December 19, 2007

Rick Libra, BWRVIP Chairman
Exelon Corporation
200 Exelon Way, Suite 210 (M/S KSA-2-N)
Kennett Square, PA 19348

SUBJECT: SAFETY EVALUATION OF PROPRIETARY EPRI REPORT, "BWR VESSEL AND INTERNALS PROJECT, TECHNICAL BASIS FOR THE REDUCTION OF INSPECTION REQUIREMENTS FOR THE BOILING WATER REACTOR NOZZLE-TO-VESSEL SHELL WELDS AND NOZZLE INNER RADIUS (BWRVIP-108)"

Dear Mr. Libra:

The Nuclear Regulatory Commission (NRC) staff has completed its review of the Electric Power Research Institute (EPRI) proprietary report, “BWR Vessel and Internals Project, Technical Basis for the Reduction of Inspection Requirements for the Boiling Water Reactor Nozzle-To-Vessel Shell Welds and Nozzle Inner Radius (BWRVIP-108),” dated October 2002. This report was originally submitted to the NRC staff by a Boiling Water Reactor Vessel and Internals Project (BWRVIP) letter dated November 25, 2002, and supplemented by Tennessee Valley Authority (TVA) letter dated November 15, 2004, and BWRVIP letters dated July 25, 2006, and September 13, 2007. The BWRVIP also submitted the non-proprietary version of this report by letter dated November 21, 2007.

The BWRVIP--108 report was submitted for the purpose of presenting the technical basis to reduce inspection requirements of BWR reactor vessel nozzle-to-shell welds and nozzle blend radii. The BWRVIP-108 report was originally referenced by TVA in a letter dated July 25, 2003, to support the use of the American Society of Mechanical Engineers (ASME) Code Case N-702, “Alternative Requirements for Boiling Water Reactor (BWR) Nozzle Inner Radius and Nozzle-to-Shell Welds,” in relief requests for Browns Ferry, Units 2 and 3 from the inservice inspection (ISI) requirements of the ASME Code, Section XI, regarding the volumetric (UT) examination of reactor pressure vessel (RPV) nozzle-to-vessel shell welds and nozzle inner radius sections. ASME Code Case N-702 proposed that, “a minimum of 25% of nozzle inner radii and nozzle-to-shell welds, including at least one nozzle from each system and nominal pipe size, may be performed for Table IWB-2500-1, Examination Category B-D Item Nos. B3.10, B3.20, B3.90, and B3.100.” TVA withdrew the requests to use the BWRVIP-108 report on November 15, 2004, and was acknowledged by the NRC staff’s letter dated December 20, 2004. However, since BWRVIP-108 is the technical-basis document for ASME Code Case N-702, which is likely to be used in future plant-specific relief requests regarding RPV nozzle-to-vessel shell welds and nozzle inner radius examinations, the NRC decided to interact directly with the BWRVIP to seek completion of the review of the BWRVIP-108 report.

The BWRVIP-108 report intends to demonstrate, through a probabilistic fracture mechanics (PFM) evaluation, that the probability of failure considering these inspection changes meets the NRC requirements.

The NRC staff has reviewed the BWRVIP-108 report and the finds the report acceptable as documented in the attached staff's safety evaluation. The staff requests that the BWRVIP submit the -A version of the BWRVIP-108 report within 180 days of receipt of this letter.

From a regulatory process perspective, we recognize that BWRVIP-108 was submitted to address significant, complex technical issues raised by the NRC staff, and left unresolved by the ASME Code's consensus process, regarding ASME Code Case N-702. These issues led to the incorporation of Code Case N-702 in Revision 2 of Regulatory Guide 1.193, "ASME Code Cases Not Approved for Use." Although we have reviewed the BWRVIP-108 report as an efficient and effective way of addressing these issues after this Code Case was approved and issued by the ASME Code, this should not be taken as a precedent for how such issues should be typically handled. We would emphasize that it is the NRC position that, if at all possible, technical concerns with a Code Case should be resolved through the consensus process before a Code Case's formal issuance.

Please contact Simon Sheng of my staff at (301) 415-2708 if you have any further questions regarding this subject.

Sincerely,

/RA/

Matthew A. Mitchell, Chief
Vessels & Internals Integrity Branch
Division of Component Integrity
Office of Nuclear Reactor Regulation

Project No. 704

Enclosure:
Safety Evaluation

cc: BWRVIP Service List

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
BWRVIP-108
BWR VESSEL AND INTERNALS PROJECT TECHNICAL BASIS FOR THE REDUCTION OF INSPECTION REQUIREMENTS FOR THE BOILING WATER REACTOR NOZZLE-TO-VESSEL SHELL WELDS AND NOZZLE INNER RADII

1.0 INTRODUCTION

The Boiling Water Reactor Vessel Internals Project (BWRVIP) report BWRVIP-108, "BWR Vessel and Internals Project Technical Basis for the Reduction of Inspection Requirements for the Boiling Water Reactor Nozzle-to-Vessel Shell Welds and Nozzle Blend Radii," was originally referenced by Tennessee Valley Authority (TVA) in a letter dated July 25, 2003, to support the use of the American Society of Mechanical Engineers (ASME) Code Case N-702, "Alternative Requirements for Boiling Water Reactor (BWR) Nozzle Inner Radius and Nozzle-to-Shell Welds," in relief requests for Browns Ferry, Units 2 and 3 from the inservice inspection (ISI) requirements of the ASME Code, Section XI, regarding the volumetric (UT) examination of reactor pressure vessel (RPV) nozzle-to-vessel shell welds and nozzle inner radius sections. ASME Code Case N-702 proposed that, "a minimum of 25% of nozzle inner radii and nozzle-to-shell welds, including at least one nozzle from each system and nominal pipe size, may be performed for Table IWB-2500-1, Examination Category B-D Item Nos. B3.10, B3.20, B3.90, and B3.100." TVA withdrew the requests to use the BWRVIP-108 report on November 15, 2004, and was acknowledged by the Nuclear Regulatory Commission (NRC) staff's letter dated December 20, 2004. However, since BWRVIP-108 is the technical-basis document for ASME Code Case N-702, which is likely to be used in future plant-specific relief requests regarding RPV nozzle-to-vessel shell welds and nozzle inner radius section examinations, the NRC decided to interact directly with the BWRVIP to seek completion of the review of the BWRVIP-108 report. This review includes the BWRVIP's responses dated November 15, 2004 (through TVA), July 25, 2006, and September 13, 2007, to NRC's requests for additional information (RAIs). The BWRVIP-108 report intends to demonstrate, through a probabilistic fracture mechanics (PFM) evaluation, that the probability of failure considering these inspection changes meets the NRC requirements.

2.0 REGULATORY IMPLICATIONS

The 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). 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. Currently, 10 CFR 50.55a endorses all versions of the ASME Code, Section XI up to the 2001 Edition through the 2003 Addenda.

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-108 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-year. Therefore, upon approval of BWRVIP-108, 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. Licensees may submit relief requests in accordance with 10 CFR 50.55a(a)(3)(i).

3.0 SUMMARY OF THE BWRVIP-108 REPORT

The BWRVIP-108 report addresses the technical topics in the following order:

3.1 Background

This section of the BWRVIP-108 report presented the current ASME Code inspection requirements for RPV nozzle-to-vessel shell welds and nozzle inner radius sections, the proposed alternative, examples of ASME Code inspection requirement relaxations for some other ASME Code examination categories, an overview of issues to be discussed in this report, and the use of PFM and deterministic fracture mechanics (DFM) as analytical tools to assess the impact of reducing the inspection of these areas from 100 percent to 25 percent each 10-year interval.

3.2 Inspection History and Examination Effectiveness Based on Performance Demonstrations

Section 2 of the BWRVIP-108 report discussed the use of historical data from the Electric Power Research Institute (EPRI) - Performance Demonstration Initiative (PDI) database to establish the skill levels of personnel performing examinations on the RPV nozzle-to-vessel shell welds and the nozzle inner radius sections. PDI is a nuclear power industry initiative established to develop and administer the qualification requirements of ASME Section XI, Appendix VIII, "Performance Demonstration for Ultrasonic Examination Systems," and to develop and administer the demonstrations and qualifications of ultrasonic examinations of butt welds that are associated with other EPRI programs. The historical data is from inspections conducted to ASME Code, Section XI, Appendix VIII, Supplement 4, "Qualification Requirements for the Clad/Base Metal Interface of Reactor Vessels," which is required in conjunction with an add-on RPV nozzle-to-vessel shell weld performance demonstration (PD) from the outside surface. This section presented a series of probability of detection (POD) curves based on the PDI database to be used in the PFM analyses supporting the proposed inspection reduction. Sizing accuracy and flaw acceptability in light of examination uncertainties were also discussed in this section. Inspection history, including inspections performed during manufacturing, pre-service examinations, and ISI for the nozzle-to-vessel shell welds and the nozzle inner radius region, was presented to further support the use of the POD curves and the flaw distribution used in the BWRVIP-108 report PFM analyses.

3.3 Survey of BWR Nozzles, Data Collection and Selection of Representative Nozzles for Analysis

Section 3 of the BWRVIP-108 report discussed BWR nozzles generically. The subjects include vessel geometry data and design features, vessel/nozzle materials and fabrication, nozzles and penetration features, and the selection of nozzles for PFM and DFM analyses. Recirculation outlet, recirculation inlet, steam outlet, and core spray nozzles were selected for PFM and DFM analyses because they are typically larger in size, increasing the probability of flaw existence, and are subjected to significant stresses due to design transients and normal startup shutdown operation. The nozzles being considered in the BWRVIP-108 report were those that were fabricated with full penetration welds. As a result, the instrumentation, control rod drive (CRD), and in-core instrumentation nozzles, which use partial penetration welds, were eliminated from BWRVIP's current consideration.

3.4 Nozzle Stress Analysis

The BWRVIP performed stress analyses on representative (as opposed to bounding) core spray, recirculation inlet, recirculation outlet, and steam outlet nozzles using existing finite element method (FEM) models. Each FEM model contained a portion of the RPV vessel and a full nozzle, with boundary conditions specified around the RPV vessel portion to simulate the effect of an entire vessel. In the analysis, the SA-302, Grade B, Modified RPV material was assumed to be equivalent to SA-533 Grade B, Class 1 and the SA-336 nozzle material was assumed to be equivalent to SA-508, Class 2. Loading included pressure and thermal transients corresponding to the operating condition of each of these four types of nozzles.

The stresses in the vicinity of each nozzle from the FEM analysis were presented in the BWRVIP-108 report. The axial and hoop stresses at the surface along the nozzle circumference were also plotted for the four types of nozzles.

3.5 Probabilistic Fracture Mechanics Evaluation

The BWRVIP performed the PFM analyses using a computer program called VIPERNOZ. The PFM analysis utilizes a Monte Carlo simulation to randomly choose key parameters for each of the 1 million or so vessel-nozzle simulations to determine the probability of failure for the nozzle-to-vessel shell welds and the nozzle inner radii for different ISI sampling levels (i.e., 0 percent, 25 percent, and 90 percent). The purpose of the PFM evaluation was to assess the effect of the ISI sampling level on the probability of failure for the nozzle-to-vessel shell welds and the nozzle inner radii to justify a proposal to relax the ASME Code required 100 percent inspection each 10-year interval to 25 percent.

The key random parameters used in the PFM analysis in VIPERNOZ included a stress corrosion crack (SCC) growth rate and a fatigue crack growth rate. Another time-dependent random parameter was the SCC initiation time. The POD curve in the VIPERNOZ code was the "pass plus fail" curve for ASME Code Appendix VIII, Supplement 4 examinations. Consistent with the approach used in BWRVIP's evaluation for axial welds as discussed in the supplement dated March 7, 2000, to the final SE on BWRVIP-05, "BWR Vessel and Internals Project, BWR Reactor Pressure Vessel Shell Weld Inspection Recommendations (BWRVIP-05)," the BWRVIP-108 crack size distribution was based on Pressure Vessel Research Users Facility (PVRUF) data. The BWRVIP performed PFM evaluations for 0, 25, and 90 percent ISI sampling levels, from which the PFM results do not show a single failure in one million simulations (10 million for some cases) for any of the four nozzle geometries. However, after a revision of input values for some variables and modifications of the PFM methodology as documented in the BWRVIP's September 13, 2007, RAI response, the probabilities of failure for all the RPV nozzles considered in the BWRVIP-108 report can be obtained from the PFM analyses based on the calculated number of failed vessels. This revision of inputs and of the PFM methodology which supplement the original BWRVIP-108 report consisted of:

Revised input parameter values:

- Number of flaws per nozzle inner radii = 0.1,
- Upper shelf K_{Ic} = 200 ksi $\sqrt{}$inch, and
- SCC K threshold = 10 ksi $\sqrt{}$inch.

Revised PFM methodology:

- The SCC initiation time was revised to 1/5 of that in the original BWRVIP-108 report,
- Initial RT_{ndt} for the nozzle forging was changed to a new random variable with a mean value of 24.13 °F and a standard deviation of 26.48 °F,
- The SCC growth law was based on BWRVIP-60-A, "BWRVIP-60-A: BWR Vessel and Internals Project, Evaluation of Stress Corrosion Crack Growth in Low Alloy Steel Vessel Materials in the BWR Environment,"
- K_{Ic} was changed to a new random variable with a mean value as that in the ASME Code, Section XI, Appendix A and a 15 percent of the mean K_{Ic} as the standard deviation,
- The flaw models were expanded to include circumferential cracks in a cylinder,
- Copper content (percent Cu) for the nozzle forging was changed to a new random variable with a mean value of 0.09189 and a standard deviation of 0.04407, and
- Nickel content (percent Ni) for the nozzle forging was changed to a new random variable with a mean value of 0.78 and a standard deviation of 0.068.

Based on the probabilities of failure for the RPV nozzles in the September 13, 2007, RAI response, the BWRVIP concluded that these probabilities of failure are consistent with NRC safety goals.

4.0 STAFF EVALUATION

The staff's evaluation of the BWRVIP-108 report focused on the acceptability of the technical basis for the proposed alternative inspection for RPV nozzle-to-vessel shell welds and nozzle inner radii. For ease of referencing the essential elements of the BWRVIP-108 report, this section of the SE is structured according to the organization of the BWRVIP-108 report.

4.1 Background

This section of the BWRVIP-108 report provided general background information. The details of the PFM and DFM methodologies and results in support of the proposed relaxation of ISI requirements were discussed in other sections of the BWRVIP-108 report. This section had no effect on the staff's evaluation.

4.2 Inspection History and Examination Effectiveness Based on Performance Demonstrations

By letter dated March 24, 2004, the staff asked a number of RAIs (RAI 2-14 to RAI 2-19) regarding this subject, especially about the POD and the probability of correct flaw sizing (PCS) curves. The BWRVIP's November 15, 2004, responses to these RAIs were not completely satisfactory. To resolve the remaining issue about the compatibility of the PVRUF fabrication flaw data and the RPV nozzle ISI flaw data, the staff requested, in a letter dated September 6, 2005, that the BWRVIP categorize the nozzle-to-vessel shell weld inspection data according to the various UT examination requirements such as those in ASME Code, Section XI, Appendix VIII, Supplements 4 and 6 and Appendix VIII, Supplement 7. A similar request was also made for the nozzle inner radius inspection data according to requirements in Report GE-NE-523-A71-0594, "Alternate BWR Feedwater Nozzle Inspection Requirements," ASME Code Case N-552, "Qualification for Nozzle Inside Radius Section from the Outside Surface," and Appendix VIII, Supplement 5.

On November 22, 2000, an NRC rulemaking (10 CFR 50.55a) made performance-based Appendix VIII, Supplements 4 and 6 mandatory for the UT qualification of procedures and personnel. The major difference between combined Supplement 4 and 6 RPV weld examinations and RPV-to-nozzle shell weld examinations are the limitations caused by the proximity of nozzle configurations to the RPV-to-nozzle shell welds. On November 22, 2002, NRC rulemaking made ASME Code, Section XI, Appendix VIII, Supplement 7 mandatory which uses procedures and personnel qualified to Supplements 4 and 6. Supplement 7 has an add-on PD for examinations conducted from the nozzle bore.

In response to the staff's September 6, 2005, RAI, the BWRVIP indicated that of the 1057 BWR RPV nozzle-to-vessel shell welds, 384 (36 percent) nozzle-to-vessel shell welds have received performance-based UT examinations. Adjusting for coverage limitations, approximately 26 percent of the total nozzle-to-vessel shell weld volume has received performance-based UT examination. Of the 1055 BWR RPV nozzle inner radii, there were 359 (34 percent) acceptable nozzle inner radius examinations performed with either ASME Code, Section XI, Appendix VIII, Supplement 5 or ASME Code Case N-522 qualified procedures and personnel. Every type of BWR RPV nozzle-to-vessel shell weld and nozzle inner radii was examined with performance-based UT qualified procedure and personnel.

BWRVIP-108 used historical data from the EPRI - PDI database to establish the skill levels of personnel performing examinations on the RPV-to-nozzle shell welds and the nozzle inner radius regions. The database contains detailed information associated with the administration of the supplements to the ASME Code, Section XI, Appendix VIII. The historical data is from Appendix VIII, Supplement 4 examinations. ASME Code, Section XI, Appendix VIII, Supplement 4 is required in conjunction with an add-on RPV-to-nozzle shell weld PD from the outside surface. The Supplement 4 techniques used for detecting flaws perpendicular to the vessel shell weld from the outside surface are similar to the techniques used for detecting radia l flaws at the nozzle inner radius region from the outside surface.

The BWRVIP-108 report used Supplement 4 PD data to establish the POD and the PCS curves. This data was from both manual and automated UT techniques used for Supplement 4 PDs. The PDs used through-wall planar flaws with depths greater than 50 percent of the ASME Code, Section XI, IWB-3500 acceptable flaw depths. The BWRVIP-108 report provided POD and PCS curves for personnel passing the PD test and for personnel passing plus those that missed passing the PD by one detection or one false call. The curves made from data of all personnel passing the PD test showed that essentially all flaws greater than 1/4-inch were detected and sized correctly. However, one of the stipulations for passing is to detect all of the flaws. The curves made from data of all personnel completing the PD test (which included individuals that failed) showed that essentially all flaws greater than ½-inch were detected and sized correctly (within the 0.15-inch root mean square measurement accuracy requirement). The curves made from data that included personnel not passing the PDs are more indicative of personnel not subject to the rigorous training prior to a PD and are considered by the staff to include conservatism within the POD and PCS curves. Therefore, the POD and PCS curves for personnel passing and failing the PDs are acceptable for use in the PFM evaluation.

4.3 Survey of BWR Nozzles, Data Collection and Selection of Representative Nozzles for Analysis

Section 3 of the BWRVIP-108 report presented vessel geometries for all U.S. BWR RPVs. The staff found that, except for Nine Mile Point, Unit 1 and Oyster Creek, Unit 1 having vessel inner radius-to-thickness ratios (R_i/t) of approximately 15, the R_i/t values for all other U.S. BWR RPVs are about 20. The impact of this difference in R_i/t ratios on nozzle-to-vessel shell welds and nozzle inner radius stresses will be discussed in Section 4.4 of this SE. Section 3 of the BWRVIP-108 report addressed vessel geometry data and design features, vessel/nozzle materials and fabrication, nozzle and penetration features, and the selection of nozzles for PFM and DFM analyses. The BWRVIP appropriately selected representative core spray, recirculation inlet, recirculation outlet, and steam outlet nozzles for PFM and DFM analyses because they are typically larger in size, increasing the probability of flaw existence, and are subjected to significant stresses (stresses are proportional to nozzle radius) due to design transients and normal startup shutdown operation. The BWRVIP-108 report considered nozzles which are joined with full penetration welds. As a result, the instrumentation, CRD, and in-core instrumentation nozzles, which use partial penetration welds, are outside the scope of the BWRVIP-108 report.

4.4 Nozzle Stress Analysis

To best utilize its resources, the BWRVIP made a decision to use existing FEM models for the four representative nozzles mentioned above. These were, specifically, an Oyster Creek core spray nozzle, a Brunswick recirculation inlet nozzle, a Pilgrim recirculation outlet nozzle, and an Oyster Creek steam outlet nozzle. Since stresses due to pressure are proportional to R_i/t, using the Oyster Creek core spray and steam outlet nozzle models based on their RPV R_i/t of 15 may not have been completely representative because all but two RPVs have R_i/t of 20. The nozzles with R_i/t of 20 may have stresses due to pressure 33 percent higher than those generated by the Oyster Creek nozzle FEM models. However, the overall impact is less because the thermal stresses are not proportional to R_i/t. This concern was resolved based on the PFM results shown in Figure 5 of BWRVIP's July 25, 2006, response. This figure demonstrated that for all sensitivity cases, which were performed to study the sensitivity of each key random variable on the final results, the conditional probabilities of failure, P(F|E)s, for the Oyster Creek core spray and steam outlet nozzles are an order of magnitude lower than the other two nozzles. For typical PFM analyses, an increase of stresses due to pressure by 33 percent will not increase the P(F|E) 10 fold. Therefore, the Brunswick recirculation inlet nozzle and the Pilgrim recirculation outlet nozzle remain the limiting nozzles.

In addition, by letter dated March 24, 2004, the staff issued a number of RAIs regarding the nozzle stress analyses, and the BWRVIP provided its response in its November 15, 2004, letter. RAI 2-2 requested an assessment of the impact of the assumption that the RPV material SA-302, Grade B, Modified is equivalent to SA-533 Grade B, Class 1 and the nozzle material SA-336 is equivalent to SA-508, Class 2 on nozzle stresses. The BWRVIP presented a comparison between these materials, which indicated that the mechanical material properties of SA-302 and SA-533 were about the same while the largest difference for thermal properties was 5.62 percent in diffusivity at 100 °F. A similar conclusion was reached from a comparison of SA-336 and SA-508 material, except that the largest corresponding difference for diffusivity was

1.5 percent. The staff determined that these differences will have insignificant effect on the analysis results, especially on the PFM results, since for any of the one million deterministic simulations in a PFM calculation a random parameter can vary from its mean value significantly.

RAIs 2-3, 2-4, and 2-6 were related to FEM modeling concerns, including the simulation of the applied moment by a distributed force, exclusion of twisting moment on nozzles, and the specification of boundary conditions. Satisfactory responses to these concerns were provided by the BWRVIP in TVA's November 15, 2004, response, which demonstrated that the FEM models are reasonably good and adequate for the current application.

RAI 2-5 requested justification for selection of the thermal transients for the four types of nozzles. The BWRVIP replied that several thermal cycle diagrams for various plants were reviewed and the selected transients were considered representative. Further, the BWRVIP cited information which indicated that actual transients were much less severe than those assumed in the thermal stress analyses. Considering the conservative nature of the assumed transients versus the actual transients, and the fact that many assumed transients for emergency conditions are based on near-instantaneous temperature/flow changes, the staff considers the assumed transients appropriate.

RAI 2-7 requested the physical explanation of the sinusoidal stress distribution at the nozzle inner radii and the nozzle-to-vessel shell weld of all four nozzles. The BWRVIP replied that the shell shape has a significant effect on the stress in the nozzle inner radius region. To substantiate this point, the BWRVIP reproduced stress distributions for an RPV nozzle from EPRI Report NP-339, "Improved Evaluation of Nozzle Corner Cracking," in their response to RAI 2-7. This information showed that the nozzle stress patterns from the EPRI report were similar to the current application, and therefore adds credibility to BWRVIP's nozzle stress analysis results. Since all RAIs for this section have been resolved satisfactorily, the staff concludes that the FEM stress results are appropriate and can be used in the PFM analyses.

4.5 Probabilistic Fracture Mechanics Evaluation

The PFM methodology used in BWRVIP-108 was similar to that in the staff approved BWRVIP-05 report. Although modifications had been made, such as the fabrication flaw size distribution having been revised from the Marshall distribution to the PVRUF distribution, the core Monte Carlo simulation algorism remained the same. The same limiting loading event, a low temperature over-pressure (LTOP) transient that was used in the BWRVIP-05 report, was used in this application. The pressure for this loading event was 1150 psi, and the temperature was 88 °F. The staff asked a number of RAIs regarding the PFM analyses, mostly about justification for deviations from the established staff positions on the PFM analysis as stated in the final SE dated July 28, 1998, for the BWRVIP-05 report. The BWRVIP provided its responses in TVA's letter dated November 15, 2004, and the BWRVIP letter dated July 25, 2006.

In the staff's letter dated March 24, 2004, RAI 2-8 requested test and service data to support a PFM assumption of a 2 to 1 flaw aspect ratio for all assumed flaws which remains the same during crack growth. The BWRVIP's November 15, 2004, response to RAI 2-8 stated that a larger crack aspect ratio was not used due to the weld configurations, the crack propagation along the welds, and the constant crack aspect ratio used in the crack growth analyses. Since inspection history shows no apparent degradation or failure mechanism in the nozzle-to-vessel shell welds and the nozzle inner radii, and since flaw aspect ratio is a secondary factor in a PFM analysis, the staff concludes that using this assumption will still provide meaningful PFM results.

RAI 2-9 raised a series of questions about the consistency of the PFM methodologies in the BWRVIP-108 and BWRVIP-05 reports. RAI 2-9a asked about the use of RPV copper and nickel weight percentages as random variables under the assumed negligible fluence condition. The BWRVIP's response in its letter dated November 15, 2004, clarified that copper and nickel contents have a negligible effect in the PFM results, and the final adjusted reference temperature, ART, depends primarily on the initial reference temperature (initial RT_{NDT}). Therefore, RAI 2-9a is resolved.

RAI 2-9b, which was related to the first item of the revised PFM methodology listed in Section 3.5 of this SE, requested test data supporting the SCC initiation equation used in the BWRVIP-108 report. The BWRVIP's November 15, 2004, letter provided relevant test data from which the mean SCC initiation time (a random parameter in the PFM analysis) was derived. The SCC initiation time is the time needed for an SCC crack to develop. Therefore, a longer initiation time would decrease the P(F|E) of the nozzle. The original BWRVIP-108 report assumed that the nozzle weld cladding is non-susceptible to SCC and applied a factor of 5 to the curve based on cast austenitic stainless steel weld data as the mean SCC initiation curve in the PFM analyses. Since this assumption was not justified, the staff requested that the BWRVIP use a mean curve without the factor of 5 in this evaluation. This change increased the P(F|E) for nozzles significantly. The BWRVIP's September 13, 2007, response contains PFM results using the mean curve without the factor of 5 on the SCC initiation curve. Therefore, RAI 2-9b is resolved.

RAI 2-9c, which was related to the second item of the revised PFM methodology listed in Section 3.5 of this SE, requested justification for using -20 °F as the mean RT_{NDT} for the weld and forging. The BWRVIP's November 15, 2004, response stated that -20 °F was an average value

of RPV shell vertical weld data for the BWR fleet, while 24.13 °F was the average value for the SA508 Class 1 and 2 RPV forgings. The BWRVIP's September 13, 2007, response contains PFM results using 24.13 °F as the mean initial RT_{NDT} for the RPV forging. Therefore, RAI 2-9c is resolved.

RAI 2-9d requested justification for using a mean fatigue crack growth rate based on limited data. The BWRVIP's November 15, 2004, response includes a comparison of the BWRVIP mean fatigue crack growth rate with the ASME Code, Section XI linear (1974) and bilinear (1986) crack growth rates. The staff determined that, except for the bilinear curve with K_{min}/K_{max} greater than 0.65, where K_{min} and K_{max} is the minimum and maximum applied stress intensity factor values, the BWRVIP mean fatigue crack growth rate is in reasonable agreement with those used by the BWRVIP for comparison. Regardless of whether the BWRVIP mean fatigue crack growth rate is bounding or not, since the fatigue crack growth is significantly less than the SCC crack growth, its impact to the final PFM results is small. Therefore, the staff considers that RAI 2-9d is resolved.

RAI 2-9e, which was related to the first revised input parameter value listed in Section 3.5 of this SE, requested a basis for the assumed flaw density, flaw distribution, flaw number due to SSC initiation, and POD curves for the nozzle-to-vessel shell welds and nozzle inner radii. The BWRVIP's November 15, 2004, response stated that the flaw distribution was based on the PVRUF data, which represents a major improvement in the RPV probabilistic assessments. It also stated that the number of flaws per nozzle for the nozzle-to-vessel shell welds used in the PFM analyses was based on a flaw density of 30 flaws/m^3.

In the supplement dated March 7, 2000, to the final SE on BWRVIP-05, the NRC staff established an interim position regarding the flaw density for surface-breaking flaws in RPV axial welds: the NRC determined that the 95 percent confidence bound for the frequency of a surface-breaking flaw is 3 per vessel. This determination was based on the results of no surface-breaking flaws with inspection of 800 feet of PVRUF welds. Subsequently, an expert elicitation was conducted to further refine the staff's position on flaw distributions. The expert elicitation results, along with experimental evidence, physical models, and conservative judgments, formed the basis for the flaw models used in the PFM analyses supporting the current NRC effort in the pressurized thermal shock (PTS) rule revision, as described in draft NUREG-1806, "Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10CFR 50.61): Summary Report," Volume 1, dated May 24, 2006. In draft NUREG-1806, the surface-breaking flaws are estimated as 1/1000 of the observed density of buried cladding flaws, and the resulting flaw density for surface-breaking flaws is 0.01 flaw/ft^3 (see draft NUREG-1806, Volume 1, Figure 7.3). Based on the nozzle-to-vessel shell weld area for a representative RPV nozzle and the accepted flaw density, the BWRVIP-108 flaw density assumption of 1 flaw per nozzle is conservative, and the PFM results reported in BWRVIP's September 13, 2007, response are appropriate. Therefore, RAI 2-9e is resolved.

RAI 2-10 requested that the BWRVIP perform a sensitivity study using the PFM approaches and random variables in accordance with the positions established in the final SE for the BWRVIP-05 report. In response to this RAI, the BWRVIP's July 25, 2006, submittal provided sensitivity studies by varying the mean value or the standard deviation of certain key random variables. All eight cases presented below show higher P(F|E)s:

- Case 1 used a forging initial RT_{NDT} of 24.13 °F instead of -20 °F,
- Case 2 used an SCC initiation time of $0.842x10^{20}\sigma^{-10.5}$ instead of $4.21x10^{20}\sigma^{-10.5}$, where σ is the applied stress, and used the Case 1 initial RT_{NDT} of 24.13 °F,
- Case 3 used a forging flaw density of 0.3 flaw per nozzle instead of 0.001 and used the Case 1 initial RT_{NDT} of 24.13 °F,
- Case 4 used a standard deviation of fracture toughness K_{Ic} of 15 percent of its mean value instead of 0 percent and used the Case 1 initial RT_{NDT} of 24.13 °F,
- Case 5 used a standard deviation of the upper-shelf K_{Ic} of 15 percent of its mean value instead of 2.5 percent and used the Case 1 initial RT_{NDT} of 24.13 °F,
-
- Case 6 used an SCC growth rate of $1.18^{-12} K^4$ instead of $1.18^{-13} K^4$ and used the Case 1 initial RT_{NDT} of 24.13 °F,
- Case 7 used a mean SCC growth threshold of 10 ksi√inch instead of 33 ksi√inch and used the Case 1 initial RT_{NDT} of 24.13 °F, and
- Case 8 is similar to Case 6 but use a forging initial RT_{NDT} of -20 °F.

The PFM results from the sensitivity studies described above are informative. However, the staff concluded that the combined effect of Cases 1 to 7 should be evaluated because they, collectively, reflect the relevant material property for forging and represent established positions regarding PFM analysis inputs as a result of the BWRVIP-05 review. The BWRVIP addressed the staff's position by performing additional PFM analyses for the recirculation inlet nozzle, combining these effects, but with modifications to upper-shelf K_{Ic} (Case 5 above) and SCC growth rate (Cases 6 and 7). Specifically, the BWRVIP's final PFM analyses used a constant upper-shelf K_{Ic} of 200 ksi√inch, an SCC growth rate from the BWRVIP-60-A report, and an SCC growth threshold of 10 ksi√inch. Two sets of inputs and their corresponding PFM results designated as Revision 1 and Revision 2 are documented in BWRVIP's response dated September 13, 2007.

Using a constant upper-shelf K_{Ic} of 200 ksi√inch in the BWRVIP's final PFM analysis is consistent with conventional PFM analyses and is conservative, considering that the 2004 Edition of the ASME Code, Section XI, Appendix A revised the maximum K_{Ic} to 220 ksi√inch. Using the approved BWRVIP-60-A SCC growth rate for low alloy steels in the BWR environment in the BWRVIP's final PFM analyses is appropriate. Although there is no SCC data (BWRVIP-60-A Figures 4-1, 4-2, and 4-8) which was conducted at a K of 10 ksi√inch or below, using an SCC growth threshold of 10 ksi√inch appears to be reasonable. Whether to use a SCC growth threshold of 0 ksi√inch (no threshold) or 10 ksi√inch is a secondary issue as evidenced by the close P(F|E) values shown in Table 4 of the BWRVIP's September 13, 2007, response based on two PFM analyses using SCC growth thresholds of 20 ksi√inch and 10 ksi√inch for nozzle inner radii under the LTOP event. Although the two PFM analyses also treated upper-shelf K_{Ic} differently, its effect on the P(F|E)s under the LTOP event should be small.

The fourth item of the revised PFM methodology listed in Section 3.5 of this SE related to treating K_{Ic} as a new random variable with a mean value represented by the K_{Ic} curve from the ASME Code, Section XI, Appendix A and a value of 15 percent of the mean K_{Ic} curve as the standard deviation. This is conservative because the current PTS rule is based on the results from PFM analyses using 10 percent of the mean K_{Ic} as the standard deviation. The fifth item of the revised PFM methodology listed in Section 3.5 of this SE was related to adding a flaw model considering circumferential flaws in a cylinder. The BWRVIP's September 13, 2007, response indicated that the P(F|E) for a circumferential crack in the nozzle-to-shell weld is insignificant. This finding is noteworthy, though it does not affect the staff's evaluation. The ASME Code approach and the draft NUREG-1806 approach consider only axial flaws in axial welds and only circumferential flaws in circumferential welds. Since BWRVIP-108 Figures 4-34 to 4-37 show that the nozzle hoop stress due to pressure is about three times larger than the axial stress due to pressure, the hoop stress due to thermal, or the axial stress due to thermal, considering only circumferential flaws in the nozzle-to-vessel shell welds should lower the P(F|E) for the welds significantly. The BWRVIP may not have taken the full benefit of the permitted flaw orientation assumption. The last two items of the revised PFM methodology listed in Section 3.5 of this SE were related to treating the copper and nickel contents of the forging as new random variables. These changes should have insignificant impact because the forging is located at a low-fluence region and embrittlement due to neutron irradiation should be limited.

In BWRVIP's response dated September 13, 2007, the BWRVIP used the final, or Revision 2, inputs specified in Table 3 of the response to produce the PFM results presented in Table 4 of the response. These PFM results show that the total probability of failure for the recirculation inlet nozzle inner radii is 1.19E-7 for the same LTOP event used in BWRVIP-05 and 1.98E-6 for the normal operation. The LTOP event frequency was assumed to be 1E-3 per reactor year, consistent with that in the final SE on the BWRVIP-05 report. The staff, hence, agrees with the BWRVIP conclusion that these probabilities of failure are consistent with NRC safety goals.

Performing the final PFM analysis only for the recirculation inlet nozzle is acceptable because the July 25, 2006, response demonstrated that the recirculation inlet nozzle is limiting for all sensitivity cases based on the four RPV nozzles. Although the BWRVIP did not calculate the corresponding total nozzle failure frequency for the recirculation inlet nozzle-to-vessel shell weld using the inputs from Table 3 of the BWRVIP's September 13, 2007, response, the staff determined that the above BWRVIP conclusion applies to this weld as well. This is because the Revision 1 PFM results using inputs from Table 1 of the BWRVIP's September 13, 2007, response, which differ from the Table 3 inputs only in the treatment of SCC growth threshold (20 ksi√inch versus 10 ksi√inch) and the upper-shelf K_{Ic} (a random upper-shelf K_{Ic} with a mean value of 200 ksi√inch and a standard deviation of 5 ksi√inch versus a constant upper-shelf K_{Ic} of 200 ksi√inch), showed that the total probabilities of failure for the nozzle inner radii bound the total probabilities of failure for the nozzle-to-vessel shell weld by a factor of 2 for the LTOP case and a factor of 243 for the normal case. It is extremely unlikely that this bounding trend would be reversed by simply using the SCC growth threshold of 10 ksi√inch and a constant upper-shelf K_{Ic} of 200 ksi√inch instead in the PFM analysis.

5.0 PLANT-SPECIFIC APPLICABILITY

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-108 report as the technical basis for the use of ASME Code Case N-702 as an alternative. However, each licensee should demonstrate the plant-specific applicability of the BWRVIP-108 report to their units in the relief request by showing that all the following general and nozzle-specific criteria are satisfied:

(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,
r = RPV inner radius,
t = RPV wall thickness, and
C_{RPV} = 19332 (i.e., 1000 psi x 110 inch/5.69 inch, based on the BWRVIP-108 recirculation inlet nozzle/RPV FEM model);

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

p = RPV normal operating pressure,
r_o = nozzle outer radius,
r_i = nozzle inner radius, and
C_{NOZZLE} = 1637 [i.e., 1000 psi x$(13.988^2 + 6.875^2)/(13.988^2 - 6.875^2)$], based on the BWRVIP-108 recirculation inlet nozzle/RPV FEM model];

<u>For recirculation outlet nozzles</u>

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

p = RPV normal operating pressure,
r = RPV inner radius,

t = RPV wall thickness, and
C_{RPV} = 16171 (i.e., 1000 psi x 113.2 inch/7.0 inch, based on the BWRVIP-108 recirculation outlet nozzle/RPV FEM model); and

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

p = RPV normal operating pressure,
r_o = nozzle outer radius,
r_i = nozzle inner radius, and
C_{NOZZLE} = 1977 [i.e., 1000 psi x($22.31^2 + 12.78^2$)/ ($22.31^2 – 12.78^2$)], based on the BWRVIP-108 recirculation outlet nozzle/RPV FEM model].

It should be noted that only the recirculation inlet and outlet nozzles need to be checked because the P(F|E)s for other nozzles are an order of magnitude lower. Also, only the driving force needs to be checked because the nozzle material fracture toughness-related RT_{NDT} values used in the PFM analyses were based on data from the entire fleet of BWR RPVs.

6.0 CONCLUSIONS

The NRC has completed the review of the BWRVIP-108 report and found that the total probabilities of failure 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 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-108 report as the technical basis for the use of ASME Code Case N-702 as an alternative. However, each licensee should demonstrate the plant-specific applicability of the BWRVIP-108 report to their units in the relief request by meeting the criteria discussed in Section 5 of this SER. The licensees may submit their relief requests pursuant to 10 CFR 50.55a(a)(3)(i).

The supplemental information concerning the additional PFM analyses that was provided in the BWRVIP letter dated September 13, 2007, should be incorporated in the -A version of the BWRVIP-108 report.

ASME Code Case N-702 has been incorporated in Revision 2 of Regulatory Guide 1.193, “ASME Code Cases Not Approved for Use.” Based upon the review of BWRVIP-108, the staff will consider the approval or conditional approval of the ASME Code Case N-702 in the next revision (Revision 16) of Regulatory Guide 1.147, “In Service Inspection Code Case Acceptability, ASME Section XI Division 1.”

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