SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BWRVIP-100, REVISION 2

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT:

UPDATED ASSESSMENT OF THE FRACTURE TOUGHNESS

OF IRRADIATED STAINLESS STEEL BWR INTERNAL COMPONENTS

1. INTRODUCTION

1.1. Background

By letter dated July 11, 2023 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML23198A334), Electric Power Research Institute (EPRI) submitted to the U.S. Nuclear Regulatory Commission (NRC) Licensing Topical Report (TR) BWRVIP-100, Revision 2, “Boiling Water Reactor (BWR) Vessel and Internals Project, Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel BWR Internal Components” (ADAMS Accession No. ML23198A335). By letters dated May 9 and November 1, 2024 (ADAMS Accession Nos. ML24131A043 and ML24306A156), EPRI responded to NRC Requests for Additional Information (RAIs).

BWRVIP-100, Revision 2, contains updated fracture toughness, yield stress, and flow stress correlations for irradiated stainless steels. These correlations provide mechanical property inputs to flaw evaluation procedures. The TR also defines neutron fluence thresholds to determine failure mode. The correlations and fluence thresholds impact calculations of examination frequencies of BWR reactor vessel internals (RVI), as licensees implement BWRVIP RVI-specific aging management guidance. The mechanical property correlations and neutron fluence thresholds in BWRVIP-100, Revision 1-A, are also referenced in RVI aging management guidance for pressurized water reactors (PWRs) (see WCAP-17096, Revision 3, at ADAMS Accession No. ML23248A258 and MRP-227, Revision 2 at ADAMS Accession No. ML25142A177).

1.2. Purpose

BWRVIP-100, Revision 2, introduces updated mechanical property correlations and neutron fluence thresholds based upon recent data obtained from EPRI- and NRC-sponsored research programs. These parameters impact a broad range of BWRVIP guidance related to inspection and flaw evaluation of BWR and PWR RVI. Primarily, the BWRVIP RVI guidance documents constitute RVI aging management programs in license renewal and subsequent license renewal applications. Since information in this TR is referenced in PWR aging management guidance, as well, this report may impact aging management programs for PWRs. Therefore, the NRC staff’s independent review of BWRVIP-100, Revision 2, focused on ensuring the updated correlations are appropriately justified.

1.3. Regulatory Requirements

1.3.1. License Renewal and Subsequent License Renewal

The regulations in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 54 address the requirements for nuclear power plant license renewal. The regulation at 10 CFR 54.21, "Contents of application–technical information," requires that each application for a renewed operating license contain an integrated plant assessment and an evaluation of time limited aging analyses. As stated in 10 CFR 54.21(a), the integrated plant assessment shall identify and list those structures and components subject to an aging management review and demonstrate that the effects of aging will be adequately managed so that their intended functions will be maintained consistent with the current licensing basis for the period of extended operation as required by 10 CFR 54.29(a). In addition, 10 CFR 54.22 requires that applications for renewed operating licenses include any technical specification changes or additions necessary to manage the effects of aging during the period of extended operation as part of the application.

Structures and components subject to an aging management program (AMP) shall encompass those structures and components that: (1) perform an intended function, as described in 10 CFR 54.4, "Scope," without moving parts or without a change in configuration or properties and (2) are not subject to replacement based on a qualified life or specified time period. These structures and components are referred to as "passive" and "long-lived," respectively. The scope of components considered for inspection under a BWRVIP TRs meet these criteria.

The BWRVIP RVI TRs may be informed by the 10 program elements described in NUREG-2192, "Standard Review Plan for Subsequent License Renewal Applications," also known as SRP-SLR (ADAMS Accession No. ML17188A158), and NUREG-2191, "Generic Aging Lessons Learned Report for Subsequent License Renewal," also known as GALL-SLR, (ADAMS Accession Nos. ML17187A031 and ML17187A204). GALL-SLR AMP XI.M9, "BWR Vessel Internals," includes various BWRVIP reports that address aging management strategies for RVI components that serve an intended safety function pursuant to criteria in 10 CFR 54.4(a)(1). The scope of the program does not include consumable items such as fuel assemblies, reactivity control assemblies, and nuclear instrumentation because these components are not typically within the scope of the components that are required to be subject to an AMP, as defined by the criteria set out in 10 CFR 54.21(a)(1).

In accordance with 10 CFR 54.21(d), applicants for a renewed facility operating license are required to provide a Final Safety Analysis Report (FSAR) supplement for the facility that must contain a summary description of the programs and activities for managing the effects of aging and the evaluation of time-limited aging analyses for the period of extended operation. In some instances, BWRVIP TRs are referenced in the FSAR supplements for demonstrating that the effects of aging are adequately managed and time-limited aging analyses are adequately addressed during the period of extended operation as part of the license renewal process. BWRVIP TRs are living documents and may be periodically updated based on new operating experience and data from research programs. These BWRVIP TR updates may occur following the issuance of a renewed facility operating license, and any revisions to the FSAR supplement to make use of newly NRC-approved TRs or updated TRs must be made in accordance with established regulatory processes (e.g., 10 CFR 50.59, "Changes, tests and experiments").

1.3.2. Inservice Inspection of Reactor Vessel Internals

The regulations in 10 CFR 50.55a(g)(4) state, in part, that components classified as ASME Code Class 1, 2, and 3 must meet the requirements, except the design and access provisions and the preservice examination requirements, set forth in the American Society of Mechanical Engineers *Boiler and Pressure Vessel Code*, Section XI, to the extent practical within the limitations of design, geometry, and materials of construction of the components. The Section XI examination requirements for vessel internals are specified in IWB-2500, Table IWB-2500-1, Examination Categories B-N-2 and B-N-3. These requirements specify that visual examinations must be performed on core support structures and interior attachments to the reactor vessel each inspection interval.

The regulations in 10 CFR 50.55a(z) state, in part, that alternatives to the requirements in paragraphs (b) through (h) of 10 CFR 50.55a may be used when authorized by the NRC if the licensee demonstrates that: (1) the proposed alternative would provide an acceptable level of quality and safety or (2) compliance with the specified requirements would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.

The NRC licensees have requested through 10 CFR 50.55a(z) to implement BWRVIP TRs for examination of RVI as an alternative to the examination requirements of Section XI (e.g., see ADAMS Accession No. ML17305B279). Therefore, BWRVIP TRs may impact licensee inservice inspection programs.

1.3.3. Applicable Guidance to Fluence Estimation

Regulatory Guide (RG) 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence," Revision 0 (ADAMS Accession No. ML010890301), provides guidance on methods for calculating pressure vessel neutron fluence, including qualifying the methods and estimating the calculational uncertainty, that are acceptable to the NRC staff. This guidance was developed in consideration of estimating fluence in the traditional reactor pressure vessel beltline. Outside of the traditional beltline, the methods that RG 1.190 recommends for beltline fluence estimates may require refinement, because the geometry becomes more complex, the neutron transport distance is longer, and the neutron energy spectrum changes. While the RG 1.190, Revision 0, is not fully applicable because BWRVIP-100, Revision 2, is for reactor internal components, RG 1.190, Revision 0, is the most closely related guidance, so was used to inform the review of the fluence estimates.

2. <u>FRACTURE TOUGHNESS APPROACH</u>

In Section 1.6 of BWRVIP-100, Revision 2, EPRI stated that the TR should override material property guidance in existing flaw evaluation guidance (i.e., other BWRVIP TRs). In response to RAIs #1, #3, and #4, the BWRVIP clarified that BWRVIP-100, Revision 2, does not provide flaw evaluation guidance. Rather the purpose of BWRVIP-100, Revision 2, is to develop fracture toughness models. The BWRVIP stated that component-specific flaw evaluation procedures, including acceptable structural margins, are found in various TRs. The BWRVIP stated that it would issue updated component-specific guidance on flaw evaluation procedures. The NRC staff finds this response acceptable because it clarifies the purpose of BWRVIP-100, Revision 2, by explicitly stating that the TR only provides the fracture toughness models to be employed in flaw evaluations.

2.1. Fracture Toughness Correlations

BWRVIP-100, Revision 2, provides a general discussion of flaw evaluation procedures based on elastic-plastic fracture mechanics (EPFM). The fracture toughness is characterized by curve-fitting experimental fracture data with Equation 1,

$$J = C(\Delta a)^n \qquad \text{Equation 1}$$

where J is the J-integral resistance to crack growth, Δa is the crack growth increment, and C and n are fitting parameters. As discussed in detail in Sections 3 and 4 of this SE, BWRVIP-100, Revision 2, provides empirical correlations with neutron fluence for C and n.

EPRI proposed separate C and n correlations for weld and base metal, since the weld metal tended to transition from ductile to brittle fracture at lower fluences than the base metal. The staff noted that when applying this guidance, licensees must make a judgment call on whether the flaw is close enough to the weld to warrant applying the weld metal correlations. In response to RAI #2, the BWRVIP stated that licensees must demonstrate that no part of the crack tip be in contact with the fusion boundary or be projected to grow in contact with the fusion boundary before using the base material correlations. The NRC staff finds this response to be acceptable because it clarifies the BWRVIP position on use of the correlations and ensures that licensees are making technically-justified decisions.

2.2. Tearing Modulus

BWRVIP-100, Revision 2, discusses the J-tearing modulus approach to assess engineering margin against unstable ductile fracture. The tearing modulus, is defined by Equation 2,

$$T = \left(\frac{dJ}{da}\right)\left(\frac{E}{\sigma_f^2}\right) \qquad \text{Equation 2}$$

where T is the tearing modulus, E is the elastic modulus, and σ_f is the flow stress. Differentiating Equation 1 accordingly leads to Equation 3.

$$T = Cn(\Delta a)^{n-1}\left(\frac{E}{\sigma_f^2}\right) \qquad \text{Equation 3}$$

The BWRVIP-100, Revision 2, EPFM approach to fracture toughness, therefore, is to calculate the tearing modulus through the C and n correlations with neutron fluence described in Sections 3 and 4 of this SE.

2.3. Linear Elastic Fracture Mechanics

In response to RAI #5, the BWRVIP clarified that BWRVIP-100, Revision 2, Table 6-1 provides the recommended evaluation procedure and associated fluence thresholds for weld material and base material. For linear elastic fracture mechanics in particular, Table 6-1 states that the lower bound fracture toughness to be assumed in flaw evaluations is K_{Ic} = **[[** [redacted] **]]** ksi-√in., which is unchanged from BWRVIP-100, Revision 1. The NRC staff finds this response to be acceptable because the latest available data confirmed the previous staff position on lower-bound toughness for brittle fracture.

3. <u>MECHANICAL PROPERTY CORRELATIONS AND NEUTRON FLUENCE THRESHOLDS FOR IRRADIATED STAINLESS STEEL WELD METAL</u>

3.1. Weld Fracture Toughness Models

Tables 2-1 and 2-2 of BWRVIP-100, Revision 2, provide the irradiated weld metal fracture toughness test results that were used in developing the weld fracture toughness correlations in BWRVIP-100, Revision 1. Table 2-3 of BWRVIP-100, Revision 2, provides newly acquired data through testing of irradiated material harvested from the decommissioned José Cabrera and Barsebäck nuclear power plants. Table 2-4 of BWRVIP-100, Revision 2, shows the unirradiated fracture toughness data used to formulate the weld metal fracture toughness correlations.

Based upon this data, EPRI formulated correlations for *C* and *n* with neutron fluence, as shown in Equations 4 and 5.

[[[redacted] **]]** Equation 4

[[[redacted] **]]** Equation 5

where f is fluence (E > 1 MeV).

EPRI stated that Equations 4 and 5 (and, therefore, EPFM analysis) are valid for f < **[[** [redacted] **]]** n/cm^2. The BWRVIP stated that this proposed threshold for EPFM was chosen based on the testing results shown in Table 2-3 of BWRVIP-100, Revision 2. Specifically, the BWRVIP noted that the specimens that demonstrated little to no stable ductile crack extension were irradiated to a fluence of **[[** [redacted] **]]** n/cm^2, leading to the proposed threshold.

The NRC staff independently plotted the data in Tables 2-1 through 2-4 of BWRVIP-100, Revision 2, along with Equations 4 and 5, and verified EPRI's analysis of the data. Therefore, the NRC staff finds that the proposed models for C and n (Equations 4 and 5, respectively) are conservative representations of the experimental data.

The proposed fluence threshold (f < **[[** [redacted] **]]** n/cm^2) for EPFM was based on the latest weld metal fracture toughness data presented in Table 2-3 of BWRVIP-100, Revision 2. These test results showed that the specimens exhibited unstable crack growth above a neutron fluence value of **[[** [redacted] **]]** n/cm^2. The BWRVIP also noted that the predicted J-T curves above **[[** [redacted] **]]** n/cm^2 (see Figures A-13 through A-17 of BWRVIP-100, Revision 2) were nonconservative when compared to the experimental data. The proposed value is more conservative than the previously defined threshold of **[[** [redacted] **]]** n/cm^2 in BWRVIP-100, Revision 1, and is supported by the new data. As such, the NRC staff finds that the new EPFM threshold for irradiated weld material is appropriate for use in flaw evaluations for vessel internals.

3.2. Weld Yield and Flow Stress Models

Table 2-5 of BWRVIP-100, Revision 2, provides the irradiated tensile properties that were used in developing the weld yield and flow stress correlations. Table 2-6 of BWRVIP-100, Revision 2, shows the unirradiated tensile property data used to formulate the weld yield and flow stress correlations. Based upon this data, the BWRVIP formulated correlations for σ_{yield} and σ_{flow} with neutron fluence, as shown in Equations 6 and 7,

[[[redacted] **]]** Equation 6

[[[redacted] **]]** Equation 7

where σ_{yield} is the yield stress. The BWRVIP stated that the data fit excluded all data points beyond the fluence of **[[** [redacted] **]]** n/cm^2, since EPFM is not allowed beyond **[[** [redacted] **]]** n/cm^2.

The NRC staff independently plotted the data in Tables 2-5 and 2-6 of BWRVIP-100, Revision 2 along with Equations 6 and 7 and verified the BWRVIP's analysis of the data. The NRC staff notes that excluding the data beyond **[[** [redacted] **]]** n/cm^2 is conservative, since this leads to a higher flow stress prediction and a lower T prediction (see Equation 3). To evaluate whether Equation 7 leads to appropriately conservative toughness predictions for flaw evaluation purposes, the NRC staff reviewed calculation of J-T curves in Section 3.3 of this SE.

3.3. *J-T* Calculation

EPRI presented J-T curves for stainless steel welds in Figure 2-6 of BWRVIP-100, Revision 2. These curves are calculated using Equations 1, 3, 4, 5, and 7 of this SE. Therefore, calculation of J-T curves relies on the correlations proposed by the BWRVIP (see Sections 3.1 and 3.2 of this SE). The staff performed confirmatory calculations of J-T curves at select fluence values. The staff found that the J-T curves presented in Figure 2-6 of BWRVIP-100, Revision 2, either agree with or are conservative relative to the NRC staff's confirmatory calculations.

The BWRVIP compared the calculated J-T curves to those obtained from experimental data in Figures A-1 through A-17 of BWRVIP-100, Revision 2. These plots showed that the predicted J-T curves were conservative compared to the experimental curves up to a fluence of **[[** [redacted] **]]** n/cm^2. Since the NRC staff independently confirmed the BWRVIP's calculation of

J-T curves, the NRC staff finds that proposed fracture toughness models for the weld metal are conservative representations of the available data.

4. MECHANICAL PROPERTY CORRELATIONS AND NEUTRON FLUENCE THRESHOLDS FOR IRRADIATED STAINLESS STEEL BASE METAL

4.1. Base Metal Fracture Toughness Models

Tables 3-1 through 3-3 of BWRVIP-100, Revision 2, provide the irradiated base metal fracture toughness test results that were used in developing the fracture toughness correlations in BWRVIP-100, Revision 1. Table 3-4 of BWRVIP-100, Revision 2, provides newly acquired data through testing of irradiated material harvested from the decommissioned José Cabrera and Barsebäck nuclear power plants. Table 3-5 of BWRVIP-100, Revision 2, shows the unirradiated fracture toughness data used to formulate the base metal fracture toughness correlations.

Based upon this data, the BWRVIP formulated correlations for C and n with neutron fluence, as shown in Equations 8 and 9.

[[[redacted]]] Equation 8

[[[redacted]]] Equation 9

where f is fluence (E > 1 MeV).

The BWRVIP stated that Equations 8 and 9 (and, therefore, EPFM analysis) are valid for f < [[[redacted]]] n/cm^2. The BWRVIP stated that this proposed threshold for EPFM was chosen based on the testing results shown in Table 3-2 of BWRVIP-100, Revision 2. Specifically, Table 3-2 of BWRVIP-100, Revision 2, suggests that the specimens that demonstrated little to no stable ductile crack extension were irradiated to a fluence of [[[redacted]]] n/cm^2 or higher, leading to the proposed threshold.

The NRC staff independently plotted the data in Tables 3-1 through 3-5 of BWRVIP-100, Revision 2, along with Equations 8 and 9, and verified the BWRVIP's analysis of the data. The NRC staff notes that Equation 9 is not a conservative representation of the experimental data (see Figure 3-2 of BWRVIP-100, Revision 2), which is inconsistent with the corresponding model for the weld material (see Figure 2-2 of BWRVIP-100, Revision 2). In response to RAI #6, the BWRVIP clarified that it is not necessary to employ a conservative model for n to obtain a conservative fracture toughness. The BWRVIP stated that the conservative model for C combined with the chosen model for n lead to a conservative prediction of fracture toughness, relative to the experimental data, as illustrated in BWRVIP-100, Revision 2, Appendix A. The staff finds this response acceptable because the BWRVIP compared the fracture toughness prediction to the available experimental data to ensure the prediction was conservative, even though the n correlation is not a lower bound model.

Figure 3-1 of BWRVIP-100, Revision 2, shows that one data point at a fluence of **[[** [redacted] **]]** n/cm^2 falls below the model prediction, meaning that the prediction is potentially nonconservative. The BWRVIP excluded this data point in determining the C correlation, stating that it is not consistent with the observed trend of the data. In the November 1, 2024, response to RAI #8, EPRI provided additional justification for excluding this data point. Specifically, EPRI pointed out several experimental anomalies described by the researchers, including discontinuous crack propagation behavior during the test and microstructural features that may have impacted the crack initiation and propagation behavior. The NRC staff finds this response acceptable because the data point is inconsistent with the apparent trends in the larger data set and there are experimental reasons to question the validity of the data point.

The proposed fluence threshold (f < **[[** [redacted] **]]** n/cm^2) for EPFM was based on the base metal fracture toughness data presented in Tables 3-1 through 3-5 of BWRVIP-100, Revision 2. These test results showed that the specimens exhibited unstable crack growth at a neutron fluence value of **[[** [redacted] **]]** n/cm^2, except for specimen 12, CT 304 HAZ in Table 3-1 of BWRVIP-100, Revision 2. In response to RAI #7, the BWRVIP provided justification for excluding this data point, drawing upon a detailed description of the test from NUREG-6960 (ADAMS Accession No. ML081130709). Specifically, the BWRVIP pointed out that (1) the specimen did not necessarily fail in a brittle manner, (2) the crack did not propagate perpendicular to the applied load, and (3) a test performed on a different specimen of the same material exhibited stable ductile crack extension. The BWRVIP agreed to add a note to BWRVIP-100, Revision 2, Table 3-1 that clarifies why the data point was excluded from the analysis of the TR. The NRC staff finds this response acceptable because it provides sufficient evidence that this data point is not reliable. As such, the NRC staff finds that the proposed threshold of **[[** [redacted] **]]** n/cm^2 for irradiated base material is consistent with the available data.

4.2. Base Metal Yield and Flow Stress Models

Table 3-6 of BWRVIP-100, Revision 2, provides the irradiated tensile properties that were used in developing the base metal yield and flow stress correlations. Table 3-7 of BWRVIP-100, Revision 2, shows the unirradiated tensile property data used to formulate the base metal yield and flow stress correlations.

Based upon this data, the BWRVIP formulated correlations for σ_{yield} and σ_{flow} with neutron fluence, as shown in Equations 10 and 11.

[[[redacted] **]]** Equation 10

[[[redacted] **]]** Equation 11

The BWRVIP stated that the fit excluded all data points beyond the fluence of **[[** [redacted] **]]** n/cm^2, since EPFM is not allowed beyond **[[** [redacted] **]]** n/cm^2.

The NRC staff independently plotted the data in Tables 3-5 and 3-6 of BWRVIP-100, Revision 2, along with Equations 10 and 11 and verified the BWRVIP's analysis of the data. The staff notes that excluding the data beyond **[[** [redacted] **]]** n/cm^2 is conservative, since this leads to a higher flow stress prediction and a lower *T* prediction (see Equation 3). To evaluate whether Equation 11 leads to appropriately conservative toughness predictions for flaw evaluation purposes, the staff reviewed calculation of *J-T* curves in Section 4.3 of this SE.

4.3. *J-T* Calculation

The BWRVIP presented *J-T* curves for stainless steel base metal in Figure 3-6 of BWRVIP-100, Revision 2. These curves are calculated using Equations 1, 3, 8, 9, and 11 of this SE. Therefore, calculation of *J-T* curves relies on the toughness and flow stress correlations proposed by the BWRVIP (see Sections 4.1 and 4.2 of this SE). The NRC staff performed confirmatory calculations of *J-T* curves at select fluence values. The NRC staff found that the *J-T* curves presented in Figure 3-6 of BWRVIP-100, Revision 2, either agree with or are conservative relative to the staff's confirmatory calculations.

The BWRVIP compared the calculated *J-T* curves to those obtained from experimental data in Figures A-19 through A-35 of BWRVIP-100, Revision 2. These plots showed that, except for Figure A-19, the predicted *J-T* curves were conservative compared to the experimental curves up to a fluence of **[[** [redacted] **]]** n/cm^2. The nonconservative toughness prediction at a fluence of **[[** [redacted] **]]** n/cm^2 results from the low *C* value described in RAI #8. In Section 4.1 of this SE, the NRC staff accepted EPRI's RAI response that provided further justification for excluding that data point in determining the base metal *C* correlation. As such, the staff finds that the apparent nonconservative toughness prediction in Figure A-19 of BWRVIP-100, Revision 1-A, is likely the result of experimental anomalies noted by the original researchers.

5. NEUTRON FLUENCE EVALUATION

As previously stated, BWRVIP-100, Revision 2, provides newly acquired data through testing of irradiated materials harvested from the decommissioned José Cabrera (also known as Zorita) and Barsebäck nuclear power plants. Most of the correlations presented in the TR are functions of neutron fluence, so the adequacy of the correlations relies, in part, on the adequacy of the fluence estimates. In the case of this TR, it is conservative to use a lower bound fluence, as that would translate to radiation having a deleterious effect on material performance at lower exposures. Therefore, it would be undesirable for the fluence estimates reported in the TR to be overpredictions, as that could lead to the effects of radiation being underpredicted at a particular exposure level. This is counter to what the NRC typically considers to be conservative when reviewing fluence calculational methodologies.

EPRI provided information in the response to RAI #9 (ADAMS Accession No. ML241131A043) indicating that, to the best of its knowledge, the estimates were done to the industry standards within the countries that they were performed in and were to a similar pedigree to those incorporated into BWRVIP-100, Revision 1-A. The Zorita fluence calculations were performed in Spain and the Barsebäck fluence calculations were performed in Sweden. The NRC staff was unable to judge the acceptability of the fluence estimates based on this RAI response; the NRC regulates according to the U.S. regulations, which may be different than those in different countries. EPRI later supplemented this RAI response with more details, as described below.

The NRC did not evaluate the adequacy of fluence estimates for the data that was not new to Revision 2 (i.e., the data that was in Revision 1 and 0) as a part of this review.

5.1. Barsebäck Fluence Estimates

In a supplement to RAI #9 (ADAMS Accession No. ML24306A156), EPRI clarified which data were from Zorita and which were from Barsebäck. EPRI stated that there were only 4 data points from Barsebäck and they are all located in Table 2-3 of the TR. In the supplemental response to RAI-9, EPRI highlighted those 4 data points on Figures 2-1 and 2-2 of the TR and stated that due to their location relative to the proposed power law coefficient (C) and power law exponent (n) curves, they do not affect where the curves are drawn and therefore the details of the Barsebäck fluence calculational methodology are not relevant.

The NRC took the location of these data points into consideration and agree, even if the reported fluence estimates for these data points were drastic overpredictions, the correlations in the TR would not be expected to be significantly altered, as these data points are located above the lower bound correlations in the region where the correlation is flat (i.e., not changing with fluence) in Figures 2-1 and 2-2 of the TR. As a result, the NRC staff did not request further information on the Barsebäck fluence estimates and only used this information indirectly as additional assurance that the curves are acceptable.

5.2. Zorita Fluence Estimates

EPRI provided supplemental information on the Zorita fluence calculations with the submission of MRP-392 (ADAMS Accession No. ML24295A210). This report contained details of the Zorita fluence calculations. The NRC staff did not do a comprehensive review of MRP-392 in its entirety, nor did the NRC staff evaluate the document for uses beyond its application in BWRVIP-100, Revision 2. The Zorita calculations were performed with the Monte Carlo N-Particle (MCNP) transport code. Specifically, MCNP5 version 1.40 was cited. The NRC observed several aspects of the calculations that are in line with RG 1.190, Revision 0, but also observed major deficiencies. The major deficiencies lie in the areas of methodology qualification. Per Regulatory Position 1.4 of RG 1.190, Revision 0, fluence methodology qualification should include the comparison with benchmarks and operating reactor measurements (Regulatory Position 1.4.2). There was no documented attempt to qualify the method against calculational benchmarks or measurement data. As a result of this major gap, the NRC staff decided not to review MRP-392 in detail.

The Zorita reactor was shut down in 2006, so in 2025 it is likely not possible to validate the method against any Zorita plant-specific measurements (e.g., from surveillance capsules). However, the NRC has licensed fluence methodologies that employ the MCNP code. For example, NuScale's fluence methodology employs MCNP and was approved for use in Chapter 4 of the NRC staff's Final Safety Evaluation Report for the NuScale reactor design (ADAMS Accession No. ML20205L411) and Framatome uses MCNP as a part of its SVAM fluence methodology described in ANP-10348-NP-A (ADAMS Accession No. ML21221A334). While others' use of MCNP does not automatically make the use of MCNP acceptable within any given fluence calculation, it does show that MCNP is an appropriate software tool for similar fluence related applications.

The NRC staff also noted that the harvesting of the Zorita materials was carried out, at least in part, by an international research program, the Zorita Internals Reactor Project (ZIRP). EPRI led the multinational ZIRP project team, which included funding or in-kind contributions from the NRC, Spanish Nuclear Safety Council (Spanish regulator), Swedish Radiation Safety Authority (Swedish regulator), Mitsubishi Heavy Industries (MHI), Axpo Holding (Swiss utility), and Tractebel (Belgian engineering consultancy). The NRC's Office of Research evaluated the ZIRP data in Research Information Letter (RIL)-2022-05, "NRC Technical Assessment of Zorita Materials Testing Results" (ADAMS Accession No. ML22132A039). The MRP-392 fluence calculations were performed to support this work. This international group contained many reputable organizations and regulators around the world, giving some additional credibility to the data from Zorita.

As noted in other parts of the NRC staff's SE, the correlations proposed in the TR and the calculated J-T curves are generally conservative. Therefore, the existing margin could help offset the impact of some non-conservatisms in the fluence estimates. The NRC staff quantitively examined the impact of potential overpredictions in the reported Zorita fluence data on the power law coefficient and power law exponent correlations in Equations 2-1, 2-2, 3-1, and 3-2 of the TR (i.e., the impact of the true fluence values being less than those stated in the TR). The NRC staff found that even if many of the Zorita fluence estimates in the TR were significant overpredictions, the power law coefficient and power law exponent correlations would likely not be invalidated. For example, if the true Zorita fluences were 40 percent less than the estimates reported in the TR, Equation 2-2 of the TR would be less conservative, but would still bound 11 of the 14 new Zorita data points. Hypothesizing an underprediction of 40 percent is conservative, as it is double the uncertainty that is typically seen in similar fluence calculations (i.e., RG 1.190 states that the uncertainty in pressure vessel beltline fluence should be 20 percent or less).

Overall, the NRC staff conclude that the Zorita fluence estimates are acceptable because (1) a detailed MCNP study was carried out; (2) if the reported fluence estimates were significant overpredictions relative to reality, it would not be expected to completely invalidate the power law coefficient and power law exponent curves correlations; and (3) the Zorita materials were harvested under an international research program consisting of reputable organizations, including the NRC. The NRC staff also considered that if comparison to fluence measurements was required, that there would likely be no way to do so, and therefore the material data gained from Zorita may not be able to be used at all. Getting irradiated data from vessel internals is difficult and rare. The Zorita materials were harvested as a part of ZIRP, which is attempting to advance the understanding of irradiated materials behavior.

5.3. Fluence Evaluation Conclusion

The NRC staff evaluated the new neutron fluence data from the Barsebäck and Zorita nuclear power plants described in BWRVIP-100, Revision 2, and find them to be acceptable for the development of fracture toughness correlations for reactor vessel internals for reasons described above.

6. CONCLUSIONS

The NRC staff reviewed the new toughness models proposed in BWRVIP-100, Revision 2, that account for the latest testing data from industry and NRC research programs. The NRC staff found that the updated models are appropriately conservative given the current state of knowledge of irradiation embrittlement of stainless-steel base and weld metal. These models may, therefore, be used in licensee aging management programs for reactor vessel internals.

Principal Reviewers: Michael Benson
Joseph Messina
Steven Levitus
John Tsao

Date:

<u>APPENDIX A – COMMENT RESOLUTION</u>

Comment #	Comment	Comment Page/Line	Reason for Comment	NRC Response
1	Editorial; Please also reference to MRP-227, Revision. 2, Pressurized Water Reactor Internals Inspection and Evaluation Guidelines, ML22129A141 here. BWRVIP-100 is Reference 26 in MRP-227, Revision 2.	Pg. 1, Lines 24-25	Editorial	Added reference to MRP-227
2	Weld material properties (which exhibit lower fracture toughness than base material) must be used unless the licensee can demonstrate that no part of a crack tip will grow into contact with the weld material or be sufficiently close to the weld material that crack extension, either by stable ductile tearing, or crack growth during the evaluation interval, will cause the crack tip to contact the weld material. This clarification/correction ensures that the more conservative set of material properties (weld metal) is used if a flaw is in fusion boundary or projected to grow into the fusion boundary.	Pg. 4, Line 20	Clarification/Correction	Made recommended change to clarify that the weld metal fracture toughness correlation should be used before the base material fracture toughness correlation is used in the flaw evaluation.
3	The highlighting here should be updated to ensure the whole number is covered by the proprietary marking.	Pg. 8, Line 35	Proprietary Marking Correction	Fixed marking