboratory for analysis and recording. The intervals between samples can range from hours to days to weeks, limiting the accuracy of trend analysis. This year, EPRI is undertaking a comprehensive demonstration of water chemistry automation, providing continuous data so assumptions about what happened between intervals will be a thing of the past.

Researchers have built three skids, housing up to eight instruments each for continuous online sampling and analysis of various chemicals and parameters. The skids operate independently of one another and are strategically placed to draw water streams from the reactor coolant system, the steam generator blowdown line, and the main feedwater system. During the demonstration, data from the instruments will be captured and retained on the skids. The skids are being engineered to enable future wired or wireless connectivity with the plant's data acquisition system.

"Automation is just the first part of it," said EPRI Senior Program Manager Lisa Edwards. "As instruments and sensors collect a flood of data, we'll need smart analytics layered on top to interpret the information. This allows utilities to identify incipient events earlier and act faster. EPRI's online chemistry monitoring (Smart Chemistry) approach will allow utilities to pursue better information with fewer resources."

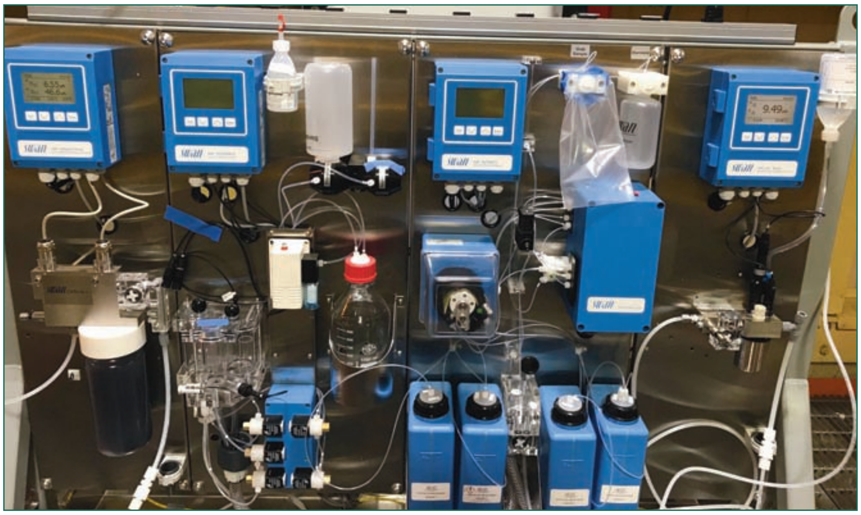

Figure 5. A cart of instruments for EPRI's Smart Chemistry demonstration.

EPRI research will build on previously developed monitoring technologies in diverse fields but will tailor their use for nuclear plant applications. "Having the tools, techniques, and analytics for real-time processing of plant conditions is going to become a cornerstone of LTO," Austin said.

Aging Management Programs (AMPs), based on decades of materials research and utility experience, are in use around the world to support safe, reliable, long-term operations. Continuous improvements in the AMPs are made through research results, inspection findings, and the sharing of global operating experience. Broad international collaboration remains essential to ensure a sound technical foundation for the life extension of nuclear power plants. ■