SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

FOR TOPICAL REPORT BWRVIP-158,

"FLAW PROXIMITY RULES FOR ASSESSMENT OF BWR INTERNALS"

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT

PROJECT NO. 704

1.0 INTRODUCTION

By letter dated September 28, 2006 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML062760198), the Boiling Water Reactor Vessel and Internals Project (BWRVIP) transmitted to the Nuclear Regulatory Commission (NRC) for review and approval Electric Power Research Institute Technical Report (TR) 1014387, “BWR Vessel and Internals Project, Flaw Proximity Rules for Assessment of BWR Internals (BWRVIP-158).” The BWRVIP-158 report provided revised guidelines for evaluating adjacent cracks in the same plane (in-plane cracks) and parallel cracks in different planes (parallel cracks) for BWR vessel internals such as the core shroud and the internal core spray piping. These guidelines are based on the results of BWRVIP’s effort to validate the American Society of Mechanical Engineers (ASME) Code, 2004 Edition flaw proximity rules for application to stainless steel BWR vessel internals. For simplicity, 2004 Edition will be dropped whenever the staff mentions the ASME Code in this safety evaluation (SE). The revised guidelines to the flaw proximity rules will reduce the conservatism in the existing BWRVIP guidance. The NRC’s review includes the BWRVIP-158 report and the BWRVIP’s response, dated April 17, 2008, to the staff’s request for additional information (RAI) for this submittal. This SE provides the basis for our approval of the BWRVIP-158 report.

2.0 REGULATORY EVALUATION

The inservice inspection (ISI) of the ASME Code Class 1, 2, and 3 components shall be performed in accordance with Section XI, “Rules for Inservice Inspection of Nuclear Power Plant Components,” of the ASME Code and applicable editions and addenda as required by Title 10 of the *Code of Federal Regulations* (10 CFR) 50.55a(g). When a flaw is detected by inservice volumetric or surface examinations, acceptance of it by an analytical evaluation shall be in accordance with the established procedures in the ASME Code, Section XI, such as that in Subarticle IWB-3600, “Analytical Evaluation of Flaws,” to demonstrate that the unit can be operated for a requested period of time without repair of the affected component. This ASME Code flaw evaluation does not require adding NDE uncertainties to the characterized flaw size.

BWR vessel internals are usually not ASME Code Class 1, 2, and 3 components. Therefore, the ISI of BWR vessel internals and the subsequent evaluation of flaws that were found in them

Enclosure

during the ISI have been conducted in accordance with inspection and evaluation guidelines established in the numerous approved BWRVIP reports for a variety of BWR vessel internals. A typical BWRVIP flaw evaluation acceptable to the staff starts with flaw characterization (or sizing), which involves flaw proximity rules and NDE uncertainty: flaw proximity rules are used to determine whether adjacent flaws should be treated separately or be combined; NDE uncertainty is used to finalize the detected flaw size considering measurement uncertainty. BWRVIP-specific flaw proximity rules were developed in the mid-1990's for the core shroud and were considered to be very conservative at that time. The BWRVIP proximity rules were applied to other components such as core spray piping, jet pumps, etc. The BWRVIP-158 report was created to document the technical basis for revisions to these rules based on changes to ASME Code and various tests conducted on in-plane and parallel flaws. The revised proximity rules would be used in flaw evaluations related to future inspection and evaluation of BWR vessel internals. NDE uncertainty, however, appeared in many BWRVIP reports such as the BWRVIP-03, "Reactor Pressure Vessel and Internals Examination Guidelines," BWRVIP-63, "Shroud Vertical Weld Inspection and Evaluation Guidelines," BWRVIP-76, "BWR Core Shroud Inspection and Flaw Evaluation Guidelines," and BWRVIP-158 reports. The NDE uncertainty issue is currently under staff review as a BWRVIP-63 open item, and the staff expects to issue an evaluation related to the open item within the first quarter of calendar year 2010. The information contained in the staff's SEs regarding the BWRVIP-03, Revision 6, (ADAMS Accession No. ML081500812) and BWRVIP-63 open item reports will constitute the staff's position on treatment of NDE uncertainty as it applies to BWR internals evaluations.

For parallel cracks, flaw proximity rules and NDE uncertainty are separate issues. However, for in-plane, surface cracks, NDE uncertainty significantly affects determination of the distance between the crack tips of two adjacent flaws and, therefore, significantly affects the outcome of applying the proposed flaw proximity rules. The applicant that applies the BWRVIP-158 shall use the staff guidelines on NDE uncertainty to be established in the SE for the BWRVIP-63 open item. The BWRVIP-158 report guidelines are only applicable to flaws identified during inspections performed to meet BWRVIP requirements.

3.0 TECHNICAL EVALUATION

3.1 BWRVIP Evaluation

The BWRVIP presented its technical bases for using the ASME Code, Section XI flaw proximity rules for evaluating BWR vessel internals in Chapter 3 to Chapter 5 of BWRVIP-158. Chapter 3 presented test results regarding interaction of two in-plane surface flaws under cyclic loading to validate the application of the ASME Code, Section XI flaw proximity rules to BWR vessel internals. ASME Code, Section XI flaw proximity rules allow two cracks be treated independently if their separation distance divided by the crack depth is greater than 0.5 ($s/d > 0.5$). Chapter 4 presented analytical (fracture mechanics) results regarding interaction of parallel cracks with and without offset to explore application of the ASME Code, Section XI flaw proximity rules to BWR vessel internals. ASME Code, Section XI flaw proximity rules allow two cracks be treated independently if they are separated by 0.5 inch. Chapter 4 also pointed out issues to be addressed when the failure mechanism is limit load. Chapter 5 presented a proposed methodology for evaluating reduction of limit load capability for BWR vessel internals with parallel cracks and compared them to test data: Miller data on plates with four symmetric parallel cracks (TR Figure 5-5), Connors data on bars with two offset parallel edge cracks (TR Table 5-4), Hasegawa data on plates with two and three offset parallel cracks (TR Table 5-5), and Battelle data on piping with one to three parallel cracks (TR Table on Page 5-7). The test data from all four tests are plotted against predicted results in TR Figure 5-14 for comparison. Based on this figure, the BWRVIP concluded that the predictive model proposed in BWRVIP-158 regarding the load capacity prediction is in good agreement with the test data.

Chapter 6 summarized the proposed BWRVIP flaw proximity rules, which supplement the ASME Code, Section XI rules, by adding guidance for resolving parallel cracks during fracture failure under limit load. The flaw proximity rules regarding resolution of in-plane and parallel cracks during crack growth under the linear elastic fracture mechanics (LEFM) mode were, however, only slightly different from those in the ASME Code, Section XI. The proposed BWRVIP flaw proximity rules are:

A. For adjacent, in-plane, surface cracks: if the distance between two in-plane surface indications is within 0.5 times the component wall thickness, the two indications must be considered as one. Further, depending on whether the inspection techniques meet certain criteria specified in this chapter, the BWRVIP proposed to apply the Evaluation Factors defined in BWRVIP-03, "Reactor Pressure Vessel and Internals Examination Guidelines," Revision 7 to characterize the length of each crack.

B. For adjacent, parallel, surface cracks: (1) if the distance between two parallel surface indications is less than the component thickness (or $d < t$, see TR Figure 5-2), then the cracks are considered as in the same plane; (2) if $d > 3t$, then the cracks are considered individually; and (3) if $t \leq d \leq 3t$, then the limit load capability is calculated according to TR Equation 5-1.

3.2 NRC Staff Evaluation

As discussed in Section 3.1 of this SE, the BWRVIP's proposed flaw proximity rules are in Chapter 6 of BWRVIP-158 and illustrate the underlying technical bases in Chapters 3 to 5. This SE evaluates BWRVIP-158 in the same order.

Chapter 3 presented stress intensity factor (K) plots for two in-plane cracks as a function of the crack separation distance divided by the crack depth (s/d) in TR Figure 3-2. Based on this figure, the BWRVIP concluded that, in bending, the interaction effects become significant at $s/d < 0.5$. Additional information in the BWRVIP's April 17, 2008, response to staff's RAI 158-1 stated that the change in the ratio of the K at the remote and adjacent crack tips of the two in-plane cracks is approximately 10% for $s/d > 0.5$ and concluded, "[t]his change is consistent with the other precedents in Section XI and was judged to be acceptable." For cases where NDE uncertainty is not an issue, the staff agrees with BWRVIP's conclusion because this 10% variation in K can be absorbed easily by the structural factors specified in the ASME Code, Section XI flaw evaluations. Flaw proximity rules affect two areas of a flaw evaluation: crack growth and fracture failure. To date, almost all crack growth rates, including those in Section XI of the ASME Code, depend on the K value at the crack tip regardless of whether the material is brittle (LEFM dominates) or ductile (elastic-plastic fracture mechanics and limit load dominate). Since TR Figure 3-2 results are based on a fatigue crack growth test under cyclic loading (i.e., the test was performed for specimens in the crack growth mode, which is far from their fracture failure limit), the above staff evaluation applies to in-plane cracks under crack growth only. Fracture failure in the limit load mode for these in-plane cracks is addressed in Chapter 5. NDE uncertainty is addressed in Chapter 6. Therefore, BWRVIP's conclusion regarding the insignificant interaction effects at $s/d > 0.5$ is acceptable, pending the staff's evaluation of Chapters 5 and 6.

Chapter 4 presented K plots for parallel cracks without offset in TR Figure 4-4. The plots indicate that the K value for parallel cracks without offset is lower than that associated with a single crack. Similar results are also observed in TR Figure 4-5 for the majority of cases for two parallel cracks with offset. The physical meaning of these two TR figures is that it is conservative to treat two adjacent cracks in different planes as separate and individual planar flaws (i.e., ignore their interaction) because, without considering the existence of adjacent cracks, an individual crack will give a higher K value than that associated with multiple adjacent flaws. This is true for a wide range of crack separation distance as indicated in both TR figures, supporting the ASME Code, Section XI flaw proximity rules of treating two parallel flaws as separate and independent planar flaws if they are separated by 0.5 inch. Again, fracture failure in the limit load mode for parallel cracks is not addressed here. Hence, extending the application of the ASME Code, Section XI flaw proximity rules regarding parallel cracks with and without offset to BWR vessel internals is acceptable, pending the staff's evaluation of Chapter 5. It should be noted, however, that NDE uncertainties associated with the crack length and depth determination has no effect on determining the distance between two cracks in parallel planes. Therefore, NDE uncertainty is not an issue in this part of the proximity rules.

Chapter 5 dealt with fracture failure in the limit load mode. As explained earlier, the ASME Code, Section XI flaw proximity rules are intended primarily for ferritic materials and are based on LEFM. Therefore, when extending them to stainless steel BWR vessel internals, an estimation of the component's limit load behavior has to be provided because the concern is no longer restricted to growth at the crack tips but the behavior of the entire section of the component (e.g., core shroud or internal core spray piping) before fracture failure. To deal with this new concern, Chapter 5 proposed an equation to estimate the limit load for two parallel cracks at a distance between 1 times the pipe thickness (where two cracks are combined as one) and 3 times the pipe thickness (where cracks are considered individually), i.e., $t \leq d \leq 3t$. This equation is derived empirically from a two dimensional finite element analysis of a pipe with two parallel 360º cracks: one inside surface flaw and one outside surface flaw. This equation was then validated against test data from Miller, Connors, Hasegawa, and Battelle. Since the materials used in the four tests are carbon steel, the staff requested the BWRVIP to justify the applicability of these test data to BWRVIP internals. The BWRVIP replied in its April 17, 2008, response to staff's RAI 158-2 that the governing mechanism for these tests was ductile limit load failure. The staff found that Hasegawa's use of slits with 0.1 mm width to simulate cracks, as described in BWRVIP-158, supported this claim because slits would promote failure in limit load instead of in LEFM. Further, TR Figure 5-14 indicated that the majority test data from all four tests clustered around the line where limit load prevails, suggesting once more that the failure mechanism is limit load.

Hence, the staff concluded that the BWRVIP has established in Chapter 5 an acceptable evaluation of the limit load capability for BWRVIP vessel internals, which supplements the ASME Code, Section XI flaw proximity rules. This conclusion applies to both in-plane cracks (Chapter 3) and parallel cracks (Chapter 4) because the Chapter 5 methodology considered cracks with a ratio of crack separation to the thickness (d/t) less than 1 as in-plane cracks. The staff acceptance of the evaluation of the limit load capability for BWRVIP vessel internals also means that the staff now considers the technical bases in Chapters 3 and 4 are appropriate because the pending conditions mentioned earlier have been resolved. Consequently, the ASME Code, Section XI flaw proximity rules can be extended to stainless steel BWR vessel internals.

The BWRVIP proposed proximity rules in Chapter 6 for adjacent in-plane cracks (Rule A) and parallel cracks (Rule B). Based on the evaluation discussed above, the staff verified that the proposed Flaw Proximity Rule A, although slightly different from the ASME Code, Section XI rules, is still supported by the technical bases presented in Chapter 3 when the staff-approved treatment of NDE uncertainty (see the staff's SEs regarding BWRVIP-03, Revision 6 and the BWRVIP-63 open item) is used in determining the effective crack length for in-plane cracks. On the other hand, the proposed Flaw Proximity Rule B is acceptable because it is fully supported by the technical bases presented in Chapters 4 and 5.

4.0 CONCLUSION

Based on the evaluation in Section 3.2 of this SE, the staff determined that the proposed proximity rules are acceptable when the staff-approved treatment of NDE uncertainty (see the staff's SEs regarding BWRVIP-03, Revision 6 and the BWRVIP-63 open item, which is projected to be issued within the first quarter of calendar year 2010) is used in determining the effective crack length for in-plane cracks. The proposed Flaw Proximity Rule B is acceptable because it is fully supported by the technical bases presented in Chapters 4 and 5 and the effect from NDE uncertainty is insignificant.

This staff evaluation and conclusion are only applicable to flaws identified during inspections performed to meet BWRVIP requirements.

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Date: November 18, 2009

DISPOSITION OF BWRVIP'S COMMENTS ON THE SAFETY EVALUATION ON
TOPICAL REPORT BWRVIP-158,
"FLAW PROXIMITY RULES FOR ASSESSMENT OF BWR INTERNALS"
VESSEL AND INTERNALS INTEGRITY BRANCH
OFFICE OF NUCLEAR REACTOR REGULATION

Comment No.	Issue	BWRVIP Discussion	Staff Disposition
1 Page 2, line 2	**Clarification:** Clarify "typical" flaw evaluation	It is not clear what flaw evaluation methodology this statement is referencing. Added "BWRVIP" to clarify that reference is to BWRVIP flaw evaluation methodology.	The staff accepts the proposed addition of "BWRVIP" as identified in the comment and will add "acceptable to the staff" following "A typical flaw evaluation…" The phrase "[a] typical flaw evaluation…" in the proposed SE was intended to refer generically to flaw evaluation procedures that the staff has previously found to be acceptable.
2 Page 2, first paragraph, Clarification: Wording revised to more accurately reflect the background of second and third sentences.	**Clarification:** Clarify background and reason for creating BWRVIP-158 report	Wording revised to more accurately reflect the background of application of flaw proximity rules to BWRVIP internal components and the reason for creating BWRVIP-158.	The staff agrees to adopt the BWRVIP rewording.
3, 4, and 5 3: Page 2, first paragraph, last three sentences and entire second paragraph. 4: Page 4, last paragraph, end of third sentence. 5: Page 5, Section 4.0, first paragraph, end of first and second sentences.	**Correction:** Delete NDE uncertainty discussion through out the SE	Application of NDE uncertainty to BWRVIP internals flaw evaluations is being addressed by an open item from the NRC review of BWRVIP-63. Application of NDE uncertainty should be deleted from this draft SE since the proximity rules in BWRVIP-158 can be approved independent of NDE uncertainty.	The staff rejects the BWRVIP rewordings at all three places of the proposed SE. It is the staff's position that the treatment of NDE uncertainty is directly related to the application of flaw proximity rules within the scope of BWRVIP-158. The references to NDE uncertainty within the BWRVIP-158 SE provide an appropriate linkage between this SE and the eventual resolution of NDE uncertainty issues within the scope of the BWRVIP-63 Open Item.