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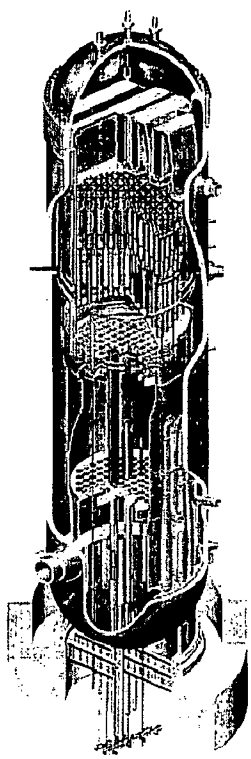
BWRVIP-100NP, Revision 1: BWR Vessel and Internals Project

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



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

1021001NP

Final Report, October 2010

EPRI Project Manager
R. Carter

This document does **NOT** meet the requirements of
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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, principal investigator R. Gamble.

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BWRVIP-100NP, 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: 2011. 1021001NP.

REPORT SUMMARY

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). A previous version of this report, BWRVIP-100-A (EPRI report 1003396), comprises the NRC-approved version of the report. This report (BWRVIP-100, Rev. 1) 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. All changes are marked with margin bars.

Background

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.

Objectives

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.*

Approach

The project team assembled relevant available fracture toughness data and defined toughness versus fluence relationships that are appropriate for evaluating fitness for service of BWR core shrouds. To determine appropriate flaw evaluation methodologies as a function of fluence for BWR core shrouds, the project team performed limit load and fracture mechanics analyses.

Results

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. It recommended that the results from this project be incorporated in BWRVIP-76-A, EPRI report 1019057. 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.

EPRI Perspective

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.

Keywords

BWR
Flaw evaluation
Core shroud
Fracture mechanics
Fracture toughness
Vessel and internals

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.

It is recommended that the results from this project be incorporated in BWRVIP-76-A [16].

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.

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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-A, until BWRVIP-76 is revised to incorporate these flaw evaluation procedures.

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/cm² < fluence < 3E21 n/cm²

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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/cm² ≤ fluence < 6E21 n/cm²

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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/cm² ≤ fluence < 1E22 n/cm²

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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 (ἀa) of an existing flaw under load. This relationship is called the J-R curve and is expressed as

$$J_{mat} = C(\Delta a)^n$$ **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-Zone, 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 ($6E21\ n/cm^2 \bullet$ 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

[[**Equation 2-2**

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Equation 2-3
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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]] TS **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 [[[illegible]]] TS. 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 [[[illegible]]] TS 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 REFERENCES

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A
COMPARISON OF EXPERIMENTAL AND PREDICTED J/T CURVES

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B
COMPARISON OF PREDICTED AND EXPERIMENTAL YIELD STRENGTHS

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

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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 $1x10^{21}$ 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 $1x10^{21}$ 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,

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 $n/cm^2 \leq$ 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 $n/cm^2 \leq$ 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 $n/cm^2 \leq$ 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.

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