April 12, 2016

Mr. Tim Hanley
Senior Vice President West Operations, Exelon
Chairman, BWR Vessel and Internals Project
3420 Hillview Avenue
Palo Alto, CA 94304-1395

SUBJECT: FINAL SAFETY EVALUATION FOR ELECTRIC POWER RESEARCH INSTITUTE TOPICAL REPORT BWRVIP-100, REVISION 1, "BWRVIP VESSEL AND INTERNALS PROJECT: UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS" (TAC NO. ME8329)

Dear Mr. Hanley:

By letter dated February 7, 2012 (Agencywide Documents Access and Management System (ADAMS) Package Accession No. ML120440348), as supplemented by letters dated June 6, 2013, and July 15, 2015 (ADAMS Accession Nos. ML131560537 and ML15201A145), the Electric Power Research Institute (EPRI) Boiling Water Reactor Vessel and Internals Program (BWRVIP) submitted topical report (TR) BWRVIP-100, Revision 1, "BWRVIP Vessel and Internals Project: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds."

By letter dated November 12, 2015 (ADAMS Accession No. ML15294A003), an NRC draft safety evaluation (SE) was provided for your review and comment. By letter dated January 19, 2016 (ADAMS Accession No. ML16028A277), EPRI provided comments on the NRC draft SE. The comments provided by EPRI were related to the identification of proprietary information in the draft SE, clarifications and accuracy.

The NRC staff has found that TR BWRVIP-100, Revision 1 is acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that EPRI publish approved proprietary and non-proprietary versions of TR BWRVIP-100 within three months of receipt of this letter. The approved versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The approved versions shall include an “-A” (designating approved) following the TR identification symbol.

As an alternative to including the RAIs and RAI responses behind the title page, if changes to the TRs provided to the NRC staff to support the resolution of RAI responses, and the NRC staff reviewed and approved those changes as described in the RAI responses, there are two ways that the accepted version can capture the RAIs:

1. The RAIs and RAI responses can be included as an Appendix to the accepted version.
2. The RAIs and RAI responses can be captured in the form of a table (inserted after the final SE) which summarizes the changes as shown in the approved version of the TR. The table should reference the specific RAIs and RAI responses which resulted in any changes, as shown in the accepted version of the TR.

If future changes to the NRC’s regulatory requirements affect the acceptability of this TR, EPRI will be expected to revise the TR appropriately. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

Sincerely,

/RA/

Kevin Hsueh, Chief
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 704

Enclosure:
Final Safety Evaluation

In accordance with the guidance provided on the NRC website, we request that EPRI publish approved proprietary and non-proprietary versions of TR BWRVIP-100 within three months of receipt of this letter. The approved versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The approved versions shall include an "-A" (designating approved) following the TR identification symbol.

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/RA/

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Enclosure:
Final Safety Evaluation

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U.S. NUCLEAR REGULATOYR COMMISSION FINAL SAFETY EVALUATION OF

BWRVIP-100, REVISION 1, "BWRVIP VESSEL AND INTERNALS PROJECT:

UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS

STEEL FOR BWR CORE SHROUDS"

(TAC NO. ME8329)

1.0 INTRODUCTION

1.1 Background

By letter dated February 7, 2012 (Ref. 1), as supplemented by letters dated June 6, 2013 (Ref. 2) and July 15, 2015 (Ref. 3), the Electric Power Research Institute (EPRI) Boiling Water Reactor Vessel and Internals Program (BWRVIP) submitted topical report (TR) BWRVIP-100, Revision 1, "BWRVIP Vessel and Internals Project: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds."

A previous version of this report, BWRVIP-100-A (Ref. 4), comprises the U.S. Nuclear Regulatory Commission (NRC)-approved version of the report, and incorporates the NRC staff safety evaluation (SE) dated March 1, 2004 (Ref. 5). In the conclusions of its SE, the NRC staff recommended that the BWRVIP perform additional fracture toughness testing of irradiated stainless steel material, to explore the effect of specimen orientation, and to include testing of additional materials from the heat affected zone (HAZ) or welds in stainless steel welds. In addition, the staff's letter approving BWRVIP-100-A with comments, dated November 1, 2007 (Ref. 6), stated that the staff has determined that the BWRVIP-100-A report is acceptable provided that the BWRVIP, in the future, provides the amount of delta ferrite in the stainless steel weld metal to facilitate an effective assessment of the synergistic effect of neutron embrittlement and thermal embrittlement on stainless steel welds. In the same letter, the staff reiterated the following issues that were stated in the staff's SE dated March 1, 2004, which require future actions, but which do not affect the acceptability of the BWRVIP-100-A report.

1. A plant-specific flaw evaluation is necessary to determine inspection intervals for cracked core shroud welds exposed to a neutron fluence value greater than 1×10^{21} (E > 1 MeV) and must be submitted to the NRC staff for approval.

2. The fracture toughness values (as a function of neutron fluence) shown in Section 2.0 of the BWRVIP-100-A report should be included in Appendix C of the BWRVIP-76 report, "BWR Core Shroud Inspection and Flaw Evaluation Guidelines."

3. Due to limited availability of data concerning the effects of different parameters (i.e., orientation, temperature, etc.) on fracture toughness of irradiated stainless steel materials, the staff recommends that the BWRVIP-100-A report be updated when new data becomes available. The BWRVIP should update the proposed fracture toughness curves for irradiated austenitic stainless steel to ensure consistency with the new data when it becomes available.

The BWRVIP-100, Revision 1, report incorporates new data from materials irradiated in operating BWRs, and from materials irradiated in a test reactor as reported in NUREG/CR-6960, which supersedes NUREG/CR-6826.

1.2 Purpose

The staff reviewed the BWRVIP-100, Revision 1, report to determine whether it provides sufficiently conservative methods for predicting fracture toughness of irradiated stainless steel and defines appropriate flaw evaluation methodologies for assessing the integrity of irradiated BWR core shrouds. The review assessed the adequacy of the experimental data, the choice of the correlation for predicting fracture toughness, and the applicability of the flaw evaluation methodologies to irradiated BWR core shrouds. Additionally, the staff reviewed the report to determine whether the BWRVIP addressed the recommendations and conditions from the staff's SE of BWRVIP-100 (Ref. 5), and the staff's approval letter for BWRVIP-100-A (Ref. 6).

1.3 Organization of this Report

A brief summary of the contents of the subject report is given in Section 2 of this SE, with the staff's evaluation presented in Section 3. The conclusions are summarized in Section 4. Section 5 contains the references. The presentation of the evaluation is structured according to the organization of the BWRVIP-100, Revision 1, report.

2.0 SUMMARY OF BWRVIP-100, REVISION 1, REPORT

The BWRVIP-100, Revision 1 report contains the following information:

2.1 Fracture Toughness Data

Section 2.1 of the report presents data showing the variation in fracture toughness as a function of neutron fluence. The data presented in the report are for wrought stainless steel base metal, weld metal, and HAZ materials that were tested under conditions simulating BWR operation. The materials were either obtained from operating BWRs or were irradiated in test reactors.

2.2 Fracture Toughness Curves for Integrity Assessments

Section 2.2 of the report uses the data from the tables in Section 2.1 to develop conservative fracture toughness curves that can be used to assess margin against failure, establish inspection intervals, and define the likely failure mode as a function of neutron fluence.

2.3 Application to BWR Core Shroud Cracking

Section 2.3 of the report provides additional discussion to demonstrate the applicability of the fracture toughness relationship and the methodology described in Section 2.2 to flaw evaluation of BWR core shrouds.

2.4 Failure Mode and Margin Assessment

Chapter 3 of the report defines the neutron fluence levels at which limit load, elastic plastic fracture mechanics (EPFM), and linear elastic fracture mechanics (LEFM) methods can be used to evaluate flaws that may be found in BWR core shrouds.

2.5 Conclusions and Recommendations

Chapter 4 summarizes the data used to develop the relationship between fracture toughness and neutron fluence, the fluence range, and the fracture mechanics procedures to be used as a function of neutron fluence.

2.6 Appendices

Comparison of Experimental and Predicted J/T Curves

This appendix is completely proprietary.

Comparison of Predicted and Experimental Yield Strengths

This appendix is completely proprietary.

EPFM Analysis of a Part through Wall, Full Circumference Flaw

This appendix is completely proprietary.

3.0 TECHNICAL EVALUATION

3.1 Fracture Toughness Data

Section 2.1 of the report presents data showing the variation in fracture toughness as a function of neutron fluence. The data presented in the report are for stainless steel base metal, weld metal, and HAZ materials that were tested under conditions simulating BWR operation. The materials were either obtained from operating BWRs or were irradiated in test reactors. The report contains additional fracture toughness test data not included in BWRVIP-100-A, at all fluence levels. Some of the new data specifically addressed specimen orientation relative to the material working direction.

The relationship of the material resistance to fracture (J_{mat}) to the amount of ductile crack extension (δa) is called the J-R curve and is expressed as:

$$J_{mat} = C(\Delta a)^n$$

The C and n parameters are determined from the J-R curve of each individual specimen and are tabulated in Tables 2-1, 2-2, and 2-3. Each table also includes the data source and specimen type, material type, product form (base, HAZ, or weld), and neutron fluence > 1 MeV. The J-R curves are for materials that retain some ductility, which comprises the majority of the materials. However, some materials had no ductile crack extension, and for these materials, the linear elastic fracture toughness (K_{IC}) values were determined. Fracture toughness data were mainly measured using compact tension (CT) specimens while some used bend bar (BB) specimens. Section 2.1 of the report also provides the experimental data graphically in the form of the J-integral versus crack extension (J-R) curves for each test specimen.

The staff notes that the new data includes only one additional test of a weld metal specimen.

Section 2.3.3 of the reports indicates that thirteen CT specimens in the fluence range of $3x10^{21}$ to $5.2x10^{21}$ n/cm^2 had little or no ductile crack extension. One CT specimen exposed to lower fluence was found to have little or no ductile crack extension.

3.2 Fracture Toughness Curves for Integrity Assessments

Section 2.2 of the report contains J-R curves developed as a conservative lower bound to the experimental data. These curves were developed based on fits to the data for the two power-law parameters used in the J-R curves (C and n). This section also includes J-integral versus tearing modulus curves as a function of fluence.

Figures 2-4 and 2-5 of the report show the data for C and n, respectively, plotted against the neutron fluence for each specimen tested. The BWRVIP determined a lower bound curve for C which is shown on Figure 2-5, and an upper bound curve for n shown on Figure 2-5. Section 2.2.1 of the report states that a power law fit was used to construct a line that bounds the available data for 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 J-R curves match or are conservative compared to the experimental J-R curves. The bounding curve for C from Figure 2-4 is represented mathematically by Equation 2-2 of the report, which provides the relationships between the parameter C and the neutron fluence based on a power law fit to the data. The bounding curve from Figure 2-5 is represented mathematically by Equation 2-3 of the report, which provides the relationship between the parameter, n and neutron fluence based on a power law fit to the data.

The staff compared Equations 2-2 and 2-3 to the corresponding equations in BWRVIP-100-A, and observed that the equations have not changed. Examination of Figures 2-4 and 2-5, which include the new test data, shows the curves based on Equations 2-2 and 2-3 continue to bound the majority of the data points for C and n, respectively. Since one data point was not bounded by the lower bound fluence-dependent J-R curve in Figure 2-4, in Request for Additional Information (RAI) 1 the staff asked the BWRVIP to discuss the necessity of proposing a more conservative J-R model. The BWRVIP's response indicated that it did not consider revision to the model necessary because the curve continues to be conservative relative to almost all the data and is a close match for the one non-bounded point. The staff compared the experimentally determined C value for the one non-bounded point to the value predicted by the model, and determined that the measured data point is only 1.5 percent less than the calculated C value. The staff finds this difference to be inconsequential. Therefore, RAI 1 is resolved.

Figure 2-6 of the report includes J-R curves plotted as a function of neutron fluence using C and n values determined using Equations 2-2 and 2-3. The report indicates that these curves are lower than the measured curves for specimens at the same fluence, and therefore provide a reasonably conservative representation of the ductile crack extension characteristics of irradiated stainless steel in BWR core shrouds. The report states that the material J-R curves for structural integrity assessments are shown in Figure 2-6 with fluence as a parameter. The staff compared these curves to those in Figure 2-1 of the report, which shows the experimental curves for the specimens with various fluences over a similar range. The staff observed that curves of Figure 2-6 are conservative relative to the experimentally determined curves. Section 2.2.2 of the report discusses the material J versus tearing modulus (J/T) curves for integrity assessments. Section 2.2.2 of the report stated that the J-R data used to define the J/T curves were obtained from small specimens with planar dimensions that are much smaller than the core shroud, and that the small specimen size limits the experimental J-R data that can be obtained. The BWRVIP further stated that application of the data from small specimens to larger structures can be unnecessarily conservative if the allowable crack extension is limited to values obtained from small specimen tests. To reduce this conservativism, the BWRVIP stated that various extrapolation methods previously have been used to extend the test data for structures, and that in this application, the J/T plots are extrapolated linearly from the J/T point corresponding to 1.6 mm crack extension obtained from the small specimens to the intersection with the vertical axis (J) in the J/T plot. The BWRVIP stated this procedure is more conservative than using the power law fit J-R curve to generate the J/T curve for crack extensions greater than 1.6 mm.

For some of the extrapolated J/T plots contained in Appendix A of the report, the predicted curves are nonconservative (higher) that the experimental curves. Therefore, in RAI 7, the staff requested the BWRVIP to discuss the effect the nonconservatism of portions of the predicted J-T plots would have on EPFM evaluations of cracked core shrouds. In the BWRVIP's June 6, 2013, response to RAI 7 (Ref. 2), the BWRVIP stated that there are five specimens where the predicted values of J at T = 0 are greater than the extrapolated experimental values, and that for these five experiments the predicted values of J range from 5 percent to 21 percent higher than the experimental values. The BWRVIP stated that because applied K, (and consequently load) is proportional to the square root of J, the difference in predicted and actual loads would range from 2 percent to 10 percent at the extreme end of the extrapolation range (T=0) for these five specimens, and that in all other experiments the predicted values either match or are less than the extrapolated experimental values. Finally, the BWRVIP stated that this information demonstrates that the linear extrapolation scheme is reasonably conservative for the range of experiments shown in Appendix A.

The staff reviewed the BWRVIP's response to RAI 7, and finds it acceptable because the increase in the actual load due to the nonconservatism in the J/T curve prediction is relatively small, and this nonconservatism would not significantly affect the margins considering the safety factors used in the core shroud analyses. The staff's concern in RAI 7 is therefore resolved.

The staff reviewed the BWRVIP's method for extrapolating the J values for larger crack extensions from the small specimen data, and finds that it is reasonably conservative because the predicted J values for a given T are more conservative than J values extrapolated from measured data, or are only slightly less conservative then if extrapolated from measured data.

3.3 Application to BWR Core Shroud Cracking

As a basis for why the compiled fracture toughness data is representative of the fracture toughness that can be expected for operating BWRs, Section 2.3.1 of the report notes that 60 of 71 experiments (data points) in Tables 2-1, 2-2, and 2-3 were from materials removed from operating BWRs, and that consequently, the thermal aging of the components would be comparable to the thermal aging that could be expected in operating BWRs. The report also provides two graphs (Figures 2-9 and 2-10) of all the fracture toughness data (other than those with no ductile crack extension) with those specimens irradiated in test reactors and those irradiated in operating reactors separately identified, and the same power law fit curves represented by Equations 2 and 3. The report states that the two figures demonstrate that the database provides a reasonable representation of thermal aging effects that may exist in operating BWRs. The staff reviewed the figures and agrees that there are no identifiable trends that are different for the operating reactor versus test reactor data. The lack of difference between specimens irradiated in operating reactors versus test reactors suggests thermal aging effects are minimal in operating reactors because materials are typically irradiated in test reactors for shorter duration, therefore, should have less thermal aging exposure. However, the staff notes that the weld materials irradiated in operating reactors may not have thermal aging representative of end-of-life conditions in operating BWRs (60 years) because the materials may have been removed before end-of-life or are from decommissioned reactors shut down prior to end-of-life.

The majority of the materials in the database are base (wrought) materials, which are not affected by thermal aging. The database also contains a few data points for HAZ materials, which also are not subject to thermal aging. Further, the fact that a large majority of the data are from operating reactors, supports the staff's conclusion that the database is adequately representative for base materials. The staff's concerns regarding the conservatism of the model for weld metal are discussed later in this SE.

This section of the report also provides the basis for the maximum fluence limit for EPFM analysis. The basis of the limit is the high percentage of test specimens that exhibited ductile crack extension below this fluence value, while thirteen out of fourteen specimens that had non-ductile crack extension had exposures above this fluence value. This section also provided the basis for the fracture toughness value used for LEFM above the maximum allowable fluence for EPFM. The recommended toughness value and fluence above which this toughness should be used is unchanged from BWRVIP-100-A. The report recommended a particular fracture toughness value as adequately conservative based on the literature and the measured values for the test specimens with no ductile crack extension. However, since some of the test specimens had measured K_{IC} values less this value, the staff requested that the BWRVIP justify the conservatism of this value (RAI 2). In its June 6, 2013, response to RAI 2, the BWRVIP indicated that 42 of 47 or 89 percent of the specimens in Tables 2-2 and 2-3 had measured K_{IC} values greater than the chosen value, and that using a fracture toughness that bounds 89 percent of the total data points provides a reasonably conservative representation of the fracture toughness for fluences above the maximum fluence for EPFM.

The staff finds the BWRVIP's response to RAI 2 acceptable because a large percentage of the measured K_{IC} values for specimens with fluences greater than the maximum fluence for EPFM were greater than the chosen fracture toughness value. Further, because a large percentage of the specimens with fluences greater than the maximum fluence for EPFM had ductile crack extension, the requirement to use LEFM techniques at fluences above this fluence value is in itself conservative. RAI 2 is thus resolved.

3.3.1 Orientation Effect on Toughness

The BWRVIP considered additional data from an experimental program that included the assessment of the specimen orientation effect on toughness. The BWRVIP prepared plots of the power-law fit coefficient C, and the power-law fit exponent n versus fluence for the data from the study. Nine new specimens were tested in order for the study to assess the effect of orientation on toughness. The specimens orientations included both the L-T orientation, where the load is applied parallel to the rolling or extrusion direction and the crack front is perpendicular to the rolling or extrusion direction, and the T-L orientation, where the load is applied perpendicular to the rolling or extrusion direction and the crack front is parallel to the rolling or extrusion direction. Several specimens from the study were not included on the plots since they showed essentially no ductile crack extension. The results showed an orientation effect with the transverse (T-L) specimens showing lower C values and n values than the longitudinal (L-T) for the same material type at a given fluence value. The previous power-law fit curves are still bounding for the lower C and n values.

3.3.2 Combined (Synergistic) Effects of Thermal Aging Embrittlement and Neutron Irradiation Embrittlement on Welds

Reference 4 notes that data on the delta ferrite contents of stainless steel weld metals was not included in the BWRVIP-100-A, 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 (CASS) and austenitic stainless steel weld metals. The so-called synergistic effect refers to a loss of fracture toughness under simultaneous exposure to thermal aging and neutron irradiation that would result in a lower fracture toughness than would be predicted based on either mechanism alone. The staff prefers to use the term “combined effect” rather than “synergistic effect” when discussing the effects of aging and irradiation on CASS and weld metals, because no synergism has been proven. There is little data available to assess the combined effects of thermal embrittlement (TE) and irradiation embrittlement (IE) on CASS and austenitic stainless steel weld metals because such data can typically only be obtained from materials removed from operating light-water reactors, which is scarce and expensive to test. With the exception of BWRVIP-100-A and BWRVIP-100, Revision 1, the staff is not aware of any studies quantifying the combined effect of IE and TE on austenitic stainless steel weld metals, and only very limited studies have been performed on CASS, such as those described in References 9 and 10.

Most of the welds specimens listed in Tables 2-1, 2-2, and 2-3 of BWRVIP-100, Revision 1, are listed as Type 304 (which would indicate Type 308 weld filler metal since there is no Type 304 filler metal designation); however, one weld specimen is listed as Type 316L. The toughness parameters C and n for all of the weld metal data points are within the general data trends. As neutron exposure increases, C decreases and n increases, and the estimated fracture toughness decreases. Therefore the lower the C value and the higher the n value, the lower the predicted fracture toughness. The C values for the weld metal in Figure 2-4 are generally among the lower values for a given fluence but some C values for wrought material are around the same values. For the n values shown in Figure 2-5, some of the n values for the weld specimens are among the higher values, but others fall in the middle of the band for the general data scatter. Therefore, it cannot be concluded that the weld metal C or n values follow a different trend than the C or n values for wrought or HAZ materials. An examination of the individual J-R curves in Figures 2-1, 2-2, and 2-3, reveals that the J-R curves for the weld metal tend to have lower J-integral values for a given crack extension, compared to most of the wrought materials, indicating lower toughness. However, it cannot be determined whether this is due to a combined effect of TE plus IE or whether weld metals simply tend to lose more fracture toughness due to IE when exposed to the same neutron fluence compared to wrought materials. In any case, the predicted J integral at 2.5 mm crack extension calculated from the C and n curves (Equation 2-2 and 2-3) bound the data for both the welds and the base metal specimens, regardless of whether a combined effect acted on the weld metal specimens.

The staff agrees that any combined effects would be reflected in the fracture toughness data for the welds provided in BWRVIP-100, Revision 1, since the welds are generally from actual plant materials removed from service in BWRs, in which the materials undergo long-term thermal aging and neutron irradiation due to the reactor operating conditions. Only one new weld metal specimen was included. The report does not provide the delta ferrite content of this weld. However, since the delta ferrite content of the weld materials was not provided, it is not clear that the C and n parameters would be bounding for welds with higher delta ferrite content. Therefore, in RAI 3, the staff requested additional information to help resolve this issue. The staff requested that the BWRVIP provide the delta ferrite content for the weld materials, or provide an estimate based on the chemical composition. The staff additionally requested a discussion justifying that the fracture toughness values are bounding for all BWR core shroud weld materials considering the effects of the variation of delta ferrite content and chemical composition on the potential synergistic effects of TE and IE. In its June 6, 2013, response to RAI 3, the BWRVIP indicated that all the weld specimens shown in Figure 2-4 were irradiated in BWRs and generally have high fluences and long operating times. The BWRVIP also stated that the delta ferrite content for the welds were not reported and not available but the information in Figure 2-4 indicates the weld data are within the overall trend for the data population as a whole and have high toughnesses beyond $3x10^{21}$ n/cm^2. The BWRVIP further stated that the Type 316L weld should have a ferrite number[1] of 8-16 based on the specification for that weld, and the Type 304 stainless welds should have a ferrite number of 8-20 if the materials were procured to typical ASME specifications. The BWRVIP also stated that these delta ferrite values are consistent with the ferrite levels documented in BWRVIP-84 which has been reviewed by the NRC.

Based on the response to RAI 3, the staff finds that although the delta ferrite content of the weld metal specimens cannot be determined, these specimens should be representative of typical delta ferrite levels to be expected in other BWRs, since the weld metal was most likely procured to similar specifications as the weld metal in other operating BWRs. Provided the delta ferrite levels are within the ranges given in the BWRVIP's response, the loss of fracture toughness of the weld materials in the BWRVIP-100, Revision 1, database should be representative of the general trends to be expected for core shroud welds. RAI 3 is thus resolved.

With respect to the combined effect of IE and TE on the fracture toughness of stainless steel welds, the BWRVIP could not provide the requested delta ferrite content for the weld specimens. However, the staff recommends that if additional stainless steel weld materials are acquired for testing by the BWRVIP, the delta ferrite content should be characterized if at all possible.

In Section 2.2.1, the BWRVIP considers that the toughness for the weld and HAZ forms the lower bound of the population of the weld, HAZ and base metal toughness. Consequently, due to the relatively small number of weld metal specimens included in the BWRVIP-100, Revision 1, database, the staff was concerned that the BWRVIP-100, Revision 1, fracture toughness model may not accurately characterize the toughness of irradiated welds, which are also subject to loss of toughness due to thermal aging. The staff identified several other sources of fracture toughness data for irradiated and/or thermally aged stainless steel weld metal that determined lower bound J-R curves that appear to be more conservative than that defined by BWRVIP-100, Revision 1.

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[1] Ferrite number is a number measure via a magnetic instrument that roughly correlates with the volume percentage of ferrite.

NUREG/CR-6428, “Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds” (Ref. 7), defined a lower-bound J-R curve for fully-saturated thermally aged, non-irradiated Type 308 and 316 SMAW welds as $J=40+83.5\Delta a^{0.643}$. The BWRVIP-100, Revision 1, model predicts higher fracture toughness than the Reference 1 curve, even at low fluence ($3x10^{20}$ n/cm^2).

O’Donnell, I. J. et al., “The Fracture Toughness Behavior of Austenitic Steels and Weld Metal Including the Effects of Thermal Ageing and Irradiation,” in Int. J. Pres. Ves. & Piping 65 (Ref. 8), reports several results, including some from earlier work, for austenitic stainless steel welds irradiated to 4 -5 dpa that had low, flat J-R curves that would not be bounded by the BWRVIP-100, Revision 1, model. The welds were not thermally aged.

NUREG/CR-7027, "Degradation of LWR Core Internal Materials Due to Neutron Irradiation” (Ref. 9), presents an alternate lower bound curve for fracture toughness of irradiated austenitic stainless steel welds and cast austenitic stainless steels. This curve is also more conservative than the BWRVIP-100, Revision 1, model.

Since these references define lower bound J-R curves that indicate lower toughness than the curve defined by BWRVIP-100, Revision 1, in RAI 8 the staff requested the BWRVIP to discuss and disposition the results of the three references with respect to the BWRVIP-100, Revision 1, fracture toughness model, and to propose changes as necessary to ensure that the BWRVIP-100, Revision 1, model is conservative for evaluation of core shroud cracking located in the weld metal.

To summarize the BWRVIP’s July 15, 2015, response to RAI 8 (Ref. 3), the BWRVIP’s analysis of the data from the three references cited by the staff in RAI 8 determined that the data may not be applicable to stainless steel welds in BWRs because the materials were irradiated at temperatures significantly higher than BWR operating temperatures (for NUREG/CR/7027 and O’Donnell et al.) or thermally aged at high temperatures (for NUREG/CR-6428). In reference to the weld metal data used to develop the NUREG/CR-7027 lower bound curve, the BWRVIP stated that, based on Figure 75b of NUREG/CR-6960, “Crack Growth Rates and Fracture Toughness of Irradiated Austenitic Stainless Steels in BWR Environments,” dated March 31, 2008 (Ref. 10), it appears that these data were irradiated and tested at temperatures substantially higher (i.e., 698 °F) than BWR operating conditions.

The BWRVIP argued that its own test data in the BWRVIP-100, Revision 1, database, and its associated C and n relationships, provide the most accurate representation of the actual combined aging and irradiation effects for BWR operation. In support of this argument, the BWRVIP provided a graph in Figure 1 of the RAI 8 response of the measured C values for the materials in its database. The BWRVIP stated that 44 of 54 of these tests were on materials removed from operating reactors, while the remaining data were obtained from materials irradiated in test reactors at approximately 550 °F. The graph identifies the data points from operating reactors versus test reactors. The BWRVIP stated that Figure 1 also shows the bounding curve C defined in BWRVIP-100, Revision 1, for the fluence range of $1.5x10^{20}$ n/cm^2 to $3x10^{21}$ n/cm^2, and that this curve bounds all the data obtained for materials irradiated and tested at BWR operating temperature. The BWRVIP also stated that the data in Figure 1 show that the populations of test reactor and operating reactor data are intermingled which the BWRVIP stated indicates that there is no significant aging effect at BWR operating temperature and exposure times.

The BWRVIP further stated that the bounding curve for C defined in BWRVIP-100, Revision 1, is consistent with limits typically used in the ASME Code where the allowable toughness is based on a bound of most, but not all the available data that are associated with actual component operating conditions.

The BWRVIP stated that the only data points that lie outside the BWRVIP-100, Revision 1, curve are data that were obtained at aging, irradiation, and test temperatures that are higher than BWR operating temperatures, and that it is not clear if these outliers represent a real high temperature effect or are coincidental, and possibly associated with data scatter. The BWRVIP indicated there are not enough data available from irradiated experiments under BWR conditions to assess the magnitude of the data scatter. Therefore, the BWRVIP used results from non-irradiated welds to assess the data scatter.

In Figure 2 of the RAI response, the BWRVIP plotted non-irradiated weld data from two sources, NUREG/CR-6428 and NUREG/CR-6004, “Probabilistic Fracture Evaluations for Leak-Rate-Detection Applications, April 1995 (Ref. 11) and also included HAZ data from EPRI NP-4768, “Toughness of Austenitic Stainless Steel Pipe Welds,” EPRI Research Project 1238-2 October 1986 (Ref. 12). To define the distribution of the data, the BWRVIP used the low toughness data (150-400 kJ/m^2) from these sources but excluded some high toughness data from NUREG/CR-6004.

To support its evaluation, the BWRVIP performed a **[ ]**, which included generating **[ ]** and compared the data from NUREG/CR-7027 and O’Donnell et al. to these bounds. The distribution defined using the non-irradiated weld data scatter was used to support the statistical analysis.

For NUREG/CR-7027, the BWRVIP found a large percentage of the data lay below the **[ ]**, therefore, the BWRVIP concluded that this data is **[ ]** For O’Donnell, et al., less data lay below the **[ ]**; however, the BWRVIP still cautioned that there is uncertainty in these results because the specimens were irradiated and tested at temperatures substantially higher than BWR operating temperatures.

The BWRVIP’s response to RAI 8 also presented the results of a margin assessment in which margins against failure from ductile crack extension were determined using the toughness represented by both the **[ ]** and compared to the base case from the BWRVIP-100, Revision 1, model curve. The results of the margin assessment indicated that there is a relatively small change in margin from the base case when the toughness is represented by either the **[ ]**.

The BWRVIP also pointed to inspection results from BWRs, which show cracks usually initiate in the HAZ along the weld fusion line, and generally, except in rare cases, grow in the HAZ or the base metal, so use of a lower bound, composite fracture toughness curve based on weld, HAZ, and base metal is a realistic, conservative representation of the crack initiation and growth characteristics observed in core shrouds in operating BWRs.

The BWRVIP stated that based on the evaluation described in the RAI 8 response, it concludes that the database and the C and n curves in BWRVIP-100, Revision 1, provide the most accurate characterization of the combined effects of aging and irradiation for materials in operating BWRs, adequately characterizes the fracture toughness for BWR operating conditions, is consistent with crack initiation and growth characteristics in the core shroud and provides adequate margin against failure from ductile crack extension. The BWRVIP also stated that because there is no direct, quantitative correlation between BWR operating conditions and test results from experiments conducted at temperatures significantly higher than BWR operating temperatures, the high temperature results are not used in the BWRVIP fracture toughness data base.

Finally, the BWRVIP stated that based on these results it proposes to continue to use the BWRVIP-100, Revision 1, bounding curve, but that weld and HAZ materials have been removed from an operating reactor and will be tested later this year. The BWRVIP stated that when the results for these tests, as well as results from any future tests that may be performed are available, they will be added to the BWRVIP-100, Revision 1, database. The BWRVIP stated if the results from future tests of materials removed from operating BWRs fall below the [ ], the BWRVIP-100, Revision 1, bounding curve will be reevaluated and appropriate changes will be made to ensure that adequate margins against failure from ductile crack extension will be maintained in BWR core shrouds.

The staff reviewed Figure 75b of NUREG/CR-6960, and confirmed that some of the weld materials were irradiated at temperatures of 698 °F to 800 °F. One heat of Type 316L weld material was irradiated in a fast reactor, but with a maximum irradiation temperature of 482 °F. This heat shows significantly higher toughness values. The staff notes that NUREG/CR-6960 uses much of the same data that was used in NUREG/CR-7027 to define a lower-bound curve for the power law coefficient C. NUREG/CR-7027 also states, on page 63, that most of the data are from irradiations in fast reactors at 698 °F to 800 °F. However, the test temperature for these materials was either 698 °F or 1022 °F, both of which are substantially higher than normal BWR operating temperature of 550 °F. The staff confirmed the irradiation temperature of the weld materials reported on in O'Donnell et al. was 698 °F per Picker et al., "Effects of Low-Dose Fast Neutron Irradiation on the Fracture Toughness of Type 316 Stainless Steel and Weld Metal, Proc. Specialists Meeting on Mechanical Properties of Fast Reactor Structural Materials" (Ref. 13), which is referenced in O'Donnell, et al. with respect to the details of the material irradiations.

With respect to the effect of irradiation temperature on the toughness of stainless steels, NUREG/CR-7027 states that the available data are inadequate to establish accurately the effects of the irradiation temperature on the fracture toughness of austenitic stainless steels. The statistical analysis presented in the RAI 8 response shows that the toughness data on irradiated welds in NUREG/CR-7027 and O'Donnell et al. represents an outlier or a radically different population of data. The staff reviewed the results and methodology of this analysis, and agrees that it shows that the differences between the C values defined by the BWRVIP-100, Revision 1, database and the NUREG/CR-7027 data cannot be accounted for simply by data scatter.

According to NUREG/CR-7027, the fracture toughness of irradiated stainless steels decreases with increasing test temperature for doses up to 12 dpa, but there is little effect due to test temperature above 12 dpa. However, the BWRVIP's proposed J-R model in BWRVIP-100, Revision 1, is only used up to [ ]. Therefore, for the neutron fluence range over which the BWRVIP-100, Revision 1, model will be used, the fracture toughness of materials tested at higher temperatures may underestimate the fracture toughness at BWR operating temperatures. Based on the above discussion, the staff agrees with the BWRVIP's assertion that the irradiation temperatures and test temperatures from NUREG/CR-7027 and O'Donnell, et al. are significantly higher than normal BWR operating temperature.

The staff also notes that, in addition to irradiation temperature, there are significant differences in flux and neutron spectrum in fast reactors as compared to BWRs. These factors could also cause changes in the response of materials to irradiation in fast reactors versus BWRs, for the same fluence.

The staff reviewed the margin assessment results provided in the RAI 8 response. The margins achieved are similar to the structural factors which would be required by the ASME Code, Section XI, for the service level loading represented in the margin assessment. However, the staff noticed an inconsistency in the BWRVIP-100, Revision 1, margin curve in Figure 7 with the EPFM curve in Figure 3-9 of BWRVIP-100, Rev. 1. The staff recommends that this inconsistency be resolved in the final version of the TR. The discrepancy does not affect the resolution of RAI 8 because regardless of whether the original curve or the curve in the RAI response is correct, the staff would not expect the relative margins for the base case and the two other cases to change, and the lowest bounding curve should still provide acceptable margins.

With respect to the thermally aged but unirradiated data from NUREG/CR-6428, the staff examined the raw data for the C value for the unaged and aged welds, and notes that there are some values that are close to or slightly below the BWRVIP-100 calculated value for C at the fluence values corresponding to the lower limit of validity of the BWRVIP model. However, there are more values that are greater than the BWRVIP-100, Revision 1, C value at this fluence. There is a large range of variability in the C values. There is also large range of variability in both the unaged and aged J-R curves compiled from previous testing in NUREG/CR-6428. The irradiated weld specimens in the BWRVIP-100, Revision 1, database are bounded by the BWRVIP's proposed curve for C. Since toughness decreases with irradiation, it must be assumed that the unirradiated weld C values for the welds in the BWRVIP-100, Revision 1, database were larger than the low values of some of the NUREG/CR-6428 materials. In addition, since the C values for some of the as-welded fracture toughness data presented by the BWRVIP in the RAI response would not be bounded by the BWRVIP-100, Revision 1, curve, even at high fluence values, it can be inferred that the weld materials in the BWRVIP-100 database had higher as-welded values, since thermal aging and irradiation would tend to reduce the as-welded fracture toughness.

The staff notes that the BWRVIP argued its data shows thermal aging has little effect because its curve for C bounds both the test reactor irradiated materials (which would have less thermal aging since the irradiation times are shorter for the same fluence) and the operating reactor weld materials. However, the staff notes that no weld materials were irradiated in test reactors, and only weld materials are susceptible to thermal aging. If there were a significant loss of toughness due to thermal aging, the staff expects the weld data points would tend to fall below the curve. However, without knowledge of the as-welded properties of the welds, it is impossible to quantify the effect of thermal aging, due to the wide range of possible initial toughness values. In addition, BWRVIP-100, Revision 1, does not provide the operating time for the materials irradiated in operating BWRs. However, it is likely these materials were exposed to BWR operating temperatures for less than the expected end-of-life operating time for the BWR fleet, which could be up to 54 effective full power years (EFPY) for BWRs that are licensed to operate out to 60 calendar years. Therefore, the fracture toughness of the weld materials in the BWRVIP-100, Revision 1, database may not reflect the loss of fracture toughness due to thermal aging at the end of life for the U.S. BWR fleet. To address these issues, the staff recommends that for a future revision of BWRVIP-100, the BWRVIP should: (1) Develop an estimate of the initial as-welded toughness of core shroud welds; (2) Test materials with thermal aging representative of end-of-life in the BWR fleet; and (3) Modify the BWRVIP-100 toughness model, as necessary, to ensure it reflects expected loss of fracture toughness due to thermal aging as well as irradiation, and is conservative for weld materials at end-of-life.

The staff also agrees with the BWRVIP's argument that cracking in BWR core shrouds typically occurs in the base metal and HAZ, and does not typically propagate through the weld metal. However, there is nothing to preclude propagation of cracks into weld metal, and recent operating experience has shown this can occur. The staff does not find this a good argument for discounting valid sources of irradiated weld fracture toughness data. Therefore, the staff recommends that the BWRVIP should continue to seek additional data on irradiated weld toughness. The BWRVIP-100, Revision 1, database also includes few HAZ materials, therefore, the same recommendation applies to these.

Regarding the BWRVIP's statement that if the results from future tests of materials removed from operating BWRs fall below the [ ], the BWRVIP-100, Revision 1, bounding curve will be reevaluated and appropriate changes will be made to ensure that adequate margins against failure from ductile crack extension will be maintained in BWR core shrouds, the staff does not endorse this approach. Rather, the staff recommends that the BWRVIP ensure that J-R curves generated using its existing model continue to bound all measured J-R curves from the materials tested. Further, this adjustment should be made regardless of the source of the additional test materials (operating BWRs, PWRs, or test reactor), provided the materials are to be included in the database.

Therefore, the staff finds that the BWRVIP's evaluation of the three references cited in RAI 8, which determined that no changes to the BWRVIP's model are necessary to address weld toughness, is acceptable. The staff's finding is based on the following:

1. The BWRVIP demonstrated the irradiation, aging and test temperatures for the materials in the references cited in RAI 8 are not representative of BWR conditions, while by contrast, most of the materials in the BWRVIP-100, Revision 1, database were irradiated in operating BWRs and tested at BWR operating temperatures, and thus should be most relevant for assessing fracture toughness of stainless steel in BWRs.

2. Although unirradiated weld materials in the NUREG/CR-6428 database (both aged and unaged) exhibit a significant variability in fracture toughness; the irradiated toughness values of welds in the BWRVIP-100, Revision 1, database are fully representative of the materials in the BWR fleet.

The staff's concern in RAI 8 is thus resolved.

3.4 Failure Mode and Margin Assessment

In Section 2 of the report, the BWRVIP summarized the fracture toughness changes in austenitic stainless steels as follows. Up to some relatively high irradiation level, the fracture toughness of stainless steel is high, plastic collapse is the failure mode, and limit load is the appropriate analysis method. At higher irradiation levels, the fracture toughness is reduced so that stable, ductile tearing of the flaws rather than plastic collapse is the failure mode, and EPFM is the applicable analysis method. At very high irradiation levels, the fracture toughness reaches a lower plateau, and failure occurs when an existing crack extends rapidly with little or no stable ductile tearing. In this instance, LEFM is the appropriate analysis method.

Section 3 of the report contains an assessment of the fluence levels at which limit load, EPFM, and LEFM methods can be used to evaluate flaws that may be found in BWR core shrouds. To accomplish this, sample analyses using all three methods were performed for various hypothetical examples of core shrouds with various levels of cracking, defined in terms of the percent of the total weld cross-sectional area that is cracked in a horizontal (circumferential) core shroud weld. These sample analyses were performed for a stress level of 6 ksi, at six different degradation levels for a single through-wall crack, and for three different crack depths for a part through-wall flaw spanning 360 degrees of the weld circumference. Each of these analyses is summarized by a graph of the margin for each analysis method (limit load, LEFM, and EPFM) as a function of neutron fluence. The basic principle is that only the EPFM margins are based on experimental fracture toughness values (from the BWRVIP-100, Revision 1, model), while the LEFM fracture toughness (K_{IC}) values are assumed values chosen to result in lower, and thus, more conservative margins, while limit load analyses are simply based on the strength of the material and do not consider fracture toughness.

The fracture toughness value used for the margin assessment of LEFM for through-wall cracks has been used in LEFM analyses of BWR core shrouds in BWRVIP-76-A, and several other BWRVIP guidelines. A different, lower fracture toughness value was also used for the margin comparisons for the part through-wall cracks. In the response to RAI 4, the BWRVIP clarified that both fracture toughness values are assumed values that were selected to ensure the LEFM margins would be equally or more conservative than the EPFM margins, which are based on the actual fracture toughness model of BWRVIP-100, Rev. 1, thus allowing analysts desiring to use conventional LEFM or limit load analyses or that had previously performed LEFM or limit load analyses to continue to use these methods provided they are within the parameters defined by the results in Figures 3-1 through 3-9. The staff reviewed the figures, and agrees that the use of the more limiting of limit load or LEFM using the assumed fracture toughness values result in more conservative margins than EPFM. Therefore, RAI 4 is resolved.

The staff reviewed the margin assessments in Figures 3-1 through 3-9, and found that the margins shown in the figures support the allowable analytical methods specified in Section 3.2.1 and summarized in Section 4 of the report, with the exception that the trend for 360 degrees non-through-wall cracks suggested that EPFM might have the lowest margins for cracks deeper than 1 inch at the higher end of the fluence range. Therefore, in RAI 5 the staff requested that the BWRVIP discuss whether the recommended procedures should require that the lowest margin of all three methods should be used in some cases. In the BWRVIP's June 6, 2013, response to RAI 5, the BWRVIP indicated that it performed additional LEFM and EPFM analyses for a 1.25 inch, 360 degrees part through-wall circumferential flaw at a fluence of 2.9×10^{21} n/cm^2, and that the results of these analyses indicate that the margin on load from the

LEFM analysis with the lower of the two assumed K_{IC} fracture toughness values is 1.67 and the margin on load from the EPFM analysis is 1.93. The BWRVIP further indicated that these results indicate that the LEFM analysis with the particular K_{IC} value is limiting relative to the EPFM analysis at flaw depths up to at least 83 percent of the wall thickness and fluence up to the upper limit at which EPFM is allowed by BWRVIP-100, Revision 1.

The staff found the BWRVIP's response to RAI 5 acceptable because it demonstrates that either LEFM or limit load analysis always has a lower margin over the fluence range where EPFM is allowed, thus it is conservative to use the method (LEFM or limit load) with the lowest margin, as an alternative to EPFM over this fluence range. RAI 5 is thus resolved.
In addition, it is not clear why the margin evaluations for through-wall flaws did not use both assumed fracture toughness values. Therefore, in RAI 6, the staff requested this information. In its June 6, 2013, response to RAI 6, the BWRVIP explained that it was not necessary to use both values for the margin assessments for through-wall flaws because the toughness value used already provided lower margins than EPFM, which was the goal. For the part through-wall margin assessments, the lower fracture toughness value was needed to make the LEFM margin lower than the EPFM margin. The staff found the BWRVIP's response to RAI 6 acceptable because it clarified why both toughness values were not used in the margin assessments. Therefore, the staff concern in RAI 6 is resolved.

Based on this margin assessment, in Section 3.2.1.3 of the report, the BWRVIP recommended certain analysis procedures allowing different fracture toughness methods depending upon the neutron fluence range of the components to be evaluated.

Based on information in several General Electric (GE) Safety Communications (SCs) (Refs. 14-17), the staff was concerned that the results of the margin assessments, with respect to the recommended evaluation methods as a function of neutron fluence, could change. By email dated September 20, 2013 (Ref. 18), the BWRVIP provided clarifying information related to the staff's concern. The BWRVIP stated that these SCs have a common theme in that they relate to annulus pressurization (AP) and/or recirculation line break (RLB) loads that might affect flaw evaluations leading to either a change in allowable flaw size and/or a change in the inspection frequency. The BWRVIP emphasized that the assumed 6 ksi load is arbitrary and does not take into account AP or RLB loads, or any other actual plant applied loads. Therefore, there is no impact on the results and conclusions of BWRVIP-100, Revision 1.

The staff also notes that the recommended evaluation methods (limit load, EPFM, or LEFM) is based primarily on the behavior of the material over certain fluence ranges, and the margin assessment performed by the BWRVIP is confirmatory in nature. Further, the relative margins achieved are independent of the stress level because the margins are applied directly to the stresses for all three methods, therefore, the relative margins will not change at different arbitrary stress levels.

The staff finds that the recommended procedures for evaluation of detected flaws in BWR core shrouds are acceptable because they either use experimentally based fracture toughness (EPFM) that varies as a function of fluence, or result in conservative margins compared to EPFM (LEFM or limit load).

3.5 Plant-Specific Evaluation for High-Fluence Welds

BWRVIP-76-A, "BWR Vessel and Internals Project, BWR Core Shroud Inspection and Flaw Evaluation Guidelines" (Ref. 19), recommends inspection intervals that are based on generic flaw evaluations that used a particular assumed fracture toughness value. Since BWRVIP-100, Revision 1, recommends a lower assumed fracture toughness for LEFM analyses at fluences greater than $1x10^{21}$ n/cm^2 than BWRVIP-76-A, plant-specific LEFM analyses to determine the reinspection interval are required until the BWRVIP revises BWRVIP-76-A to incorporate the lower fracture toughness above $1x10^{21}$ n/cm^2 into the generic flaw evaluation (this has not changed from BWRVIP-100-A). The staff notes that Appendices D and F to BWRVIP-76, Revision 1, (Ref. 20), require the use of the evaluation methods specified in the latest NRC-approved version of BWRVIP-100 for plant-specific evaluations of horizontal and vertical welds. However, the generic evaluation in Appendix C of BWRVIP-76, Revision 1, is still only valid up to $1x10^{21}$ n/cm^2. In its SE of Appendix K (the license renewal appendix) to BWRVIP-76 (Ref. 21), the staff noted that the BWRVIP stated that it will incorporate the crack growth rate evaluations, specified in the BWRVIP-99 and BWRVIP-100-A TRs, in BWRVIP-76, and will develop generic inspection intervals for core shroud welds that are exposed to a neutron fluence value equal to or greater than 1 X 10^{21} n/cm^2 (E > 1 MeV). The staff expects this change will be made in a future revision to BWRVIP-76. Therefore, the staff considers this issue to be resolved since the guidance for plant-specific methodologies reference the latest approved version of BWRVIP-100, and the generic evaluation is restricted to fluences less than or equal to $1x10^{21}$ n/cm^2.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The staff has reviewed the BWRVIP-100, Revision 1, report. Based on its review, the staff concluded that, the report provides an acceptable technical basis for predicting fracture toughness of irradiated austenitic stainless steels, including (wrought) base material, HAZ and weld materials, and for defining appropriate flaw evaluation methodologies for assessing the integrity of irradiated BWR core shrouds.

With respect to the handling in BWRVIP-100, Rev. 1, of issues identified in the NRC’s approval letter of BWRVIP-100-A (Ref. 6), the staff finds the following:

- The staff’s letter approving BWRVIP-100-A with comments stated that the staff has determined that the BWRVIP-100-A report is acceptable provided that the BWRVIP, in the future, provides the amount of delta ferrite in the stainless steel weld metal to facilitate an effective assessment of the synergistic effect of neutron embrittlement and thermal embrittlement on stainless steel welds. With respect to this issue, the BWRVIP was unable to provide the requested amount of delta ferrite in the weld specimens. In an RAI response, the BWRVIP provided estimated ferrite values based on the material specifications. The staff agrees that based on the information provided, the fracture toughness of the weld materials should be representative of what can be expected in welds in operating BWRs. Also, given the source of the weld materials, the BWRVIP cannot make a precise estimate of the ferrite content. However, the staff recommends that if additional stainless steel weld materials are acquired for testing by the BWRVIP, the delta ferrite content should be characterized.

- With the respect to the need for a plant-specific flaw evaluation to determine inspection intervals for cracked core shroud welds exposed to a neutron fluence value greater than 1 x 10^{21} (E > 1 MeV), and the incorporation of the fracture toughness values (as a function of neutron fluence) shown in Section 2.0 of the BWRVIP-100-A report in Appendix C of the BWRVIP-76 report, the staff finds this issue is resolved based on the revised guidance for evaluation methodologies in Appendixes D and F of BWRVIP-76, Revision 1.

- With respect to orientation effects on fracture toughness of irradiated stainless steel, BWRVIP-100, Revision 1, reports testing of additional materials revealed there is an orientation effect, but the existing model still bounds the data. The staff finds this issue is resolved. With respect to the final version of the BWRVIP-100, Revision 1, report, the staff recommends the BWRVIP correct the inconsistency between Figure 3-9 and Figure 7 of the RAI 8 response.

The staff has the following recommendations related to future revisions of this report:

- The BWRVIP should continue to seek additional austenitic stainless steel weld materials to better characterize the toughness of weld materials affected by both irradiation and thermal aging. The ferrite content of any weld materials tested should be characterized if at all possible.

- The BWRVIP should: (1) Develop an estimate of the initial as-welded toughness of core shroud welds; (2) Test materials that with thermal aging representative of end-of-life (60 years) in the BWR fleet; and (3) Modify the BWRVIP-100 toughness model as necessary, to ensure it reflects expected loss of fracture toughness due to thermal aging as well as irradiation, and is conservative for weld materials at end-of-life.

- The BWRVIP should continue to seek additional irradiated HAZ materials for fracture toughness testing.

- To ensure the BWRVIP-100, Revision 1, model continues to be conservative for all core shroud materials, the BWRVIP should revise its model for fracture toughness as needed based on the results of testing additional specimens (exposed in operating BWRs, test reactor or PWRs), or should ensure that the measured J-R curves for the additional specimens are bounded by the predictions of the existing model.

5.0 REFERENCES

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11. NUREG/CR-6004, "Probabilistic Fracture Evaluations for Leak-Rate-Detection Applications, April 1995

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16. GE Safety Communication 11-07, "Impact of Inertial Loading and Potential New Load Combination from Recirculation Suction Line Break Acoustic Loads," issued June 10, 2013

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19. 1019057, BWRVIP-76-A: BWR Vessel and Internals Project, BWR Core Shroud Inspection and Flaw Evaluation Guidelines," dated December 31, 2009 (ADAMS Accession No. ML101530467)

20. 1022843, BWRVIP-76, Rev. 1: "BWR Vessel & Internals Project BWR Core Shroud Inspection & Flaw Evaluation Guidelines." Page D-1 to End, dated May 31, 2011 (ADAMS Accession No. ML11195A184)

21. Boiling Water Reactor Vessel and Internals Project (BWRVIP) Revision to Final Safety Evaluation of Topical Report, “BWR Core Shroud Inspection and Flaw Evaluation Guidelines (BWRVIP-76), Appendix K for License Renewal,” September 26, 2009 (ADAMS Accession No. ML092940318)

Attachment: Resolution of Comments

Principal Contributor: Jeffrey Poehler

Date: March 2016

RESOLUTION OF BWRVIP COMMENTS ON DRAFT SAFETY EVALUATION

BWRVIP-100, REVISION 1, "BWRVIP VESSEL AND INTERNALS PROJECT:

UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS"

Comment No.	Draft SE Location	Comment Type	Comment	Resolution
1	Pg. 2, Section 1.2, last sentence	Clarification	Recommend deleting "Revision 0" from the last sentence. The original version of BWRVIP-100 was not referred to as Revision 0, so for clarity and accuracy "Revision 0" should be deleted from this paragraph.	Incorporated.
2	Pg. 3, Section 2.5	Editorial	Consistent with 2.4 above, and for clarity, suggest replacing "This section" with "Chapter 4".	Incorporated.
3	Pg. 10, 4th paragraph	Editorial	Recommend deleting the word "the" before "NUREG/CR-7027"and delete the errant return.	Incorporated.
4	Pg. 10, last paragraph	Clarification	For clarification, a comma should be placed after "except in rare cases." This sentence paraphrases the 2nd to last paragraph on page 6 of the BWRVIP's response to RAI-8. The "except in rare cases" does not apply to growth in HAZ. By putting a comma after the clause, it is clearer.	Incorporated.
5	Page 11, 2nd paragraph, 2nd sentence	Editorial	Delete the 2nd "the".	Incorporated.
6	Page 15, 2nd paragraph	Clarification	Typically, for every RAI discussion the staff includes a concluding statement indicating that the RAI is resolved. No such statement is included for RAI 6. The staff may want to consider adding one.	Added the following sentences at the end of the second paragraph on page 15: "The staff found the BWRVIP's response to RAI 6 acceptable because it clarified why both toughness values were not used in the margin assessments. Therefore, the staff concern in RAI 6 is resolved."

Comment No.	Draft SE Location	Comment Type	Comment	Resolution
7	Page 16, Section 4.0, 1st paragraph	Clarification/ Inaccuracy	The last sentence implies that BWRVIP-100, Revision 1 covers CASS materials. However, the scope of BWRVIP-100 does not cover CASS materials and the BWRVIP never requested that it did. Thus, the BWRVIP does not understand why this statement was included and suggests that the staff remove it as it has no relevance with regard to the conclusions of the SE.	The staff agrees that BWRVIP-100, Rev. 1 did not state that the report is applicable to CASS. The staff therefore deleted this sentence since the scope of our approval of BWRVIP-100 is sufficiently clear without it.
8	Page 16, Section 4.0, 2nd paragraph, 1st bullet	Inaccuracy	The BWRVIP believes the lead in phrase for this sentence is inaccurate. Typically in SEs, the word "condition" is used in identifying conditional use provisions. There were no conditional use provisions for BWRVIP-100-A and the NRC's approval letter for BWRVIP-100-A does not refer to the NRC's requests for future actions as conditions. Thus the BWRVIP requests that this first phrase be deleted. Deleting the phrase such that the first sentence starts out "The staff's letter approving ..." will have no effect on the overall context of the subject paragraph.	Incorporated.

Comment No.	Draft SE Location	Comment Type	Comment	Resolution
9	Page 17, the last sentence of the bullet at the top of the page	Clarification	The BWRVIP requests deletion or clarification of the last sentence of this bullet. The staff's comment really does not apply since the BWRVIP has not changed the threshold fluence and fracture toughness values and Appendix C does not use EPFM. Furthermore, the note at the beginning of Appendix C of BWRVIP-76, Rev. 1-A states, *Note: The evaluations presented in this section form the basis for the generic shroud horizontal weld reinspection intervals in Table 2-1. Since these analyses were performed using a fracture toughness of 150 ksi √in, the application of Table 2-1 is limited to fluences less than or equal to1E21 n/cm^2. The evaluations in this Appendix should not be used as the basis for plant-specific evaluations. Plant-specific evaluations for horizontal welds should follow the guidance of Appendix D.*	This recommendation was included since BWRVIP-100, Rev.1 includes a procedure for using either limit load or LEFM to fluences up to 3E21 using a toughness of 112 ksi√in. Revision of Appendix C of BWRVIP-76 to reflect this could eliminate the need for plant-specific evaluations for horizontal welds up to 3E21 n/cm^2. However, the staff agrees that it is not necessary since BWRVIP-76, Rev. 1-A addresses higher fluences via plant-specific evaluations in Appendix D. The sentence has been deleted.