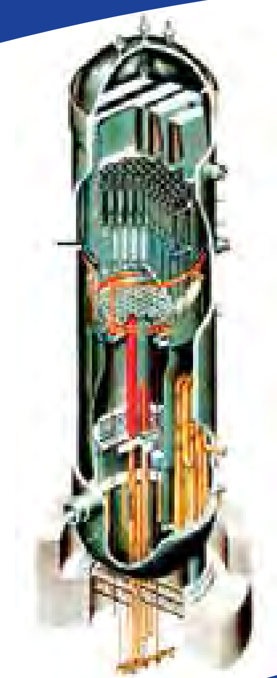
2017 TECHNICAL REPORT

BWRVIP-100NP, Revision 1-A: BWR Vessel and Internals Project

Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds



BWRVIP-100NP, Revision 1-A: BWR Vessel and Internals Project

Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds

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Final Report, February 2017

EPRI Project Manager
R. Carter

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES NO

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Electric Power Research Institute (EPRI)

NOTE

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NRC SAFETY EVALUATION

In accordance with an NRC request, the NRC Safety Evaluation immediately follows this page. Other NRC and BWRVIP correspondence are included in the appendices.

NOTE: The changes proposed by the NRC in the Safety Evaluation have been incorporated into the current version of the this report (BWRVIP-100, Rev. 1-A).

BWRVIP 2016-037B

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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,

Kevin Hsueh

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

Project No. 704

Enclosure:
Final Safety Evaluation

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.

Enclosure

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 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 [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information], which included generating [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information] 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 [Content Deleted - EPRI Proprietary Information], therefore, the BWRVIP concluded that this data is [Content Deleted - EPRI Proprietary Information Content Deleted - EPRI Proprietary Information] For O'Donnell, et al., less data lay below the [Content Deleted - EPRI Proprietary Information]; 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 [Content Deleted - EPRI Proprietary Information] 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 [Content Deleted - EPRI Proprietary Information].

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 [Content Deleted - EPRI Proprietary Information], 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 [Content Deleted - EPRI Proprietary Information]. 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 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 [Content Deleted - EPRI Proprietary Information], 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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2. BWRVIP Response to NRC Request for Additional Information on BWRVIP-100, Revision 1, June 6, 2013 (ADAMS Accession No. ML131560537)
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4. BWRVIP-100-A: BWR Vessel and Internals Project, "Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," 1013396 August 2006 (ADAMS Accession No. ML062570229)

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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

17. GE Safety Communication 12-20, "Error in Method of Characteristics Boundary Conditions Affecting Acoustic Loads Analyses," issued June 10, 2013

18. Email Clarification on BWRVIP-100 RAI on Safety Communications (ADAMS Accession No. ML15258A203)

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, Division of Engineering

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 $\sqrt{in}$, 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$\sqrt{in}$. 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.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304

This report describes research sponsored by EPRI and its BWRVIP participating members.

This report is based on the following previously published report:

BWRVIP-100-A: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds. EPRI, Palo Alto, CA: 2006. 1013396, authored by Sartrex Corp, principal investigator R. Gamble.

BWRVIP-100, Revision 1: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds. EPRI, Palo Alto, CA: 2010. 1021001, authored by Sartrex Corp., principal investigator R. Gamble.

This publication is a corporate document that should be cited in the literature in the following manner:

BWRVIP-100NP, Revision 1-A: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds. EPRI, Palo Alto, CA: 2017. 3002008388NP.

ABSTRACT

Data from previously performed experiments were collected and evaluated to determine the relationship between fracture toughness and neutron fluence for conditions representative of BWR core shrouds. A preliminary assessment of the available fracture toughness data of irradiated stainless steels is contained in *BWRVIP-85: Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWRVIP Core Shrouds* (EPRI report 1000887). Later, *BWRVIP-100-A: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds* (EPRI, Report 1013396) was published to incorporate additional experimental data, and included responses to NRC requests for additional information. Recently, additional experimental data relating fracture toughness to neutron fluence have been published in *BWRVIP-154, Revision 2: BWR Vessel and Internals Project, Fracture Toughness in High Fluence BWR Materials.* (EPRI, Report 1019077). The experimental results from this recent work have been evaluated to further validate the relationship between fracture toughness and neutron fluence and the results from that evaluation are presented in this report. This relationship was used to define applicable flaw evaluation methodologies as a function of neutron fluence for cracked BWR core shrouds and to identify changes that may be necessary to *BWRVIP-76: BWR Core Shroud Inspection and Flaw Evaluation Guidelines* (EPRI report TR-114232).

The experimental data in this report were used to develop fracture toughness curves as a function of neutron fluence over a range from 1E20 to 1E22 n/cm^2. These curves, based on conservative fits that envelope available data, provide a reasonably conservative basis to assess likely failure modes, margins against failure and inspection intervals. They were used to define the fluence levels at which limit load, elastic plastic fracture mechanics (EPFM), and LEFM analysis methods could be used for performing flaw evaluations and determining inspection intervals.

The results from this project have been incorporated in BWRVIP-76, Revision 2 [18].

Deliverable Number: 3002008388

Product Type: Final Report

BWRVIP-100, Revision 1-A: BWR Vessel and Internals Project: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shroud

PRIMARY AUDIENCE: Plant engineers responsible for reactor vessel core internals integrity

SECONDARY AUDIENCE: BWRVIP Program Owners

KEY RESEARCH QUESTION

The objectives of this project were:

- To determine the relationship between fracture toughness and neutron fluence by collecting and evaluating available experimental data; to determine applicable flaw evaluation methodologies as a function of neutron fluence for BWR core shrouds; to identify changes that may be necessary to *BWRVIP-76: BWR Core Shroud Inspection and Flaw Evaluation Guidelines*.

RESEARCH OVERVIEW

During the past several years, EPRI has completed several projects to assess the effect of irradiation on the fracture toughness of stainless steel. These projects included experimental work to determine the change in toughness due to irradiation and analyses to assess the integrity of irradiated BWR core shrouds. EPRI used results from these studies to define flaw evaluation and inspection guidelines for BWR core shrouds. These guidelines were developed using limit load and linear elastic fracture mechanics (LEFM) analysis methods. The guidelines were published in *BWRVIP-76: BWR Core Shroud Inspection and Flaw Evaluation Guidelines*. A preliminary assessment of the available fracture toughness data of irradiated stainless steels is contained in *BWRVIP-85: Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWRVIP Core Shrouds* (EPRI report 1000887). Additional experimental data relating fracture toughness to neutron fluence from *BWRVIP-154, Rev. 2: Fracture Toughness in High Fluence BWR Materials*, (EPRI report 1019077) have been evaluated and the results are presented in this report.

This study collected and evaluated data from previous experiments to determine the relationship between fracture toughness and neutron fluence for conditions representative of boiling water reactor (BWR) core shrouds. This relationship was used to define applicable flaw evaluation methodologies for cracked BWR core shrouds for various levels of neutron fluence and identify changes that may be necessary to *BWRVIP-76: BWR Core Shroud Inspection and Flaw Evaluation Guidelines* (EPRI report TR-114232). BWRVIP-100-A (EPRI report 1003396), comprises the prior NRC-approved version of the report.. Revision 1 to BWRVIP-100 (EPRI report 1021001) 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. BWRVIP-100, Revision 1-A consolidates all prior information submitted to NRC and incorporates all prior versions as well as the most recent NRC SE associated with the technical evaluation

KEY FINDINGS

- Data from previously performed experiments were collected and evaluated to determine the relationship between fracture toughness and neutron fluence. The data used in this work were from materials with heat treatments, irradiation temperatures, and test temperatures representative of BWR core shrouds.
- The experimental data were used to develop fracture toughness curves as a function of neutron fluence over a range from 1E20 to 1E22 n/cm^2. These curves, based on conservative fits that envelope available data, provide a reasonably conservative basis to assess likely failure modes, margins against failure and inspection intervals.
- They were used to define the fluence levels at which limit load, elastic plastic fracture mechanics (EPFM), and LEFM analysis methods could be used for performing flaw evaluations and determining inspection intervals.
- While this project was specifically initiated to address the fracture toughness for high fluence materials for the BWR core shroud, the fracture toughness results can be applied to other internal components that experience high fluence and are made of stainless steel.

WHY THIS MATTERS

Neutron irradiation exposure reduces the toughness of BWR core shroud materials. Accurate methods for predicting toughness of irradiated stainless steels are important to determine structural integrity and schedule appropriate inspections. The information contained in this report can be used to determine the fracture toughness of highly irradiated BWR internals made of stainless steel.

HOW TO APPLY RESULTS

Guidance and implementation criteria to determine appropriate flaw evaluation methodologies as a function of fluence for BWR core shrouds is contained in Section 4 of the report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Implementation of the flaw evaluation methodologies contained in this report have been incorporated in BWRVIP-235: BWR Vessel and Internals Project, Distributed Ligament Length (DLL) Version 3.1, Structural Analysis Software for BWR Internals," EPRI Technical Report 1018251, December 2009. This software can be used to evaluate flaws in BWR core shrouds.

EPRI CONTACTS: Robert G. Carter, Technical Executive, bcarter@epri.com

PROGRAM: BWRVIP

IMPLEMENTATION CATEGORY: Category 1 - Regulatory

RECORD OF REVISIONS

Revision Number	Revisions
BWRVIP-100	Original Report (1003016).
BWRVIP-100-A	The report as originally published (1003016) was revised to incorporate changes proposed by the BWRVIP in responses to NRC Requests for Additional Information, recommendations in the NRC Safety Evaluation (SE), and other necessary revisions identified since the last issuance of the report. All changes, except corrections to typographical errors, are marked with margin bars. In accordance with a NRC request, the SE is included here as an appendix and the report number includes an "A" indicating the version of the report accepted by the NRC staff. Non-essential format changes were made to comply with the current EPRI publication guidelines. Appendix D added: NRC Final Safety Evaluation. Details of the revisions can be found in Appendix E.
BWRVIP-100, Revision 1	This report incorporates new data, which has been reported since publication of BWRVIP-100-A. The majority of the new data were obtained from materials irradiated in international operating BWRs and reported in BWRVIP-154, Revision 2 (1019077). The data in BWRVIP-154, Revision 2 were generated in response to a recommendation in BWRVIP-100-A that additional core shroud plate and weld materials should be tested at fluences in the range from 1E21 to 8E21 n/cm^2 to obtain improved representations for material toughness and tensile properties. BWRVIP-154, Revision 2 includes an evaluation of the effect of specimen orientation on the fracture toughness. A few additional data from specimens removed from international operating plants are included and were obtained from a paper presented at the 2006 Fontevraud Conference in France. This report also includes data for materials irradiated in a test reactor from NUREG/CR-6960, which updates and supersedes the data in NUREG/CR-6826. Appendix F added: NRC approval of BWRVIP-100-A. Details of the revisions can be found in Appendix G.
BWRVIP-100, Revision 1-A	BWRVIP-100, Revision 1-A was revised to incorporate the NRC Safety Evaluation as well as NRC Requests for Additional Information (RAI) and the BWRVIP response to those RAIs

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1 INTRODUCTION

1.1 Background

Over the last several years, EPRI has completed several projects to assess the effect of irradiation on the fracture toughness of stainless steel. These projects included experimental work to determine the change in toughness due to irradiation, and analyses to assess the integrity of irradiated BWR cracked core shrouds. The results from these studies were used by EPRI to define flaw evaluation and inspection guidelines for BWR core shrouds. These guidelines were developed using limit load and linear elastic fracture mechanics (LEFM) analysis methods. The guidelines were originally published in EPRI report "BWR Core Shroud Inspection and Flaw Evaluation Guidelines" (BWRVIP-76) [1]. BWRVIP-76 was revised and has been published as BWRVIP-76-A [16], however, the conclusions from this report (BWRVIP-100, Rev. 1) were not incorporated at the time.

Experimental work funded by EPRI and others indicate the toughness for stainless steel is reduced at high irradiation levels. In a previous EPRI report, *Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWRVIP Core Shrouds* (BWRVIP-85), the reduced toughness was evaluated using elastic plastic fracture mechanics (EPFM) methods to determine the structural margin for cracked BWR core shrouds with high fluence. The results from the EPFM analyses indicate adequate structural margins are maintained when BWR core shrouds are inspected and evaluated using the guidelines in BWRVIP-76. Additional experimental data relating fracture toughness to neutron fluence have been evaluated and the results are presented in this report.

1.2 Objectives

The objectives of this work are to collect and evaluate available experimental data to determine the relationship between fracture toughness and neutron fluence. This relationship will be used to determine applicable flaw evaluation methodologies as a function of neutron fluence for cracked BWR core shrouds, and to identify changes that may be necessary to BWRVIP-76.

1.3 Approach

The approach used to complete the work in this report included the following:

1. Assemble relevant available fracture toughness data (i.e., K_{IC}, J-R curves) and associated references and data sources,

2. Develop plots of various toughness parameters or relationships as a function of fluence,

3. Define toughness versus fluence relationships that are appropriate for evaluating fitness for service of cracked BWR core shrouds,

4. Perform calculations to assess the applicability of the various flaw evaluation methodologies (i.e., limit load, EPFM, and LEFM) for various regions of the toughness versus fluence curves, and

5. Define the appropriate flaw evaluation methodologies over the fluence range of interest for cracked BWR core shrouds.

1.4 Report Organization

Section 2 of this report presents a summary of previously obtained experimental data that were used to study the relationship between fracture toughness and neutron fluence. Section 2 also provides plots of various toughness parameters as a function of fluence, including curves that can be used to assess the margin against failure due to the presence of flaws in BWR core shrouds.

Calculations to assess the applicability of the various flaw evaluation methodologies (i.e., limit load, EPFM, and LEFM) for various regions of the toughness versus fluence curves are presented in Section 3. Conclusions and recommendations for implementing the results of this work are listed in Section 4. Appendix A provides a comparison of predicted and experimental toughness curves, while a comparison of predicted and experimental yield strengths is presented in Appendix B. Appendix C provides the computational results for an example EPFM analysis for a BWR core shroud.

1.5 Implementation Requirements

In accordance with the implementation requirements of Nuclear Energy Institute (NEI) 03-08, Guideline for the Management of Materials Issues, Section 4.1.4 of this report is considered to be "needed" and the remainder of the report is for information only. The work described in this report will be used to perform calculations for irradiated stainless steel reactor internals using the appropriate toughness versus fluence relationships and flaw evaluation methods. Section 4.1.4 shall be used in lieu of the criteria in BWRVIP-76, Revision 1-A [17][1].

[1] The methodology contained in this report has been incorporated in BWRVIP-76, Revision 2 [18].

2 TOUGHNESS AND TENSILE PROPERTIES OF IRRADIATED STAINLESS STEEL

Determination of the inspection interval for BWR core shrouds is based on the operating time where adequate margins are maintained against failure from the presence of flaws. The margin against failure depends on the resistance the material has to the extension of flaws that may be present in the material. The material resistance to failure due to the presence of flaws is called fracture toughness.

The fracture toughness changes with neutron irradiation and temperature. 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 applicable 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 elastic plastic fracture mechanics (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, linear elastic fracture mechanics (LEFM) is the appropriate analysis method.

The remainder of this section presents data showing the variation in fracture toughness as a function of neutron fluence. The data presented in this report were collected from previous investigations where the test materials were obtained from operating BWRs or from materials that were irradiated in test reactors and tested under conditions simulating BWR operation. These data were used to develop various relationships between fracture toughness and neutron irradiation that can be employed to determine the margin against failure and the inspection intervals.

2.1 Fracture Toughness Data

Data from previously performed experiments [2-10] were collected and evaluated to determine the relationship between fracture toughness and neutron fluence. The data used in this work are presented in Table 2-1, Table 2-2 and Table 2-3. The data listed in the tables are from materials with heat treatments (solution annealed), irradiation temperatures (550°F), and test temperatures (300 to 570°F) representative of operating conditions for BWR core shrouds. Some of the test materials were taken from operating BWRs [2, 3, 4, 7, 8, 9, 10], while other materials were irradiated in test reactors. Table 2-1 contains data obtained in the fluence range 1E20 n/cm^2 < fluence < 3E21 n/cm^2, Table 2-2 contains data obtained in the fluence range 3E21 n/cm^2 ≤ fluence < 6E21 n/cm^2, and Table 2-3 contains data obtained in the fluence range 6E21 n/cm^2 ≤ fluence < 1E22 n/cm^2.

Table 2-1
List of previously obtained experimental results to define the fracture toughness of stainless steel as a function of neutron fluence, 1E20 n/cm^2 < fluence < 3E21 n/cm^2

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Table 2-2
List of previously obtained experimental results to define the fracture toughness of stainless steel as a function of neutron fluence, 3E21 n/cm^2 ≤ fluence < 6E21 n/cm^2

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Table 2-3
List of previously obtained experimental results to define the fracture toughness of stainless steel as a function of neutron fluence, 6E21 n/cm^2 ≤ fluence < 1E22 n/cm^2

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Each table includes the data source and specimen type, material type, product form (base, heat affected zone or weld), neutron fluence > 1 Mev, and parameters (C, n) to describe the ductile crack extension characteristics of the material subsequent to initial crack extension. In some experiments failure occurred from non-ductile failure at low toughness. In these instances, the linear elastic fracture toughness, K_{IC}, is listed in the tables. Most reports do not specify the specimen crack and applied load orientations relative to the rolling direction of the material; however, experiments described in [9] were designed to assess directional effects, and the specimen orientation for these experiments are shown in the tables and described in Section 2.3.2.

One CT specimen listed in Table 2-1 [5] and 13 CT specimens listed in Table 2-2 [3, 4, 9] were reported to have little or no ductile crack extension during testing, and no material J-R curves were provided. The test results for thirteen of these specimens [3, 4, 9] were used to define K_{IC} values as shown in the last column of Table 2-2. For the remaining specimen [5] (see Table 2-1) the value of J at which non ductile crack extension occurred was relatively high, and some limited J versus crack extension data were obtained. A more detailed evaluation of this experimental result is presented in Appendix A.

2.1.1 J-R Curves Versus Fluence

The variables C and n in Table 2-1, Table 2-2 and Table 2-3 are parameters of a power law relationship often used to represent the material resistance to fracture (J_{mat}) as a function of the amount of ductile crack extension (Δa) of an existing flaw under load. This relationship is called the J-R curve and is expressed as

$$J_{mat} = C(\Delta a)^n \quad \textbf{Equation 2-1}$$

The potential for additional load carrying capacity of the material subsequent to initial crack extension under load can be judged from the material J-R curve. The material J-R curves were obtained using Equation 2-1 with the C and n values from Table 2-1, Table 2-2 and Table 2-3. The resulting plots of the data in Table 2-1, Table 2-2 and Table 2-3 are presented in Figure 2-1, Figure 2-2, and Figure 2-3, respectively, where J_{mat} is presented as a function of crack extension for the various test materials and fluences. The first number for the various tests listed in the legend is the fluence, the following letter indicates the product form (*B*ase, *H*eat-*A*ffected-*Z*one, or *W*eld), and the last entry is the reference number. The crack extension values in the figures are limited to 1.6 mm consistent with the extent of the experimental data obtained in most small specimen tests.

The curves in Figure 2-1, Figure 2-2 and Figure 2-3 indicate a trend where there is a high potential for ductile crack extension and additional load carrying capacity at fluences lower than 1E21 n/cm^2, and lower potential for ductile crack extension at fluences greater than 1E21 n/cm^2. Each curve shown in the figures indicates some degree of ductile crack extension, including base and weld materials irradiated at up to 9E21 n/cm^2.

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Figure 2-1
Experimental J_{mat} versus crack extension curves for stainless steel (1E20 n/cm^2 < fluence < 3E21 n/cm^2)

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Figure 2-2
Experimental J_{mat} versus crack extension curves for stainless steel (3E21 n/cm^2 ≤ fluence < 6E21 n/cm^2)

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Figure 2-3
Experimental J_{mat} versus crack extension curves for stainless steel
(6E21 n/cm^2 ≤ fluence < 1E22 n/cm^2)

2.2 Fracture Toughness Curves for Integrity Assessments

The assessment of margin against structural failure due to the presence of flaws typically uses fracture toughness relationships that are reasonably conservative representations of the average values obtained from laboratory experiments. This section uses the data from Table 2-1, Table 2-2, and Table 2-3 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.

Two relationships are developed for structural margin assessments. The first is the material J-R curve as a function of neutron fluence. The second is determined from the J-R curves and is the material J versus tearing modulus (J/T) relationship as a function of neutron fluence. The tearing modulus, T, is a parameter that is used to characterize the resistance to (material J/T) or potential for (applied J/T) unstable crack extension at any specified value of J. Applied and material J/T curves are used to compare the potential for fracture created by flaws and loads on the component with the material resistance to fracture. The J/T plot provides the methodology to assess margin against failure and to determine likely failure mode as a function of neutron fluence.

2.2.1 Material J-R Curves for Integrity Assessments

The material J-R curves that are used for structural integrity assessments were determined by defining values of C and n that when used in Equation 2-1 provide reasonably conservative material J-R curves. The relationship between neutron fluence and toughness is developed using the values of the power law parameters C and n from Table 2-1, Table 2-2 and Table 2-3. A power law fit was used to construct a line that bounds the available data for C as a function of fluence. 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 resulting power law fits for C and n are presented in Equations 2-2 and 2-3, respectively. The power law relationship for C as a function of fluence, F, is

Content Deleted -
EPRI Proprietary Information **Equation 2-2**

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Figures 2-4 and 2-5, show plots of the power law fits for C and n, respectively, as a function of fluence, along with the data points from Tables 2-1, 2-2, and 2-3. The location of the data points for the weld, HAZ and base metal also are identified in the figures. The total number of data points in Figure 2-4 and Figure 2-5 (and some subsequent figures) may appear to be less than the number of data points in Tables 2-1, 2-2, and 2-3 because there are coincident values of C and n at some fluences. In these instances, two data points from the table would appear as one in the figures.

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Figure 2-4
J-R curve power law coefficient C as a function of neutron fluence for stainless steel base, HAZ and weld materials, applicable for fluence less than 3E21 n/cm^2

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Figure 2-5
J-R curve power law parameter n as a function of neutron fluence for stainless steel base, HAZ and weld materials, applicable for fluence less than 3E21 n/cm^2

Cracking in BWR core shrouds occurs primarily in the material heat affected zone (HAZ). Most experimental data have been obtained for base metal. The data shown in Figure 2-4 indicate that the toughness for the weld and HAZ materials forms the lower bound of the population of the weld, HAZ and base metal toughness. Consequently, this report uses the lowest points of the population of weld, HAZ and base metal data to determine a conservative relationship between neutron irradiation and toughness for BWR core shrouds.

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Substituting values of C and n from Equations 2-2 and 2-3, respectively, into Equation 2-1 will provide predicted J-R curves that match or are lower than the measured curves shown in Figures 2-1, 2-2 and 2-3 at the indicated fluences (see Section 2.3.5). Consequently, the J-R curves obtained by using the C and n values from Equations 2-2 and 2-3, respectively, provide reasonably conservative representation of the ductile crack extension characteristics of irradiated stainless steel in BWR core shrouds. The material J-R curves for structural integrity assessments are shown in Figure 2-6 with fluence as a parameter.

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Figure 2-6
J-R curves as a function of neutron fluence for structural integrity assessments of irradiated stainless steel

2.2.2 Material J/T Curves for Integrity Assessments

The material J/T curves used for structural integrity assessments are developed using the material J-R curves from Section 2.2.1 (see Figure 2-6) and are determined by plotting various values of J_{mat} from the material J-R curve as a function of the tearing modulus, T. T is a function of the slope of the J-R curve and is computed using the relationship

$$T = (dJ/da) * (E/\sigma_f^{\,2})$$ **Equation 2-4**

where dJ/da is the slope of the material J-R curve, E is the elastic modulus, and σ_f is the flow stress, which is half the sum of the material ultimate and yield strengths.

The flow stress was determined as a function of fluence using the data reported in [2] for weld and base metals at test temperatures in the range from 300 to 550°F. Figure 2-7 is a plot of flow stress as a function of the natural logarithm of fluence, ln(Fluence), and includes a mean curve through the data. The flow stress can be obtained from the relationship

Content Deleted - EPRI Proprietary Information **Equation 2-5**

For a J-R curve that can be described by a power law fit as indicated in Equation 2-1, the expression for T in Equation 2-4 can be written as

$$T = C * n * (\Delta a)^{n-1} * (E/\sigma_f^{\,2})$$ **Equation 2-6**

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. The small specimen size limits the experimental J-R data that can be obtained. 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 conservatism, various extrapolation methods previously have been used to extend the test data for structures. 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. This procedure is more conservative than using the power law fit J-R curve to generate the J/T curves for crack extensions greater than 1.6 mm.

The material J/T curves are presented as a function of fluence in Figure 2-8, and were generated using the J-R curves in Figure 2-6, and T computed using Equations 2-6, 2-2, 2-3, and 2-5, and E = 1.93E5 MPa (28E6 psi). The J and T relationships represented by Equations 2-1, 2-2, 2-3, and 2-6 are applicable for EPFM analyses in the fluence range from 1E20 and up to 3E21 n/cm^2.

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Figure 2-7
Flow stress as a function of ln (fluence) for stainless steel

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Figure 2-8
Flaw evaluation material J/T curves as a function of fluence for structural integrity assessments of irradiated stainless steel

2.3 Application to BWR Core Shroud Cracking

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

2.3.1 Irradiation in Power and Test Reactors

Sixty of the 71 experiments listed in Table 2-1, Table 2-2 and Table 2-3 (including 13 base metal specimens that had non ductile crack extension, all six weld specimens, and one of the HAZ specimens) were from materials removed from operating BWRs. Consequently, most of the data are from materials that would have thermal aging comparable to in-reactor components. Data irradiated in operating BWRs or test reactors are identified separately in Figures 2-9 and 2-10 for C and n, respectively. The information in Figures 2-9 and 2-10 indicates that the data base provides a reasonable representation of thermal aging effects that may exist in operating BWRs.

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Figure 2-9
J-R curve power law coefficient c as a function of neutron fluence for stainless steel irradiated in test and power reactors, applicable for fluence less than 3E21 n/cm^2

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Figure 2-10
J-R curve power law parameter n as a function of neutron fluence for stainless steel irradiated in test and power reactors, applicable for fluence less than 3E21 n/cm^2

2.3.2 Orientation Effect on Toughness

During a previous review of the available literature there was some evidence that there may be a directionality effect on material toughness. As part of the experimental program initiated to obtain additional toughness data at relatively high fluence levels [9] experiments were conducted to assess the effect of orientation on material toughness. This study included irradiated materials from two components removed from operating BWRs and two specimen orientations.

The specimen orientations included 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.

The results from these experiments are shown in Figures 2-11 and 2-12, where the power law parameters C and n, respectively, are plotted as a function of neutron fluence for each of two specimen orientations.

The results presented in Figure 2-11 show the presence of an orientation effect on the toughness of irradiated stainless steel. In this instance, the specimens with the L-T orientation (the solid symbols) have higher toughness compared to the specimens with the T-L orientation (the open symbols) at each of the corresponding fluences. Data for the base metal T-L orientation specimens are not shown in Figures 2-9 and Figure 2-10 at fluence = 4.7 E21 and 5.2 E21 n/cm^2, because as indicated in Table 2-2 the failures occurred from unstable non-ductile failure and the ductile crack extension parameters C and n could not be obtained.

A comparison of the J/T plots for specimens with L-T and T-L orientations at a fluence of 1.1E21 n/cm^2 is shown in Appendix A.

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Figure 2-11
Effect of specimen orientation on the J-R curve power law coefficient c as a function of neutron fluence for irradiated stainless steel

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Figure 2-12
Effect of specimen orientation on the J-R curve power law parameter n as a function of neutron fluence for irradiated stainless steel

2.3.3 Basis for the Fluence Limits for Application of EPFM

Table 2-1, Table 2-2 and Table 2-3 contains data from 71 experiments. The test materials for these experiments were obtained from 25 separate heats of material. Nineteen of the heats were obtained from 11 operating BWRs, and the remaining six heats were irradiated in two separate test reactors.

Five of the heats from operating BWRs had specimens that exhibited non ductile behavior; all the material in these heats were irradiated in the relatively narrow range from 3E21 to 5.2E21 n/cm^2. In one of these heats six of ten specimens exhibited non ductile crack extension, and in another heat three of six specimens exhibited non ductile crack extension. In the other three heats non ductile crack extension occurred in four specimens having the T-L orientation.

Forty-seven of the 71 experiments used specimens irradiated to fluence equal to or greater than 3E21 n/cm^2. Thirty-four of these 47 experiments exhibited ductile crack extension, while 13 of the 47 exhibited non ductile fracture in the fluence range from 3E21 to 5.2E21 n/cm^2. All 47 test specimens with fluence equal to or greater than 3E21 n/cm^2 were obtained from operating BWRs.

Twenty-four of the 71 specimens had been irradiated at fluences ranging from 1.5E20 to 2E21 n/cm^2. Thirteen of the 24 test specimens were obtained from operating BWRs. All but one of the 24 specimens in this fluence range exhibited ductile crack extension. The specimen where ductile crack extension was not observed was machined from a shielded metal arc weld (SMAW) that had been fabricated in the laboratory and irradiated in a test reactor [5].

In summary, 23 of 24 available experiments exhibited ductile crack extension at fluences ranging from 1.5E20 to 2E21 n/cm^2, and 34 of 47 available experiments exhibited ductile crack extension at fluences ranging from 3E21 to 1E22 n/cm^2. Thirteen of the 14 specimens that had non ductile crack extension were in the relatively narrow fluence range between 3E21 to 5.2E21 n/cm^2. Based on these data there is reasonable assurance that ductile crack extension will be the failure mode for fluence less than 3E21 n/cm^2.

2.3.4 Basis for the Fracture Toughness for LEFM Analyses

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2.3.5 Comparison of Predicted and Experimental J/T Curves

The methodology described in Section 2.2 was defined to provide conservative J-R curves and associated J/T plots for assessing margin against failure in the fluence range where elastic-plastic fracture mechanics (EPFM) analysis is applicable, i.e., less than Content Deleted -EPRI Proprietary Information. As described in Section 2.2.1, C was selected to bound the available data, and n was defined so that when used in combination with the bounding relationship for C, the predicted J-R curves match or are conservative compared to the experimental J-R curves.

A review of the information in Figures 2-6 and 2-8 shows that the J-R and J/T curves predicted by the methodology described in Section 2.2 decrease with increasing fluence. To demonstrate that the correlations for C and n provide conservative toughness curves for flaw evaluation, the methodology was used to generate J/T plots for all specimens listed in Table 2-1 and tested at fluences less than Content Deleted -EPRI Proprietary Information. The predicted J/T curves were compared to J/T curves developed from the experimental data. The comparisons are presented in Appendix A, and show the methodology described in Section 2.2 matches the experimental data for three tests and provides conservative predictions compared to the experiments for the remaining tests.

3
FAILURE MODE AND MARGIN ASSESSMENT

3.1 Failure Mode Assessment

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

First, an assessment is made to determine the maximum fluence for which limit load analysis can be used to determine if adequate margin against failure exists. This assessment is based on the requirement that for any specified degradation level, limit load can be used up to the fluence at which the margin against failure determined by EPFM analysis is equal to or greater than the margin against failure determined by limit load analysis. A similar assessment is made for LEFM analysis with K_{IC} = 150 ksi-(in)$^{0.5}$. These conditions were selected to be consistent with the margin assessments defined in [1]. Both circumferential through-wall and part-through-wall flaws are included in the assessment.

3.2 EPFM Failure Mode and Margin Analysis

EPFM analyses were performed to determine the margin against failure for a range of degradation and stress conditions from [1]. The analyses used through-wall flaws and full circumference part-through-wall flaws. The purpose of these calculations was to compare the safety margins in the core shroud using LEFM, EPFM and limit load analyses. The input for the analyses included: mean shroud radius = 88 inches; shroud thickness = 1.5 inches; Young's modulus = 28x10^6 psi; Poisson's Ratio = 0.3; and R_m/t = 88/1.5 = 58.67.

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Table 3-1
Yield strength values as a function of fluence

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3.2.1 Failure Mode Assessment

The results from the EPFM, limit load, and LEFM margin assessments are summarized in the remainder of this section. The results for through-wall flaws are presented in Section 3.2.1.1, and in Section 3.2.1.2 for part-through-wall flaws. The results from a composite of the through-wall and part-through-wall flaw results are presented in Section 3.2.1.3. A detailed example of the EPFM calculation procedure described in the preceding paragraph is presented in Appendix C for a part-through-wall flaw depth.

3.2.1.1 Through-Wall Flaws

The computational results in Appendix C of [1] are used for this assessment. Specifically, the computational results in Figures C-3 and C-6 for a nominal 6 ksi (primary membrane) stress level are used to determine the margins against failure for various operating times. These results were obtained for a core shroud assumed to contain multiple circumferential through-wall cracks distributed around the shroud circumference.

The results from Appendix C of [1] are summarized in Table 3-2 for an operating time of 16,000 hours. The first column in Table 3-2 is the degradation level at the beginning of an operating interval. The second and third columns in Table 3-2 present the margins obtained from the limit load (LL) analysis (Figure C-3) and linear elastic fracture mechanism (LEFM) analyses (Figure C-6), respectively, at the end of 16,000 hours of operation [1].

Table 3-2
Limit load and LEFM margins as a function of degradation level for stainless steel BWR core shrouds [1]

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The LEFM and limit load evaluations in [1] were performed using multiple circumferential through-wall cracks distributed around the circumference of the shroud. This model is the basis for the results shown in Table 3-2.

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Table 3-3 presents the applied stress intensities and equivalent single, through-wall flaw size for the various degradation levels. The half crack lengths associated with the equivalent applied stress intensity factors were determined using the DLL software [13]. The half crack lengths and applied stress intensity factors in Table 3-3 were used to start the EPFM analysis procedure [12], which is summarized in Section 3.2.

Table 3-3
Equivalent single through-wall half crack lengths as a function of degradation level for stainless steel BWR core shrouds

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The results from the margin calculations for through-wall cracks are summarized in Figures 3-1 through 3-6 for the 40%, 35%, 30%, 25%, 20%, and 10% degradation levels, respectively. The results indicate:

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Based on the results in Figures 3-1 through 3-6, the following analysis methods can be used for through-wall flaws with degradation levels ranging from 10 to 40% in the indicated fluence ranges.

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Figure 3-1
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 40% degradation level, applied stress = 6 ksi

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Figure 3-2
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 35% degradation level, applied stress = 6 ksi

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Figure 3-3
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 30% degradation level, applied stress = 6 ksi

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Figure 3-4
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 25% degradation level, applied stress = 6 ksi

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Figure 3-5
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 20% degradation level, applied stress = 6 ksi

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Figure 3-6
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a single through-wall cracks representative of a 10% degradation level, applied stress = 6 ksi

3.2.1.2 Part Through-Wall Flaws

Current flaw evaluation procedures for cracked core shrouds can include both part through-wall and through-wall flaws. Consequently, EPFM analyses also were performed for part through-wall flaws. These analyses used a uniform depth, 360° circumferential part-through-wall flaw. The margin calculations were performed for flaw depths of 0.5, 0.75, and 1-inch. The limit load and applied stress intensity factors for the uniform depth, 360° part-through-wall circumferential flaws were determined from Chapter 4 of [14]. The assumed loading and shroud geometry used in the evaluation of the through-wall flaws were used for evaluation of the part-through-wall flaws. Appendix C provides an example of the detailed computational results from the EPFM analysis for a 0.5-inch deep part-through-wall flaw.

The results from the limit load, LEFM, and EPFM margin calculations for part-through-wall cracks are summarized in Figures 3-7 through 3-9 for flaw depths of 0.5, 0.75, and 1-inch, respectively. The results indicate:

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Based on the results in Figures 3-7 through 3-9, the following analysis methods can be used for uniform depth, 360° circumferential part-through-wall flaws.

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Figure 3-7
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a 0.5-inch deep part through-wall crack, applied stress = 6 ksi

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Figure 3-8
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a 0.75-inch deep part through-wall crack, applied stress = 6 ksi

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Figure 3-9
Limit load, EPFM, and LEFM margins against failure as a function of neutron fluence for core shrouds with a 1-inch deep part through-wall crack, applied stress = 6 ksi

3.2.1.3 Failure Modes for Through-Wall and Part Through-Wall Flaws

Based on the results from the limit load, LEFM, and EPFM analyses in Sections 3.2.1.1 and 3.2.1.2, the failure modes and analysis methods can be defined for cracked core shrouds as a function of neutron fluence. Considering the composite results from both through-wall and part through-wall cracks the following analysis methods can be used in the identified fluence ranges.

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3.2.2 Margin Assessment at Various Stress Levels

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4
CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

1. Data from previously performed experiments were collected and evaluated to determine the relationship between fracture toughness and neutron fluence. The data used in this work were from materials with heat treatments, irradiation temperatures, and test temperatures representative of BWR core shrouds. Some of the test materials were taken from operating BWRs, while other materials were irradiated in test reactors.
2. The experimental data were used to develop fracture toughness curves as a function of neutron fluence over a range from 1E20 to 1E22 n/cm^2. These plots are based on conservative fits that envelope available data. These fits provide a reasonably conservative basis to assess the likely failure mode, margins against failure, and inspection interval.
3. The J/T plots and analyses of part-through-wall and through-wall flaw were used to define the fluence levels at which limit load, EPFM and LEFM analysis methods could be used for performing flaw evaluations and determining inspection intervals for BWR core shrouds.
4. Three procedures can be used for flaw evaluations of core shrouds.

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The evaluation procedures are summarized in Table 4-1.

Table 4-1
Summary of limit load, EPFM and LEFM evaluation procedures, fracture toughness and fluence limits

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4.2 Recommendations

It is recommended that the evaluation procedures in Section 4.1 be incorporated in BWRVIP-76-A.

5
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A
COMPARISON OF EXPERIMENTAL AND PREDICTED J/T CURVES

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Figure A-1
Comparison of experimental and predicted J/T plots, 1.5E20 n/cm^2, base metal

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Figure A-2
Comparison of experimental and predicted J/T plots, 1.5E20 n/cm^2, base metal

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Figure A-3
Comparison of experimental and predicted J/T plots, 1.5E20 n/cm^2, base metal

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Figure A-4
Comparison of experimental and predicted J/T Plots, 3E20 n/cm², base metal

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Figure A-5
Comparison of experimental and predicted J/T plots, 3.5E20 n/cm^2, heat affected zone

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Figure A-6
Comparison of experimental and predicted J/T plots, 4E20 n/cm^2, weld metal

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Figure A-7
Comparison of experimental and predicted J/T plots, 4.8E20 n/cm^2, weld metal

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Figure A-8
Comparison of experimental and predicted J/T plots, 6.3E20 n/cm^2, base metal

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Figure A-9
Comparison of experimental and predicted J/T plots, 6.4E20 n/cm^2, base metal

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Figure A-10
Comparison of experimental and predicted J/T plots, 8E20 n/cm^2, base metal

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Figure A-11
Comparison of experimental and predicted J/T plots, 8E20 n/cm², base metal

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Figure A-12
Comparison of experimental and predicted J/T plots, 9E20 n/cm^2, base metal

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Figure A-13
Comparison of experimental and predicted J/T plots, 9E20 n/cm^2, base metal

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Figure A-14
Comparison of experimental and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-15
Comparison of experimental and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-16
Comparison of experimental and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-17
Comparison of experimental and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-18
Comparison of experimental and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-19
Comparison of experimental and predicted J/T plots, 1.44E21 n/cm^2, HAZ

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Figure A-20
Comparison of experimental and predicted J/T plots, 1.44E21 n/cm^2, HAZ

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Figure A-21
Comparison of experimental and predicted J/T plots, 1.44E21 n/cm^2, HAZ

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Figure A-22
Comparison of experimental and predicted J/T plots, 1.9E21 n/cm^2, base metal

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Figure A-23
Comparison of experimental and predicted J/T plots, 2E21 n/cm^2, base metal

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Figure A-24
Comparison of experimental L-T and T-L and predicted J/T plots, 1.1E21 n/cm^2, base metal

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Figure A-25
Comparison of experimental and power law fit JR curves, 1.44E21 n/cm^2, SMAW HAZ

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Figure A-26
Comparison of experimental and predicted J/T plots, 1.44E21 n/cm^2, HAZ for SMAW and SAW

B
COMPARISON OF PREDICTED AND EXPERIMENTAL YIELD STRENGTHS

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Figure B-1
Comparison of irradiated yield strength in Table 3-1 with predicted values [15], and experimental data

C
EPFM ANALYSIS FOR A PART-THROUGH-WALL, FULL CIRCUMFERENCE FLAW

C.1 Introduction

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Content Deleted -EPRI Proprietary Information Equation C-1

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C.2 Results

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Table C-1
Results from EPFM analysis to calculate margin for a core shroud with a full circumference, part-through-wall

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Table C-1
Results from EPFM analysis to calculate margin for a core shroud with a full circumference, part-through-wall (continued)

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D
NRC SAFETY EVALUATION OF BWRVIP-100

2004-081A

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 1, 2004

Bill Eaton, BWRVIP Chairman
Entergy Operations, Inc.
Echelon One
1340 Echelon Parkway
Jackson, MS 39213-8202

SUBJECT: SAFETY EVALUATION OF EPRI PROPRIETARY REPORT "BWR VESSEL AND INTERNALS PROJECT, UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS - BWRVIP-100" (TAC No: MB3946)

Dear Mr. Eaton:

The NRC staff has completed its review of the Electric Power Research Institute (EPRI) proprietary report TR-1003016, "BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds (BWRVIP-100)." This report was submitted by letter dated December 10, 2001, and was supplemented by letter dated June 9, 2003, in response to the staff's request for additional information (RAI) dated January 8, 2003.

In the enclosed safety evaluation (SE), the staff has found that the BWRVIP-100 report provides an acceptable technical justification for predicting fracture toughness of irradiated stainless steel, and defining appropriate flaw evaluation methodologies for assessing the integrity of irradiated BWR core shrouds. The BWRVIP-100 report is considered by the staff to be applicable for licensee usage, as modified and approved by the staff, at any time during either the current operating term or the extended license period.

The BWRVIP-100 report acknowledges the limited amount of experimental data available for the fracture toughness analyses. The staff agrees with this assessment and recommends that, as more data become available, the BWRVIP update the proposed fracture toughness curves for irradiated austenitic stainless steel.

In addition, the evaluation results in the BWRVIP-100 report show that the analysis presented in BWRVIP-76 to determine acceptable inspection intervals may not be valid for sufficiently high fluences. The appropriate inspection intervals would need to be justified on a case-by-case basis. The staff agrees with the BWRVIP's assessment of the analysis results for high fluence levels.

B. Eaton -2-

The staff requests that the BWRVIP review and resolve the issues discussed in the enclosed SE, and incorporate the staff recommendations into a revised BWRVIP-100 report. Please inform the staff within 90 days of the date of this letter as to your proposed actions and schedule for such a revision.

Please contact Andrea Lee of my staff at 301-415-2735 if you have any further questions regarding this subject.

Sincerely,

William H. Bateman

William H. Bateman, Chief
Materials and Chemical Engineering Branch
Division of Engineering
Office of Nuclear Reactor Regulation

Enclosure: As stated

cc: BWRVIP Service List

U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
SAFETY EVALUATION OF THE BWRVIP VESSEL AND INTERNALS PROJECT,
"BWR VESSEL AND INTERNALS PROJECT, UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS OF IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS (BWRVIP-100)" EPRI PROPRIETARY REPORT TR -1003016

1.0 INTRODUCTION

1.1 Background

By letter dated December 10, 2001, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) submitted for staff review and approval the Electric Power Research Institute (EPRI) proprietary Report TR-1003016, "BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds (BWRVIP-100)," dated December 2001. It was supplemented by letter dated June 9, 2003, in response to the staff request for additional information (RAI), dated January 8, 2003. BWRVIP-100 presents experimental data on the change in fracture toughness of irradiated austenitic stainless steel and analyses to assess the integrity of irradiated BWR cracked core shrouds. Consequently, this report defines applicable flaw evaluation methodologies for cracked BWR core shrouds for various levels of fluence and identifies changes to the conclusions of BWRVIP-76, "BWR Core Shroud Inspection and Flaw Evaluation Guidelines."

1.2 Purpose

The staff reviewed the BWRVIP-100 report to determine whether it provides accurate 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.

1.3 Organization of this Report

Because the BWRVIP-100 report is proprietary, this SE does not include proprietary information contained in the report. The staff does not discuss, in detail, the provisions of the guidelines, nor the parts of the guidelines it finds acceptable. A brief summary of the contents of the subject report is given in Section 2 of this SE, with the evaluation presented in Section 3. The conclusions are summarized in Section 4. The presentation of the evaluation is structured according to the organization of the BWRVIP-100 report.

ATTACHMENT

2.0 SUMMARY OF BWRVIP-100 REPORT

The BWRVIP-100 report addresses the following topics in the following order:

(a) Fracture Toughness Data - 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 heat affected zone (HAZ) materials that were tested under conditions simulating BWR operation. The materials were either obtained from operating BWRs or were irradiated in test reactors.

(b) Fracture Toughness Curves for Integrity Assessments - Analyzes available data and provides values of various toughness parameters as a function of neutron fluence that can be employed in fracture mechanics analyses to determine the margin against failure and the inspection intervals.

(c) Fracture Mode and Margin Assessment - Provides fluence thresholds for application of flaw evaluation methodologies, limit load, elastic plastic fracture mechanics (EPFM), and linear elastic fracture mechanics (LEFM) for different fluence levels. Provides a comparison of results using limit load and LEFM analyses with EPFM results to determine ranges of validity for simplified structural integrity analyses.

(d) Conclusions and Recommendations - Lists the overall recommendations for implementing the results of this work, including changes to the conclusions of BWRVIP-76, for core shroud inspection and flaw evaluation guidance, and for obtaining additional fracture toughness data on materials that are representative of the operating conditions for BWR core shrouds.

3.0 STAFF EVALUATION

The determination of appropriate inspection intervals for BWR core shrouds must ensure that adequate margins against failure from the presence of flaws are maintained. For an existing or postulated flaw, the margin against failure depends on the resistance of the material to extension of flaws, which is referred to as the fracture toughness of the material.

In the non-irradiated state, the fracture toughness of austenitic stainless steel such as the BWR core shroud materials is high. Failure occurs by plastic collapse, and limit load analysis is the applicable analysis method. However, exposure to neutron irradiation for extended periods changes the microstructure and leads to a significant increase in yield strength and reduction in ductility and fracture resistance. As the fluence level in the material increases, the failure mode changes from plastic collapse to ductile tearing of the flaws, and EPFM is the applicable analysis method. At very high irradiation levels, flaws can extend rapidly with little or no stable ductile tearing, and LEFM is the appropriate analysis method under these conditions. Appropriate methods for predicting fracture toughness of irradiated stainless steel are needed to determine structural integrity and inspection intervals for BWR core shrouds in order to maintain adequate margins against failure. In addition, since the core shroud is constantly exposed to neutron irradiation, the flaw evaluation method may change depending on the level of increased fluence.

3.1 Fracture Toughness Data

The staff reviewed the adequacy of the experimental data used to develop relationships for predicting fracture toughness of stainless steel as a function of neutron fluence. The review examined the existing data to determine how representative it is of material and operating conditions for BWR core shrouds. The data are from stainless steel base metal, weld metal, and HAZ, with heat treatments, irradiation temperatures, and test temperatures that are representative of operating conditions for BWR core shrouds.

The potential effects of synergistic embrittlement of stainless steel welds by thermal aging and neutron irradiation are not considered in either the correlations between fracture toughness and neutron fluence or the proposed threshold toughness values in various flaw evaluation methodologies. However, all the weld specimens were obtained from operating BWRs and thus had representative thermal aging histories. The ferrite content of these weld specimens is not reported, so no systematic assessment of a synergistic effect is possible.

The BWRVIP-100 report acknowledges the limited amount of available experimental data. The staff requests that, as material becomes available, additional tests be performed to better define the effects of different parameters on fracture toughness. Experimental data on austenitic stainless steel HAZ material is particularly limited. The staff recommends that these tests be conducted under material and service conditions where data are missing in the existing database. This issue should be addressed in the BWRVIP-100-A report, or in another correspondence.

3.2 Fracture Toughness Curves for Integrity Assessments

The BWRVIP-100 report provides material fracture toughness J–R and J/T curves, which decrease with increasing fluence, as would be expected, and are conservative with respect to the existing experimental data. The degree of conservatism varies. The staff finds the use of these curves acceptable over the range of fluences covered by the data.

There are data for some HAZ specimens with circumferential flaws for which the J–R curves are marginally lower and the J/T curves are significantly lower than the BWRVIP lower–bound curves. These results were obtained on materials irradiated at much lower temperatures than those that would occur in a commercial BWR, and hence are most likely not directly relevant to BWRs. However, the significant variation in toughness with orientation observed in these specimens indicates a need for additional data on austenitic stainless steel HAZ to explore orientation effects. The staff requests that, as more data on the toughness of HAZ materials becomes available, the BWRVIP update the proposed fracture toughness curves for irradiated austenitic stainless steel to ensure consistency with the additional data.

The estimated flow stress and yield stress values as a function of fluence in BWRVIP-100 are lower than most of the experimental data. Consequently, the estimated flow stress and yield stress values tend to give a more conservative estimate on the performance of structural integrity of the core shroud. This is especially true for primary loading. The effective crack size and applied tearing modulus, T (a function of the slope of J-R curve), are conservative using the lower estimated yield strength values.

3.3 Fracture Mode and Margin Assessment

BWRVIP-100 presents an estimate of the threshold fluence below which materials exhibit ductile crack extension. Below this fluence level, EPFM is appropriate for describing the behavior of the material. Above this fluence level, LEFM is appropriate. The value of K_{IC} provided in the BWRVIP-100 report for the analysis at high fluences, is acceptable because it is consistent with available experimental data.

Below the threshold fluence for non-ductile behavior, EPFM is the appropriate method to calculate structural margins. The BWRVIP-100 report compares predictions for other flaw evaluation methodologies, specifically limit load and LEFM, with a higher value of K_{IC}, with EPFM predictions for some representative through-wall and part through-wall flaws. The results show that there is a range of degradation and fluence conditions for which the simpler flaw evaluation techniques of LEFM or limit load give results that are conservative compared to EPFM, and could be used instead of EPFM. In some cases (e.g. specific combinations of limit load analyses and K_{IC} values) and for lower fluences, these results validate the use of limit load and LEFM calculations in BWRVIP-76 to determine acceptable inspection intervals.

The results also show that for sufficiently high fluences (greater than 1×10^{21} n/cm^2) the analysis presented in BWRVIP-76 to determine acceptable inspection intervals may not be valid and the choice of inspection intervals would need to be justified on a case by case basis, and submitted to the regulatory authorities for approval on a plant specific basis. The staff agrees with this evaluation of the analysis results.

3.4 Conclusions and Recommendations

BWRVIP-100 presents an estimate of the fluence below which materials exhibit ductile crack extension. The report states that, below this fluence level, EPFM is appropriate for describing the behavior of the material, and above this fluence, LEFM is appropriate. The value proposed for this threshold fluence for non-ductile behavior is acceptable, and the staff agrees that below this threshold fluence EPFM can be used to assess the integrity of cracked core shrouds.

The EPFM analyses are based on the J/T approach. The proposed J-R and J/T curves are conservative compared to the available data and are acceptable for use in EPFM analyses of cracked core shrouds. The EPFM analyses can be used to predict margins to failure for core shrouds, and to assess the validity of other methods of flaw evaluation as a function of fluence.

For fluences greater than that for which a transition to non-ductile behavior occurs, the BWRVIP-100 report requires that the analysis of cracked core shrouds be done using LEFM, and proposes a value of K_{IC} that should be used for these analyses. The staff agrees that for high fluences, LEFM methods are the appropriate method to assess structural integrity of cracked core shrouds and the proposed K_{IC} is appropriate.

The assessment of the adequacy of limit load and LEFM analyses in the BWRVIP-100 report shows that for sufficiently high fluences (greater than 1×10^{21} n/cm^2), the analysis presented in the BWRVIP-76 report to determine acceptable inspection intervals may not be valid and the choice of inspection intervals would need to be justified on a case-by-case basis. The staff agrees with the BWRVIP's assessment of the analysis results for high fluence levels, and the need for a case-by-case evaluation to determine acceptable inspection intervals. This evaluation should be submitted to the regulator for review.

A significant variation in toughness with flaw orientation has been observed in some specimens. The staff recommends that additional data be tested to explore orientation effects. Experimental data on austenitic stainless steel HAZ material is limited. The staff requests that, as more data become available, the BWRVIP update the proposed fracture toughness curves for irradiated austenitic stainless steel. The staff recommends that these tests be conducted under service conditions for materials not in the existing database. This issue should be addressed in the BWRVIP-100-A report, or in another correspondence.

Future actions of the BWRVIP include determining long term plans to develop additional data by conducting necessary experiments within three to five years. This approach is reasonable since it allows the BWRVIP time to plan and complete testing of additional data, however, it is sufficiently near term such that the reasonably conservative information in the BWRVIP-100 report can be utilized until new data are developed and tested.

The staff notes that the additional information provided by the BWRVIP in response to the RAIs on BWRVIP-100 is important to the technical adequacy of the BWRVIP-100 report and should be incorporated into the BWRVIP-100-A report as additional appendices.

The NRC staff has reviewed the BWRVIP-100 report and found that the report, as modified and clarified to incorporate the staff's comments above, provides an acceptable technical justification for predicting fracture toughness of irradiated stainless steels, and defining appropriate flaw evaluation methodologies for assessing the integrity of irradiated BWR core shrouds. The modifications addressed above should be incorporated in a revision to the BWRVIP-100 report. The BWRVIP-100 report is considered by the staff to be acceptable for licensee usage, as modified and approved by the staff, anytime during either the current operating term or during the extended license period.

4.0 REFERENCES

4.1 "BWR Vessel and Internals Project Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds (BWRVIP-100), dated December 2001.

4.2 Project No. 704 BWRVIP Response to NRC Request for Additional Information on BWRVIP-100, Dated June 9, 2003.

E
RECORD OF REVISIONS (BWRVIP-100-A)

NOTE: The revision described in this appendix were incorporated into BWRVIP-100-A (EPRI report 1013396). Changes due to the revisions are NOT marked with margin bars in the current version of the report (BWRVIP-100, Rev. 1).

BWRVIP-100-A	Information from the following documents was used in preparing the changes included in this revision of the report: 1. *BWRVIP-100: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds*. EPRI, Palo Alto, CA: 2001. 1003016. 2. Letter from Meena Khanna (NRC) to Carl Terry (BWRVIP Chairman), “Proprietary Request for Additional Information – Review of BWR Vessel and Internals Project Reports, BWRVIP-96, -97, -99, and -100 (TAC NOS. MB3947, MB3948, MB3951, and MB3946),” dated 1/8/03 (BWRVIP Correspondence File Number 2003-022). 3. Letter from Carl Terry (BWRVIP Chairman) to Meena Khanna (NRC) “Project 704 – BWRVIP Response to NRC Request for Additional Information on BWRVIP-100,” dated 6/9/03 (BWRVIP Correspondence File Number 2003-166). 4. Letter from William Bateman (NRC) to Bill Eaton (BWRVIP Chairman), “Safety Evaluation of EPRI Proprietary Report “BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds – BWRVIP-100” (TAC NO. MB3946)” dated 3/1/04 (BWRVIP Correspondence File Number 2004-081A). Details of the revisions can be found in Table E-1.

Table E-1
Revision details

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
NEI 03-08 requirements added	Materials Initiative	Old section 1.4 (“Implementation”) deleted; text from 1.4 combined into new section 1.5 (“Implementation Requirements”).
Revised Table 2-1.	Reference [8]	Added J-R data for HAZ material from Reference [8][, which was unavailable when BWRVIP-100 was published.
Revised Table 2-1.	Reference [5]	Updated citation for Reference [5], and included updated material type and values of C and n, and new data contained in Reference [5].
Revised Figure 2-1.	New and updated data in References [5 and 8]	Updated Figure 2-1 to include new and updated data from References [5 and 8], as shown in Table 2-1.
Revised Section 2.2.1, first paragraph.	RAI 100-1	Clarified procedure used to define values of C and n as a function of fluence.
Revised Section 2.2.1, second paragraph.	RAI 100-3(c)	Clarified procedure used to define toughness for HAZ material.
Revised Section 2.2.1, Figures 2-2 and 2-3.	RAI 100-3(a)	Updated Figures to include updated data from References [5 and 8], and to show location of data points for weld, base, and HAZ materials.
Added Section 2.3.1, including Figures 2-7 and 2-8.	RAI 100-3(b)	Added information to demonstrate that the data used to develop the relationship between fracture toughness and fluence include materials that have thermal aging comparable to in-reactor components.
Added Section 2.3.2, and modified Figures 2-2, 2-3, 2-7 and 2-8 to show fluence demarcation for EPFM and LEFM analyses.	RAI 100-2	Added information to demonstrate that EPFM is the appropriate analysis method at fluences less than 3E21 n/cm^2.
Added Section 2.3.3.	RAI 100-3(d)	Added information to justify the value of K_{IC} to be used in the LEFM analyses for fluences equal to or greater than 3E21 n/cm^2.
Added Section 2.3.4 and Appendix A.	RAI 100-1	Added Figures A-1 through A-21 in Appendix A to show that the methodology defined in Section 2.2 provides J-R and J/T curves that match or are conservative compared to experimental data.
Added last paragraph in Section 3.2, and added Appendix B.	RAI 100-4	Added Appendix B to compare the yield data in Table 3-1 with available experimental data from References [2, 3 and 6], and the prediction methodology in Reference [15].

F
NRC APPROVAL OF BWRVIP-100-A

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

November 1, 2007

Rick Libra, BWRVIP Chairman
DTE Energy
Fermi Nuclear Plant (M/S 280 OBA)
6400 N. Dixie Highway
Newport, MI 48166-9726

SUBJECT: 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'

Dear Mr. Libra:

By letter dated September 12, 2006, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) submitted Proprietary Report BWRVIP-100-A, "Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds," for Nuclear Regulatory Commission (NRC) staff review.

The BWRVIP-100-A report was submitted as a means of exchanging information with the staff for the purpose of supporting the assessment of the integrity of core shrouds.
The BWRVIP-100-A report provides accurate methods for predicting fracture toughness of irradiated stainless steel and defines appropriate flaw evaluation methodologies for assessing the integrity of irradiated core shrouds.

The BWRVIP-100-A report presents a compilation of information from the BWRVIP-100 report and the NRC staff's final safety evaluation (SE) dated March 1, 2004, which includes the BWRVIP's associated responses to NRC staff requests for additional information.

The NRC staff has reviewed the information in the BWRVIP-100-A report and has found that the report accurately incorporates all of the relevant information which was submitted by the BWRVIP in the documents noted above to support NRC staff approval of the report. The staff found that minimal revisions were made to the BWRVIP-100 report in the production of the BWRVIP-100-A report. These revisions are discussed in detail below.

The first revision was that the BWRVIP revised Section 1.4 and added a new Section 1.5 to include the implementation requirements of Nuclear Energy Institute Guideline 03-08 (NEI 03-08), "Guideline for the Management of Materials Issues." This section states that the BWRVIP-100-A report is considered "needed" in accordance with the implementation requirements of NEI 03-08. The staff finds this revision acceptable because the NEI 03-08 requirements would provide adequate guidelines for implementing the BWRVIP-100-A report at each BWR unit.

The second revision was that the BWRVIP added recently available fracture toughness data related to the heat affected zone (HAZ) of the stainless steel welds to Table 2-1. The staff finds this revision acceptable because the new data can be used for the evaluation of flaws in the HAZ of stainless steel welds.

The third revision consisted of a revision to Table 2-1 to include recently available data on the power fit coefficient (C), and power exponent (n) variables, which are used to determine the material resistance to fracture when stainless steel materials are subject to exposure to neutron radiation. The staff finds this revision acceptable because the new data can be used for the evaluation of flaws in core shroud stainless steel welds.

The fourth revision included an updated version of Figure 2-1 in which new data indicating a correlation between the neutron fluence and fracture toughness was added. The staff finds this revision acceptable as this data can be used by licensees for the evaluation of flaws in core shroud stainless steel welds.

In the fifth revision, the BWRVIP, in response to the staffs RAI 100-1 dated January 8, 2003, revised the first paragraph in Section 2.2.1 of the BWRVIP-100 report to indicate the method used for defining values of C and n as a function of neutron fluence. The staff determined that the BWRVIP adequately provided information on the definition of C and n.

The sixth revision addressed the staffs RAI 100-3(c) dated January 8, 2003, in which the BWRVIP revised the second paragraph in Section 2.2.1 of the BWRVIP-100 report to address the procedure used for the definition of HAZ toughness. The staff verified Section 2.2.1 of the report and concluded that the BWRVIP adequately addressed the HAZ toughness issue and, therefore, the staffs concern in RAI 100-3(c) is resolved.

The seventh revision, in response to the staffs RAI 100-3(a), the BWRVIP revised Figures 2-7 and 2-8 in which new toughness data values for HAZ, weld, and base material were added. In addition, Section 2.2.1 was revised to include the relationship between neutron fluence and fracture toughness for base metal and HAZ. The staff concluded that this revision provided adequate information regarding the relationship between neutron fluence and fracture toughness for base metal and HAZ and, therefore, the staffs concern in RAI 100-3(a) is resolved.

In the eighth revision, in response to the staffs RAI 100-3(b) dated January 8, 2003, the BWRVIP added Section 2.3.1 and Figures 2-7 and 2-8 which included data related to the effect of neutron irradiation on the thermally aged stainless steel weld metal. This data was obtained from operating BWR plants and, therefore, represents thermal aging histories in stainless steel welds. However, data on delta ferrite contents of the weld metal specimens was not included in the BWRVIP-100-A report. Since delta ferrite affects thermal embrittlement, the staff concludes that an effective assessment of synergistic effects of neutron embrittlement and thermal embrittlement cannot be made at this time. Since this is an on-going study, delta ferrite contents should be included in future work so that an effective assessment of the synergistic effects of neutron embrittlement and thermal embrittlement on the austenitic stainless steel welds can be made. Therefore, the staff concludes the data in the BWRVIP-100-A report provides reasonable assurance that the material used is representative of operating BWR plants, but that the BWRVIP, in the future, needs to provide the delta ferrite content so that the effects of delta ferrite on neutron and thermal embrittlement in austenitic stainless steel welds can be assessed. In the ninth revision, in response to the staffs RAI 100-2 dated

January 8, 2003, the BWRVIP added Section 2.3.2 and modified Figures 2-2, 2-3, 2-7 and 2-8 to indicate the application of an appropriate flaw evaluation method for the stainless steel materials based on their exposure to neutron radiation. The staff reviewed the information that was submitted and concluded that by providing this information related to the proper application of a flaw evaluation methodology for the irradiated stainless steel materials, the BWRVIP adequately addressed the staffs concern in RAI 100-2.

The tenth revision addressed the staffs RAI 100-3(d) dated January 8, 2003, in which the BWRVIP added Section 2.3.3 to the BWRVIP-100-A report in which information related to the use of a fracture toughness value was provided. The BWRVIP provided a technical justification for using this fracture toughness value for evaluating flaws in stainless steel welds exposed to neutron fluence values equal to or greater than 3×10^{21} (E > 1 MeV). After reviewing the submitted information, the staff concluded that the BWRVIP adequately addressed the staffs RAI 100-3(d).

In the eleventh revision, in response to the staffs RAI 100-1 dated January 8, 2003, the BWRVIP added Section 2.3.4, Appendix A and Figures A-1 through A-2 to include recent experimental results related to fracture toughness values for stainless steel materials irradiated to various neutron fluences. The staff reviewed the data and concluded that predicted fracture toughness values for irradiated stainless steel materials addressed in the original BWRVIP-100 report are more conservative than the experimental results and, therefore, the staffs concern in RAI 100-1 is resolved.

In the final revision, the BWRVIP responded to the staffs RAI 100-4 dated January 8, 2003, by adding Section 3.2 and Appendix B in which a comparison was made between the experimental data and predicted values related to yield strength variation with neutron fluence. After the review, the staff concluded that the information presented in the original BWRVIP-100 report adequately represented irradiated yield strength values for application to the evaluation of flaws in core shroud welds. Therefore, the staffs concern in RAI 100-4 is considered closed.

Based on the discussion above, the staff has determined that the BWRVIP-100-A report is acceptable provided that the BWRVIP, in the future, provide 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 addition, the staff reiterates the following issues that were stated in the staffs 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.

Please contact John Honcharik of my staff at (301) 415-1157 if you have any further questions regarding this subject.

Sincerely,

W. H. Bateman

William H. Bateman, Deputy Director
Division of Component Integrity
Office of Nuclear Reactor Regulation

Project No. 704

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G
RECORD OF REVISIONS (BWRVIP-100, REV. 1)

BWRVIP-100, Revision 1	Information from the following documents was used in preparing the changes included in this revision of the report: 1. *BWRVIP-100-A: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds*. EPRI, Palo Alto, CA: 2001. 1003016. 2. *BWRVIP-154, Revision 2: BWR Vessel and Internals Project, Fracture Toughness in High Fluence BWR Materials*. EPRI, Palo Alto, CA: 2009. 1019077. 3. O. K. Chopra and W. J. Shack, "Crack Growth Rates and Fracture Toughness of Irradiated Austenitic Stainless Steels in BWR Environments", NUREG/CR-6960, Argonne National Laboratory, August 2008. 4. U. Ehrnsten, et. al.,"Fracture Toughness of Stainless Steel Irradiated up to ~ 9 dpa in Commercial BWRs", *Proc. 6th Fontevraud Conf. on the Contribution of Materials Investigations to Improve the Safety and Performance of LWRs*, SFEN, Paris, France, (2006), p. 661. Details of the revisions can be found in Table G-1.

Table G-1
Revision details

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Revised Section 2-1.	References [5, 9 and 10]	Updated text, table and figures to include new data contained in References [5, 9 and 10], which were unavailable when BWRVIP-100-A was published.
Revised Table 2-1.	Reference [5]	Updated citation for Reference [5], and included updated material type and values of C and n, and new J-R data contained in Reference [5].
Revised Table 2-1.	References [9 and 10]	Added J-R data from References [9 and 10], which were unavailable when BWRVIP-100-A was published.
Revised Table 2-1.	Expanded data base from reference [9]	Included only data where fluence is in the range 1E20 n/cm^2 ≤ fluence < 3E21n/cm^2.
Added New Table 2-2.	Expanded data base from reference [9]	Included only data where fluence is in the range 3E20 n/cm^2 ≤ fluence < 6E21n/cm^2.
New Table 2-2.	References [9 and 10]	Includes J-R data from References [9 and 10], which were unavailable when BWRVIP-100-A was published.
Added New Table 2-3.	Expanded data base from reference [9]	Included only data where fluence is in the range 6E20 n/cm^2 ≤ fluence < 1E22n/cm^2.
New Table 2-3.	References [9 and 10]	Includes J-R data from References [9 and 10], which were unavailable when BWRVIP-100-A was published.
Revised Figure 2-1.	New fluence range and updated data in References [5, 9 and 10]	Updated Figure 2-1 to include new and updated data from References [5, 9 and 10] and revised fluence range, as shown in Table 2-1.
Added New Figure 2-2.	New fluence range and updated data in References [9 and 10]	Created new Figure 2-2 to include data from References [9 and 10] and other data in the fluence range, as shown in Table 2-2.
Added New Figure 2-3.	New fluence range and updated data in References [9 and 10]	Created new Figure 2-3 to include data from References [9 and 10] and other data in the fluence range, as shown in Table 2-3.
Old Figure 2-2 renumbered to Figure 2-4	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Revised Figure 2-4.	Data from References [5, 9 and 10]	Updated Figure 2-4 to include new data from References [5, 9, and 10].

Table G-1
Revision details (continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Old Figure 2-3 renumbered to Figure 2-5.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Revised Figure 2-5.	Data from References [5, 9 and 10]	Updated Figure 2-5 to include new data from References [5, 9, and 10].
Revised Section 2.2.1.	Data from Reference [5]	Update text discussion to more accurately describe toughness of HAZ material relative weld and base metal based on new data in Reference [5], which was unavailable when BWRVIP-100-A was published.
Old Figure 2-4 renumbered to Figure 2-6.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Old Figure 2-5 renumbered to Figure 2-7.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Old Figure 2-6 renumbered to Figure 2-8.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Old Figure 2-7 renumbered to Figure 2-9.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Revised Figure 2-9.	Data from References [5, 9 and 10]	Updated Figure 2-9 to include new data from References [5, 9, and 10].
Old Figure 2-8 renumbered to Figure 2-10.	Editorial	Renumbering due to addition of new Figure 2-2 and new Figure 2-3.
Revised Figure 2-10.	Data from References [5, 9 and 10]	Updated Figure 2-10 to include new data from References [5, 9, and 10].
Added new Section 2.3.2	New Data from Reference [9]	Added new Section 2.3.2 to describe effect of specimen orientation on toughness from data in Reference [9], which was unavailable when BWRVIP-100-A was published.
Added new Figure 2-11	New Data from Reference [9]	Added new Figure 2-11 illustrating effect of specimen orientation on J-R curve parameter “C” from data in Reference [9], which was unavailable when BWRVIP-100-A was published.
Added new Figure 2-12	New Data from Reference [9]	Added new Figure 2-12 illustrating effect of specimen orientation on J-R curve parameter “n” from data in Reference [9], which was unavailable when BWRVIP-100-A was published.

Table G-1
Revision details (continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Old Section 2.3.2 renumbered to Section 2.3.3	Editorial	Renumbering due to addition of new Section 2.3.2.
Revised Section 2.3.3.	New data from References [5, 9 and 10]	Modified text to account for new data from References [5, 9 and 10], which were unavailable when BWRVIP-100-A was published.
Old Section 2.3.3 renumbered to Section 2.3.4.	Editorial	Renumbering due to addition of new Section 2.3.2.
Old Section 2.3.4 renumbered to Section 2.3.5.	Editorial	Renumbering due to addition of new Section 2.3.2.
Revised Section 3.2.1.3.	New data from Reference [5]	Deleted sentence describing relative position of HAZ data in scatter band based on new data in Reference 5, which was unavailable when BWRVIP-100-A was published.
Revised Section 3.2.2.	BWRVIP-76-A	Deleted last paragraph to be consistent with update to BWRVIP-76-A, which implements this on a plant specific basis.
Revised Section 4.	Clarification	Revised Conclusion 4 to clarify limits of applicability for limit load, EPFM and LEFM. Added Table 4-1 to clarify the failure modes and conditions and fluence ranges associated with each mode.
Revised Section 4.	BWRVIP-76-A	Deleted Conclusion 5 to be consistent with update to BWRVIP-76-A, which implements this on a plant specific basis
Revised Section 4.	BWRVIP-76-A	Deleted Recommendation 1 because it has been implemented in BWRVIP-76-A on a plant-specific basis.
Revised Section 4.	Reference [9]	Deleted Recommendation 2 because it has been implemented by completion of the work described in Reference [9].
Revised Section 5.	New data from Reference [5]	Deleted old Reference [9] which indicated only HAZ trend. New data from Reference [5], which was unavailable when BWRVIP-100-A was published, coupled with data from Reference [8] provide more accurate data for HAZ.
Revised Appendix A.	New data from References [5 and 9]	Revised text and figures to describe new data from Reference [5] for HAZ specimen with little or no ductile crack extension, and Reference [9] for orientation effects.

Table G-1
Revision details (continued)

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Revised Appendix A.	Remove data not applicable in EPFM range	Eliminated original Figures A-13 through A-14 to remove figures where fluence was outside the applicable EPFM range, i.e., fluence ≥ 3E21 n/cm^2.
Revised Appendix A.	New data from References [5, 9 and 10]	Added figures for new data in fluence range 1E20 n/cm^2 ≤fluence < 3E21 n/cm^2 from References [5, 9; and 10], which were unavailable when BWRVIP-100-A was published.
Revised Appendix A.	Editorial	Reordered figures to be in order of increasing fluence.
Revised Appendix A.	New Data from Reference [5]	Added Figures A-25 and A-26 to provide a more detailed analysis of an SMAW specimen the showed little or no crack extension at fluence = 1.44E21 n/cm2 from Reference [5], which was unavailable when BWRVIP-100-A was published.

H
NRC REQUEST FOR ADDITIONAL INFORMATION

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

BWRVIP 2012-135A

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,

Joseph J. Holonich

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

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).

I
BWRVIP RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION ON BWRVIP-100, REV. 1

ELECTRIC POWER RESEARCH INSTITUTE

2013-088 BWR Vessel & Internals Project (BWRVIP)

May 23, 2013

Document Control Desk
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Joseph Holonich

Subject: Project No. 704 – BWRVIP Response to NRC Request for Additional Information on BWRVIP-100, Revision 1

Reference: Letter from Joseph J. Holonich (NRC) to Dennis Madison (BWRVIP Chairman), "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)," dated August 22, 2012.

Enclosed are five (5) copies of the BWRVIP proprietary response to the NRC Request for Additional Information (RAI) on the BWRVIP report entitled "BWRVIP-100, Revision 1: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds." The RAI was transmitted to the BWRVIP by the NRC letter referenced above.

Please note that the enclosed response contains proprietary information. A letter requesting that the response be withheld from public disclosure and an affidavit describing the basis for withholding this information are provided as Attachment 1. The response includes yellow shading to indicate the proprietary information. The proprietary information is also marked with the letters "TS" in the margin indicating the information is considered trade secrets in accordance with 10CFR2.390A.

Two (2) copies of a non-proprietary version of the BWRVIP response to the RAI are also enclosed. This non-proprietary response is identical to the enclosed proprietary response except that the proprietary information has been deleted.

If you have any questions on this subject please call Ron DiSabatino (Exelon, BWRVIP Assessment Committee Technical Chairman) at 610.765.5753.

Sincerely,

Dennis Madison
Southern Nuclear
Chairman, BWR Vessel and Internals Project

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Responses to NRC 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

Proprietary Version

Responses to NRC 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

Each item from the NRC Request for Additional Information (RAI) is repeated below verbatim followed by the BWRVIP response to that item.

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.

Response to RAI 1

Review of the comparisons between the predicted and actual J-R curves in Appendix A shows that the predicted curves represented by Equations 2-2 and 2-3 provide a close match to the experimental data for two of the experiments and are conservative for the remaining experiments. Because the predicted J-R curves either match or are conservative relative to the actual data there is no need to modify the predictive relationships in Equations 2-2 and 2-3.

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.

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.

Response to RAI 2

Table 2-2 and Table 2-3 together list 47 experiments performed at fluence levels equal to or greater than 3E21 n/cm^2. Of these 47 experiments, 34 had ductile crack extension. Thirty-three of the 34 specimens with ductile crack extension have equivalent fracture toughness considerably higher than [[Content Deleted - EPRI Proprietary Information]]. One of the specimens with ductile crack extension has an equivalent fracture toughness less than [[Content Deleted - EPRI Proprietary Information]]. Nine of the 13 specimens that did not have ductile crack extension have fracture toughness greater than [[Content Deleted - EPRI Proprietary Information]]. Consequently, 42 of 47 specimens or about 89 percent of the experiments with fluence 3E21 n/cm^2 or greater have fracture toughness greater than [[Content Deleted - EPRI Proprietary Information]]. Using a fracture toughness that bounds 89 percent of 47 total data points provides a reasonably conservative representation of the fracture toughness for fluence 3E21 n/cm^2 or greater.

TS

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 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 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, Rev. 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 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 staff to assess whether the weld metal results should be considered bounding for all weld materials, the 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.

Response to RAI 3

All the weld specimens shown in Figure 2-4 were irradiated in BWRs and generally have high fluence and long operating times. While the delta ferrite contents for the welds were not reported and are not available, the information in Figure 2-4 indicates that the weld data are within the overall trend for the data population as a whole, and have high toughness at fluences beyond 3E21 n/cm^2. However, for the 316L weld, it is known that ASME SFA 5.9-95 was specified for manufacture of this weld. This typically results in a ferrite number (FN) of 8-16. Additionally, if the material was 304 stainless and procured via typical ASME specifications, FN would be in the range of 8-20. These values are consistent with delta ferrite levels documented in BWRVIP-84 which has been reviewed by the NRC. Consequently, these data provide reasonable representation of thermal aging effects that may exist in operating BWRs.

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.

<u>Response to RAI 4</u>

The EPFM flaw evaluation methodology defined in Section 2 is applicable in the transition toughness region where ductile tearing is the failure mechanism. Both limit load and LEFM flaw evaluation procedures may not be appropriate in the transition toughness region because they are associated with different failure mechanisms. The results shown in Figures 3-1 through 3-9 were used to determine the flaw, toughness and load conditions where limit load or LEFM could be used to assess margin on load in the transition toughness region. This information was defined so that analysts who want to use conventional LEFM or limit load analyses or had previously performed LEFM or limit load analyses could continue to use the conventional analyses procedures and results provided they are within the parameters defined by the results in Figures 3-1 through 3-9.

Determination of the appropriate conditions for application of limit load or LEFM analyses was accomplished by comparing the margins calculated using the EPFM evaluation methodology with the margins calculated using LEFM and limit load analyses. The flaw, toughness and load conditions for which the margins computed by either LEFM or limit load are lower than the margins calculated by EPFM define the conditions where LEFM or limit load can be used conservatively. Because the material actually has the EPFM toughness properties shown in Equations 2-2 and 2-3 K_{IC} is used only as a computational variable to define where LEFM margins would be less than the true margins, which are determined from the EPFM analysis. Consequently, there is no need to determine a physical value of K_{IC}.

A review of the information in Figures 3-1 through 3-9 indicates that the smaller of the margins determined from either LEFM analysis with K_{Ic} equal [[Content Deleted - EPRI Proprietary Information]] or limit load provides margins less than the EPFM margins at all fluence levels for the flaw conditions shown in Figures 3-1 through 3-8. However, for the flaw conditions represented in Figures 3-9 both LEFM analysis with K_{Ic} equal [[Content Deleted - EPRI Proprietary Information]] and limit load result in margins greater than the EPFM margins at fluence levels between 1E21 and 3E21 n/cm^2. To ensure that either the limit load or LEFM margins are less than the EPFM margins at fluence levels between 1E21 and

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3E21 n/cm^2 the LEFM analysis must be used with K_{IC} equal [[Content Deleted - EPRI Proprietary Information]] as shown in Figure 3-9.
It is not necessary to use a lower toughness (i.e. K_{IC} equal [[Content Deleted - EPRI Proprietary Information]] for those conditions represented in Figures 3-1 through 3-8 where the margin from either LEFM analysis with K_{Ic} equal [[Content Deleted - EPRI Proprietary Information]] or limit load are less than the EPFM margins because the lower of the limit load and LEFM margins are already lower than the EPFM margins.

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<u>RAI 5</u>

The 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 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.

<u>Response RAI 5</u>

In response to this RAI additional LEFM and EPFM analyses were performed for a 1.25-inch deep, 360° part-through-wall circumferential flaw at a fluence of 2.9E21 n/cm^2. The results from these analyses indicate that the margin on load from the LEFM analysis with K_{IC} = [[Content Deleted - EPRI Proprietary Information]] is 1.67 and margin on load from the EPFM analysis is 1.93. These results indicate that the LEFM analysis with K_{IC} = [[Content Deleted - EPRI Proprietary Information]] is limiting relative to the EPFM analysis at flaw depths up to at least 83% of the wall thickness and fluence up to approximately 3E21 n/cm^2. **TS**

As already demonstrated in Figures 3-1 through 3-9 the margins from the LEFM analyses are lower than the margins from the EPFM analyses at fluence levels less than 3E21 n/cm^2. At higher fluences EPFM analyses are not permitted due to the concern that the EPFM analyses would overestimate the margins. Nevertheless, if EPFM analyses were permitted at the higher fluence levels it is unlikely that the EPFM analyses would result in margins lower than those from the LEFM analyses. For example, K_{IC} = [[Content Deleted - EPRI Proprietary Information]] is the allowable toughness at fluence 3E21 n/cm^2 or greater. Using Equation 2-1 with Equations 2-2 and 2-3 and a crack extension of 1.6 mm the J_{mat} at fluences of [[Content Deleted - EPRI Proprietary Information]] respectively. The equivalent values of K_{IC} are [[Content Deleted - EPRI Proprietary Information]], respectively. Consequently, the J_{mat} equivalent toughness values at fluence equal to or greater than 3E21 n/cm^2 are higher than [[Content Deleted - EPRI Proprietary Information]], and it is unlikely that the EPFM margins would be lower than the LEFM margins at higher fluences.

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<u>RAI 6</u>

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 partthroughwall flaws, in the margin evaluations of throughwall flaws described in Section 3.2.1 of the report.

<u>Response to RAI 6</u>

The LEFM analysis with K_{IC} = [[Content Deleted - EPRI Proprietary Information]] was used for Figures 3-1 through 3-6 because in all cases the margins provided by the LEFM analyses with K_{IC} = 150 ksi-√in were lower than the margins provided by the EPFM analyses. Consequently, there is no need to use lower values of K_{IC} because the LEFM margins with K_{IC} = [[Content Deleted - EPRI Proprietary Information]] are already low enough. It was necessary to use the lower value of K_{IC} = [[Content Deleted - EPRI Proprietary Information]] in Figures 3-7 through 3-9 because that was the maximum toughness that would provide LEFM margins less than the margins obtained from the EPFM analyses. **TS**

<u>RAI 7</u>

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.

<u>Response to RAI 7</u>

The linearization procedure was used to limit the amount of crack extension and allowable J associated with the power law fit in the extrapolated region where there are no available data. Using the linearization scheme rather than the power law fit to extrapolate the data is a conservatism in itself. There are five specimens where the predicted values of J at T = 0 are greater than the extrapolated experimental values. For these five experiments the predicted values of J range from 5 percent to 21 percent higher than the experimental values. Because applied K_I (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. In all other experiments the predicted values either match or are less than the extrapolated experimental values. This information demonstrates that the linear extrapolation scheme is reasonably conservative for the range of experiments shown in Appendix A.

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)

J
SECOND NRC REQUEST FOR ADDITIONAL INFORMATION ON BWRVIP-100, REV. 1

BWRVIP 2014-001A

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

January 7, 2014

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

SUBJECT: SECOND REQUEST FOR ADDITIONAL INFORMATION RELATED TO BWRVIP [BOILING WATER REACTOR (BWR) VESSEL INTERNALS PROJECT]-100, REVISION 1, "BWR VESSEL 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 (NRC) 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" (Agencywide Documents Access and Management System (ADAMS) Accession No. ML12044A187). By letter dated August 22, 2012, the NRC staff transmitted request for additional information (RAI) questions (ADAMS Accession No. ML12164A862) and on May 23, 2013, EPRI provided its responses to the RAI questions (ADAMS Accession No. ML13156A386).

The NRC staff completed its review of these RAI responses, and has identified additional areas for which information is needed to complete the review. The additional RAI question is enclosed to this letter.

In an email dated November 20, 2013, Mr. Larry Steinert, representing the BWRVIP agreed that the NRC staff will receive the response to the enclosed RAI question by June 30, 2014. If you have any questions regarding the enclosed RAI question, please contact me at 301-415-7297.

Sincerely,

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

Project No. 704

Enclosure:
RAI question

SECOND REQUEST FOR ADDITIONAL INFORMATION RELATED TO
BWRVIP-100, REVISION 1, BWR [BOILING WATER REACTOR] VESSEL
INTERNALS PROJECT - UPDATED ASSESSEMENT OF THE FRACTURE TOUGHNESS OF
IRRADIATED STAINLESS STEEL FOR BWR CORE SHROUDS
ELECTRIC POWER RESEARCH INSTITUTE
PROJECT NO. 704

RAI 8

NUREG/CR-6428 (Ref. 1) 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 et al. (Ref. 2) 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 (Ref. 3) 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.

Although the studies described above do not report on testing of welds subject to both thermal aging and irradiation, the results suggest that either thermal aging or irradiation independently can produce fracture toughness in austenitic stainless steel welds that would not be bounded by the BWRVIP-100, Revision 1 model.

Requested Information

Discuss and disposition the results of the studies cited above with respect to the BWRVIP-100, Revision 1 fracture toughness model. 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.

References

1. NUREG/CR-6428, Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds, April 30, 1996 (ADAMS Accession No. ML052360567).

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 (1996), pp. 209-220, Elsevier Science Limited.

3. NUREG/CR-7027, "Degradation of LWR Core Internal Materials Due to Neutron Irradiation," December 31, 2010 (ADAMS Accession No. ML102790482).

ENCLOSURE

K
BWRVIP RESPONSE TO SECOND NRC REQUEST FOR ADDITIONAL INFORMATION ON BWRVIP-100, REV. 1

ELECTRIC POWER
RESEARCH INSTITUTE

2015-088 BWR Vessel & Internals Project (BWRVIP)

July 15, 2015

Document Control Desk
U.S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Joseph Holonich

Subject: Project No. 704 – BWRVIP Response to NRC Second Request for Additional Information on BWRVIP-100, Revision 1

Reference: Letter from Joseph J. Holonich (NRC) to Dennis Madison (BWRVIP Chairman), Second Request for Additional Information Related to BWRVIP [Boiling Water Reactor Vessel Internals Project]-100, Revision 1, "BWR Vessel Internals Project – Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds" (TAC NO. ME8329), dated January 7, 2014

Enclosed are five (5) copies of the BWRVIP response to the NRC's second Request for Additional Information (RAI) on the BWRVIP report entitled "BWRVIP-100, Revision 1: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds." The RAI was transmitted to the BWRVIP by the NRC letter referenced above.

Please note that the enclosed response contains proprietary information. A letter requesting that the response be withheld from public disclosure and an affidavit describing the basis for withholding this information are provided as Attachment 1. The response includes yellow shading and brackets to indicate the proprietary information. The proprietary information is also marked with the letters "TS" in the margin indicating the information is considered trade secrets in accordance with 10CFR2.390.

Two (2) copies of a non-proprietary version of the BWRVIP response to the RAI are also enclosed. This non-proprietary response is identical to the enclosed proprietary response except that the proprietary information has been deleted.

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BWRVIP 2015-088

If you have any questions on this subject please call Ron DiSabatino (Exelon, BWRVIP Assessment Committee Technical Chairman) at 717.456.3685.

Sincerely,

Andrew McGehee, EPRI, BWRVIP Program Manager
Tim Hanley, Exelon, BWRVIP Chairman

EPRI Proprietary Licensed Material

Proprietary BWRVIP Response to NRC's Second Request for Additional Information on BWRVIP-100, Rev 1

EPRI Proprietary Licensed Material

Second Request for Additional Information Related to 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 Electric Power Research Institute Project No. 704

Each item from the NRC Request for Information (RAI) is repeated below verbatim followed by the BWRVIP response to that item.

<u>RAI-8</u>

NUREG/CR-6428 (Ref. 1) 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 et al. (Ref. 2) 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, Rev. 1 model. The welds were not thermally aged. NUREG/CR-7027 (Ref. 3) 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, Rev. 1 model.

Although the studies described above do not report on testing of welds subject to both thermal aging and irradiation, the results suggest that either thermal aging or irradiation independently can produce fracture toughness in austenitic stainless steel welds that would not be bounded by the BWRVIP-100, Rev. 1 model.

Requested Information:

Discuss and disposition the results of the studies cited above with respect to the BWRVIP-100, Revision 1 fracture toughness model. 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.

References:

1. NUREG/CR-6428, Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds, April 30, 1996 (ADAMS Accession No. ML052360567).

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 (1996), pp. 209-220, Elsevier Science Limited.

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3. NUREG/CR-7027, "Degradation of LWR Core Internal Materials Due to Neutron Irradiation," December 31, 2010, (ADAMS Accession No. ML102790482).

BWRVIP Response to RAI-8:

Because the exposure time for materials in operating BWRs exceeds one hundred thousand hours it is impractical in laboratory studies to conduct long term aging tests consistent with BWR operating conditions. Consequently, a number of laboratory experiments have been performed to assess aging effects using materials that have been aged for short times at temperatures (e.g., 752°F) significantly greater than BWR operating temperatures (550°F).

Fracture toughness tests on specimens aged for short times at temperatures significantly higher than BWR operating temperature were used to define a J-R curve for fully-saturated thermally aged, non-irradiated Type 308 and 316 SMAW welds, $J = 40+83.5\bullet\Delta a^{0.643}$ as shown in Figure 16 in NUREG/CR-6428 (Ref. 1).

Other test programs where specimens were irradiated and tested at temperatures significantly higher than BWR operating temperature were used to define a lower bound for the ductile fracture parameter "C". This lower bound was defined as $C = 20 + 205\bullet EXP(-0.65\bullet dpa)$ as shown in Figure 75(b) of NUREG/CR-6960 (Ref. 2) and later as $C = 25 + 175\bullet EXP(-0.35\bullet dpa)$ as shown in Figure 63(b) of NUREG/CR-7027 (Ref. 3). The values of "C" in these relationships is a parameter used to describe the material resistance to ductile crack extension, J_{mat}, or $J_{mat} = C(\Delta a)^n$, where Δa is the amount of ductile crack extension and C and n are the power law coefficients. The coefficient C represents the resistance to a small amount of crack extension (1 mm) just following initial crack extension while n represents the change in crack extension for an increased load increment. The coefficient C has been observed to be generally correlated to the level of neutron fluence and is often plotted as a function of neutron fluence to provide a visual picture of the variation in stainless steel fracture toughness as a function of neutron fluence.

Stainless steel fracture toughness degradation is a complex function of the level of neutron irradiation, irradiation temperature, irradiation flux and spectrum, exposure time and temperature, test temperature, material grain orientation (TL or LT), heat treatment and element content. Currently there is no direct, quantitative correlation between exposure time, exposure temperature, irradiation level and fracture toughness, and we know of no technical basis that demonstrates that the effect on toughness from irradiation and short time thermal aging at temperatures substantially above BWR operating temperatures is equivalent to the effect on toughness from long term aging or irradiation at BWR operating temperatures. Using data obtained substantially outside BWR operating conditions only adds to the uncertainty in defining the fracture toughness for materials irradiated in BWRs.

To reduce the uncertainty associated with potential long term aging and combined irradiation effects on fracture toughness at operating BWR conditions, the industry is using test specimens manufactured from materials removed from operating reactors, many of which have accumulated up to 175,000 hours of exposure time and irradiation at 550°F, to assess material toughness (Ref.

4). The most accurate representation of the actual combined aging and irradiation effects for BWR operation are included in the data presented in BWRVIP-100, Rev. 1 and the associated "C" and "n" relationships (Ref. 5).

This is illustrated in the plot presented in Figure 1, where material irradiated in test reactors and tested at BWR operating temperature (open squares) are presented along with materials that have been irradiated in operating reactors, removed from the reactor and tested at BWR operating temperature (solid diamonds and X). Most of the data (44 of 54 experiments), including all the welds, shown at fluences greater than 1E20 n/cm^2 were obtained using specimens manufactured from material removed from operating BWRs; the remaining data were obtained from specimens (base metal and HAZ) that had been irradiated in test reactors at approximately 550°F. Also shown in Figure 1 is the bounding curve for "C" defined in BWRVIP-100, Rev. 1 in the fluence range from 1.5E20 n/cm^2 to 3E21 n/cm^2. This curve bounds all the data obtained for materials irradiated and tested at BWR operating temperature. The data in Figure 1 show that the populations of test reactor and operating reactor data are intermingled. This indicates that there is no significant aging effect at BWR operating temperature and exposure times. The bounding curve for "C" defined in BWRVIP-100, Rev. 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, of the available data that are associated with actual component operating conditions.

The only data points that lie outside the BWRVIP-100, Rev. 1 bound curve are data that were obtained at aging, irradiation and test temperatures that are higher than BWR operating temperatures. It is not clear whether these outliers represent a real high temperature effect or are coincidental, and possibly associated with data scatter. To assess the possibility that the outliers are due to data scatter requires a significant number of data points; however, as indicated in NUREG/CR-7027 there are not enough data available from irradiated experiments at BWR conditions to make this assessment. Consequently, the distribution associated with data scatter will be estimated using results obtained from non-irradiated welds.

Figure 2 shows a plot of "C" as a function of neutron fluence for the results from experiments using non-irradiated material (plotted for visual convenience at fluence = 2E18 n/cm^2 for welds, 2.5E18 n/cm^2 for HAZ and 3E18 n/cm^2 for base metal) and irradiated material at fluences greater than 1E20 n/cm^2. All the data shown in Figure 2 were obtained from experiments conducted at 550°F. The non-irradiated data shown in Figure 2 were obtained from Table B.9 in NUREG/CR-6004 (Ref. 6) and Table 5 in NUREG/CR-6428. The data shown for the HAZ material are reported in EPRI NP-4768 (Ref. 7). These HAZ specimens were obtained from material adjacent to low toughness welds where "C" for the weld material ranged from about 200 kJ/m^2 to 400 kJ/m^2. There is scatter in the data all along the fluence range, but some of the lowest values of "C" are seen for the non-irradiated weld data at the left of the figure.

A review of the data indicates there are three distinct groups of non-irradiated weld data shown in Figure 2. One data set, reported in NUREG/CR-6004, has low toughness where "C" ranges from approximately 150 kJ/m^2 to 400 kJ/m^2 and was obtained using 1TCT and 2TCT specimens. There are two specimens reported in NUREG/CR-6428 that appear to have intermediate toughness where "C" has values of 400 kJ/m^2 and 650 kJ/m^2, which were obtained using 1TCT specimens. The third data set, reported in NUREG/CR-6004, has high toughness where "C" ranges from approximately 600 kJ/m^2 to 1000 kJ/m^2 and was obtained using pipe specimens that contained small surface cracks. The data used to estimate the distribution for the irradiated low toughness welds include the non-irradiated welds where “C” ranges from 150 kJ/m^2 to 400 kJ/m^2. The other data were not included because they appear to have toughness that is not consistent with the low toughness weld population, especially the results from the shallow surface flaw pipe experiments.

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Figure 63(b) in NUREG/CR-7027 presents an alternate lower bound curve for fracture toughness of irradiated austenitic stainless steel welds and cast austenitic stainless steels. The lower bound curve shown in Figure 63(b) apparently is based primarily on the data represented by the open circles. Although the origin of these data is not clear in NUREG/CR-7027, it appears that these data were irradiated and tested at temperatures substantially higher (i.e., 698°F) than BWR operating conditions (see Figure 75(b), NUREG/CR-6960).

[[Content Deleted - EPRI Proprietary Information]] Using these high temperature data only adds to the uncertainty in defining a reasonably conservative representation of the fracture toughness for materials in operating BWRs. TS

K-8

EPRI Proprietary Licensed Material

The work reported by O'Donnell et al. (Ref. 8) used various irradiation and thermal aging conditions to determine the fracture toughness for austenitic stainless steel base metal and welds. These experiments included aging, irradiation and test temperatures ranging from 698°F to 1022°F, which are substantially above BWR operating temperatures. A comparison of the data reported in the O'Donnell work with data from BWRVIP-100, Rev. 1 and the estimated [[Content Deleted - EPRI Proprietary Information]] are presented in Figure 6. TS

The comparisons in Figure 6 indicate that the irradiated data from the O'Donnell paper are either within or close to the bounding C curve defined in BWRVIP-100, Rev. 1. The two data points with low "C" values just outside (to the left of) the EPFM limit at 3E20 n/cm^2 could be a result of irradiation and testing at temperatures significantly greater than BWR operating temperature. Again, there is uncertainty in these results because the specimens were irradiated and tested at temperatures substantially higher than BWR operating temperatures.

To evaluate the sensitivity associated with the margins against failure from ductile crack extension, the toughness represented by both the [[Content Deleted - EPRI Proprietary Information]] were compared to the margins against failure determined using the toughness represented by the BWRVIP-100, Rev. 1 bounding "C" line. [[Content Deleted - EPRI Proprietary Information]] The results from the margin analyses are presented in Figure 7. TS TS

The results in Figure 7 show the margins remain [[Content Deleted - EPRI Proprietary Information]] This result indicates that there is a relatively small change in margin when the toughness is represented by either [[Content Deleted - EPRI Proprietary Information]] relative to the BWRVIP-100, Rev. 1 bounding curve. TS TS

Inspection results from core shroud examinations show that cracks initiate in the HAZ along the weld fusion line and not in the weld. However, some cracks can propagate away from the HAZ into the base metal and, in some rare instances, across the weld perpendicular to the weld direction. The observed crack initiation and growth characteristics indicate that the crack extension generally occurs in the HAZ or the base metal; consequently, the lower bound, composite weld, HAZ and base metal fracture toughness curve in BWRVIP-100, Rev. 1 is a realistic, conservative representation of the crack initiation and growth characteristics observed in core shrouds in operating BWRs.

Based on this evaluation the BWRVIP concludes that the data base and the bounding "C" and "n" curves in BWRVIP-100, Rev 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 margins against failure from ductile crack extension. Because there is no direct, quantitative correlation between BWR operating conditions and test results from experiments conducted at temperature significantly higher than BWR operating temperatures, the high temperature results are not used in the BWRVIP fracture toughness data base.

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Based on these results the BWRVIP proposes to continue to use the BWRVIP-100, Rev. 1 bounding curve. However, weld and HAZ materials have been removed from an operating reactor and will be tested later this year. When the results from these tests, as well as results from any future tests that might be performed, are available they will be added to the data base presented in Figure 1 and Figure 4. If the results from future experiments with material removed from operating BWRs fall below the [[Content Deleted - EPRI Proprietary Information]] shown in Figure 4, the BWRVIP-100, Rev. 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. TS

<u>References:</u>

1. NUREG/CR-6428, Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds, April 30, 1996 (ADAMS Accession No. ML052360567).
2. NUREG/CR-6960, Crack Growth Rates and Fracture Toughness of Irradiated Austenitic Stainless Steels in BWR Environments, March 2008.
3. NUREG/CR-7027, "Degradation of LWR Core Internal Materials Due to Neutron Irradiation," December 31, 2010, (ADAMS Accession No. ML102790482).
4. BWRVIP 154, Revision 2: BWR Vessels and Internals Project, Fracture Toughness in High Fluence BWR Materials, EPRI, Palo Alto, CA: 2009. 1019077.
5. BWRVIP-100, Revision 1: BWR Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Core Shrouds, EPRI Technical Report 1021001, October 2010.
6. NUREG/CR-6004, Probabilistic Fracture Evaluations for Leak-Rate-Detection Applications, April 1995.
7. Topical Report NP-4768, Toughness of Austenitic Steel Pipe Welds, EPRI Research Project 1238-2, October 1986.
8. 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 (1996), pp. 209-220, Elsevier Science Limited.

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Figure 1. Comparison of Fracture Toughness Power Law Coefficient C Values Obtained from Materials Irradiated in Test Reactors with Values Determined from Materials Irradiated in Operating BWRs, Test Temperature = 550°F.

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Figure 2. Comparison of the Power Law Toughness Coefficient, C, from BWRVIP-100, Rev. 1 Irradiated Data and Bounding Curve with Non-irradiated Data, Test Temperature = 550°F.

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Figure 3. Distribution for Fracture Toughness Power Law Coefficient, C, Non-irradiated Austenitic Stainless Steel Low Toughness Welds, Test Temperature = 550°F.

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Figure 4. Comparison of the Estimated Mean, 90% and 95% Curves for Irradiated Welds with the Fracture Toughness Power Law Parameter C in BWRVIP-100, Rev. 1.

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Figure 5. Comparison Between the Data and the Bounding "C" Curve in BWRVIP-100, Rev. 1, the Estimated 90% and 95% Bounds for Irradiated Welds, and the Data Used in NUREG/CR-7027 to Construct the Bounding Toughness Curve for Austenitic Stainless Steel Welds.

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Figure 6. Comparison Between the Data and the Bounding "C" Curve in BWRVIP-100, Rev. 1, the Estimated 90% and 95% Bounds for Irradiated Welds, and the Data from O'Donnell for Austenitic Stainless Steel Welds.

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Figure 7. Comparison of Margin Against Failure by Ductile Crack Extension for the BWRVIP-100, Rev. 1 Bounding "C" Curve and the Estimated 90% and 95% Bound Curves for Irradiated Welds in the Fluence Range from 1.5E20 n/cm^2 to 3E21 n/cm^2. Shroud thickness = 1.5-inch, R/t = 58, Nominal Stress = 6 ksi and Flaw Depth for 360° Circumferential, Inside Surface Flaw = 1-inch (a/t = 0.67).

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RECORD OF REVISIONS – BWRVIP-100, REV. 1-A

BWRVIP-100, Revision 1	Information from the following document was used in preparing the changes included in this revision of the report: 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, Palo Alto, CA: 2010. 1021001. 2. Letter from Kevin Hsueh (NRC) to Tim Hanley (BWRVIP Chairman), Final Proprietary 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), April 12, 2016. 3. Letter from Joe Holonich (NRC) to Dennis Madison (BWRVIP Chairman), Second Request for Additional Information Related to BWRVIP- 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), January 7, 2014. Details of the revisions can be found in Table L-1.

Table L-1
Revision details

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
	Editorial	NRC final Safety Evaluation on BWRVIP- 100, Rev. 1 inserted in front matter of report
Update Section 1.5	Editorial	Revised statement to require use of BWRVIP-100, Rev. 1-A methodology in lieu of BWRVIP-100-A for BWRVIP-76, Rev. 1-A. Added footnote regarding BWRVIP-76, Rev. 2
Revise Figure 3-9	NRC final Safety Evaluation on BWRVIP-100, Rev. 1	Revised figure to correct EPFM curve per Figure 7 of the second RAI on BWRVIP-100, Rev. 1
	NRC request	Appendix: H, I, J, K and L added. NRC/BWRVIP correspondence

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