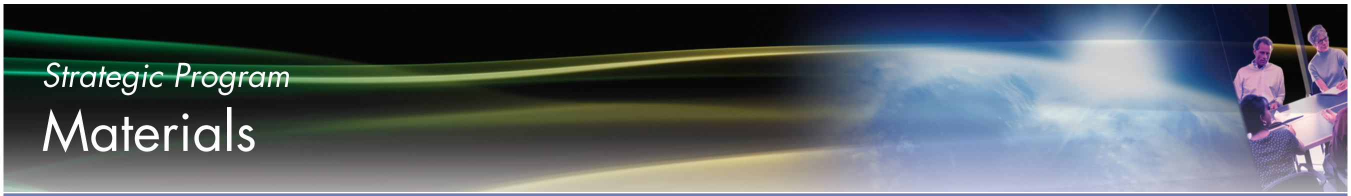
EPRI | ELECTRIC POWER RESEARCH INSTITUTE



Strategic Program

Materials

Technology Innovation

Innovative materials and manufacturing processes and advanced knowledge of in-service damage and aging mechanisms are critical for long-term operations of nuclear and fossil plants.

STRATEGIC DRIVERS

Long-Term Operations

Near-Zero Emissions

INNOVATION TARGETS

- **Reduce capital costs**
- **Reduce O&M costs**
- **Enhance durability and reliability and extend lifetime**

EPRI is leading development of powder metallurgy fabrication methods for large and complex components, a creep-resistant austenitic stainless steel for advanced ultrasupercritical (A-USC) coal plants, welding technology for thick-section components, and an alternative weld filler for mitigating primary water stress corrosion cracking (PWSCC) in pressurized water reactors. In addition, fundamental understanding is being advanced for PWSCC, irradiation-assisted cracking, corrosion fatigue, creep and creep fatigue, and high-temperature solid-particle erosion. Building on successful proof-of-concept work performed in strategic research, functionally graded compositional control methods are being pursued as a *Breakthrough Technology* for manufacturing higher-performance components (1022767).

Strategic Value

This program is delivering advanced materials, processes, and knowledge to EPRI's Generation and Nuclear sectors for application-oriented development and field demonstration in collaboration with power producers and commercial manufacturers. Innovative materials and manufacturing processes could lead to a significant reduction in the capital and life-cycle costs of components in high-efficiency coal plants and in existing and new nuclear units. New understanding and predictive tools for major damage mechanisms will enhance condition and remaining life assessment to improve operations and maintenance (O&M) practices while avoiding catastrophic failures. These advances also will support development of methods and materials for mitigating or preventing damage, with substantial savings and reliability and safety benefits.

Technology Gaps

Ongoing strategic work is building knowledge and advancing the technology readiness level (TRL) of innovations to address the following capability gaps:

- Advanced fabrication methods for manufacturing large and complex components and using high-performance alloys
- Lower-cost, higher-reliability materials for A-USC plants and existing and new nuclear capacity
- Basic mechanistic understanding and remaining life assessment tools for key damage modes
- New analytical tools for understanding and optimizing materials performance at the atomic scale

Improved understanding and quantitative characterization of corrosion fatigue damage underlies a new remaining life assessment approach for steam turbine blades in fossil and nuclear power plants.

R&D Highlights

Powder Metallurgy (PM) Fabrication. Relative to conventional forging and casting, PM and hot isostatic processing (HIP) methods offer breakthrough potential for faster, lower-cost manufacturing of higher-performance components for both nuclear and fossil plants. In 2009 feasibility testing, EPRI used an austenitic (316L) stainless steel (SS) powder to produce a 12-inch-diameter valve body in near-net-shape (NNS) form. The component incorporated intricate features, required no finish machining, offered exceptional toughness, demonstrated improved mechanical performance, and provided superior inspectability relative to conventional cast 316LSS components.

Subsequently, three NNS valve bodies of different geometries were produced from multiple heats of 316LSS, creep-strength-enhanced ferritic (CSEF) Grade 91 steel, and nickel-based Inconel 625 alloy, representing a broad cross-section of materials for nuclear and coal plant applications. Extensive characterization, inspectability, and weldability studies performed in conjunction with valve manufacturers have generated property and performance data to validate practical potential and support code cases to U.S. and international agencies for PM/HIP fabrication of large pressure-retaining components.

To date, EPRI has advanced PM/HIP manufacturing from TRL3 to TRL6 for power industry applications. NNS valves produced from Grade 91 powders during 2013 will undergo test-loop demonstration at host plants through the Fossil Materials & Repair Program (P87), and future demonstration of 316LSS valves is planned through the Nuclear Welding Technology & Repair Center (P41.01.05). Work on PM/HIP methods for nickel-based components in A-USC plants continues, and research cofunded by the U.S. Department of Energy is developing advanced fabrication methods for very large, damage-resistant NNS components for nuclear reactor pressure vessel (RPV) internals.

Commercial production of NNS components suitable for immediate deployment is expected in 2014. This could reduce lead times and costs in both replacement and new construction applications, while continuing EPRI work is expected to alleviate major challenges to the use of higher-performance materials platforms in advanced fossil and nuclear generation systems.

Powder metallurgy will enable fabrication of higher-performance components in near-net-shape form, enabling high-efficiency coal plants and reliable long-term operations for nuclear and fossil capacity.

PROGRAM LEVERAGE

>40%

INNOVATION NETWORK

University

- **Ohio State University**
- **Tohoku University (Japan)**
- **University of California, Berkeley**
- **University of Michigan**
- **University of Oxford (UK)**

Public & Private Sector

- **Areva**
- **Battelle Pacific Northwest Labs**
- **BOKU (Austria)**
- **Carpenter Technology Corp.**
- **Chubu Electric Power Co.**
- **CRIEPI (Japan)**
- **EDF**
- **General Electric-Hitachi**
- **Kansai Electric Power Co.**
- **Mitsubishi Heavy Industries**
- **National Physical Labs (UK)**
- **STI Technologies, Inc.**
- **Southwest Research Institute**
- **Tohoku Electric Power Co.**
- **TurboMet International**
- **U.S. Department of Energy**
- **Wyman-Gordon**

2013-14 Milestones

- Manufacture P91 and 316LSS valves and collaborate with regulatory and standards agencies (TRL7) to support demonstration and commercialization through P87 and P41.01.05
- Develop and refine PM/HIP methods, fabricate test components, and conduct materials characterization studies (TRL3-5) to support future A-USC and RPV applications

Corrosion Fatigue of Steam Turbine Blades. For low-pressure steam turbine blades and disks, life-limiting cracking often begins in corrosion pits subject to high steady-state and dynamic stresses. Building on years of fundamental work, EPRI has developed the first practical method for predicting and managing this critical failure mechanism in fossil and nuclear plants. Through an accelerated fatigue testing program, ultrasonic imaging and other methods are applied to monitor the corrosion-fatigue damage progression in blade materials, elucidate effects of environmental and operational conditions, and quantify the pit-to-crack transition. Predictive algorithms for the pitting, transition, and cracking stages are then developed for review and refinement by an international team of experts.

Benchmarking of life prediction criteria derived for 403/410SS blades will be completed in 2013, bringing this approach to TRL6 from a starting point of TRL2 in 2009. Follow-on work will address 17-4PH steel and alloy components. Validated algorithms transition to the Steam Turbines-Generators & Auxiliary Systems Program (P65) for implementation in commercial blade life assessment codes. Enhanced predictive capabilities will allow plant personnel to optimize O&M practices, extend lifetimes, and prevent failures based on in-service history and observed pitting for turbine blade components.

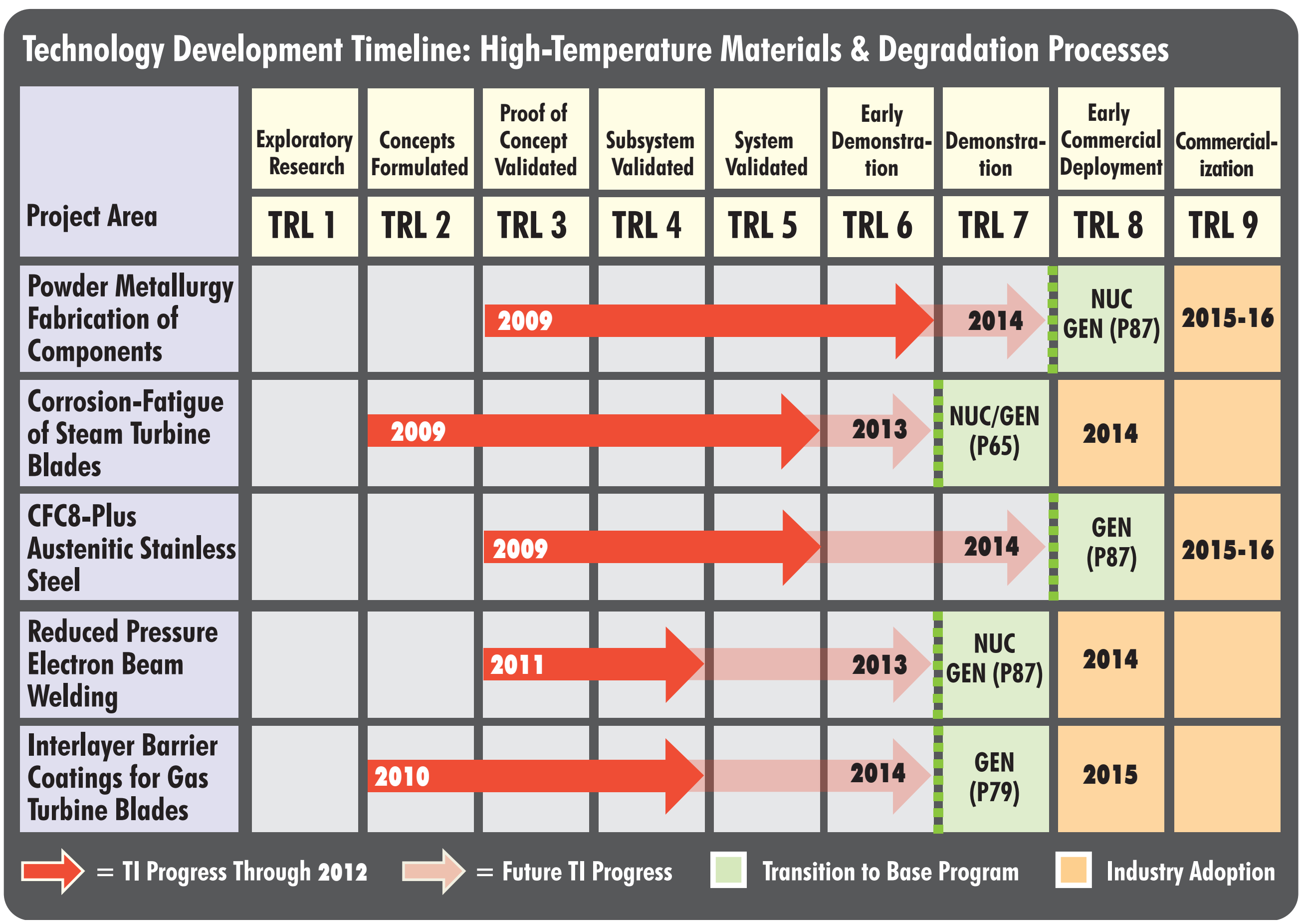
2013-14 Milestones

- Transition validated remaining life assessment algorithms for 403/410SS materials (TRL7) to P65 for implementation in commercial codes
- Complete accelerated fatigue testing of 17-4PH steel and alloy materials and develop and benchmark predictive algorithms (TRL3-6) for commercial application through P65

Creep-Resistant Steel for A-USC Plants. Nickel-based superalloys planned for headers and piping operating at 650°C and higher are costly and pose fabrication and welding challenges. CF8C-Plus, a creep-resistant austenitic stainless steel currently available only in cast form, offers potential as a more durable, less expensive alternative. In 2009, a CF8C-Plus ingot was worked to simulate the extrusions required to fabricate thick-section components. Relative to as-cast material, wrought CF8C-Plus demonstrated favorable strength, creep resistance, and other characteristics, and its performance proved similar to that of solid-solution nickel-based superalloys at A-USC conditions.

In bringing the technology from TRL3 to TRL5, EPRI and commercial vendors have conducted extensive experimental work to optimize ingot chemistry and extrusion parameters and successfully fabricate 20-foot-long, 8-inch-diameter pipe sections from multiple heats of CF8C-Plus. These large samples are undergoing comprehensive mechanical evaluation, including long-term creep rupture tests. Additional pipe sections are scheduled to begin in-plant test-loop demonstration in 2013, and code qualification cases for wrought header and piping applications are scheduled for submittal in 2014. Early commercial application through P87 is anticipated by 2015. At an estimated cost 5 to 7 times less than nickel-based alloys, CF8C-Plus could produce capital savings of $10 million to $30 million per A-USC plant. Additional

EPRI's Technology Innovation (TI) program helps maintain a full pipeline for the Generation (GEN) and Nuclear (NUC) sectors. Technology readiness levels (TRLs) mark the progress of individual technologies and guide their transition from TI into sectors and toward commercial application.



CF8C-Plus applications are anticipated in lower-temperature coal plants and gas turbine, fuel cell, and advanced nuclear systems.

2013-14 Milestones

- Complete manufacturing, characterization, and demonstration of an additional large-diameter pipe extrusion and submit code case (TRL6-7) for commercialization through P87

Standardization of Elevated-Temperature Solid Particle Erosion Testing. EPRI completed an evaluation of existing methods for assessing resistance to high-temperature solid particle erosion, then led an international round-robin laboratory program to develop a standardized test approach. Strategic work, completed in 2012, has transitioned to P87 for practical use in comparative evaluation of remedial measures such as coatings, hardfacings, and shields for mitigating erosion damage. The testing standard, to be introduced in draft form in 2013, fills a critical capability gap for mitigating solid particle erosion in steam turbine, combustion turbine, and other applications.

Reduced-Pressure Electron Beam (RPEB) Welding. In 2011, a feasibility study identified RPEB welding as a promising technology for single-pass welding of thick-section components in piping, header, and RPV applications. Ongoing work is designed to optimize welding parameters on test coupons of nickel-based alloy (IN740) suitable for A-USC operation and of RPV materials. In addition, extensive mechanical and metallurgical evaluations of welded thick-section samples are planned. These activities are expected to bring RPEB welding technology to TRL6, supporting transfer to P87 and P41.01.05 for further development, qualification, and demonstration in conjunction with industry partners.

2013-14 Milestones

- Refine RPEB parameters for IN740 and RPV coupons and complete characterization studies (TRL5-6) to support application-oriented development through P87 and P41.01.05

Interlayer Barrier Coatings for Gas Turbine Blades. In 2010, EPRI completed laboratory cyclic furnace tests to demonstrate proof of concept for nanocrystalline interlayer barrier coatings as a method for eliminating or significantly retarding development of the thermally grown oxides that can lead to delamination of the bond coat. As this damage mode reduces coating efficacy and may lead to blade failures, interlayer technology promises to extend maintenance intervals and could at least double blade lifetimes. Now at TRL4, the technology will be validated through long-term cyclic testing beginning in 2013 after nanocrystalline interlayer coatings are successfully applied to multiple full-section turbine blade samples in conjunction with a commercial partner. Demonstrations are anticipated through the Combined Cycle Turbomachinery Program (P79).

2013-14 Milestones

- Apply interlayer coatings to full-section blade samples and complete long-term cyclic tests (TRL5-6) for commercialization through P79

Alternatives for Alloy 52 Weld Filler. Weldability limitations for the high-chromium Alloy 52 materials widely used for mitigating PWSCC in welds joining the RPV with coolant piping have created costly problems. To develop alternative filler metals, an innovative approach based on computational thermodynamics modeling and accelerated weldability testing methods is being applied. Compositional modeling initiated in 2010 has determined that certain carbide-forming alloying elements may serve as viable substitutes to the currently used niobium, which provides resistance to ductility-dip cracking but promotes solidification cracking during welding. Candidate filler alloy formulations have been identified that promise superior welding performance, are thermally compatible with the base material, and maintain the properties required for the targeted application.

Data from screening-level characterization studies of candidate compositions and weld samples are being compared to modeling results, helping advance this innovative filler development approach to TRL3. During 2013, candidate materials with validated performance will continue to be fabricated for examination using new accelerated weldability testing techniques, and selected formulations will be converted to weld wire for larger-scale assessments. Full-scale mockup development and characterization studies scheduled for 2014 will bring one or more validated Alloy 52 alternatives to TRL6, and P41.01.05 will support follow-on work to secure regulatory approval and initiate commercial demonstrations.

2013-14 Milestones

- Complete modeling, characterization, and weldability studies on promising formulations and conduct full-scale mockup tests (TRL4-6) to support demonstration through P41.01.05

Internal Oxidation and Surface Film Processes: Characterization of Properties & Damage Processes Prior to SCC Initiation Using Advanced Analytical Methods. The earliest stages of SCC in nickel-based alloys in primary water system components remain poorly understood because the interactions among environmental conditions, surface properties, microstructural characteristics, and materials behavior cannot be quantified using conventional analytical techniques. In long-term fundamental research funded by and conducted in collaboration with organizations from around the world, EPRI is developing and applying advanced analytical tools to elucidate properties that determine whether a surface film allows initiation of intergranular SCC under primary water conditions, to assess whether internal oxidation represents the dominant PWSCC mechanism, and to identify factors influencing susceptibility to irradiation-assisted SCC (IASCC).

Accelerated aging studies are under way to characterize oxygen penetration along grain boundaries in Alloy 600 and Alloy 52 weldment coupons under strain. IASCC susceptibility is being examined at the atomic scale in irradiated 304SS samples. Additional experimental work is illuminating relationships between the surface characteristics of Alloy 600 and 690 and the composition and electrochemical properties of their oxide films. Microstructural techniques, surface-enhanced raman spectroscopy, atom probe tomography, and synchrotron X-rays are among the analytical techniques being applied. The latter two innovations, which have undergone significant application-specific development since 2009, are beginning to deliver unprecedented nanoscale insights into surface film behavior, grain boundary conditions, crack initiation, and crack propagation under strain.

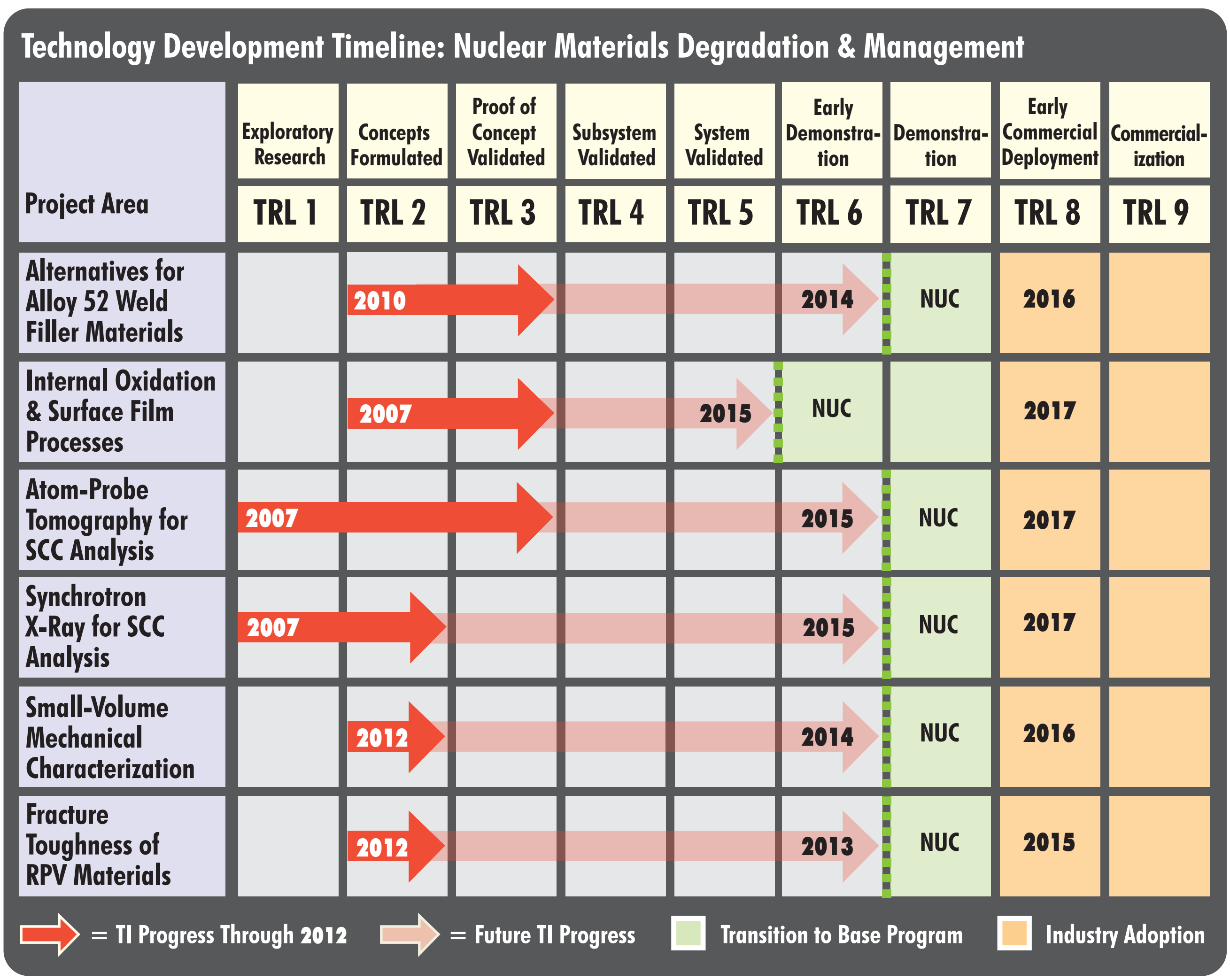
Intergranular oxidation studies show that chromium carbides decorating the grain boundary of Alloy 600 may slow oxygen diffusion and penetration. This helps explain the increased PWSCC resistance of thermally treated Alloy 600 with grain boundary carbides, relative to mill-annealed material. Surface film experiments suggest that the presence of iron and nickel cations in solution can affect the phase identity of the oxides that form and the composition of the protective inner layer of the oxide film. This finding has implications for SCC as well as for flow-accelerated corrosion of nickel-based alloys in boiling water reactor environments and for shutdown radiation dose associated with incorporation of cobalt species into surface films on primary system piping.

Atomic-level investigation of proton- and neutron-irradiated 304SS samples has revealed microstructural/microchemical features highlighting the impact of silicon concentration on intragranular precipitate formation leading to increased crack initiation and IASCC susceptibility.

As laboratory work continues, new knowledge and advanced analytical capabilities are being incorporated in predictive models maintained by EPRI and other project participants and being applied to address O&M considerations. In 2013, feasibility testing of a new, small-volume mechanical testing method will begin as a possible approach for measuring localized deformation or other parameters to create an index of IASCC susceptibility and support condition assessment and lifing based on small samples removed from in-service components. Planned work also will illuminate the effects of hydrogen on PWSCC initiation and of zinc addition on surface film properties in nickel-based alloys, as well as the use of post-irradiation annealing to remediate damage due to neutron exposure.

Even as some fundamental studies extend beyond 2014, the Primary Systems Corrosion Research Program (P41.01.01) will

EPRI's Technology Innovation (TI) program helps maintain a full pipeline for the Nuclear Sector (NUC). Technology readiness levels (TRLs) mark the progress of individual technologies and guide their transition from TI into the sector programs and toward commercial application.



continue to transfer findings to power producers and additional stakeholders through guidance documents and other resources. Also, new mechanistic understanding of PWSCC and IASCC will be applied to support near-term efforts to optimize inspection intervals, O&M practices, and asset management decisions and longer-term efforts to develop mitigation and prevention strategies, including materials with increased damage resistance.

2013-14 Milestones

- Continue internal oxidation, surface film characterization, and other studies to advance basic knowledge (TRL3-5) and enhance quantitative modeling, condition assessment, and asset management tools developed by P41.01.01
- Establish proof of concept for small-volume mechanical characterization of IASCC susceptibility and define and demonstrate predictive algorithms (TRL3-6) to support development of a condition assessment tool through P41.01.01

SCC Initiation and Propagation Modeling: Alloy 182 & Irradiated Stainless Steel. In 2007, EPRI began a focused collaboration with major research institutes to conduct controlled laboratory tests and incorporate state-of-the-art knowledge in predictive crack growth rate models for Alloy 600 and Alloy 182 weld metals in primary water conditions and for neutron-irradiated stainless steels. Strategic research, which concluded with validation testing in 2012, integrated comprehensive experimental data and new theoretical understanding to advance quantitative modeling from TRL3 to TRL6. Follow-on work by P41.01.01 will support regulatory review and industry adoption of new models providing more accurate predictions of materials behavior and remaining lifetime than the current empirical approaches. This will support decisions toward continued operation, inspection, and repair or replacement based on the latest knowledge of the importance of mechanical properties and crack-tip strain rates on crack growth rates and remaining lifetime.

Fracture Toughness of RPV Materials Using Miniature Samples. In 2013, an international round-robin testing program is being initiated to extend the usefulness of Charpy specimens applied in light water reactor surveillance programs and allow the fracture toughness of RPV materials to be assessed across the lifetime involved in long-term operations. Present fracture toughness testing methods involve destructive analysis of relatively large specimens; the EPRI-led project is exploring miniature-specimen techniques, first to determine their efficacy, then to compare results with those from standard large-sample tests. Planned work will provide the data required to establish a miniature-sample test standard and support an initial demonstration. This will help bring the technology from the current TRL2 to TRL6 by 2014, and the Boiling Water Reactor Vessel & Internals Project (P41.01.03) is expected to develop application guidance supporting commercial adoption.

2013-14 Milestones

- Establish feasibility and refine, validate, and standardize miniature-sample fracture toughness method through round-robin testing and early demonstration (TRL3-6) to support commercialization through P41.01.03

Recent Deliverables

A Preliminary Hybrid Model of Irradiation-Assisted Stress Corrosion Cracking of 300-Series Stainless Steels in Low-Electrochemical Potential Light Water Reactor Environments (1024863)

Hybrid Models of Stress Corrosion Crack Propagation for Nickel Alloy Welds in Low-Electrochemical Potential (ECP) Pressurized Water Reactor (PWR) Primary Water Environments (1025120)

Prediction and Evaluation of Environmentally Assisted Cracking in LWR Structural Materials: 2011 PEACE-E Phase II Report (1025123)

Proceedings: International Conference on Solid Particle and Liquid Droplet Erosion (1025837)

In Situ Surface-Enhanced Raman Spectroscopic Studies of Surface Films on Ni-Base Alloys (1025629)

Manufacture of Large Nuclear and Fossil Components Using Powder Metallurgy and Hot Isostatic Processing Technologies (1025491)

Evaluation of the Creep-Fatigue Behavior of Grade 92 Steel and Its Predictability (1024588)

Development of a Corrosion-Fatigue Prediction Methodology for Steam Turbines (1023196)

For more information

For more information, contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com).

Contact

David Gandy, Technical Executive, Nuclear
davgandy@epri.com, 704.595.2695

Raj Pathania, Program Manager, Nuclear
rpathani@epri.com, 650.855.8762

1023481 January 2013

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com