

Boiling Water Reactor Vessel and Internals

Program Overview

Program Description

As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared, first in the recirculation piping, then in the reactor pressure vessel internals. Typically, cases of poor materials performance have been addressed by analyses focused on the specific component or system. This near-term, reactive approach has resulted in costly unplanned outages and expensive weld-by-weld mitigation and repair methods. A longer-term, strategic approach can address a broader range of factors impacting pressure vessel internals.

The Boiling Water Reactor Vessel and Internals Project (BWRVIP) provides an integrated approach for managing materials-related degradation issues in reactor coolant system components in boiling water reactors. The program assesses all facets of operation, maintenance, and repair to develop reliable and cost-effective detection, inspection, and mitigation techniques.

Research Value

The BWRVIP Program maintains alignment with current industry internals integrity concerns affecting boiling water reactors. Research results lead to cost-effective solutions to reduce damage related to stress corrosion cracking; cost savings due to reduced inspection scope, extended intervals between inspections, and improved operating characteristics; reduced personnel radiation exposure; and improved models to better characterize the mitigation of internals components. BWRVIP participants gain access to the following:

- Technologies and technical guidance that drive increased capacity factors (less unplanned or extended outages).
- Cost-effective techniques to mitigate stress corrosion cracking of reactor internal components; economic evaluations indicate that cost savings for implementing hydrogen water chemistry or noble metal chemical application exceed \$40 million per plant.
- Cost-effective options for replacing or repairing reactor components.
- Technical solutions to internals inspection needs.
- Industry operating experience and technical insights driving reduced inspection requirements, outage critical path times, and regulatory scrutiny.

Approach

The BWRVIP Program takes an integrated approach to degradation management, encompassing assessment, mitigation, and inspection. Through improved inspection techniques, new results from materials research and development, and plant operating experiences, best practices can be deployed to make cost-effective decisions.

- Develop guidelines to ensure prompt detection of material degradation and a variety of solutions for addressing observed problems.
- Develop and demonstrate cost-effective means to implement techniques to mitigate stress corrosion cracking of reactor internal components.
- Devise unique solutions to internals inspection needs such that BWR plants are not limited to vendors' nondestructive evaluation offerings.
- Formulate design criteria and develop unique solutions to repair or replace reactor internals and piping.
- Improve the understanding of materials performance in areas such as fracture toughness of stainless steel exposed to high fluence levels, weldability of irradiated materials, and crack growth rates.

Accomplishments

EPRI's Boiling Water Reactor Vessel and Internals Program supports nuclear power industry efforts to assess and implement effective countermeasures for stress corrosion cracking of reactor internal components. BWRVIP research provides utilities with the information necessary to make cost-effective decisions for managing degradation of boiling water reactor vessel and internal components.

- Formulated guidelines for inspecting boiling water reactor safety-related internal components for degradation indications.
- Prepared and submitted for regulatory review a steam dryer loads methodology report to support reactor power uprates.
- Designed, developed and demonstrated a remotely operated ultrasound evaluation system to facilitate corrosion detection in difficult-to-access BWR drain lines.
- Developed guidelines for maintaining optimal chemistry in BWRs.
- Provided technical justification supporting the elimination of certain reactor pressure vessel circumferential weld inspections.
- Provided technical guidance for establishing and maintaining an integrated surveillance program for boiling water reactors.
- Demonstrated noble metal chemical addition as a mitigation technique for stress corrosion cracking. Field tests indicate critical path savings of up to 60 hours.

Current Year Activities

BWRVIP R&D for 2010 will continue to focus on the technical gaps defined in the BWR Issue Management Tables. Highest priority gaps include the impacts of fluence on the material properties of BWR materials, high-cycle fatigue in jet pump assemblies, and flow-assisted corrosion of the BWR bottom head drain line. Specific efforts will include the following:

- Continue testing of the full-scale jet pump facility to better understand the operating degradation mechanism and to evaluate mitigation technologies.
- Support the steam dryer loads methodology as it works its way through Nuclear Regulatory Commission review.
- Continue crack growth and fracture toughness evaluations of highly irradiated materials.
- Develop advanced mitigation techniques for stress corrosion cracking.
- Complete inspection and evaluation guidelines for all BWR internals' components.

Selected reports will be developed in whole or in part under Title 10 of the Code of Federal Regulations Part 50 (10 CFR50) Appendix B, Quality Assurance, 10 CFR 21, and the EPRI Quality Assurance Program. Additional products may be developed under 10 CFR 50 Appendix B, and 10 CFR 21 at the discretion of the BWRVIP member utilities or EPRI, when such action is deemed appropriate.

Estimated 2010 Program Funding

\$9.0 million

Program Manager

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Summary of Projects

Project Number	Project Title	Description
P41.01.03.01	BWRVIP Integration	Electric Power Research Institute (EPRI) activities in this task include overall BWRVIP technical and administrative program management to support the Integration Committee; costs for conducting and attending BWRVIP meetings; interface with the Nuclear Regulatory Commission (NRC) on all associated BWRVIP matters; coordination and interface with international BWRVIP members and potential members; BWRVIP report licensing and distribution; contract management with BWRVIP contractors; and coordination and interface regarding EPRI contracts with all U. S. and international BWRVIP members. This task includes preparing materials for BWRVIP training sessions and conducting domestic and international training sessions. The task also includes participating in Institute of Nuclear Power Operations' review visits and developing and documenting interpretations and implementation issues associated with BWRVIP products.
P41.01.03.02	BWRVIP Assessment	The BWRVIP continues to research and develop solutions to provide utilities with the necessary information to make cost-effective decisions for managing degradation of boiling water reactor vessel and internal components. The products that come from this task are directly applied at nuclear power plants through inspection, maintenance, and repair programs. The inspection and evaluation guidelines provide the scope for what needs to be inspected and a methodology for evaluating or repairing any indications that are found. Other products such as the Radiation Analysis Modeling Application (RAMA) fluence methodology, integrated surveillance, and Distributed Ligament Length (DLL) provide tools that plants can use to evaluate their material condition. In addition, research examining irradiation effects on materials provides valuable information for managing license renewal activities.
P41.01.03.03	BWRVIP Mitigation	As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared, first in the recirculation piping then in the reactor pressure vessel internals. This program will provide guidance for implementing effective countermeasures for stress corrosion cracking of reactor internal components. Research results and guidelines will enable members to effectively implement techniques for mitigating stress corrosion cracking, such as hydrogen water chemistry and noble metal chemical application. Work also will be conducted to demonstrate the effectiveness of mitigation techniques and the effect of noble metal chemical application on fuel.

Project Number	Project Title	Description
P41.01.03.03B	BWRVIA - BWR Vessel and Internals Application for Radiolysis/ECP (ISO 9001)	The BWR Vessel & Internals Application (BWRVIA) computer code was developed under the sponsorship of the BWR Vessel and Internals Program (BWRVIP) to perform radiolysis analysis and electrochemical corrosion potential (ECP) calculations for BWRs. Version V1.0 was released in 1998, and its application to support IGSCC mitigation was described in BWRVIP-62, <i>Technical Basis for Inspection Relief for BWR internal Components with Hydrogen Injection</i> . Version 2.0 was released on 2003 and improved V1.0 by replacing empirical correlation between chemistry and ECP with a theoretical approach based on the mixed potential model. Version 3.0, released in 2008, upgraded the model's benchmark for neutron and gamma dose rates and provides for model calculations under beginning, middle, and end of cycle conditions. Improved reaction rate expressions also were incorporated. The release of V3.0 to the industry will be followed closely with sensitivity testing and comparisons to actual plant data. The BWRVIA User Group will provide training and ongoing support to all BWR utilities using the model and participating in this program.
P41.01.03.04	BWRVIP Inspection	As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared. Advanced nondestructive evaluation techniques can improve detection of indications in internals' components so they can be assessed and repaired/mitigated to maintain safety margins. This program develops or refines nondestructive evaluation techniques to address emerging issues in internals inspection. Past examples of inspection programs developed under this activity include creeping wave ultrasonic testing; phased-array ultrasonic and eddy current testing for the shroud; core plate bolt nondestructive evaluation from the annulus; ultrasonic testing for shroud support legs; and alternative ultrasonic testing for jet pump beams.
P41.01.03.05	BWRVIP Improved Materials Performance	Utilities must manage current and potential future degradation of boiling water reactor internal components. This program provides members with improved understanding of materials performance in the areas of fracture toughness of stainless steel exposed to high fluence levels, weldability of irradiated materials, and crack growth rates of internal components subjected to irradiation-assisted stress corrosion cracking and intergranular stress corrosion cracking.
P41.01.03.06	BWRVIP Integrated Surveillance	Each BWR has a surveillance program for monitoring changes in reactor pressure vessel (RPV) material properties due to neutron irradiation. Substantial cost savings and improvements in data quality are possible by integrating these individual surveillance programs. This program and sourcebook data will help utilities optimize the quality of data and number of materials that will be used to monitor embrittlement of BWR reactor vessel materials and ensure that the ISP will comply with the requirements for an integrated surveillance program in 10CFR50, Appendix H.
P41.01.03.07	BWRVIP Repair	As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared, first in the recirculation piping then in the reactor pressure vessel internals. As these components have continued to degrade, repair and replacement options have become necessary for continued operation. This project provides the tools necessary to make decisions on which repair and replacements should be performed at a given plant. Members can better evaluate options and determine the most cost-effective solution.

BWRVIP Integration (062248)

Key Research Question

Maintain alignment of the Boiling Water Reactor Vessel and Internals Project (BWRVIP) Integration Committee with current industry internals integrity concerns. Manage, develop, and modify, as appropriate, the overall BWRVIP issue management strategy. Assist the Integration Committee in ensuring that BWRVIP task activities are coordinated and that work priorities reflect the best industry information.

Approach

Electric Power Research Institute (EPRI) activities in this task include overall BWRVIP technical and administrative program management to support the Integration Committee; costs for conducting and attending BWRVIP meetings; interface with the Nuclear Regulatory Commission (NRC) on all associated BWRVIP matters; coordination and interface with international BWRVIP members and potential members; BWRVIP report licensing and distribution; contract management with BWRVIP contractors; and coordination and interface regarding EPRI contracts with all U. S. and international BWRVIP members. This task includes preparing materials for BWRVIP training sessions and conducting domestic and international training sessions. The task also includes participating in Institute of Nuclear Power Operations' review visits and developing and documenting interpretations and implementation issues associated with BWRVIP products.

Impact

- Successful overall BWRVIP program management and regulatory interface
- Close coordination and prioritization of the various task activities within the BWRVIP

How to Apply Results

The work performed under this task provides the information necessary for members to better manage BWR power plants. Program results enable nuclear plants to apply the operating experience and lessons learned from other plants, respond to emerging industry issues, and better understand the regulatory aspects of the program.

2010 Products

Product Title & Description	Planned Completion Date	Product Type
BWRVIP-167, Rev 2: BWR Issue Management Tables: Ongoing issues related to degradation of boiling water reactor (BWR) pressure vessels, reactor internals, and American Society of Mechanical Engineers (ASME) Class 1 piping components have resulted in the need for a summary tool to assist in prioritizing and addressing research and development (R&D) issues. This BWR Vessel and Internals Project (BWRVIP) report provides BWR Issue Management Tables that identify, rank, and describe R&D gaps.	12/31/10	Technical Report

BWRVIP Assessment (052371)

Key Research Question

Maintenance and repairs at boiling water reactors entail significant costs. Through improved inspection techniques, new results from materials research and development, plant operating experiences, and best practices can be deployed to make cost-effective decisions. To best serve the industry, these best practices should be communicated fleet-wide such that they are consistently applied and continually updated as new information is available.

Approach

The BWRVIP continues to research and develop solutions to provide utilities with the necessary information to make cost-effective decisions for managing degradation of boiling water reactor vessel and internal components.

Impact

- Standardized and regulator-approved methodology for fluence evaluation
- *Inspection and Evaluation Guidelines* to ensure prompt detection of degradation, reduce outage time due to unanticipated degradation, and provide cost-effective solutions for reducing inspections and damage related to stress corrosion cracking
- Eliminated testing of some surveillance program capsules of low value to the industry
- Improved data and information on changes in reactor pressure vessel material properties due to neutron irradiation

How to Apply Results

The products that come from this task are directly applied at nuclear power plants through inspection, maintenance, and repair programs. The inspection and evaluation guidelines provide the scope for what needs to be inspected and a methodology for evaluating or repairing any indications that are found. Other products such as the Radiation Analysis Modeling Application (RAMA) fluence methodology, integrated surveillance, and Distributed Ligament Length (DLL) provide tools that plants can use to evaluate their material condition. In addition, research examining irradiation effects on materials provides valuable information for managing license renewal activities.

2010 Products

Product Title & Description	Planned Completion Date	Product Type
BWRVIP-60, Rev 1: Evaluation of Stress Corrosion Crack Growth in Low Alloy Steel Vessel Materials in the BWR Environment: This report will provide a methodology for assessing crack growth in boiling water reactor (BWR) low alloy steel pressure vessels and nozzles.	12/31/10	Technical Report
BWRVIP-139-A: Steam Dryer Inspection and Flaw Evaluation Guidelines: This document will provide <i>Steam Dryer Inspection and Flaw Evaluation Guidelines</i> consistent with those developed for other boiling water reactor (BWR) reactor internal components. It will include 1) documentation of the steam dryer configurations for the different plants, 2) a summary of dryer cracking incidents based on field experience, 3) documentation of the regions of susceptibility for fatigue cracking and intergranular stress corrosion cracking (IGSCC), 4) a review of the failure modes and effects of cracking in steam dryer components, 5) an overview of the relative stresses in the different steam dryer components emphasizing the steam dryer's outer surface, 6) detailed inspection recommendations for the different dryer designs, 7) limited examples of evaluation approaches that have been used to justify continued operation with IGSCC cracking or cracking in non-structural components that will not result in risk of loose parts generation, and 8) operational guidance for monitoring moisture carryover. The report will also discuss previously used repair methods and approaches.	12/31/10	Technical Report

Product Title & Description	Planned Completion Date	Product Type
Thermal Aging and Neutron Embrittlement Evaluation of Cast Austenitic Stainless Steels for BWR Internals: This report will provide a thermal aging and neutron embrittlement evaluation of cast austenitic stainless steels in a boiling water reactor (BWR) environment.	12/31/10	Technical Report
BWRVIP-06, Rev. 1: Safety Assessment of BWR Reactor Internals: This report will provide a safety assessment of potential failures due to cracking of internal components in a boiling water reactor (BWR).	12/31/10	Technical Report

BWRVIP Mitigation (052372)

Key Research Question

As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared, first in the recirculation piping then in the reactor pressure vessel internals.

Approach

This program will provide guidance for implementing effective countermeasures for stress corrosion cracking of reactor internal components. Research results and guidelines will enable members to effectively implement techniques for mitigating stress corrosion cracking, such as hydrogen water chemistry and noble metal chemical application. Work also will be conducted to demonstrate the effectiveness of mitigation techniques and the effect of noble metal chemical application on fuel.

Impact

- Cost-effective techniques to mitigate stress corrosion cracking of reactor internal components; economic evaluations conducted for five plants indicate that cost savings for implementing hydrogen water chemistry or noble metal chemical application exceed \$40 million per plant.
- Cost savings due to reduced inspection scope, extended intervals between inspections, and improved operating characteristics.
- Savings also expected in optimized use of costly chemicals.

How to Apply Results

Members would use the results from this project to optimize water chemistry programs, allowing plants to mitigate stress corrosion cracking of reactor internals and recirculation piping without affecting other plant parameters (for example, dose and fuel).

2010 Products

Product Title & Description	Planned Completion Date	Product Type
BWRVIP-62-A: Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection: This report will provide a systematic methodology for evaluating the effectiveness of hydrogen water chemistry (HWC) for the mitigation of intergranular stress corrosion cracking (IGSCC) of reactor internals when direct measurements of the internals' corrosion potential is not feasible.	12/31/10	Technical Report

BWRVIA - BWR Vessel and Internals Application for Radiolysis/ECP (ISO 9001) (047065)

Key Research Question

Two technologies—moderate hydrogen injection, known as hydrogen water chemistry (HWC), and noble metal chemical addition, known as NMCA—have been applied in boiling water reactors (BWRs) to mitigate intergranular stress corrosion cracking (IGSCC) by lowering primary water electrochemical corrosion potential (ECP). This user group provides information and training on the use of the radiolysis and ECP models used in the Electric Power Research Institute (EPRI) BWR Vessel and Internals Application (BWRVIA) software program. Ongoing development of the codes also is evaluated and reported out at the annual member's meeting.

Approach

The BWRVIA User Group provides technology that operating BWRs can use to help mitigate IGSCC of reactor piping and internals. The technical project team performs comprehensive reviews of research and development in the areas of radiation chemistry and ECP modeling. Sensitivity analyses are performed to evaluate the model's response due to changes in input parameters such as chemical reaction rate constants and dose rate profiles. Adjustments are then made to these sensitive parameters to provide the best possible correlations. Finally, the results of the sensitivity analyses are compared to actual plant data to provide a technical basis for plant application of the calculated results.

Impact

The objective of this ongoing technical area and user group is to improve the BWRVIA model by incorporating the current state of the art in radiation chemistry and ECP formulation as well as benchmarking the revised code against all plant and laboratory data available to date. By doing so, this user group facilitates the ongoing development of an improved model that will be accurately used by all BWRVIA members.

How to Apply Results

The BWRVIA User Group provides annual training workshops and ongoing support to run the software program used to predict the amount of hydrogen injection needed for IGSCC mitigation of susceptible reactor internals and piping in BWRs.

BWRVIP Inspection (061776)

Key Research Question

As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared. Advanced nondestructive evaluation techniques can improve detection of indications in internals' components so they can be assessed and repaired/mitigated to maintain safety margins.

Approach

This program develops or refines nondestructive evaluation techniques to address emerging issues in internals inspection. Past examples of inspection programs developed under this activity include creeping wave ultrasonic testing; phased-array ultrasonic and eddy current testing for the shroud; core plate bolt nondestructive evaluation from the annulus; ultrasonic testing for shroud support legs; and alternative ultrasonic testing for jet pump beams.

Impact

- Develops technical solutions to internals inspection needs
- Provides unique solutions such that BWRVIP participants are not limited to vendors' nondestructive evaluation offerings
- Reduces inspection and outage critical path times and personal radiation exposure
- Results in an estimated \$25,000 to \$100,000 savings per member per year

How to Apply Results

This project will provide members with the latest technology necessary to inspect reactor internals. The results of this project are demonstration techniques that members can use to determine which vendor and which inspection technique should be used for specific inspection needs.

2010 Products

Product Title & Description	Planned Completion Date	Product Type
<p>BWRVIP-03, Rev. 13: Reactor Pressure Vessel and Internals Examination Guidelines: Procedure standards have been developed for ultrasonic, visual, and eddy current inspection. Many inspection techniques have been demonstrated and documented. In support of these demonstrations, realistic mockups of reactor internal components have been manufactured with controlled flaws. Boiling water reactor (BWR) owners can use these documented techniques to inspect their vessel internal components in compliance with Boiling Water Reactor Vessel and Internals Project (BWRVIP) guidance.</p>	12/31/10	Technical Report
<p>NDE Development: This report will provide the 2010 results of the Nondestructive (NDE) Development task of the Boiling Water Reactor Vessel and Internals Project (BWRVIP) Inspection Focus Group. The scope of activity includes applications of various NDE techniques to boiling water reactor (BWR) vessels and vessel internal components.</p>	12/31/10	Technical Report

BWRVIP Improved Materials Performance (052368)

Key Research Question

Utilities must manage current and potential future degradation of boiling water reactor internal components.

Approach

This program provides members with improved understanding of materials performance in the areas of fracture toughness of stainless steel exposed to high fluence levels, weldability of irradiated materials, and crack growth rates of internal components subjected to irradiation-assisted stress corrosion cracking and intergranular stress corrosion cracking.

Impact

- This program will provide cost-effective tools to enable members to identify and manage degradation for current license terms and for the license renewal period.
- The Nuclear Regulatory Commission (NRC) approval of many of the products allows members to effectively address regulatory issues.
- The direct benefit from this program will be due to reduced inspection scope, extended intervals between inspections, and improved operating characteristics.

How to Apply Results

This program will be delivered through a combination of guidance documents and technical reports throughout its duration. Many of the guidance documents will be submitted to the NRC by the BWRVIP for approval, which will result in effective member implementation of regulatory-approved guidance.

2010 Products

Product Title & Description	Planned Completion Date	Product Type
<p>Crack Growth of Irradiated Stainless Steels: The BWR Vessel and Internals Project (BWRVIP) has developed methodologies to evaluate crack growth in internal components of stainless steel and nickel-base alloys in the boiling water reactor (BWR) vessel. One BWRVIP report—BWRVIP-14—developed an approach to evaluate crack growth by intergranular stress corrosion cracking in austenitic stainless steel core shrouds exposed to a limited amount of neutron irradiation. This report will provide crack growth rates applicable to irradiated BWR stainless steel internal components for fluence levels above 5×10^{20} n/cm².</p>	12/31/10	Technical Report

BWRVIP Integrated Surveillance (052373)

Key Research Question

Each boiling water reactor (BWR) has a surveillance program for monitoring changes in reactor pressure vessel (RPV) material properties due to neutron irradiation. Substantial cost savings and improvements in data quality are possible by integrating these individual surveillance programs.

Approach

Researchers collected all available BWR reactor vessel fabrication records and surveillance program results. The Integrated Surveillance Program (ISP) design included evaluating existing surveillance specimens, along with other available specimens, to develop an integrated plan for monitoring BWR RPV embrittlement, which would be an improvement compared to individual programs. A test matrix was developed to identify those specimens that best meet the needs of each BWR. Materials for the ISP were specifically chosen to best represent the limiting plate and weld materials for each plant using specimens from the entire BWR fleet. Specimens that were not chosen as a best representative were not included for testing because other materials in the integrated program provided better quality and more representative data. The ISP is now a regulatory commitment that all U.S. BWRs follow through the end of life.

Impact

Neutron irradiation exposure reduces the toughness of reactor vessel steel plates, welds, and forgings. Accurate methods for monitoring radiation embrittlement are important for evaluating the remaining life of RPV materials. The ISP will result in significant cost savings to the BWR fleet and provide more accurate monitoring of embrittlement in BWRs.

How to Apply Results

This program and sourcebook data will help utilities optimize the quality of data and number of materials that will be used to monitor embrittlement of BWR reactor vessel materials and ensure that the ISP will comply with the requirements for an integrated surveillance program in 10CFR50, Appendix H.

BWRVIP Repair (065840)

Key Research Question

As boiling water reactors have aged, various forms of operation-limiting stress corrosion cracking have appeared, first in the recirculation piping then in the reactor pressure vessel internals. As these components have continued to degrade, repair and replacement options have become necessary for continued operation.

Approach

The Boiling Water Reactor Vessel and Internals Program (BWRVIP) provides repair and replacement options and the associated design requirements that must be met.

Impact

- Generic design criteria approved by the Nuclear Regulatory Commission (NRC)
- Generic repair and replacement options

How to Apply Results

Indications continue to be found in boiling water reactor internals. Some indications are beyond critical flow sizes and must be repaired. This project provides the tools necessary to make decisions on which repair and replacements should be performed at a given plant. Members can better evaluate options and determine the most cost-effective solution.

2010 Products

Product Title & Description	Planned Completion Date	Product Type
BWRVIP-84-A: Guidelines for Selection and Use of Materials for Repairs to BWR Internal Components: This Boiling Water Reactor Vessel and Internals Project (BWRVIP) report will help members properly specify and use materials in designing repairs to BWR internal components, particularly in the ex-core environment.	12/31/10	Technical Report