XI.M9 BWR VESSEL INTERNALS

Program Description

The program includes inspection and flaw evaluations in conformance with the guidelines of applicable and staff-approved boiling water reactor vessel and internals project (BWRVIP) documents to provide reasonable assurance of the long-term integrity and safe operation of boiling water reactor (BWR) vessel internal components.

The BWRVIP documents provide generic guidelines intended to present the applicable inspection recommendations to assure safety function integrity of the subject safety-related reactor pressure vessel internal components. The guidelines provide information on component description and function; evaluate susceptible locations and safety consequences of failure; provide recommendations for methods, extent, and frequency of inspection; discuss acceptable methods for evaluating the structural integrity significance of flaws detected during these examinations; and recommend repair and replacement procedures.

In addition, this program provides screening criteria to determine the susceptibility of cast austenitic stainless steels (CASS) components to thermal aging on the basis of casting method, molybdenum content, and percent ferrite, in accordance with the criteria set forth in the May 19, 2000 letter from Christopher Grimes, Nuclear Regulatory Commission (NRC), to Mr. Douglas Walters, Nuclear Energy Institute (NEI). The susceptibility to thermal aging embrittlement of CASS components is determined in terms of casting method, molybdenum content, and ferrite content. For low-molybdenum content steels (SA-351 Grades CF3, CF3A, CF8, CF8A, or other steels with ≤0.5 wt.% molybdenum), only static-cast steels with >20% ferrite are potentially susceptible to thermal embrittlement. Static-cast low-molybdenum steels with >20% ferrite and all centrifugal-cast low-molybdenum steels are not susceptible. For high-molybdenum content steels (SA-351 Grades CF3M, CF3MA, CF8M or other steels with 2.0 to 3.0 wt.% molybdenum), static-cast steels with >14% ferrite and centrifugal-cast steels with >20% ferrite are potentially susceptible to thermal embrittlement. Static-cast high-molybdenum steels with ≤14% ferrite and centrifugal-cast high-molybdenum steels with ≤20% ferrite are not susceptible. In the susceptibility screening method, ferrite content is calculated by using the Hull's equivalent factors (described in NUREG/CR-4513, Rev. 1) or a staff approved method for calculating delta ferrite in CASS materials.

The screening criteria are applicable to all cast stainless steel primary pressure boundary and reactor vessel internal components with service conditions above 250°C (482°F). The screening criteria for susceptibility to thermal aging embrittlement are not applicable to niobium-containing steels; such steels require evaluation on a case-by-case basis. For "potentially susceptible" components, the program considers loss of fracture toughness due to neutron embrittlement or thermal aging embrittlement.

This AMP addresses aging degradation of X-750 alloy-, and precipitation-hardened (PH) martensitic stainless steel (e.g., 15-5 and 17-4 PH steel) materials and martensitic stainless steel (e.g., 403, 410, 431 steel) that are used in BWR vessel internal components. When exposed to a BWR reactor temperature of 550°F, these materials can experience neutron embrittlement and a decrease in fracture toughness. PH-martensitic stainless steels and martensitic stainless steels are also susceptible to thermal embrittlement. Effects of thermal and neutron embrittlement can cause failure of these materials in vessel internal components. In addition, X-750 alloy in a BWR environment is susceptible to intergranular stress corrosion cracking (IGSCC).

Evaluation and Technical Basis

1. ***Scope of Program:*** The program is focused on managing the effects of cracking due to stress corrosion cracking (SCC), IGSCC, or irradiation-assisted stress corrosion cracking (IASCC), cracking due to fatigue and loss of material due to wear. This program also includes loss of toughness due to neutron and thermal embrittlement. The program applies to wrought and cast reactor vessel internal components. The program contains in-service inspection (ISI) to monitor the effects of cracking on the intended function of the components, uses NRC-approved BWRVIP reports as the basis for inspection, evaluation, repair and/or replacement, as needed, and evaluates the susceptibility of CASS, X-750 alloy, precipitation-hardened (PH) martensitic stainless steel (e.g., 15-5 and 17-4 PH steel), and martensitic stainless steel (e.g., 403, 410, 431 steel) components to neutron and/or thermal embrittlement.

   The scope of the program includes the following BWR reactor vessel (RV) and RV internal components as subject to the following NRC-approved applicable BWRVIP guidelines:

   Core shroud: BWRVIP-76-A provides guidelines for inspection and evaluation; BWRVIP-02-A, Rev. 2, provides guidelines for repair design criteria.

   Core plate: BWRVIP-25 provides guidelines for inspection and evaluation; BWRVIP-50-A provides guidelines for repair design criteria.

   Core spray: BWRVIP-18-A provides guidelines for inspection and evaluation; BWRVIP-16-A and 19A provides guidelines for replacement and repair design criteria, respectively.

   Shroud support: BWRVIP-38 provides guidelines for inspection and evaluation; BWRVIP-52-A provides guidelines for repair design criteria.

   Jet pump assembly: BWRVIP-41 provides guidelines for inspection and evaluation; BWRVIP-51-A provides guidelines for repair design criteria.

   Low-pressure coolant injection (LPCI) coupling: BWRVIP-42-A provides guidelines for inspection and evaluation; BWRVIP-56-A provides guidelines for repair design criteria.

   Top guide: BWRVIP-26-A and BWRVIP-183 provide guidelines for inspection and evaluation; BWRVIP-50-A provides guidelines for repair design criteria. Inspect five percent (5%) of the top guide locations using enhanced visual inspection technique, EVT-1 within six years after entering the period of extended operation. An additional 5% of the top guide locations will be inspected within twelve years after entering the period of extended operation.

   Reinspection Criteria:

   BWR/2-5 - Inspect 10% of the grid beam cells containing control rod drives/blades every twelve years with at least 5% to be performed within six years.

   BWR/6 - Inspect the rim areas containing the weld and heat affected zone (HAZ) from the top surface of the top guide and two cells in the same plane/axis as the weld every six years.

The top guide inspection locations are those that have high neutron fluences exceeding the IASCC threshold. The extent of the examination and its frequency will be based on a ten percent sample of the total population, which includes all grid beam and beam-to-beam crevice slots.

Control rod drive (CRD) housing: BWRVIP-47-A provides guidelines for inspection and evaluation; BWRVIP-58-A provides guidelines for repair design criteria.

Lower plenum components: BWRVIP-47-A provides guidelines for inspection and evaluation; BWRVIP-57-A provides guidelines for repair design criteria for instrument penetrations.

Steam Dryer: BWRVIP-139 provides guidelines for inspection and evaluation for the steam dryer components.

Although BWRVIP repair design criteria provide criteria for repairs, aging management strategies for repairs are provided by the repair designer, not the BWRVIP.

2. ***Preventive Actions:*** The BWR Vessel Internals Program is a condition monitoring program and has no preventive actions. Maintaining high water purity reduces susceptibility to SCC or IGSCC. Reactor coolant water chemistry is monitored and maintained in accordance with the Water Chemistry Program. The program description, evaluation and technical basis of water chemistry are presented in GALL AMP XI.M2, "Water Chemistry." In addition, for core shroud repairs or other IGSCC repairs, the program maintains operating tensile stresses below a threshold limit that precludes IGSCC of X-750 material.

3. ***Parameters Monitored/Inspected:*** The program monitors the effects of cracking on the intended function of the component by detection and sizing of cracks by inspection in accordance with the guidelines of applicable and approved BWRVIP documents and the requirements of the American Society of Mechanical Engineers (ASME) Code, Section XI, Table IWB 2500-1 (2004 edition[9]).

   Loss of fracture toughness due to neutron embrittlement in CASS materials can occur with a neutron fluence greater than $1x10^{17}$ n/cm^2 (E>1 MeV). Loss fracture toughness of CASS material due to thermal embrittlement is dependent on the material's casting method, molybdenum content, and ferrite content. The program does not directly monitor for loss of fracture toughness that is induced by thermal aging or neutron irradiation embrittlement. The impact of loss of fracture toughness on component integrity is indirectly managed by using visual or volumetric examination techniques to monitor for cracking in the components.

   Neutron embrittlement of X-750 alloys, PH-martensitic stainless steels, and martensitic stainless steels cannot be identified by typical in-service inspection activities. However, by performing visual or other inspections, applicants can identify cracks that could lead to failure of a potentially embrittled component prior to component failure. Applicants can thus indirectly manage the effects of embrittlement in the PH steels, martensitic stainless steels, and X-750 components by identifying aging degradation (i.e., cracks), implementing early corrective actions, and monitoring and trending age-related degradation.

[9] Refer to the GALL Report, Chapter I, for applicability of other editions of the ASME Code, Section XI.

4. ***Detection of Aging Effects:*** The extent and schedule of the inspection and test techniques prescribed by the applicable and NRC-approved BWRVIP guidelines are designed to maintain structural integrity and ensure that aging effects will be discovered and repaired before the loss of intended function of BWR vessel internals. Inspection can reveal cracking. Vessel internal components are inspected in accordance with the requirements of ASME Section XI, Subsection IWB, Examination Category B-N-2. The ASME Section XI inspection specifies visual VT-1 examination to detect discontinuities and imperfections, such as cracks, corrosion, wear, or erosion, on the surfaces of components. This inspection also specifies visual VT-3 examination to determine the general mechanical and structural condition of the component supports by (a) verifying parameters, such as clearances, settings, and physical displacements, and (b) detecting discontinuities and imperfections, such as loss of integrity at bolted or welded connections, loose or missing parts, debris, corrosion, wear, or erosion. BWRVIP program requirements provide for inspection of BWR reactor internals to manage loss of material and cracking using appropriate examination techniques such as visual examinations (e.g., EVT-1, VT-1) and volumetric examinations (e.g., UT).

   The applicable and NRC-approved BWRVIP guidelines recommend more stringent inspections, such as EVT-1 examinations or ultrasonic methods of volumetric inspection, for certain selected components and locations. The nondestructive examination (NDE) techniques appropriate for inspection of BWR vessel internals, including the uncertainties inherent in delivering and executing NDE techniques in a BWR, are included in BWRVIP-03.

   Thermal and/or neutron embrittlement in susceptible CASS, PH-martensitic steels, martensitic stainless steels, and X-750 components are indirectly managed by performing periodic visual inspections capable of detecting cracks in the component. The 10-year ISI program during the renewal period may include a supplemental inspection covering portions of the susceptible components determined to be limiting from the standpoint of thermal aging susceptibility, neutron fluence, and cracking susceptibility (i.e., applied stress, operating temperature, and environmental conditions). The inspection technique is capable of detecting the critical flaw size with adequate margin. The critical flaw size is determined based on the service loading condition and service-degraded material properties. One example of a supplemental examination is VT-1 examination of ASME Code, Section XI, IWA-2210. The initial inspection is performed either prior to or within 5 years after entering the period of extended operation. If cracking is detected after the initial inspection, the frequency of re-inspection should be justified by the applicant based on fracture toughness properties appropriate for the condition of the component. The sample size is 100% of the accessible component population, excluding components that may be in compression during normal operations.

5. ***Monitoring and Trending:*** Inspections are scheduled in accordance with the applicable and approved BWRVIP guidelines provide timely detection of cracks. Each BWRVIP guideline recommends baseline inspections that are used as part of data collection towards trending. The BWRVIP guidelines provide recommendations for expanding the sample scope and re-inspecting the components if flaws are detected. Any indication detected is evaluated in accordance with ASME Code, Section XI or the applicable BWRVIP guidelines. BWRVIP-14-A, BWRVIP-59-A, BWRVIP-60-A, BWRVIP-80NP-A and BWRVIP-99-A documents provide additional guidelines for evaluation of crack growth in stainless steels (SSs), nickel alloys, and low-alloy steels, respectively.

Inspections scheduled in accordance with ASME Code, Section XI, IWB-2400 and reliable examination methods provide timely detection of cracks. The fracture toughness of PH-martensitic steels, martensitic stainless steels, and X-750 alloys susceptible to thermal and/or neutron embrittlement need to be assessed on a case-by-case basis.

6. ***Acceptance Criteria:*** Acceptance criteria are given in the applicable BWRVIP documents or ASME Code, Section XI. Flaws detected in CASS components are evaluated in accordance with the applicable procedures of ASME Code, Section XI, IWB-3500. Flaw tolerance evaluation for components with ferrite content up to 25% is performed according to the principles associated with ASME Code, Section XI, IWB-3640 procedures for SAWs, disregarding the ASME Code restriction of 20% ferrite. Extensive research data indicate that the lower-bound fracture toughness of thermally aged CASS materials with up to 25% ferrite is similar to that for SAWs with up to 20% ferrite (Lee et al., 1997). Flaw evaluation for CASS components with >25% ferrite is performed on a case-by-case basis by using fracture toughness data provided by the applicant. A fracture toughness value of 255 kJ/m^2 (1,450 $in.\text{-}lb/in.^2$) at a crack depth of 2.5 mm (0.1 in.) is used to differentiate between CASS materials that are susceptible to thermal aging embrittlement and those that are not. Extensive research data indicate that for non-susceptible CASS materials, the saturated lower-bound fracture toughness is greater than 255 kJ/m^2 (NUREG/CR-4513, Rev. 1).

   Acceptance criteria for the assessment of PH-martensitic steels, martensitic stainless steels, and X-750 alloys susceptible to thermal aging and/or neutron embrittlement are assessed on a case-by-case basis.

7. ***Corrective Actions:*** Repair and replacement procedures are equivalent to those requirements in ASME Code Section XI. Repair and replacement is performed in conformance with the applicable and NRC-approved BWRVIP guidelines listed above. For top guides where cracking is observed, sample size and inspection frequencies are increased. As discussed in the Appendix for GALL, the staff finds that licensee implementation of the corrective action guidelines in the staff-approved BWRVIP reports will provide an acceptable level of quality accordance with 10 CFR Part 50, Appendix B.

8. ***Confirmation Process:*** Site quality assurance procedures, review and approval processes, and administrative controls are implemented in accordance with the requirements of 10 CFR Part 50, Appendix B. As discussed in the Appendix for GALL, the staff finds that licensee implementation of the guidelines in the staff-approved BWRVIP reports will provide an acceptable level of quality for inspection and flaw evaluation of the safety-related components addressed in accordance with the 10 CFR Part 50, Appendix B, confirmation process and administrative controls.

9. ***Administrative Controls:*** As discussed in the Appendix for GALL, the staff finds the requirements of 10 CFR Part 50, Appendix B acceptable to address the administrative controls.

10. ***Operating Experience:*** There is documentation of cracking in both the circumferential and axial core shroud welds, and in shroud supports. Extensive cracking of circumferential core shroud welds has been documented in NRC Generic Letter 94-03 and extensive cracking in vertical core shroud welds has been documented in NRC Information Notice 97-17. It has affected shrouds fabricated from Type 304 and Type 304L SS, which is generally considered to be more resistant to SCC. Weld regions are most susceptible to SCC, although it is not clear whether this is due to sensitization and/or impurities associated with

the welds or the high residual stresses in the weld regions. This experience is reviewed in NRC GL 94-03 and NUREG-1544; some experiences with visual inspections are discussed in NRC IN 94-42.

Both circumferential (NRC IN 88-03) and radial cracking (NRC IN 92-57) have been observed in the shroud support access hole covers that are made from Alloy 600. Instances of cracking in core spray spargers have been reviewed in NRC Bulletin 80-13, and cracking in core spray pipe has been reviewed in BWRVIP-18.

Cracking of the core plate has not been reported, but the creviced regions beneath the plate are difficult to inspect. BWRVIP-06R1-A and BWRVIP-25 address the safety significance and inspection requirements for the core plate assembly. Only inspection of core plate bolts (for plants without retaining wedges) or inspection of the retaining wedges is required. NRC IN 95-17 discusses cracking in top guides of United States and overseas BWRs. Related experience in other components is reviewed in NRC GL 94-03 and NUREG-1544. Cracking has also been observed in the top guide of a Swedish BWR.

Instances of cracking have occurred in the jet pump assembly (NRC Bulletin 80-07), hold-down beam (NRC IN 93-101), and jet pump riser pipe elbows (NRC IN 97-02).

Cracking of dry tubes has been observed at 14 or more BWRs. The cracking is intergranular and has been observed in dry tubes without apparent sensitization, suggesting that IASCC may also play a role in the cracking.

Two CRDM lead screw male couplings were fractured in a pressurized-water reactor (PWR), designed by Babcock and Wilcox (B&W), at Oconee Nuclear Station (ONS), Unit 3. The fracture was due to thermal embrittlement of 17-4 PH material (NRC IN 2007-02). While this occurred at a PWR, it also needs to be considered for BWRs.

IGSCC in the X-750 materials of a tie rod coupling and jet pump hold-down beam was observed in a domestic plant.

The program guidelines outlined in applicable and approved BWRVIP documents are based on an evaluation of available information, including BWR inspection data and information on the elements that cause SCC, IGSCC, or IASCC, to determine which components may be susceptible to cracking. Implementation of the program provides reasonable assurance that cracking will be adequately managed so the intended functions of the vessel internal components will be maintained consistent with the current licensing basis (CLB) for the period of extended operation.

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