August 22, 2012

Dennis Madison
Southern Nuclear
Chairman, BWR Vessel and Internals Project
3420 Hillview Avenue
Palo Alto, CA 94304-1395

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION RELATED TO BWRVIP-100, REVISION 1, BWR VESSEL AND INTERNALS PROJECT - UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS (TAC NO. ME8329)

Dear Mr. Madison:

By letter dated February 7, 2012, the Electric Power Research Institute (EPRI) submitted for U.S. Nuclear Regulatory Commission staff review topical report BWRVIP-100, Revision 1: “BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds.” Upon review of the information provided, the NRC staff has determined that additional information is needed to complete the review. On August 14, 2012, Mr. Larry Steinert representing EPRI and I agreed that the NRC staff will receive your response to the enclosed Request for Additional Information (RAI) questions by January 31, 2013. If you have any questions regarding the enclosed RAI questions, please contact me at 301-415-7297.

Sincerely,

/RA/

Joseph J. Holonich, Sr. Project Manager
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 704

Enclosure:
RAI questions

cc w/encl: See next page

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REQUEST FOR ADDITIONAL INFORMATION

BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO BWRVIP-100, REVISION 1, BWR [BOILING WATER REACTOR] VESSEL AND

INTERNALS PROJECT - UPDATED ASSESSEMENT OF THEFRACTURE TOUGHNESS OF

IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS

ELECTRIC POWER RESEARCH INSTITUTE

PROJECT NO. 704

RAI 1

Section 2.2.1 of BWRVIP-100, Revision 1, “BWR [Boiling Water Reactor] Vessel and Internals Project: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds” (Ref. 1, referred to hereafter as “the report”) states that a power law fit was used to construct a line that bounds the available data for the power loss coefficient (C) as a function of fluence. The report further states that the power law fit for n was defined as a function of fluence so that when it is used in combination with the bounding relationship for C, the resulting predicted material resistance to fracture as a function of ductile-crack extension (J-R) curves match or are conservative compared to the experimental J-R curves.

The proposed lower bound fluence-dependent J-R curve does not bound one data point in Table 2-1 (the only point not bounded by the curve in Figure 2-4 of the report). Considering the significant scatter of the data points shown in Figures 2-4 and 2-5 of the report, discuss the necessity of proposing a J-R model that is more conservative than the model based on Equations 2-2 and 2-3 of the report.

RAI 2

Section 2.3.4 of the report provides a discussion of the basis for the fracture toughness values to be used for the linear elastic fracture mechanics (LEFM) analyses of core shrouds with fluences equal to or greater than a particular value. The proposed fracture toughness K_{IC} value in the fluence range where LEFM must be used is justified based on M. L. Herrera, et al., “Evaluation of the Effects of Irradiation on the Fracture Toughness of BWR Internal Components,” ICONE, Vol 5, American Society of Mechanical Engineers 1996, and W. J. Mills, “Fracture Toughness of Type 304 and 316 Stainless Steel and Their Welds,” Intl. Materials Reviews, Vol. 42, No. 2, 1997, pp. 45-82. Section 2.3.4 states that [Mills] provides a range for the saturation fracture toughness K_{JC} values for welds exceeding a particular dpa (displacements per atom) value. Based on these results, Section 2.3.4 indicated that the proposed K_{IC} value was considered reasonably conservative.

ENCLOSURE

Table 2-2 of the report lists several K_{IC} values determined for specimens over a range of neutron fluence/dpa values. Some of these K_{IC} values are lower than the proposed value to be used for the LEFM analyses.

Based on the above, since the proposed K_{IC} value does not bound all the K_{IC} values from the literature or the data listed in Table 2-2 of the report, justify why the use of K_{IC} value proposed for the LEFM analyses of core shrouds above a particular fluence value continues to be conservative, or propose a different K_{IC} value to be used in these evaluations.

RAI 3

The potential for a synergistic effect of thermal aging embrittlement and irradiation embrittlement on austenitic stainless steel weld materials was identified as an open issue in the NRC staff's approval letter of BWRVIP-100-A, "BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," dated November 1, 2007 (Ref. 2). Reference 2 notes that data on the delta ferrite contents of stainless steel weld metals was not included in BWRVIP-100-A (Ref. 3), and should be included in future work (i.e. if additional weld metal specimens are tested) so that an effective assessment of synergistic effects of neutron embrittlement and thermal embrittlement can be made. Delta ferrite content is a key parameter used in assessing thermal aging embrittlement of cast austenitic stainless steels and austenitic stainless steel weld metals. The NRC staff notes that only one new weld metal specimen was included in the report, a transversely oriented compact tension specimen of Type 316L weld metal. The report does not provide the delta ferrite content of this weld.

The response to RAI 100-3(b) related to BWRVIP-100, Revision 0, addressed the similarity of the thermal aging history of the weld materials tested to the thermal aging history of weld metals in operating reactors. While the NRC staff agrees the response demonstrated that the test materials should have similar thermal aging exposure to those in operating reactors for a given neutron fluence, the potential for a synergistic effect of thermal aging embrittlement combined with neutron embrittlement could vary based on the delta ferrite content of the weld materials. Therefore, in order for the NRC staff to assess whether the weld metal results should be considered bounding for all weld materials, the NRC staff requests the following:

1. Provide the delta ferrite content in terms of weight percent for all the weld materials listed in the report.

2. If the delta ferrite content is not available, provide an estimate of the delta ferrite content based on the chemical composition of the weld materials.

3. Provide a discussion of why the fracture toughness values in the report are considered bounding for all BWR core shroud weld materials, considering the effects of variation of delta ferrite content and chemical composition on the potential synergistic effects of thermal aging embrittlement and neutron irradiation embrittlement.

RAI 4

For LEFM evaluations of core shrouds with fluences in an intermediate range, Section 4 of the report recommends the use of a particular K_{IC} fracture toughness. For LEFM evaluation of core shrouds with fluences in a higher range, the report recommends the use of a different, lower K_{IC} value. These K_{IC} values are also recommended in BWRVIP-100-A, “BWR Vessel and Internals Project Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds (Ref. 3),” and BWRVIP-76-A, “BWR Vessel and Internals Project: BWR Core Shroud Inspection and Flaw Evaluation Guidelines (Ref. 4),” and the higher K_{IC} value was included in predecessor documents such as BWRVIP-01, “BWR Vessel and Internals Project: BWR Core Shroud Inspection and Flaw Evaluation Guideline (Ref. 5),” and BWRVIP-63, “BWR Vessel and Internals Project Shroud Vertical Weld Inspection and Evaluation Guidelines (Ref. 6).” BWRVIP-01 Section 4.3, p. 4-6 states that, “a conservative K_{IC} value of { } ksi√in, based on the material J-R curve of Figure 4-2 [of BWRVIP-01], can be used in [LEFM evaluations].” Figure 4-2 of BWRVIP-01 shows a J-R curve based on two stainless steel specimens irradiated to a particular fluence. The NRC staff agrees that a K_{IC} value converted from a J_{IC} value based on this figure would be at least equal to the K_{IC} value recommended for LEFM analyses of materials fluence in the intermediate range. However, the amount of data on which this K_{IC} value is apparently based appears very limited. Much more J-R data now exists, as documented in the report. Further, no data supporting the lower K_{IC} value for the higher fluence range have been presented.

The NRC staff therefore requests the following information:

1. Provide the basis for the use of the two different K_{IC} values for LEFM evaluations of core shrouds as described above. Specifically, describe the fracture toughness data used to derive the values including:

    a. Material type (e.g. Type 304 stainless), condition (i.e. solution annealed, cold worked)

    b. Neutron fluence(s)

    c. Specimen type(s)

    d. Test procedures or standards.

2. Justify why the two K_{IC} values are conservative for LEFM evaluations of BWR core shroud materials over the applicable neutron fluence ranges.

RAI 5

The NRC staff reviewed the margin assessment based on Figures 3-1 through 3-9 of the report and agrees that evaluation using either the limit load method or LEFM method results in the lowest margins for all the cases over the fluence range and range of flaw sizes and configurations evaluated. However, based on the trends in Figures 3-7 through 3-9 it appears that for 360° part-throughwall flaws, the elastic-plastic fracture mechanics (EPFM) method

could potentially produce the lowest margins for flaws deeper than 1 inch at the higher end of the fluence range.
The NRC staff requests that EPRI discuss whether margin evaluations have been performed for such flaw configurations, and whether there are certain conditions under which EPFM may be the most limiting, such as higher fluences. If EPFM can be limiting for certain flaw configurations, justify not recommending the evaluation of flaws based on the most limiting margin determined by the LEFM, limit load and EPFM methods.

RAI 6

Section 3.2.1 of the report provides the results of margins assessments in which the margins for three different evaluation methods, limit load, LEFM, and EPFM, are compared over a particular fluence range. The margin assessments for through-wall cracks, the results of which are shown in Figures 3-1 through 3-6, used a particular fracture toughness (K_{IC}) value for the LEFM analyses. The margin assessments for part-throughwall 360° flaws, the results of which are shown in Figures 3-7 through 3-9 of the report, used two different fracture toughness values for LEFM analyses. It is not clear why both K_{IC} values were not used in the margin evaluations for throughwall flaws. It appears that if the lower of the two fracture toughness values had been used for the throughwall flaw margin assessments, the LEFM margins would be below the ASME Code, Section XI required margins for faulted conditions for throughwall flaws with greater degradation levels (The degradation level of the throughwall flaws represents the percentage of the weld cross-sectional area that is cracked.). This is because the LEFM margins for higher degradation levels were already close to the ASME Code minimum margin.

The NRC staff therefore requests that EPRI explain why LEFM margins were not calculated using the same two fracture toughness (K_{IC}) values used in the margin evaluation of the part-throughwall flaws, in the margin evaluations of throughwall flaws described in Section 3.2.1 of the report.

RAI 7

Appendix A to the report contains graphs comparing the experimental and predicted J-integral material resistance (J) versus tearing modulus (T) plots (J-T plots). The predicted J-T plots are conservative if they lie below the experimental J-T plots. In a few cases the predicted plots are higher than the experimental plots close to the vertical axis of the graph. Appendix A states that the plots include a linear extrapolation from the J/T point corresponding to a certain experimental crack extension value to T=0. The portion of the plot where the predicted J value lies above the experimental J value generally appears to be in the extrapolated portion of the graph. The NRC staff requests EPRI discuss the effect the nonconservatism of portions of the predicted J-T plots would have on EPFM evaluations of cracked core shrouds.

References

1. BWRVIP-100, Revision 1: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," [EPRI Product No. 1021001], February 7, 2012 (ADAMS Accession No. ML12044A187).

2. NRC Approval Letter with Comment for BWRVIP-100-A, "BWR Vessel and Internals Project, Updated Assessment of The Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," dated November 1, 2007 (ADAMS Accession No. ML073050135).

3. BWRVIP-100-A, "BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," [EPRI Product No.] 1013396, August 31, 2006 (ADAMS Accession No. ML062570229)
4. BWR Vessel and Internals Project: BWR Core Shroud Inspection and Flaw Evaluation Guideline, Revision 2, (BWRVIP-01),TR-106107079, Research Project B301, Final Report, October, 1996.

5. BWR Vessel and Internals Project Shroud Vertical Weld Inspection and Evaluation Guidelines (BWRVIP-63), TR-113170 Final Report, June 1999.

6. BWRVIP-76-A: BWR Vessel and Internals Project: BWR Core Shroud Inspection and Flaw Evaluation Guidelines, [EPRI Product No.] 1019057, Final Report, December 2009 (ADAMS Accession No. ML101530467).