SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

BWR VESSEL AND INTERNALS PROJECT

BWRVIP-241, PROBABILISTIC FRACTURE MECHANICS EVALUATION FOR THE BOILING WATER REACTOR NOZZLE-TO-VESSEL SHELL WELDS AND NOZZLE BLEND RADII

1.0 INTRODUCTION

By letter dated April 26, 2011, the Boiling Water Reactor (BWR) Vessel Internals Project (BWRVIP) submitted the topical report (TR) BWRVIP-241, “BWR Vessel and Internals Project Probabilistic Fracture Mechanics [(PFM)] Evaluation for the Nozzle-to-Vessel Shell Welds and Nozzle Blend Radii” (hereafter referred to as the TR), for NRC review and approval. This TR documents supplemental analyses for BWR reactor pressure vessel (RPV) recirculation inlet and outlet nozzle-to-shell welds and nozzle inner radii to address the limitations and conditions specified in the December 19, 2007, safety evaluation (SE) for the BWRVIP-108NP report, “BWR Vessel and Internals Project, Technical Basis for the Reduction of Inspection Requirements for the Nozzle-to-Vessel Shell Welds and Nozzle Inner Radii.” The BWRVIP-108NP report contains the technical basis supporting American Society of Mechanical Engineers *Boiler and Pressure Vessel Code* (ASME Code) Case N-702, “Alternative Requirements for Boiling Water Reactor (BWR) Nozzle Inner Radius and Nozzle-to-Shell Welds,” for reducing the inspection of RPV nozzle-to-vessel shell welds and nozzle inner radius areas from 100 percent to 25 percent of the nozzles for each nozzle type during each 10-year interval, and the TR may be considered as a supplement to the BWRVIP-108NP report. This review includes the BWRVIP’s responses dated October 10, 2012, to NRC’s requests for additional information (RAI).

The TR intends to demonstrate, through the supplemental PFM evaluation, that the proposed modification of the limitations and conditions specified in the SE for the BWRVIP-108NP report still meets the NRC requirements.

2.0 REGULATORY EVALUATION

The inservice inspection (ISI) of ASME Code Class 1, Class 2, and Class 3 components shall be performed in accordance with Section XI 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), except where specific written relief has been granted by the Commission pursuant to 10 CFR 50.55a(g)(6)(i). The regulation at 10 CFR 50.55a(a)(3) states, in part, that alternatives to the requirements of paragraph (g) may be used, when authorized by the NRC, if the licensee demonstrates that: (i) the proposed alternatives would provide an acceptable level of quality and safety, or (ii) compliance with the specified requirements would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.

ENCLOSURE

Pursuant to 10 CFR 50.55a(g)(4), ASME Code Class 1, 2, and 3 components (including supports) shall meet the requirements, except the design and access provisions and the preservice examination requirements, set forth in the ASME Code, Section XI, to the extent practical within the limitations of design, geometry, and materials of construction of the components. Specifically, IWB-2400, "Inspection Schedule," specifies requirements on when and what percentage to inspect for each ASME Code examination category of components. IWB-2500, ""Examination and Pressure Test Requirements," defines in Table IWB-2500-1, "Examination Categories," the components to be inspected within each ASME Code examination category and specifies the appropriate inspection method, the acceptance standard, and the extent and frequency of examination for each component. For RPV nozzle-to-vessel shell welds and nozzle inner radii, Section XI requires 100 percent inspection each 10-year interval.

The BWRVIP-108NP report is the technical-basis document for ASME Code Case N-702 regarding reduction of the inspection of RPV nozzle-to-vessel shell welds and nozzle inner radius areas from 100 percent to 25 percent of the nozzles for each nozzle type every 10 years. The SE on BWRVIP-108NP specified the following limitation and conditions (or evaluation criteria) for the licensees to demonstrate that, with the proposed reduction of the inspection frequency for the RPV nozzles, the nozzles can still maintain structural integrity acceptable to the NRC:

(1) the maximum RPV heatup/cooldown rate is limited to less than 115 ºF/hour;

<u>For recirculation inlet nozzles</u>

(2) $(pr/t)/C_{RPV} < 1.15$

p = RPV normal operating pressure (psi),
r = RPV inner radius (inch),
t = RPV wall thickness (inch), and
C_{RPV} = 19332;

(3) $[p(r_o^2 + r_i^2)/ (r_o^2 - r_i^2)]/C_{NOZZLE} < 1.15$

p = RPV normal operating pressure (psi),
r_o = nozzle outer radius (inch),
r_i = nozzle inner radius (inch), and
C_{NOZZLE} = 1637;

For recirculation outlet nozzles

(4) $(pr/t)/C_{RPV} < 1.15$

p = RPV normal operating pressure (psi),
r = RPV inner radius (inch),
t = RPV wall thickness (inch), and
$C_{RPV} = 16171$; and

(5) $[p(r_o^2 + r_i^2)/ (r_o^2 - r_i^2)]/C_{NOZZLE} < 1.15$

p = RPV normal operating pressure (psi),
r_o = nozzle outer radius (inch),
r_i = nozzle inner radius (inch), and
$C_{NOZZLE} = 1977$.

The TR contains additional PFM results to support revision of these limitations and conditions. Upon approval of the TR, licensees may request relief from the ASME Code Section XI requirements for these RPV areas and request to use ASME Code Case N-702 as an alternative, addressing the revised limitations (criteria) documented in the TR. Licensees may submit relief requests in accordance with 10 CFR 50.55a(a)(3)(i).

3.0 SUMMARY OF THE BWRVIP-241 REPORT

Section 1 of the TR presented the current ASME Code inspection requirements for RPV nozzle-to-vessel shell welds and nozzle inner radius sections and the proposed alternative. It also described the connection of this report to the BWRVIP-108NP report and the ASME Code Case N-702 that is supported by both the TR and the BWRVIP-108NP report. Section 2 of the report discussed the NRC additional requirements, i.e., the five criteria specified in the SE for the BWRVIP-108NP report, and presented the calculated parameters used in evaluating these criteria for 35 BWR RPVs. Section 3 described selection of two recirculation inlet nozzles and two outlet nozzles for additional PFM analyses based on the calculated parameters for these BWR RPVs mentioned in Section 2 of this report. They are summarized in Table 3-2 of the TR. Since the plant names are considered proprietary by the BWRVIP, the plant from the top to the bottom of Table 3-2 will be referred to as Plant 1 to Plant 4 throughout this SE. Section 4 presented pressure and thermal stress analysis results based on finite element method (FEM) modeling of the two recirculation inlet nozzles (Plants 1 and 2) and two outlet nozzles (Plants 3 and 4) that were selected in Section 3. Detailed plant-specific thermal transients for the four RPV nozzles are also provided. The nozzle stresses serve as inputs to the subsequent PFM evaluation. Section 5 discussed the evaluation of the PFM results which were generated using the VIPER-NOZ computer code. VIPER-NOZ was designed specifically for RPV nozzles and was also used to generate results reported in the BWRVIP-108NP report. Section 6 provided conclusions and the proposed alternative criteria to replace the NRC staff criteria that were specified in the SE for the BWRVIP-108NP report.

4.0 STAFF EVALUATION

In the SE for the BWRVIP-108NP report, the NRC staff set a limit of 1.15 on four key parameters contributing to the probability of failure (POF): the RPV pressure stress factor for the recirculation inlet nozzle (Criterion 2), the nozzle pressure stress factor for the recirculation inlet nozzle (Criterion 3), the RPV pressure stress factor for the recirculation outlet nozzle (Criterion 4), and the nozzle pressure stress factor for the recirculation outlet nozzle (Criterion 5). The factor of 1.15 was set to limit the plant-specific key parameters to be less than 1.15 times the corresponding generic parameters of the BWRVIP-108NP report. Since the PFM results of the BWRVIP-108NP report showed that the POF for the recirculation inlet nozzle inner radii are 1.19×10^{-7} per reactor year (/yr) for the low temperature over-pressurization (LTOP) event and 1.98×10^{-6}/yr for the normal operation for the generic analysis, the NRC staff, based on simple extrapolation, determined that 15 percent more driving force for plant-specific recirculation nozzles will not cause the POF values to go beyond the NRC safety goal of 5×10^{-6}/yr underlying the pressurized thermal shock (PTS) criteria of 10 CFR 50.61. To revise Criterion 2 through Criterion 5 of the BWRVIP-108NP report, the BWRVIP performed additional PFM analyses in the TR using the bounding recirculation inlet and outlet nozzles instead of the typical recirculation inlet and outlet nozzles of the BWRVIP-108NP report. The BWRVIP's additional PFM analyses are to demonstrate that the limits can be higher than 1.15 and the corresponding POFs are still below 5×10^{-6}/yr.

Since the PFM methodology and the nozzle stress analyses have already been reviewed and accepted as indicated in the SE for the BWRVIP-108NP report, the NRC staff's evaluation of the TR focused on the nozzle stresses, PFM analysis results, and the BWRVIP's use of these results to support its proposed revision of Criterion 3 and Criterion 5 discussed above.

4.1 Selection of Nozzles and Nozzle Stresses

The BWRVIP performed calculations for the stress factors in Criterion 2 to Criterion 5 for 35 BWR RPVs and selected two recirculation inlet and two recirculation outlet nozzles which have the highest stress factors for further FEM analyses and evaluation. This ranking criterion based on stress factors is consistent with the NRC staff's position in the SE for the BWRVIP-108NP report regarding use of stress factors in Criteria 2 to 5 to screen out RPV nozzles not suitable for the requested reduction of inspection requirements. Hence, the TR's selection of nozzles based on bounding stresses for further study is appropriate.

Regarding the nozzle stresses, the NRC staff confirmed that selection of the thermal transients and the subsequent nozzle stress analysis reported in this report is similar to those in the BWRVIP-108NP report. One effective way to gain confidence in the fidelity of the FEM modeling of the RPV nozzles and the resulting stress analysis results is to compare the current stress distributions and patterns with those in the BWRVIP-108NP report to identity any peculiarities and make sure that they are explainable and are not caused by modeling errors. The NRC staff issued Request for Additional Information (RAI) 1 to RAI 4, questioning the FEM results in order to obtain confidence in the BWRVIP's FEM modeling.

RAI 1 requested the BWRVIP explain the different stress patterns under the heatup transient between the group of recirculation inlet and outlet nozzles in this TR (the Plant 1 recirculation inlet nozzle (Figure 4-9), the Plant 2 recirculation inlet nozzle (Figure 4-21), the Plant 3 recirculation outlet nozzle (Figure 4-33), and the Plant 4 recirculation outlet nozzle (Figure 4-45), which showed high compressive stresses at the inside surface when the steady state is approached, and the group of recirculation inlet and outlet nozzles in BWRVIP-108NP, which showed no or insignificant compressive stresses at the inside surface under the same heatup transient. In addition, RAI 1 requested the BWRVIP explain the opposite trend of the through-thickness stress distributions due to pressure at the nozzle blend radius region and the nozzle-to-shell weld region for the Plant 1 recirculation inlet nozzle (decreasing from the inside surface as shown in Figure 4-8 of the TR) and the Plant 2 recirculation inlet nozzle (increasing from the inside surface as shown in Figure 4-19 of the TR).

The BWRVIP's response dated October 10, 2012, to RAI 1 states that the differences for inside surface stresses between the TR and BWRVIP-108NP reports are due to the inclusion of cladding in the nozzle stress analyses in the TR, and at the steady state operating temperature, a compressive stress is introduced in the cladding due to its higher thermal expansion coefficient. The BWRVIP-108NP analysis, however, did not consider cladding for additional conservatism. This explanation is consistent with the physical behavior of metals with cladding; therefore, the first part of RAI 1 is resolved.

The second part of RAI 1 regards the opposite stress distributions due to pressure at the nozzle blend radius region and the nozzle-to-shell weld region for the Plant 1 and the Plant 2 recirculation inlet nozzles. The BWRVIP's response to RAI 1 states that the Plant 2 nozzle is unique, of which the nozzle-to-shell weld is located between the pipe and vessel shell, while the corresponding weld of the Plant 1 recirculation inlet nozzle (and other plants') is located between the nozzle forging and vessel shell. In addition, the Plant 2 recirculation inlet nozzle is in the RPV bottom head region, while the Plant 1 recirculation inlet nozzle is in the RPV cylindrical body. Thus, the Plant 2 nozzle is connected to a spherical shell instead of a cylindrical shell like Plant 1. The NRC staff considers these geometry differences significant and could cause drastic differences in stress distribution. Therefore, the second part of RAI 1 is also resolved.

The NRC staff's review of the FEM results in Section 4 of the TR indicated that for Plant 3 the maximum through-thickness hoop stress shape of the nozzle blend radius region for recirculation outlet nozzle under the loss of feedwater pump transient (Figure 4-34(a) of the TR) occurred sooner in the transient than the minimum through-thickness hoop stress shape. However, the corresponding FEM results for Plant 4 show an opposite trend i.e., the maximum through-thickness hoop stress shape occurred later in the transient than the minimum through-thickness hoop stress shape. To ensure that the opposite trend is not due to FEM modeling errors, the NRC staff issued RAI 2 for clarification.

The BWRVIP's October 10, 2012, response to RAI 2 states that the differences between Plant 3 and Plant 4 are due to their different definitions for the loss of feedwater pump transient. The NRC staff confirmed that the maximum through-thickness hoop stress shape of the nozzle blend radius region for recirculation outlet nozzle occurred several minutes after the highest thermal gradient for either Plant 3 or Plant 4. However, for Plant 3, the highest thermal gradient happened early in its loss of feedwater pump transient while for Plant 4, the highest thermal gradient happened late in its corresponding transient. Hence, the NRC staff determined that this difference is not due to any FEM modeling errors, but due to the different characteristics of each plant's loss of feedwater pump transient. RAI 2 is resolved.

Additionally, information is provided in the RAI 2 response to ensure that the transient definitions analyzed in the TR are representative and bounding. The BWRVIP examined three additional recirculation nozzles, ranking right below the selected nozzles in Table 3-2 of the TR, and found that (1) the transient definitions of the recirculation inlet nozzle for the first of the three are identical to those of Plant 2 and (2) the transient definition of the remaining two recirculation outlet nozzles are identical to those of Plant 3. Based on this finding, the NRC staff concludes that the thermal transient definitions used in the TR are representative and bounding for the BWR fleet, given additional credibility to the BWRVIP's methodology.

RAI 3 regards the compressive stresses of the RPV and nozzle inside surfaces caused by sudden pump start of a cold recirculation loop (Figure 4-10 of the TR). It appears that right after the beginning of the transient, the RPV and nozzle inside surfaces are still under the effect of deep cooldown and are not likely to produce compressive stresses as indicated in the figure. RAI 3 was issued for further clarification.

The BWRVIP's October 10, 2012, response to RAI 3 states that the compressive stresses are results of the different thermal expansion between the cladding and the RPV. The NRC staff's reexamination of this issue revealed that the transient was experienced by the nozzle only while the RPV was at the constant temperature due to the shielding provided by the nozzle thermal sleeve. At a constant high temperature, the cladding will see compressive stresses because its additional expansion due to higher coefficient of thermal expansion will be restricted by the RPV. RAI 3 is resolved.

RAI 4 regards a sharp change of slope close to the inside surface for the hoop stress distribution in Figure 4-21(a) during heatup. The BWRVIP's October 10, 2012, response to RAI 4 states that the sharp change of slope of the hoop stress distribution close to the inside surface in Figure 4-21 (a) is due to the difference in the thermal expansion coefficients for the cladding and vessel and due to the thermal effect. This explanation applies to other nozzles showing similar sharp change of stress close to the inside surface. This is acceptable because during heatup the RPV base metal tend to hold back the expansion of the cladding which has a higher thermal expansion coefficient, causing compressive stresses in the cladding and a sharp change of the stress distribution close to the interface of cladding and base metal. RAI 4 is resolved.

Based on the BWRVIP's responses to RAI 1 to RAI 4 regarding selection of nozzles and nozzle stresses and the NRC staff's evaluation, the NRC staff concludes that all concerns of the FEM modeling and results have been resolved and, therefore, these nozzle stresses can be used in the subsequent PFM analyses.

4.2 PFM Acceptance Criteria, Methodology, and Results

In the PFM analyses, the TR used the same acceptance criterion of 5×10^{-6}/yr as in the BWRVIP-108NP report for the RPV POF evaluation. This criterion is borrowed from RG 1.154, "Format and Content of Plant-Specific Pressurized Thermal Shock Safety Analysis Reports for Pressurized Water Reactors [(PWRs)]" (1987) and is also the NRC safety goal underlying the PTS criteria of 10 CFR 50.61. Although 10 CFR 50.61a, "Alternative Fracture Toughness Requirements for Protection against [PTS] Events," which is provided in the 2011 Edition of the 10 CFR, is based on a through-wall-crack-frequency (TWCF) acceptance criterion of 1 x 10^{-6}/yr, using the acceptance criterion of 5 x 10^{-6}/yr in this application is still valid because the 10 CFR 50.61 PTS screening criteria which are currently used by almost all licensees are based on the acceptance criterion of 5 x 10^{-6}/yr. For PWRs, 10 CFR 50.61a is an alternative.

Regarding the PFM methodology, Section 5.1 of the TR states, "[a] modified version, VIPER-NOZ [21] was developed to include the evaluation capability for nozzles." This suggests that the supplemental PFM analyses reported in the report were performed using the VIPER-NOZ Code. The NRC staff issued RAI 5, requesting BWRVIP identify the part of the VIPER-NOZ Code methodology which goes beyond what were discussed in the SE for the BWRVIP-108NP report and, therefore, requires NRC staff review. This RAI also asked the BWRVIP to justify the inputs (except for plant-specific geometries and thermal loading) which go beyond what were accepted in the SE for the BWRVIP-108NP report.

The BWRVIP's October 10, 2012, response to RAI 5 states that the VIPER-NOZ Code is the same as that used in the BWRVIP-108NP analysis and accepted in the NRC staff's SE. It further states that the inputs for VIPER-NOZ (except for plant-specific geometries and thermal loading) are consistent with those accepted by the NRC staff and documented in the SE for the BWRVIP-108NP report. Since the BWRVIP confirmed that the same approved PFM methodology of BWRVIP-108NP was applied in this application and the inputs are consistent with what were approved by the NRC staff, RAI 5 is resolved.

RAI 6 was issued to request BWRVIP quantify the conservatism in the fatigue crack growth (FCG) part of the PFM analyses that was mentioned in Section 5.3.1 of the TR so that the extra margin in the overall assessment can be determined. The BWRVIP's October 10, 2012, response to RAI 6 states that the approach used in the TR is the same as that used in the BWRVIP-108NP report. Consequently, the conservatism is unchanged between BWRVIP-108NP and the TR. This is acceptable because extra margin from the FCG analyses is supplemental, not essential. RAI 6 is resolved.

Regarding the FM models used in the analyses, Section 5.4 of the TR states that, "For the nozzle blend radius region, a nozzle blend radius corner fracture mechanics model [26] was used…. For the nozzle-to-vessel shell weld, the following crack models [27] were used." Reference 26 is a private communication from P. M. Besunner to P. C. Riccardella. These references did not appear in the BWRVIP-108NP report. Therefore, RAI 7 requests the BWRVIP cite any NRC SE on submittals using the FM models in these two references to save the NRC staff's review time, or provide them for NRC staff review.

The BWRVIP's October 10, 2012 response to RAI 7 indicated that the two references were used in the GE NEDO-21821 report, "Boiling Water Reactor Feedwater Nozzle/Sparger Final Report," June 1978, and the NRC's evaluation of the report was documented in NUREG-0619, "BWR Feedwater Nozzle and Control Rod Drive Return Line Nozzle Cracking," November 1980. Therefore, RAI 7 is resolved.

Based on the above evaluation, the NRC staff confirmed that the TR PFM methodology using FEM is acceptable and, therefore, the POF results presented in Section 5.5 of the TR are credible and can be used as basis in modifying the evaluation criteria (or conditions and limitations) that the NRC staff specified in the SE for the BWRVIP-108NP (reproduced in Section 2.0 of this SE).

4.3 Evaluation of the Proposed Criteria

A review of the proposed changes to the NRC staff's criteria indicated that Criterion 2 and Criterion 4 remain unchanged. Hence, examination of the revised conditional POF results can be limited to Table 5-6 (for Plant 1 recirculation inlet nozzle) of the TR, which is related to Criterion 3 and Table 5-9 (for Plant 4 recirculation outlet nozzle) of the TR, which is related to Criterion 5. The NRC staff reviewed the calculated conditional POF results in Table 5-6 and Table 5-9 for both the LTOP event and the normal operating condition. These results were obtained using the set of random parameters input consistent with that discussed in the SE on the BWRVIP-108NP report. The NRC staff found that the results of Table 5-6 and Table 5-9 are at least two orders of magnitude lower than the NRC safety goal of 5×10^{-6}/yr for the PTS concern. Consequently, the NRC staff determined that the suggested modifications, i.e., Criterion 3 ≤ 1.47, and Criterion 5 ≤ 1.59, are appropriate and acceptable.

The revised limit of 1.47 for Criterion 3 is based on the geometry of the Plant 1 recirculation inlet nozzle, and the revised limit of 1.59 for Criterion 5 is based on the geometry of the Plant 4 recirculation outlet nozzle. Deriving the criteria based on the Plant 1 recirculation inlet nozzle and the Plant 4 recirculation outlet nozzle is appropriate because Section 4.1 of this SE indicated that the Plant 1 recirculation inlet nozzle and the Plant 4 recirculation outlet nozzle are two of the four nozzles selected for detailed FEM and PFM analyses in the TR based on their bounding nozzle stresses.

Since the TR PFM results supporting the proposed criteria supplement the BWRVIP-108NP PFM results, the TR is best considered as a supplement to the BWRVIP-108NP report, not a replacement. However, it should be made clear that the conditions and limitations specified below in Section 5.0 of this SE supersede those of the SE for the BWRVIP-108NP report.

5.0 CONDITIONS AND LIMITATIONS

Licensees who plan to request relief from the ASME Code, Section XI requirements for RPV nozzle-to-vessel shell welds and nozzle inner radius sections may reference the BWRVIP-241 report as the technical basis for use of ASME Code Case N-702 as an alternative. However, each licensee should demonstrate the plant-specific applicability of the BWRVIP-241 report to their units in the relief request by demonstrating all of the following:

(1) the maximum RPV heatup/cooldown rate is limited to less than 115 ºF/hour;

<u>For recirculation inlet nozzles</u>

(2) $(pr/t)/C_{RPV} \leq 1.15$

p = RPV normal operating pressure (psi),

r = RPV inner radius (inch),
t = RPV wall thickness (inch), and
C_{RPV} = 19332;

(3) $[p(r_o^2 + r_i^2)/ (r_o^2 - r_i^2)]/C_{NOZZLE} \leq 1.47$

p = RPV normal operating pressure (psi),
r_o = nozzle outer radius (inch),
r_i = nozzle inner radius (inch), and
C_{NOZZLE} = 1637;

<u>For recirculation outlet nozzles</u>

(4) $(pr/t)/C_{RPV} \leq 1.15$

p = RPV normal operating pressure (psi),
r = RPV inner radius (inch),
t = RPV wall thickness (inch), and
C_{RPV} = 16171; and

(5) $[p(r_o^2 + r_i^2)/ (r_o^2 - r_i^2)]/C_{NOZZLE} \leq 1.59$

p = RPV normal operating pressure (psi),
r_o = nozzle outer radius (inch),
r_i = nozzle inner radius (inch), and
C_{NOZZLE} = 1977.

6.0 CONCLUSIONS

The NRC has completed the review of the TR and found that the POF for the nozzle-to-vessel shell weld and the nozzle inner radii of the limiting RPV nozzle are consistent with the NRC safety goals. Based on the PFM results, along with the BWR RPV inspection results showing no indications of inservice degradation, the NRC staff determined that the inspection of 25 percent of each RPV nozzle type each 10-year interval is justified. Licensees who plan to request relief from the ASME Code, Section XI requirements for RPV nozzle-to-vessel shell welds and nozzle inner radius sections may reference the BWRVIP-241 report as the technical basis for the use of ASME Code Case N-702 as an alternative. However, the licensees should demonstrate the plant-specific applicability of the BWRVIP-241 report to their units in the relief request by addressing the conditions and limitations specified in Section 5.0 of this SE. The licensees may submit their relief requests pursuant to 10 CFR 50.55a(a)(3)(i).

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