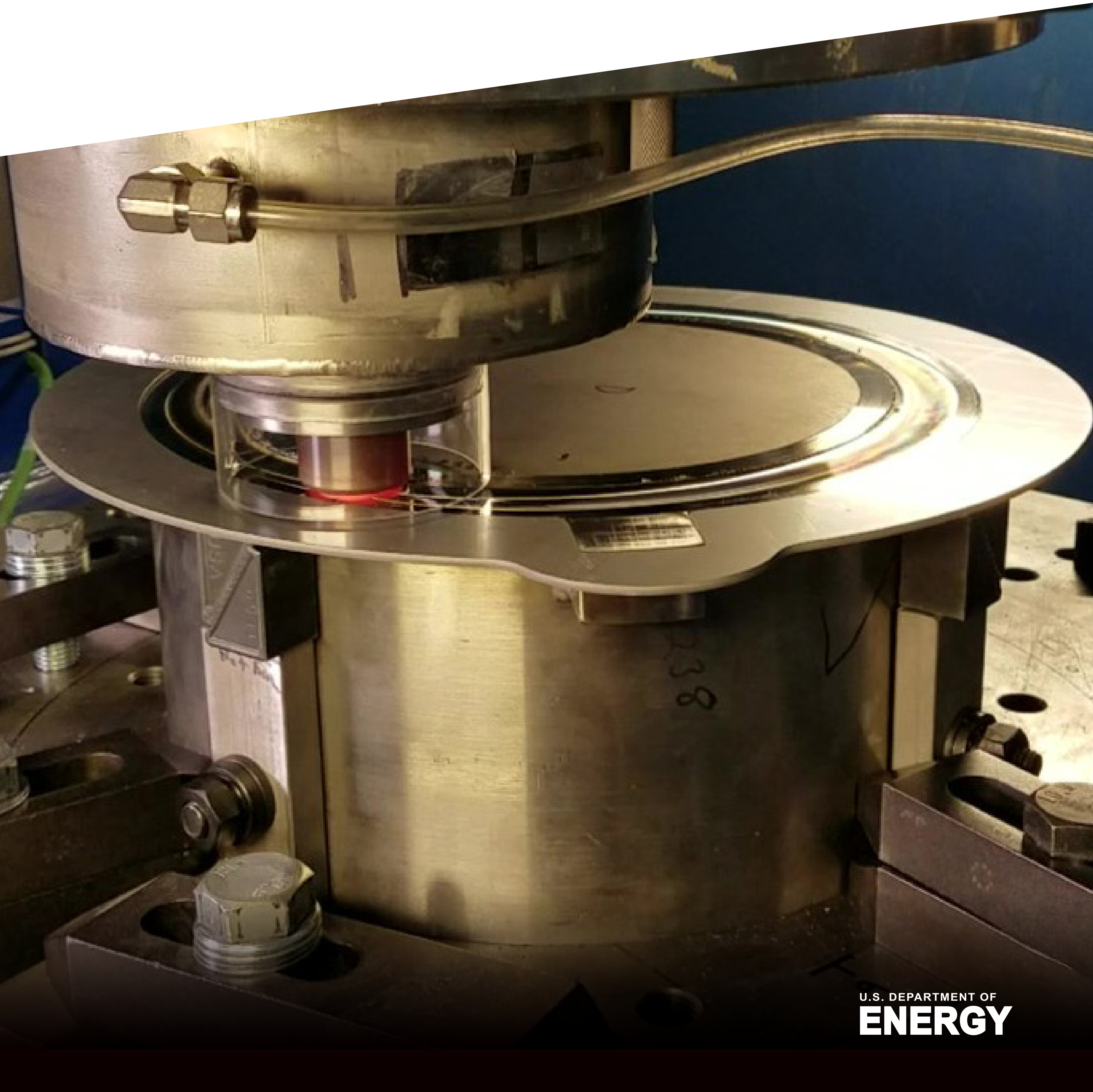
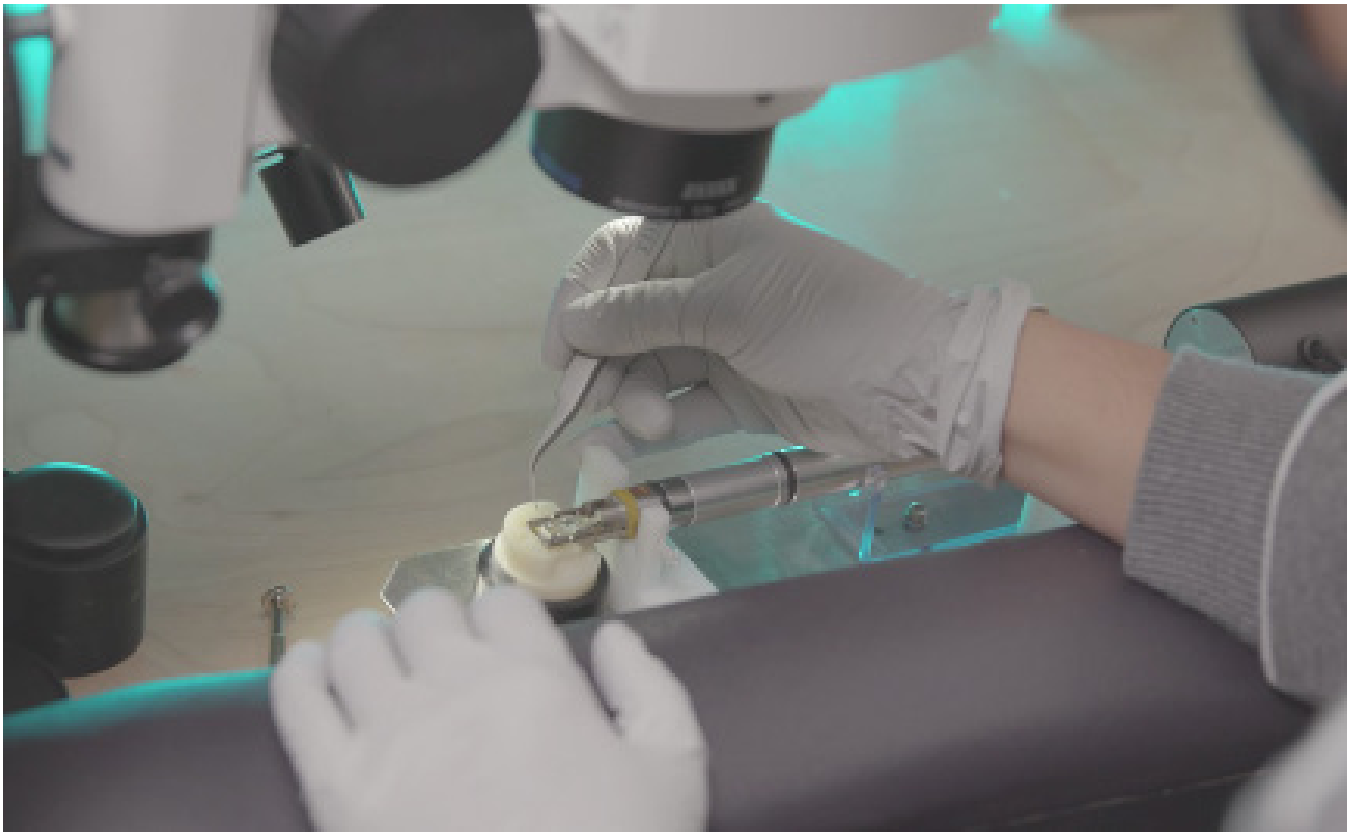
AGING MANAGEMENT OF NUCLEAR FACILITY MATERIALS AND COMPONENTS

Pacific Northwest
NATIONAL LABORATORY

Understanding the degradation effects of extreme environments to more efficiently repair or prevent damage



U.S. DEPARTMENT OF
ENERGY



PNNL's materials science researchers identify and predict degradation to materials in extreme environments—such as components within nuclear power plants—before damage leads to failure.

Material and component aging is important to the safe, secure, and economic operation of nuclear power plants and other nuclear facilities. Aging impacts how often inspections have to be performed, how often components have to be repaired or replaced, and ultimately the lifetime of a nuclear facility. Pacific Northwest National Laboratory's (PNNL's) scientists and engineers understand the importance of aging and apply our expertise to developing more robust materials, to understand the conditions under which materials degrade, to detect defects before they lead to failure, and to develop techniques for repairing or mitigating age-related damage. The research and development conducted at PNNL have supported the continued operation of the current fleet of light water reactors (LWRs) operating in the U.S. and can support the deployment of future nuclear systems that operate more safely and economically.

ADVANCED MATERIAL DEVELOPMENT

Materials used in advanced nuclear facilities are expected to experience more extreme environments and last longer. PNNL can help develop improved materials for use in advanced nuclear facilities that are more durable and have longer operating lifetimes. We apply our expertise and equipment to identify and predict how materials degrade in extreme environments, particularly before macroscopic damage propagates and leads to the failure of systems, structures, and components important to safety. We focus on advancing the understanding of how materials age and degrade using a host of capabilities including atomic-resolution electron microscopy, materials testing in realistic environments, mechanical design, material qualification, and multiscale modeling.

STRESS CORROSION CRACKING

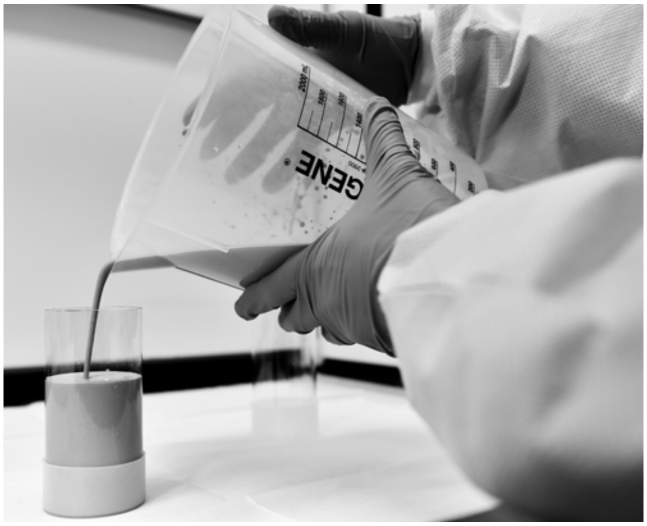
Research and development on material and environment compatibility in nuclear systems are important—the experience with stress corrosion cracking in pressurized water reactor coolants is evidence of this. PNNL has a world-class capability for the in situ, quantitative measurement of stress corrosion crack initiation and crack growth in a range of environments, including simulated LWR and atmospheric chloride salt environments. We have pioneered high-resolution characterization of crack tips providing unique insights into failure mechanisms. Our combination of material examination and testing helps identify what materials and what conditions lead to degradation.

PNNL's Stress Corrosion Cracking (SCC) Laboratory contains multiple SCC initiation test measurement systems designed and built by PNNL researchers to identify the onset of SCC in pressurized water nuclear reactors.

STRUCTURAL COMPONENT INTEGRITY

Materials and components used in nuclear reactors are required to perform their functions over their service lives. The extreme environments that they are exposed to can result in their properties degrading, potentially leading to failure, earlier than anticipated repairs, or replacements. PNNL has extensive experience in studying the degradation of structural components exposed to the extreme environment in the core of nuclear reactors. Applying a suite of the most modern characterization tools available has allowed PNNL staff to probe microscopic and macroscopic changes induced by the coupling of neutron flux, temperature, and stress. These changes include the formation of atomic-scale defects that agglomerate into visible nanometer-scale defects such as voids and dislocations, helium introduced by transmutation, and precipitation of new phases. Any of these defects can lead to extreme radiation hardening and loss of ductility that limits the lifetime of various components in a nuclear reactor such as core shrouds, baffle bolts, thimble tubes, and top guides in the existing fleet of LWRs.

PNNL materials scientists evaluate the mechanical properties of nuclear materials using an Instron tensile tester with an atmosphere-controlled high-temperature Centorr furnace.



CONCRETE AND CEMENT

Concrete and cementitious materials are used extensively in the construction of nuclear facilities, including nuclear reactors and spent fuel storage facilities. As the lifetime of these facilities extends the need to understand how these materials degrade and the development of more robust concretes and cements is essential. PNNL has decades of experience in the design, formulation, testing, characterization, qualification, and modeling of cement-based systems. Testing capabilities range from standardized testing procedures, advanced microscopy/spectroscopy techniques, scaled testing, and long-term physical, structural, and chemical modeling. These capabilities can be coupled with environmental exposure capabilities including expansive irradiation exposure facilities and allow in situ and ex situ characterization of irradiated cementitious materials.

Material scientists and computational modeling experts at PNNL have also developed Self-Healing Cement, the first technology with the ability to self-repair cracks throughout the entire life span of the concrete structure. PNNL's Self-Healing Cement could be engineered specifically for environments such as those at nuclear plants, particularly those including high-temperature settings and/or under varying levels of irradiation.

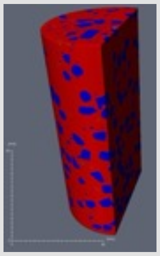
Formulation Development

- Cementitious Waste Forms—decades of formulation design experience supporting Hanford Site waste streams
- Novel cement material development, e.g., geopolymer, ultra-high-performance cement composites
- Geothermal well applications
- Subsurface barriers
- Infrastructure for subsurface field monitoring and sensing
- Leaders in glass/silica corrosion for mitigating deleterious alkali silica reactions

Standardized Testing Capabilities

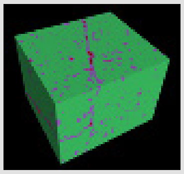
- Decades of experience qualifying waste immobilizing cementitious waste forms according to industry standards
- Expansive testing capabilities under NQA-1 protocols
- Physical (e.g., compressive strength, length change)
- Rheological (e.g., viscosity, calorimetry)
- Environmental (e.g., heat treatment, aging)
- Chemical (e.g., leach testing, composition)
- Nondestructive evaluation (e.g., tank inspection, irradiation environments)
- Specialized materials science laboratories

Advanced Characterization



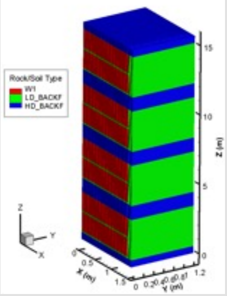
- 3D imaging and analyses
- Synchrotron characterization and method development
- Real-time radiography
- Advanced electron microscopy and spectroscopy for multi-scale characterization of material topography, structure, and composition
- Environmental Molecular Sciences Laboratory, a DOE Office of Science user facility at PNNL

Technology and Development



- Self-healing polymer composites
- Getters for radionuclide/contaminant capture
- Controlled mineralogical growth
- Ancient and natural analogues
- Signature detection

Modeling and Transport



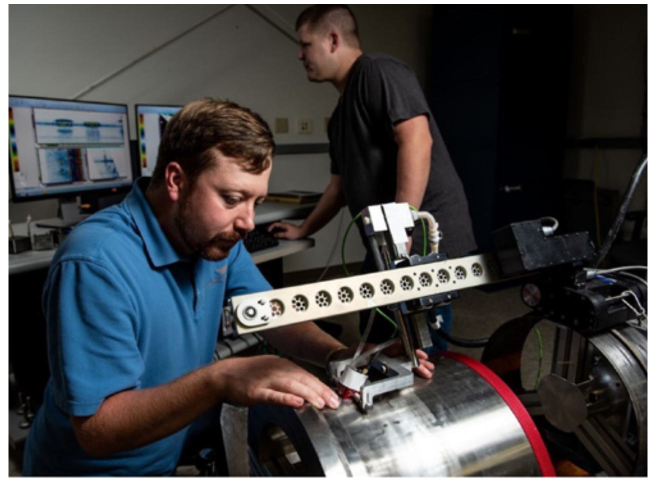
- Decades of regulatory permitting and environmental modeling experience, e.g., cementitious materials, contaminant transport, Computational fluid dynamics (CFD) modeling of non-Newtonian fluids
- Structural integrity modeling (e.g., Hanford tanks)
- Large-scale field-testing facility for lysimeter tests
- Advanced cementitious modeling, e.g., mineralogy and structural properties
- Biodegradation

Environmental Exposure

- Full capability irradiation facility
- Post-irradiation/aging characterization capabilities
- Structural, chemical, and microstructure analyses
- Hydrogen generation during irradiation
- Field testing

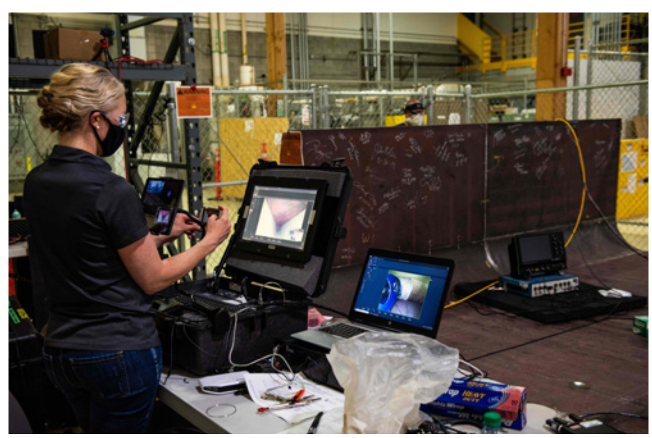
NONDESTRUCTIVE EXAMINATION

Nondestructive examination (NDE) plays a critical role in obtaining both empirical and theoretical data to provide valuable inputs into aging management programs that have been instituted for commercial nuclear power and other industries. Effective NDE is required for evaluating the structural integrity of components and materials in nuclear power plants. PNNL has a long history of NDE research, development, and deployment in aging management of components and materials relevant to nuclear power plant operation. Our capabilities include detection, characterization, and monitoring of component and material conditions using a vast array of nondestructive interrogation capabilities. These novel capabilities encompass both direct and guided wave acoustics/ultrasonics, advanced ultrasonic probes, eddy current, digital radiography, acoustic microscopy, dielectric spectroscopy, optics, and millimeter-wave imaging. PNNL also applies diagnostics and prognostics evaluations using machine learning and automated data analysis, modeling and simulation of inspection methods, and physics-based representation of degradation mechanisms. These evaluations help to gain an in-depth understanding of the material condition and degraded state of a component—including the structural integrity of advanced manufacturing technologies-fabricated components for advanced reactors—to provide information on the remaining useful life, and inform mitigation, repair, or replacement activities. PNNL's NDE experts have decades of both laboratory and in-plant experience and steward state-of-the-art NDE research facilities that house advanced NDE instrumentation, probes and sensors, an extensive inventory of vintage nuclear power plant materials and components, and the latest multi-physics based modeling and simulation capabilities. In addition, PNNL staff are actively engaged in national and international codes and standards and have been instrumental in crafting significant improvements to the use of NDE in the nuclear power industry.



PNNL researchers conducting phased-array ultrasonic inspection of reactor piping welds.

Development of a remote inspection system for spent nuclear fuel storage casks is in progress at PNNL, which will help identify the aging mechanisms associated with chloride-induced stress corrosion cracking.

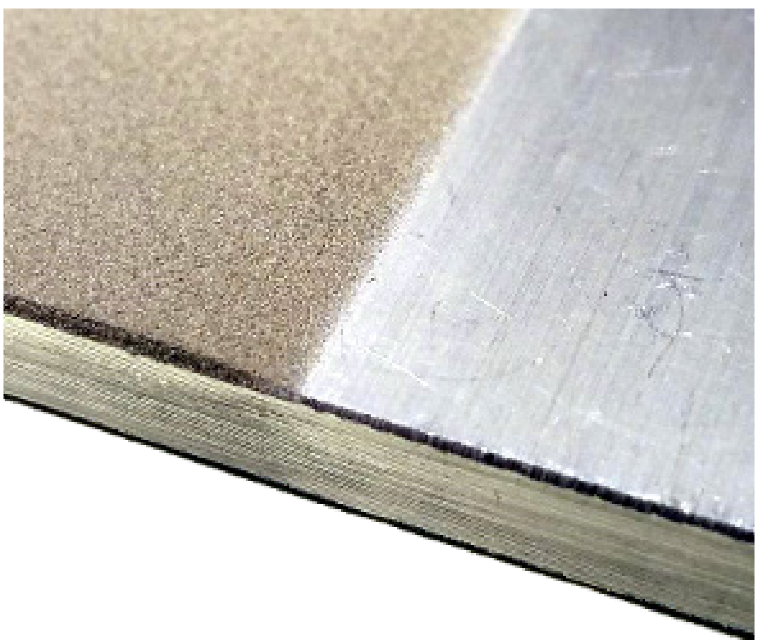


In partnership with industry and DOE contractors, PNNL is demonstrating an Electro Magnetic Acoustic Transducer (EMAT) system for inspecting aging underground double-walled radioactive waste storage tanks.

SOLID PHASE PROCESSING FOR REPAIR, REMEDIATION, AND MITIGATION

New scalable manufacturing approaches can produce high-performance materials and components that are more durable in extreme environments, allowing for longer operating life and reduced need for inspection and repair.

PNNL is leveraging two decades of experience in metals processing and performance to develop a new approach to metals manufacturing called Solid Phase Processing. Friction stir welding and friction stir processing can be used both to join materials and to selectively modify the structure of the surface. As a joining technique, friction stir welding and friction stir processing produces a weld between materials without melting them, leading to improved weld joint performance with lower defects. Cold spray deposits metal particles at high velocities onto a base metal, forming a coating without melting either the metal particles or the base substrate, resulting in a strong bond with the surface and a dense high-performance microstructure in the coating. No detrimental heat-affected zone occurs. Both friction stir welding and friction stir processing and cold spray can be used to extend the service life of components by repairing or mitigating damage during factory fabrication or service.



High-pressure cold spray coating of commercially pure nickel.

This fielded light water reactor component was repaired with cold spray as part of a collaborative effort with VRC Metal Systems and Exelon.

CABLE DEGRADATION

Cables of several hundred different types, including power, control, and instrument cables, are essential for the operation of a nuclear power plant. The ramifications of cable failure can be significant, especially for cables connecting to offsite power, emergency service water, and emergency diesel generators.

PNNL has extensive experience in understanding how cables degrade under the environments they are exposed to at nuclear power plants and in the development and use of techniques for detecting and locating defects in cable insulation that can lead to failure and quantifying their remaining useful life. We have a large collection of cables that have been recovered from nuclear power plants and the capability to expose cables to the environmental conditions they would see during their operation, including the delivery of precise levels of radiation exposure, to determine how they degrade and to identify the viability of different nondestructive inspection methods.

Special ovens are used to accelerate the aging of components, such as electrical cables, that are exposed to extreme environments inside nuclear power reactors.

Researchers use the ARENA Cable/Motor Test to evaluate the integrity of the wide variety of cables used inside extreme environments, including nuclear power plants.

AGING EFFECTS AND PROBABILISTIC RISK ASSESSMENT

PNNL nuclear experts conduct risk assessments and safety analyses that underpin the limiting conditions for safe reactor operations, administrative programs, and controls. Our experts emphasize decision science, probabilistic risk assessments (PRAs), and systematic analyses that reveal the strengths and weaknesses of the design, construction, operation, and siting of nuclear power plants. We understand how to incorporate material and component aging effects into analyses and assessments to allow for risk-informed decisions regarding inspections, maintenance, repair, and replacement.

Cable samples undergo temperature and high gamma testing in PNNL's High Exposure Facility, as part of a reactor life extension research project for the DOE Office of Nuclear Energy.

CONTACT:

Mark Nutt, PhD, Manager, Nuclear Market Sector | mark.nutt@pnnl.gov | (509) 375-2984

On the cover: This mock-up of a spent fuel dry storage canister closure lid shows how PNNL's Friction Stir Welding capability can be used to repair and strengthen the metal.

FEBRUARY 2022 | PNNL-SA-170468