March 1, 2004

Bill Eaton, BWRVIP Chairman
Entergy Operations, Inc.
Echelon One
1340 Echelon Parkway
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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.

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,

/RA/

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

Enclosure: As stated

cc: BWRVIP Service List

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,

/RA/

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Materials and Chemical Engineering Branch
Division of Engineering
Office of Nuclear Reactor Regulation

Enclosure: As stated

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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.