FINAL SAFETY EVALUATION FOR ELECTRIC POWER RESEARCH INSTITUTE

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT

TECHNICAL REPORT BWRVIP-63

OPEN ITEM ON THE TREATMENT OF NONDESTRUCTIVE EXAMINATION FLAW SIZING

UNCERTAINTY AS RELATED TO BWRVIP

PROJECT NO. 704

1.0 INTRODUCTION

By letter dated July 1, 1999 (Agencywide Documents Access and Management System (ADAMS) Legacy Library Accession No. 9907080217), the Boling Water Reactor (BWR) Vessel and Internals Project (BWRVIP) submitted the Electric Power Research Institute (EPRI) proprietary Technical Report (TR) 1131170, “Shroud Vertical Weld Inspection and Evaluation Guidelines (BWRVIP-63),” to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. That TR discussed many issues including nondestructive examination (NDE) uncertainty. The final Safety Evaluation (SE) for BWRVIP-63 was issued on August 20, 2001 (ADAMS Accession No. ML012320436). It treated NDE uncertainty as an Open Item (OI) (Issue 7). By letter dated October 22, 2002 (ADAMS Accession No. ML022970050), the BWRVIP responded to the OI proposing a set of NDE uncertainty criteria to be used in the flaw evaluation of BWR vessel internals. The NRC issued a request for additional information (RAI) on March 25, 2003 (ADAMS Accession No. ML030920682), requesting the BWRVIP to perform a flaw tolerance study to determine the sensitivity of the structural integrity of BWR vessel internals to NDE uncertainty. The NRC stated in the RAI that although the NDE uncertainty was an issue raised in TR BWRVIP-63, it also applies to other inspection and evaluation TRs under review or to be submitted for other components covered by the BWRVIP.

By letters dated May 25, 2004 (ADAMS Accession No. ML041530019), and June 3, 2005 (ADAMS Accession No. ML051580378), the BWRVIP provided a series of sensitivity studies to support its proposed NDE uncertainty criteria for flaw evaluations of BWR vessel internals. The May 25, 2004, response also revised the BWRVIP position by including an additional criterion for length sizing of indications found by ultrasonic testing (UT) or visual inspection testing/eddy current testing (VT/ET) of cylindrical piping components. The same NDE uncertainty criteria for flaw evaluations were repeated in TR BWRVIP-158, “BWR Vessel and Internals Project, Flaw Proximity Rules for Assessment of BWR Internals,” which was submitted on September 28, 2006 (ADAMS Accession No. ML062760223), for NRC review. Thus, the position of this SE is consistent with the TR BWRVIP-158 SE.

The NRC staff continued its review of NDE uncertainty as a generic issue affecting many BWRVIP TRs. However, since the SE for TR BWRVIP-03, Revision 6, “BWR Vessel and Internals Project, Reactor Pressure Vessel and Internals Examination Guidelines,” would have a great impact on the NRC review of NDE uncertainty, this SE was scheduled to be completed after the issuance of the SE for TR BWRVIP-03, Revision 6, on June 30, 2008 (ADAMS Accession No. ML081680732). Subsequent to the issuance of the SE for TR BWRVIP-03, Revision 6, the NRC staff continued to assess the issue of NDE uncertainty as related to BWR vessel internals. A revised staff position is presented in this SE.

This SE relates to the OI on NDE uncertainty criteria for flaw evaluations of BWR vessel internals. This SE is being treated as a generic issue affecting many BWRVIP TRs. The NRC staff evaluation and conclusion presented in this SE apply to all BWR vessel internals not covered by the American Society of Mechanical Engineers (ASME) Code, Section XI.

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 (ISI) 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) Section 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 procedure 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 during the ISI have been conducted in accordance with inspection and evaluation guidelines established in the numerous approved BWRVIP TRs for a variety of BWR vessel internals. A typical flaw evaluation 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 may be used to finalize the detected flaw size considering measurement uncertainty.

As stated in Section 1.0 of this SE, the BWRVIP-specific flaw proximity rules were proposed in the May 25, 2004, letter and were repeated in TR BWRVIP-158 for flaw evaluations related to future inspections and evaluation of BWR vessel internals. The SE for TR BWRVIP-158 was issued on November 18, 2009 (ADAMS Accession No. ML093170449). The BWRVIP has addressed the topic of NDE uncertainty in a number of BWRVIP TRs, including TRs BWRVIP-03, BWRVIP-63, BWRVIP-76, and BWRVIP-158. The June 30, 2008, SE considers the guidance in TR BWRVIP-03, Revision 6, capable of detecting cracks in BWR vessel internals, but does not comment on crack sizing. This prompted the NRC staff to continue its effort after June 2008 in assessing NDE uncertainty for BWR vessel internals. The current SE documents the revised staff position regarding NDE uncertainty as a result of this continued effort.

3.0 TECHNICAL EVALUATION

As mentioned before, the BWRVIP's May 25, 2004, and June 3, 2005, responses to the NRC staff's RAI provided flaw evaluation results for assumed flaws in welds of core shrouds, recirculation risers, and internal core spray piping and intended to demonstrate that NDE uncertainty does not have to be accounted for in the flaw evaluation of BWR vessel internals. To facilitate the NRC staff evaluation of the BWRVIP sensitivity study on BWR vessel internals, the NRC staff is summarizing the detailed technical information on BWRVIP flaw evaluation methodologies for assessing UT sizing uncertainty in Table 1 and for assessing VT sizing uncertainty in Table 2.

A typical evaluation of detected flaws includes the following five elements:

1) flaw sizing;
2) the applied stress intensity factor ($K_{applied}$) calculation and the associated crack growth evaluation based on fatigue or intergranular stress corrosion cracking (IGSCC) under various environments;
3) a driving force evaluation for the final flaw size using linear elastic fracture mechanics (LEFM), elastic plastic fracture mechanics, or limit load analysis according to the projected fracture mode;
4) a fracture resistance evaluation considering embrittlement due to various fluence conditions and the projected fracture mode; and
5) a stability evaluation using appropriate acceptance criteria and structural factors (SF) of Section XI of the ASME Code.

The BWRVIP evaluation of flaws basically followed the same procedure.

3.1 Evaluation of the BWRVIP's Position on NDE Uncertainty

In the May 25, 2004, response to the NRC RAI, the BWRVIP updated its position on consideration of NDE uncertainty in flaw evaluations. In addition to the three criteria already in place that use the same length and depth root-mean-square (RMS) errors required for ASME Code, Section XI, Appendix VIII performance demonstrations, the BWRVIP added a new criterion for piping. The BWRVIP position on consideration of NDE uncertainty in flaw evaluations is as follows:

[

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The NRC staff has considered the above criteria and found them acceptable for BWR vessel internal examinations only. In the past, the NRC staff has asserted that non-blind examinations result in RMS values that are considered to be less reliable than RMS values developed from blind performance demonstrations, resulting in a procedure whose effectiveness and reliability are undermined and considered less reliable than an ASME Code, Section XI, Appendix VIII qualified procedure. Though these are valid concerns, they are mitigated by several factors related to the BWR vessel internal examinations, as follows:

1. The BWRVIP uses non-blind UT procedure demonstrations that require definitive steps for identifying flaw indications and sizing flaws. These demonstrations are component specific and the flaws represent the range of flaws seen in the particular demonstration component. Essentially all of the BWRVIP UT data is collected using automated/encoded UT systems.

2. Personnel performing BWRVIP exams where IGSCC is involved must have ASME Code, Section XI, Appendix VIII, qualifications for automated examinations.

3. Since ASME Code, Section XI, Appendix VIII, applies to pressure boundary materials and vessel internals are not pressure boundary materials, applying the Appendix VIII requirements to vessel internals may be too conservative.

4. Additionally, for the ASME Code-required visual examinations, TR BWRVIP-03, Revision 11, tightened the remote visual standards in response to NUREG/CR-6860, “An Assessment of Visual Testing,” and NUREG/CR-6943, “A Study of Remote Visual Methods to Detect Cracking in Reactor Components,” by changing the ½ mil wire to characters and tightened viewing angles.

5. Lastly, at this time, the ASME Code allows many examinations that are not required to meet ASME Code, Section XI, Appendix VIII, performance demonstration requirements (i.e., blind testing). Additionally, to the staff’s knowledge, there are no Appendix VIII supplements being developed to address non-pressure boundary materials.

Based on the above factors, the NRC staff has found that the BWRVIP’s position on consideration of NDE uncertainty to be acceptable for application to BWR vessel internal examinations. This determination has also considered the BWRVIP’s flaw tolerance study which demonstrates that some BWR vessel internals having a history of cracking are flaw-tolerant. The following is the staff’s evaluation of this study.

3.2 Evaluation of the BWRVIP’s Flaw Tolerance Study

The NDE uncertainty discussed above is related to only the first of the five elements of a typical flaw evaluation for a detected flaw (sizing). For the remaining four elements of the flaw evaluation, the BWRVIP used the approaches, component geometries, and stresses from approved BWRVIP TRs, as indicated in Tables 1 and 2. Consequently, instead of reviewing the BWRVIP flaw evaluation methodologies, this SE section focuses on the BWRVIP flaw evaluation results. It should be mentioned, however, that the component geometries and stresses used in the BWRVIP flaw evaluation sensitivity study represented typical values, not bounding values. Using typical values in this application was justified because the purpose of the BWRVIP study was to assess the trend of the SF change when the NDE uncertainty was not considered.

3.2.1 UT Depth Uncertainty as Applied to BWR Vessel Internals

The BWRVIP performed a flaw evaluation for a range of circumferential flaws in the core shroud H5 weld and summarized the results in Figures 4 and 5 of the May 25, 2004, response to the NRC staff RAI. Figure 4 of the BWRVIP response illustrated the change of the calculated SF based on LEFM as a function of crack depth under emergency and faulted conditions for the cases, with and without a UT uncertainty of [ ]. A similar plot based on limit load analysis was shown in Figure 5 of the BWRVIP response. Figure 4 of the BWRVIP response indicated that the impact of excluding UT sizing uncertainty on the flaw evaluation using LEFM was insignificant for deep flaws (e.g., [ ]). Although Figure 5 of the BWRVIP response indicated a larger impact for the flaw evaluation using limit load analysis, the BWRVIP demonstrated in both figures that the core shroud integrity is not sensitive to flaw depth and the core shroud can tolerate deep flaws (i.e., structural integrity is maintained even when the flaw is 90 percent through-wall). Therefore, UT uncertainty for the core shroud flaw depth becomes irrelevant for the majority of core shroud inspection result evaluations.

Further, as discussed in Section 2.0 of this SE, an ASME Code, Section XI, flaw evaluation does not require adding NDE uncertainty to the characterized flaw size. Instead, an ASME Code, Section XI, flaw evaluation relies on conservatism in its evaluation methodologies and the specified SFs to address the NDE uncertainty in the flaw evaluation. Hence, similar to the ASME Code, Section XI, flaw evaluation methodologies, the BWRVIP approach can also rely on conservatism in its evaluation methodologies and the specified SFs to account for NDE uncertainty.

Therefore, for core shrouds, the NRC staff accepts the BWRVIP proposed criterion for UT depth uncertainty, [

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3.2.2 UT Length Uncertainty as Applied to BWR Vessel Internals

The BWRVIP summarized its flaw evaluation results for a range of circumferential flaws in the recirculation riser weld under normal and upset conditions in Figure 7 and under emergency and faulted conditions in Figure 8 of the May 25, 2004, response. Both figures illustrated the change of the calculated SF based on limit load analysis with and without a UT uncertainty of [ ] (length evaluation factor (LEF) is [ ]). Similar results for the internal core spray piping weld were shown in Figures 10 and 11 of the May 25, 2004, response. For the recirculation riser weld, it is evident from Figures 7 and 8 that the difference between calculated SFs with and without UT uncertainty correction is [ ] or less until the crack length becomes approximately [ ] of the circumference where the calculated SFs equal the required SFs. The corresponding difference for the internal core spray piping weld shown in Figures 10 and 11 is more than [ ]. Since the recirculation riser weld can tolerate a moderately long crack ([ ]) and the structural integrity (reflected in calculated SFs) is not sensitive to added NDE uncertainty, the NRC staff determined that it is flaw tolerant. Although the internal core spray piping weld can also tolerate a moderately long crack, it is not considered as flaw tolerant as the recirculation riser weld because its structural integrity is sensitive to added NDE uncertainty.

Therefore, for the recirculation riser weld, the NRC staff accepts the BWRVIP proposed criterion for UT length uncertainty ([ ]). Again, conservatisms in the evaluation methodology and the specified SFs can be used to account for NDE uncertainty. For internal core spray piping, although it is not as flaw tolerant as the recirculation riser weld, the BWRVIP proposed criterion for UT sizing uncertainty is still acceptable when the NRC staff's revised position on the BWRVIP's NDE capability discussed in Section 3.1 of this SE is also considered.

3.2.3 VT/ET Length Uncertainty as Applied to BWR Vessel Internals

The BWRVIP presented its flaw evaluation results based on LEFM for a range of axial flaws in the core shroud axial weld under the faulted condition in Figure 13 and flaw evaluation results based on limit load analysis in Figure 14 of the May 25, 2004, response. Both figures illustrated that the change of the calculated SFs, with and without a VT uncertainty of [ ] (LEF = [ ]), is insignificant regardless whether the evaluation was based on LEFM or limit load analysis. The NRC staff performed an independent derivation and confirmed the validity of the BWRVIP SF equation based on limit load analysis. The BWRVIP equation can be rearranged as:

$$SF/[PD/(2t\ \sigma_f)] = 1 - (2a)/L$$

where 2a is the crack length, L the shroud height, P the delta pressure across the shroud, D the shroud diameter, t the shroud thickness, and σ_f the flow stress. This equation showed that there will be a constant decrease of the SF by 0.83 percent (2a/L x 100 percent = 0.75 inch/90 inches x 100 percent) under the faulted condition for all crack lengths. A SF decrease of this amount is insignificant. On the other hand, the SF using LEFM involves more complex equations. The NRC staff calculation showed that for a crack length of 10 inches, the SF without VT uncertainty would decrease by 5.2 percent, and for a crack length of 70 inches, the SF without VT uncertainty would decrease by 3.3 percent. These SF decreases, which are the least among all flaw evaluation results reported by BWRVIP in the letter of May 25, 2004, apply to only core shroud axial weld flaws. Figures 13 and 14 also demonstrate that the core shroud is very tolerant to axial weld flaws because a 70 inch long axial weld flaw still meets the required SF.

Hence, for core shrouds, the NRC staff accepts the BWRVIP proposed criterion for VT or ET length uncertainty ([

])).

The BWRVIP response dated May 25, 2004, included an additional criterion regarding UT or VT/ET length sizing of cylindrical piping components. Technically, the NRC staff does not see distinctions between BWR vessel internals and piping components regarding flaw tolerance, as long as they have similar crack driving force and resistance; therefore, the response is acceptable.

3.2.4 Conclusion on BWRVIP's Flaw Tolerance Study

Based on the evaluation in Section 3.2 of this SE, the NRC staff determined that the proposed BWRVIP guidance on NDE uncertainty is acceptable for the core shrouds and recirculation riser welds because the BWRVIP's flaw tolerance study demonstrated that these components are flaw-tolerant. Although core spray piping is not as flaw-tolerant as core shrouds and recirculation riser welds, the proposed BWRVIP guidance on NDE uncertainty is also acceptable when the staff's revised position on BWRVIP's NDE capability discussed in Section 3.1 of this SE is also considered. Since the components chosen for flaw tolerance study all have a history of cracking, their results are representative, if not bounding.

4.0 LIMITATIONS AND CONDITIONS

Considering the revised NRC staff position on the BWRVIP's NDE capability as documented in Section 3.1 of this SE and the flaw tolerance study results as documented in Section 3.2 of this SE, the NRC staff determined that the proposed BWRVIP guidance on NDE uncertainty can be extended to all BWR vessel internals. Hence, the NRC staff imposed no limitations and conditions on the BWRVIP's guidance on consideration of the NDE uncertainty in flaw evaluation of BWR vessel internals.

5.0 CONCLUSION

The NRC staff has reviewed the BWRVIP responses provided by letters dated May 25, 2004, and June 3, 2005, related to TR BWRVIP-63. The initial SE for TR BWRVIP-63 was issued on August 20, 2001, and it treated NDE uncertainty as an OI (Issue 7 of that SE). By letter dated October 22, 2002, the BWRVIP provided a response to the OI, including a proposed set of NDE uncertainty criteria to be used in the flaw evaluation of BWR vessel internals.

The NRC staff issued a RAI by letter dated March 25, 2003, requesting the BWRVIP to perform a flaw tolerance study to determine the sensitivity of structural integrity of BWR vessel internals to NDE uncertainty. In that letter, the NRC staff stated that although the NDE uncertainty was an issue raised in TR BWRVIP-63, it also applies to other inspection and evaluation TRs under review or to be submitted for other components covered by the BWRVIP. The May 25, 2004, BWRVIP response also revised the BWRVIP position by including an additional criterion for length sizing from indications found by UT or VT/ET of cylindrical piping components.

As indicated in Sections 3.1 and 3.2, based on (1) the factors listed that mitigate the staff's previously expressed concerns stated in the SE for TR BWRVIP-03, Revision 6, regarding the

BWRVIP's NDE capability, and (2) the flaw tolerance study results which demonstrate that representative BWR vessel internals having a history of cracking are mostly flaw-tolerant, the NRC staff finds that the industry's position on consideration of NDE uncertainty to be acceptable for application to BWR vessel internal examinations only.
This SE and conclusion applies to all BWR vessel internals not covered by the ASME Code, Section XI.

Principle Contributors: Carol Nove
Simon Sheng

Date: December 23, 2011

Table 1: BWRVIP Flaw Evaluation Methodologies to Assess UT Uncertainty for Three Welds of BWR Vessel Internals - Circumferential Flaw

Component		Core Shroud Weld (Depth)		Recirculation Riser Weld (Length)	Internal Core Spray Piping Weld (Length)	
Flaw Sizing	initial flaw size (range of sensitivity study)	[ ]		[ ]	[ ]	[ ]
	UT uncertainty used in the MAY 25, 2004, response	[ ]		[ ]	[ ]	
Crack Growth	$K_{applied}$	due to residual stresses (BWRVIP-14) and pressure (May 25, 2004 submittal)		Not considered	Not considered	
	IGSCC crack growth rate	a K dependent formula (BWRVIP-14)				
Flaw Stability Analysis	applicable theory	LEFM	limit load analysis	limit load analysis (GTAW) -Levels A, B, and D	limit load analysis (GTAW) -Levels A and B	limit load analysis (SAW + SMAW) -Level D
	fracture driving force	$K_{applied}$ (Zahoor's formula used in BWRVIP-14)	$P_m + P_b$ (BWRVIP-14)	$P_m + P_b$ (May 25, 2004 submittal)	$P_m + P_b$ (May 25, 2004 submittal)	$Z(P_m + P_b + P_e/SF)$ (May 25, 2004 submittal)
	fracture resistance	[ ]	$P_m + P_b'$ (Can be deduced from figures in the May 25, 2004 submittal)	$P_m + P_b'$ (Can be deduced from figures in the May 25, 2004 submittal)	$P_m + P_b'$ (Can be deduced from figures in the May 25, 2004 submittal)	$P_m + P_b'$ (Can be deduced from figures in the May 25, 2004 submittal)

Notes: P_m is the applied membrane stress
P_b is the applied bending stress
P_b' is the plastic collapse bending stress based on flow stress
Z is the Z factor as defined in Section XI of the ASME Code for certain welds
SF is the structural factor

Table 2: BWRVIP Flaw Evaluation Methodologies to Assess VT Uncertainty for a BWR Vessel Internal Weld - Axial Flaw

Component		Core Shroud Weld (Length)	
Flaw Sizing	initial flaw size (range of sensitivity study)	[ ]	
	VT uncertainty	[ ]	
Crack Growth	$K_{applied}$	Not considered	
	IGSCC crack growth rate		
Flaw Stability Analysis	applicable theory	LEFM	limit load analysis
	fracture driving force	$K_{applied}$ (BWRVIP-76)	PDL/2 (Deduced by the staff from the May 25, 2004 submittal)
	fracture resistance	[ ]	(L-2a) σ_f t (Deduced by the staff from the May 25, 2004 submittal)

Notes: P is delta pressure across the core shroud (20 pounds per square inch)
D is the core shroud diameter (200 inches)
L is the length of core shroud vertical weld (90 inches)
t is core shroud thickness (1.5 inches)
σ_f is flow stress
a is half crack length