Welding & Repair Technology Center

Program Overview

Program Description

High-quality, reliable welds, repair methodologies, and mitigation processes are critical to safe nuclear plant operation. The safety significance of component repairs and replacements emphasizes the need for a high degree of confidence in the integrity of joining processes and implementation techniques. While maintaining this commitment to quality and safety, productivity improvements and new technology development can provide cost savings in maintenance and repair activities.

The Welding & Repair Technology Center develops advanced materials, joining, and repair technologies for nuclear plant applications, contributing to reduced operation and maintenance costs and improved plant availability. The program also supports technical interactions with code and regulatory entities to inform the development and modification of new and existing requirements.

Research Value

Research results from the Welding & Repair Technology Center help nuclear power plants find faster, less costly ways of making repairs using novel welding techniques or by applying existing techniques in new situations. Research results also are used to support technical interactions with regulators regarding code requirements. Program participants gain access to the following:

- Materials, welding, and repair experts across the Electric Power Research Institute (EPRI) and the nuclear industry
- Strategic roadmaps outlining research gaps confronting key issues—such as advanced nickel-based filler metals and welding of irradiated materials in boiling and pressurized water reactors—and the collaborative actions needed to address these gaps
- Demonstrated repair techniques and technologies that improve material performance and enable component life extension
- Benchmarking information from welding programs at nuclear utilities
- Repair options for key components, supplemented by application guidelines, procedures, and training
- Support during implementation of plant repair applications involving material interactions, weld process control, and code requirements
- Techniques that can potentially reduce repair costs and increase plant availability, including temperbead welding, socket weld fatigue solutions, and post-weld heat treatment processes
- Forums for continuous sharing of operating experience, weld program issues, and industry emerging issues

Approach

The Welding & Repair Technology Center combines extensive laboratory capabilities with detailed familiarity with industry and regulatory needs to investigate and evaluate welding and repair techniques. EPRI can replicate welding setups in the field—power supplies, weld heads, and other equipment—to create realistic welding environments in the laboratory. Through participation in many American Society of Mechanical Engineers (ASME) and industry technical committees, the program also ensures that the research results inform code requirements.

There are both base and supplemental components of the Welding & Repair Technology Center Program. The base portion focuses on repair and replacement research, code and standards support, and effective transfer of EPRI technology. As nuclear plant staffs have been reduced, personnel have less time to participate in technology transfer activities, stay abreast of changing codes and regulations, and monitor improved repair technologies and processes. This project supports access to EPRI expertise through meetings and various

information products, including unique repair/replacement applications, a database of welding procedures, repair/welding program assessments, and benchmarking activities.

Regular engagement with code organizations and other technical bodies helps inform the implementation of new repair methods, welding procedures, and weld materials within acceptable safety limits. Base research supports EPRI interactions with ASME (American Society of Mechanical Engineers) and other code and regulatory bodies regarding code cases, revisions, and technical interpretations impacting a wide range of component repairs. Examples include boiling water reactor control rod leakage repair, pre-emptive dissimilar metal weld overlays to address Alloy 600 mitigation applications, and use of specialized methods to seal leakage while under power. Finally, recognizing that the development of repair and replacement technology is an evolutionary process requires continuous sharing of experience among nuclear plants, vendors, and research organizations, the Welding & Repair Technology Center compiles best practices, experience information, and benchmarking data.

To address strategic objectives established for each of its programs, EPRI has developed roadmaps to plan, coordinate, and execute needed research among multiple entities. For the Welding & Repair Technology Center, roadmaps have been developed for the following issues: welding of irradiated materials for reactor internals, weldability assessment of Alloy 52/52M weld metals, and development of a new high-chromium welding alloy with improved weldability and superior resistance to weld cracking. Additional roadmaps will be developed as conditions warrant.

The supplemental portion of the program evaluates welding materials performance in power plant environments to assess the life of nuclear components and investigates advanced welding and repair technologies to potentially reduce time and cost of repairs. The supplemental portion also provides nuclear plant owners access to case histories, lessons learned data, and technical support in the form of materials and joining evaluations, benchmarking of programs, and procedure development.

Through a separately funded project, participants can participate in the Weld Mitigation Interest Group, which evaluates emerging repair options that address dissimilar weld metal mitigation. The project supports expanded repair and mitigation options that reduce the time, cost, and radiation exposure associated with inspection and mitigation activities, including mechanical stress improvement, inlays, onlays, and overlays.

Accomplishments

EPRI's Welding & Repair Technology Center supports nuclear power industry efforts to develop and apply welding and repair techniques that enhance safety, inform regulatory issues, reduce maintenance costs, and improve productivity.

- Issued a resource guide, the *Repair Welding Handbook,* that assists nuclear power plants in choosing appropriate repair techniques and navigating the regulatory approval and code compliance processes.
- Evaluated nickel high chromium weld filler materials for resistance to typical welding related defects, such as direct digital control, hot cracking, and general weldability. Alloy-52-type materials and derivatives have been evaluated to support alloy selection and grading to distinguish heat-to-heat variations.
- Conducted technical analysis to evaluate whether temperbead welding could be used on large-bore piping for larger surface areas. Finite element analysis demonstrated that weld overlays can be applied to areas up to 1000 square inches without generating unacceptable stress levels.
- Demonstrated the feasibility of in-vessel underwater laser beam weld repair of critical nickel alloy welds, eliminating the need to drain the reactor vessel. Areas that have been addressed include seal welding capabilities, temperbead welding, hot cracking susceptibility.
- Developed a roadmap to assist power plant personnel in conducting failure analyses for various components or for directing other organizations responsible for such work, with a focus on metallurgical and mechanical aspects.
- Provided technical support for implementing new technologies, including application guides for advanced welding methods, guidelines for installing and examining dissimilar metal weld overlays, and repair/mitigation of socket weld fatigue failures.

- Supported development of realistic code rules, including new code cases to reduce post-weld examination hold times and use of dissimilar metal weld overlays for stress corrosion cracking mitigation.
- Developed guidance for overlay applications based on lessons learned, best practices, and weld studies to support current technology. Also supported development of new and higher production welding processes such as gas-metal arc welding and dual wire feed gas tungsten arc welding.
- Conducted testing to determine the way in which concrete and reinforcing steel are affected by exposure to boric acid in concentrations typical of spent fuel pool chemistry. Improved understanding of the degradation mechanisms and degradation rates will support life extension decisions.
- Evaluated the application of new repair techniques for high-density polyethylene piping, which is gaining traction as an alternative to steel in low-energy applications.

Current Year Activities

Welding & Repair Technology Center research and development for 2012 will focus on developing repair and fabrication technologies to reduce outage time and expand the availability of repair options that may be performed during plant operation. Specific efforts include the following:

- Conduct failure analysis and stress measurements to assist utilities in repair decisions that are cost-effective, reduce downtime, and improve quality
- Establish welding criteria for repair and mitigation of irradiated material
- Development of temperbead guidance document
- Evaluate advanced filler/welding materials (Alloy 52M) for critical plant repair applications
- Develop training for new repair and replacement engineers
- Evaluate welding methods for small-bore piping and alternative joining methods for socket welded joints
- Provide benchmarking support for utility welding Risk & Reliability (R&R) programs
- Identify repair/mitigation options that address buried piping issues, fuel pool leakage, and components susceptible to stress corrosion cracking

Estimated 2012 Program Funding

$3.3 million

Program Manager

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Summary of Projects

Project Number	Project Title	Description
P41.01.05.01 (Roadmap)	Welding of Irradiated Materials for PWR and BWR Internals (Roadmap) (QA)	
P41.01.05.02 (Roadmap)	Alloy 52 Nickel-base Filler Metal Weldability Solution (Roadmap) (QA)	
P41.01.05.03 (Roadmap)	New High Chromium Weld Metal Development and Cracking Mechanisms (Roadmap) (QA)	
P41.01.05.04c	Weld Mitigation Interest Group (supplemental)	The Weld Mitigation Interest Group provides a forum for exchanging industry experience, solutions, and technology. The group evaluates emerging repair options that could reduce the time, cost, and radiation exposure related to welding operations; provide enhanced inspectability; expand repair options to include inlays, onlays, and underwater laser beam welding; validate filler metal weldability; and document industry experience.

Welding of Irradiated Materials for PWR and BWR Internals (Roadmap) (QA)

Key Research Question

The continued operation of light water reactors will require that repairs or replacement of reactor internal components be performed as degradation occurs. Welding plays an important role in the repair or replacement of degraded reactor internals. When reactor internals are subjected to irradiation, however, the weldability of the materials is altered by the formation of helium and can result in helium-induced cracking when these irradiated materials are welded. Most of the research performed to-date has been on irradiated stainless steel. A large gap exists in the understanding related to the weldability of irradiated nickel alloys and reactor pressure vessel steel as well as the ability to utilize special welding techniques to repair high-fluence materials.

Approach

This work is divided into short-term and long-term research and development (R&D) activities. The short-term activities address research needs out to 40 years of operation for welded repairs or replacement to reactor internals. Long-term research activities focus on the development of tools to address degradation that may exist in reactors with 40 or more years of operation, such as the development of models and advanced welding processes for highly irradiated material.

Short-term activities:

- Develop thermal fluence map for pressurized water reactor (PWR) reactor designs
- Develop weldability assessment for the PWR reactor designs
- Refine conventional welding model for predicting the weldability of irradiated stainless steel
- Develop laser welding predictive model for welding irradiated stainless steel
- Develop techniques for applying laser welding to reactor internal repairs
- Refine boiling water reactor (BWR) weldability assessment

Long-term activities:

- Develop a predictive model for the weldability of nickel-base materials
- Research advanced welding process for application on highly irradiated material
- Develop a process model for advanced welding technologies
- Test advanced welding processes on irradiated stainless steel and nickel-base alloys

Impact

There are a number of factors that drive the need for a comprehensive plan to weld irradiated material:

Operational Impacts—In both PWR and BWR reactor designs, there are key structural components that support internal components. If the structural integrity of these components—such as the core support lugs and the jet pump riser leaves—is compromised by degradation, the reactor could be rendered inoperable. No mechanical repair technology currently exists for repairing these components and welded repair or replacements are the only viable option.

Limitations of Existing Welding Technology—Current laser welding technology is only capable of successfully welding material with about 10 atom-part-per-million (appm) helium concentration. This level of helium will be generated in many of the reactor internals locations after about 40 years of operation. New welding technology needs to be developed to extend the weldability of irradiated materials out to 80 years of operation. Hybrid welding technologies such as multiple laser beams that alter the residual stress show significant promise for extending the weldability range of irradiated material, but extensive process development and testing is needed to implement these new technologies.

Cost—The replacement of reactor internals is a costly undertaking. This activity not only involves component removal and replacement, but cut-up and disposal as well. The welded repair is a cost-effective alternative to the repair or replacement option. In some cases, welding also is required to perform replacement of reactor internals.

Coordinated Research Approach—Researching the weldability of irradiated material is difficult for any single EPRI issue management group to fund. It requires the use of hot cell facilities for the experiments and examination of irradiated test specimens. The data produced from these experiments arenot unique to one reactor design and can be used by all EPRI issue management groups if the experiments are designed appropriately.

Regulatory—The U.S. Nuclear Regulatory Commission has stated that engineering guidance is required before welding can be performed on irradiated reactor internals. Such guidance has been provided for BWR designs in the form of BWRVIP-97, which has received a safety evaluation review by the Nuclear Regulatory Commission (NRC). A similar document needs to be produced for PWR designs.

How to Apply Results

A comprehensive plan has been developed between EPRI and the Department of Energy to address the weldability of irradiated material. The technology developed through this program will be transferred to industry in threeforms:

- Topical reports that contain thermal neutron fluence assessments and weldability maps for each reactor design. These documents will be submitted to the NRC for a safety evaluation.
- Topical reports that document the development of new welding technology that can be used for applications on highly irradiated materials.
- Transfer of newly developed welding technology to vendors for commercialization

Selected reports and products may be prepared in whole or in part in accordance with the EPRI Quality Program Manual that fulfills the requirements of 10CFR50 Appendix B, 10CFR21 and ANSI N45.2-1977. Reports and products developed under the EPRI QA program will be marked and identified as such.

Alloy 52 Nickel-base Filler Metal Weldability Solution (Roadmap) (QA)

Key Research Question

Weld Alloys 52 and 52M are used extensively for repair and mitigation of primary water stress corrosion cracking (PWSCC) in Alloy 82/182 dissimilar metal welds joining critical reactor coolant system components. Alloy 52 and 52M also are specified for use in new PWR designs. Unfortunately, the weldability and crack susceptibility of alloys 52 and 52M varies widely with minor variations of element composition within the ASME material specification limits. Further, crack susceptibility and weldability depend on weld dilution by the base material and on welding process parameters. These issues have caused extensive in-process repair and rework of Alloys 52 and 52M welds, extending refueling outages and costing the nuclear power industry tens of millions of dollars in unexpected maintenance and lost power generation. Research and testing are needed to understand and appreciate the limitations of welding with 52 and 52M for dissimilar metal applications and to develop guidelines to minimize potential for repair and rework.

Approach

The project will follow a logical approach for evaluation of high chromium nickel-base weld alloys. Major project tasks are listed below:

- Perform weldability testing to understand and rank the weldability
  - Computational modeling and laboratory weldability testing
  - Dilution studies
  - Mockup weld testing
- Assess influence of base metal composition to weldability problems
  - Develop threshold levels or charts to evaluate influence of base metals on weldability and crack sensitivity
  - Assess and validate by weldability testing and mockups with NDE
- Evaluate welding processes and influence of process parameters
  - Assess existing, modified, and new welding processes
  - Develop process parameters for existing and for promising new welding process technologies
  - Evaluate welding process and parameters by mockup testing and final NDE
- Application plan
  - Engage leading welding vendors (for example, WSI, WEC, and Areva) to advance existing welding processes and evaluate new welding processes with success potential
  - Support ASME Code rules and engage regulatory agencies for acceptance of new welding processes

Impact

Significant drivers include the following:

Outage Schedule and Cost Impact—The use of 52 and 52M for PWSCC mitigation and repair has caused the loss of tens of millions of dollars in electricity production. Industry experience shows that refueling and maintenance outages are often extended due to repeated re-welding and in-process repair of Alloys 52 or 52M. Until the weldability and crack susceptibility of 52 and 52M are fully understood and adequate composition limits and process controls are implemented to minimize problems, the continued use of these weld metals will likely continue to cause outage schedule extensions and the associated lost plant availability and lost revenue.

Regulatory Impact—The U.S. Nuclear Regulatory Commission (NRC) and other global nuclear regulatory agencies are concerned with the poor weldability and crack susceptibility of weld Alloys 52 and 52M. The NRC currently requires the use of 52 or 52M weld metal for repair and mitigation of 82/182 welds and for new PWR nuclear component fabrication.

PWSCC Mitigation—Most of the smaller diameter piping dissimilar metal welds have been mitigated by structural weld overlay. The majority of remaining dissimilar metal welds are large-bore, which will require significantly more welding. Welding mitigation options for large-bore applications—such as inside diameter inlays, outside diameter overlays, underwater laser welding, and excavation weld and repair—are considered high-risk activities due to known weldability issues with 52 and 52M.

Lack of Consolidated Welding Guidelines—Despite years of effort to optimize welding process parameters and develop specialized welding equipment, the problems with Alloys 52 and 52M continue to plague the nuclear industry. Successful welding is often based on narrow welding process parameter tweaks or on the superior weldability of a single heat of 52 or 52M. Moreover, the optimized welding process parameters or specialized welding equipment developed by a vendor are proprietary. As a result, the reasons for the better than average, or less than optimum, weldability of a specific heat of 52 or 52M are not well understood.

How to Apply Results

The products developed from this research will help welding engineers understand the weldability issues and crack susceptibility of 52 and 52M when used for PWSCC repair and mitigation or for new component fabrication. Further, the tools developed will provide utilities, vendors, and fabricators with information that will help minimize rework, improve weld quality, and ensure schedule compliance. Key project deliverables are listed here:

- Index of weldability and crack susceptibility of commercially available high-chromium nickel-base weld metals (for example, 52, 52M, 52MSS, 52i, and low-Fe 52MSS). The index will reflect the relative weldability between commercially available weld metal specifications and between heats within these specifications.
- Matrix of base metal and weld metal composition thresholds and limits that can be used to minimize weldability and cracking problems.
- Evaluation of alternative welding processes (for example, gas metal arc welding [GMAW], laser beam welding [LBW], and hybrid welding) that can be successfully used with high-chromium nickel-base weld alloys.
- Bases documents (as required) and data to support ASME code cases and NRC endorsement of new welding processes and/or other commercially available high-chromium nickel-base weld alloys.
- Final report with data, results, and guidelines.

Selected reports and products may be prepared in whole or in part in accordance with the EPRI Quality Program Manual that fulfills the requirements of 10CFR50 Appendix B, 10CFR21 and ANSI N45.2-1977. Reports and products developed under the EPRI QA program will be marked and identified as such.

New High Chromium Weld Metal Development and Cracking Mechanisms (Roadmap) (QA)

Key Research Question

Alloys 52 and 52M are high-chromium, nickel-based weld metals developed specifically for their superior resistance to stress corrosion cracking in nuclear power applications. These weld metals are used extensively for repair and mitigation of primary water stress corrosion cracking (PWSCC) in dissimilar metal 82/182 welds. Experience shows that Alloys 52 and 52M are susceptible to weld cracking and have less than optimum weldability. Repair and rework of these weld metals has cost the nuclear power industry millions of dollars. Despite years of effort to optimize welding process parameters and develop specialized welding equipment, the problems with Alloys 52 and 52M continue to plague operating plants and influence new plant deployment. A

new high-chromium welding alloy is needed that has the desired mechanical properties and corrosion resistance, but also has significantly improved weldability and superior resistance to weld cracking.

Approach

This project will perform fundamental research to understand Alloy 52/52M weldability and cracking issues by literature research, operating experience, and laboratory weldability testing. Concurrently, the project will develop, test, and validate a new high-chromium weld alloy as an alternative to Alloy 52/52M. The project will include composition development, weld alloy manufacturing, welding process and parameter development, and evaluation studies to validate use for repair and fabrication of critical nuclear power components. Proposed plans and tasks include the following:

1. Research and perform laboratory weldability testing to understand fundamental cracking mechanisms and weldability problems with high-chromium nickel-base weld metals
2. Develop alloy composition
   - Evaluate welding behavior and mechanical properties of target composition with modeling and analyses
   - Validate modeled behavior for target composition with small laboratory test samples
   - Manufacture experimental weld wire with target composition
   - Evaluate weldability of weld wire and perform mechanical, corrosion, and crack growth rate testing
- Assess welding and nondestructive evaluation of alloy composition
  - Assess and develop process parameters for gas tungsten arc and gas metal arc welding
  - Fabricate large-scale mockups and assess impact on nondestructive evaluation
  - Assess feasibility and potential of advanced welding processes (for example, laser welding, magnetic stir, and hybrid)
- Application plan
  - Engage material manufacturer (for example, Special Metals, and Sandvik) to develop weld metal specification
  - Engage leading welding vendors (for example, WSI, WEC, Areva, MHI, ENSA, and Shaw) to evaluate new weld metal
  - Facilitate acceptance of new weld metal through AWS/ASTM/ASME Codes and Standards

Impact

Significant drivers include the following:

Outage Schedule and Cost Impact—Between 2006 and 2009, the use of Alloy 52/52M associated with PWSCC mitigation and repair resulted in tens of millions of dollars in lost electricity production. Refueling and maintenance outages are often extended, causing lost generation capacity and increased outage cost, due to repeated re-welding and in-process repair with Alloy 52/52M. Until a long-term solution is realized, the continued use of Alloy 52/52M will likely continue to cause outage schedule extensions with the related lost plant availability and associated lost revenues.

Asset Management for Operating PWRs—A number of PWR owners have elected to defer Alloy 82/182 PWSCC mitigation, choosing to inspect instead. This decision resulted from insurmountable Alloy 52/52M weld cracking problems encountered at one plant during installation of a weld overlay on reactor coolant system piping in the spring of 2009. Since that time, only one utility has successfully mitigated Alloy 82/182 PWSCC by Alloy 52/52M weld overlay. Therefore, lack of a high-chromium nickel-base alloy welding solution not only impacts outage schedule and cost, but also is causing incremental inspection costs.

Regulatory Impact—The U.S. Nuclear Regulatory Commission (NRC) currently requires the use of a high-chromium (30 wt%) nickel-base weld metal for repair and mitigation of Alloy 82/182 welds and for new PWR nuclear component fabrication. Because of concerns with poor weldability and crack susceptibility of Alloy 52/52M, NRC supports a long-term solution, such as development of a new high-chromium alloy with improved weldability and superior crack resistance.

Lack of a Coordinated Approach—Historically, Alloy 52/52M development has been problem-driven and has occurred on an as-needed basis. Welding problems and cracking that occurred during refueling outages and/or during manufacture and repair of critical PWR nuclear components have driven small modifications or 'tweaks' to the base Alloy 52/52M composition. These small modifications or changes to composition may or may not have actually corrected the problem since the fundamental cause of the problem was not thoroughly researched, understood, and corrected. This ineffective approach continues today.

How to Apply Results

New alloy development tools and a new high-chromium alloy with superior weldability will be the main products of this project. Computer modeling and analyses in concert with newly developed small laboratory weldability testing techniques will be used to guide the development of the new high-chromium nickel-base welding alloy. In the past, weld alloy development was normally accomplished by starting with the matching base metal composition followed by systematic additions of minor alloying elements to achieve acceptable welding characteristics. For example, Alloy 52/52M is based on Inconel™ 690 with only minor element additions. Rather than starting with the base metal composition, the new and innovative computational modeling and laboratory weldability testing approach will be used to first formulate an alloy composition that 1) has superior welding performance, 2) is compatible with the base materials to be joined, and 3) maintains the mechanical and corrosion properties required for the reactor coolant system environment in a nuclear power plant.

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Weld Mitigation Interest Group (supplemental)

Key Research Question

The repair of dissimilar metal welds continues to provide challenges for even the most experienced vendors and utilities. Complex weld configurations, such as nozzles, offer a mix of base and weld materials including stainless steels, cast stainless steels, nickel-alloys, low-alloy steel, and a variety of weld metals used during fabrication and installation. Common repair methods, such as weld overlays, use a 30% Cr filler metal, which offers exceptional corrosion performance for PWSCC, but also provides a number of weldability challenges. New and emerging repair and mitigation technologies can provide safe, cost-effective options for nuclear plant owners. Evaluation of such technologies is necessary to ensure their application is safe, effective, and can meet code requirements. Candidate technologies may include the following:

- Inlay and only repair technologies for inside diameter (ID) mitigation techniques
- Mechanical Sress improvement process (MSIP)
- Overlay
- Excavated weld repair
- Weldability of Alloy 52, a high-chromium filler material

Approach

The Weld Mitigation Interest Group evaluates emerging repair options that could reduce the time, cost, and radiation exposure related to welding operations; provide enhanced inspectability; expand repair options to include inlays, onlays, excavated weld repair, and MSIP; date filler metal weldability; and document industry experience.

The Weld Mitigation Interest Group provides a forum for exchanging industry experience, solutions, and technology. The Interest Group produces a *Stress Corrosion Cracking Repair and Mitigation Handbook* to support effective management of primary system components susceptible to stress corrosion cracking (SCC). Related products include evaluation of advanced welding technologies.

Impact

Potential benefits include the following:

- Availability of proven, cost-effective repair and mitigation techniques
- Consistent approach for compiling operating experience and addressing regulatory issues
- Decision tree for identification of mitigation and repair processes for dissimilar Metal Weld locations
- *Overlay Welding Handbook*

How to Apply Results

Participants use technology evaluation results to analyze repair options for future plant application. The *Mitigation Handbook* provides specific guidance that can be incorporated into management and inspection plans for primary systems components susceptible to SCC. Workshop participation provides access to industry experts on weld repair and mitigation.

2012 Products

Product Title & Description	Planned Completion Date	Product Type
Mitigation Handbook	01/31/12	Technical Report