ATTACHMENT 1

Responses to NRC Requests for Additional Information (RAIs) on PWROG-18034-P, Rev. 0 (Non-Proprietary Version)

Background and Introduction

This attachment provides the responses to the U.S. Nuclear Regulatory Commission (NRC) Requests for Additional Information (RAIs) [1] associated with the NRC Staff's review [2] of PWROG-18034-P [4] and PWROG-18034-NP [3]. Each section contains the NRC RAI and the PWROG response.

RAI 1

NRC Question

Background

The TR states that [[ ]] The TR states in Section 2.3, p.25 that:

> [[ ]]

However, the staff notes that [[ ]]

Issue

Based on discrepancies between the number of specimens tested in the referenced reports and the number of data points in the dataset, and because there appears to be other product forms included in the data set, the TR does not seem to fully describe the materials in the dataset used to develop the bounding properties for the irradiated BFBs.

Request

1. Provide a list of all tests included in the database for each material, including material grade, source (component, product form), where irradiated, specimen type, cold work%, neutron fluence or dpa, temperature, yield strength, ultimate strength, uniform elongation, total elongation.

2. If specimens from components made of product forms other than [[ ]], justify why these can be considered representative of BFB tensile properties.

3. If any data from material grades other than Type 316 and Type 347 was used, justify the use of this data to represent properties of irradiated Type 316 and irradiated Type 347.

Response to RAI 1:

1. The data set contains a total of 314 tensile test data points, which includes a total of 27 specimen tests and 287 full bolt tests. The 27 specimen tests, discussed in the TR, are contained in MRP-51 [6], MRP-73 [7], and MRP-211 [5]. The data set contains 122 full bolt tests of Type 347 SS material from Point Beach Unit 2 which are documented in Framatome Technologies Incorporated Report, 51-5003385 [8]. The Point Beach Unit 2 bolt tests were performed by Framatome, and are publicly available through EPRI. The dataset also contains 165 full bolt tests of cold worked Type 316 SS from Farley, Unit 1 which are documented in a Westinghouse Proprietary document. The requested material properties are contained in Attachment 3 of this letter.

Note that the discussion in the fifth paragraph, on page 26 of Section 2.3 in the TR states: "A total of 135 data points were included in the scaled Type 316 SS data set, and 105 data points in the scaled Type 347 SS data set." Therefore, there is a typographical error in the quantity of scaled data points, and should read: "A total of 165 data points were included in the scaled cold worked Type 316 SS data set, and 122 data points for the scaled Type 347 SS data set." The redline markup of this change is shown in page 10 of Attachment 2, and will be incorporated in NRC approved version of the TR after the Final Safety Evaluation is issued.

2. The material data is obtained from either irradiated baffle-former bolts or irradiated flux thimble tubes. The applicability of the use of irradiated flux thimble tube data is discussed in the last paragraph on page 25 in Section 2.3 of PWROG-18034-P:

> *"Specimen tests on Type 316 SS flux thimbles tubes from Ringhals Unit 2 as documented in MRP-73 [10] added further high fluence data on Type 316 SS. This is acceptable due to the similarity in composition and specification minimum properties between Type 316 SS flux thimble tubes and Type 316 SS baffle bolts."*

The flux thimble tubes are made from ASTM A213 Type 316 cold drawn tubing, and the baffle-former bolts are made from Westinghouse 70041EA solution treated and strain hardened Type 316 bars. Although the form differs (i.e., tubing versus bar stock), the composition as shown in RAI 1 Table 1 and the specification minimum properties as shown in RAI Table 2 are very similar. Therefore, it is acceptable to combine the irradiated Type 316 baffle-bolt and irradiated flux thimble tube data for material properties to evaluate irradiated bolting in PWROG-18034-P.

RAI 1 Table 1. Comparison of Percent Chemical Composition

Composition (Component)	ASTM A213 Type 316 (Flux Thimble Tubing)	PD 70041 EA (Type 316 baffle-bolts)
Carbon	0.08	0.08
Manganese	2.00	2.00
Phosphorus	0.045	0.045
Sulfur	0.030	0.030
Cobalt	0.11	0.20
Nickel	10.00-14.00	10.00-14.00
Chromium	16.0-18.0	16.00-18.00
Molybdenum	2.00-3.00	2.00-3.00
Silicon	1.00	1.00

RAI 1 Table 2. Comparison of Minimum Tensile Properties

Property	ASTM A213 Type 316 (Flux Thimble Tubing)	PD 70041 EA (Type 316 baffle-bolts)
Minimum Yield Strength (ksi)	70 - 90	60 – 85
Minimum Ultimate Strength (ksi)	100	75 - 95
Minimum Elongation (%)	30	30

3. The dataset only includes Type 347 and cold worked Type 316 stainless steel materials.

RAI 2

NRC Question

Background

The TR states that

> The material properties developed in Table 1 excluded the material data from baffle bolts located at the top former. This was done because the yield strength, ultimate strength, and total elongation values indicate that saturated fluence has not been achieved. However, a sensitivity study was performed considering the top former bolts to be irradiated or unirradiated. This study indicated small changes to the baffle bolt stress margins that are localized to the baffle bolts on the top row former. Therefore, it is acceptable to model the top row former bolts as either irradiated or unirradiated.

Issue

The TR indicates a sensitivity study was performed which demonstrates top former level bolts may be treated as either irradiated or unirradiated, even though these bolts receive low fluence compared to other former levels, and therefore, the tensile properties of the bolts on the top former level may not be fully saturated. However, the TR provides no detail on how the sensitivity study was conducted; for example, what level of bolt loads were considered, what bolt configurations were considered, etc.

It is also not clear from the TR if there is a minimum fluence value for which the irradiated material properties of Table 2 are applicable, and whether bolts on former levels other than the top former could potentially fall below this minimum fluence.

Request

1. Provide additional details on the sensitivity study performed to demonstrate top former bolts may be treated as irradiated or unirradiated. The description should be sufficient to justify applicability of the sensitivity study conclusions to all plant designs and to varying bolt configurations that may be analyzed (such as configurations with some failed bolts not repaired).

2. Discuss whether there should be a minimum fluence for which the Table 2 irradiated material properties can be applied, excluding the bolts on the top former level.

Response to RAI 2:

1. A comparative analysis was performed for the sensitivity study that considered elastic-plastic material model cases with all baffle-former bolts having irradiated material properties, versus cases that considered an unirradiated material model for baffle-former bolts on the top former and the remainder of the baffle-former bolt locations with an irradiated material model. The limiting loss-of-coolant accident (LOCA) dynamic analysis was evaluated using the bolting patterns from the acceptable bolting pattern analysis (ABPA) for representative 2-, 3-, and 4-loop Westinghouse NSSS plants. Seven bolting patterns were

evaluated for the 2-loop plant, and three bolting patterns were evaluated for the 3- and 4-loop plants. The percentage of intact bolts in the bolting patterns ranged from 50% to 90%, where failed baffle-former bolts are considered in the bolting pattern on the top former row and for baffle-former bolts at former locations other than the top former. It is important to clarify that the scope of the sensitivity study discussed above included the modeling of irradiated barrel-former bolts when the top row baffle-former bolts were modeled as unirradiated. In addition, a second case was evaluated, which considered all the baffle-former bolts to be irradiated, and all barrel-former bolts to be unirradiated.

The overall result from the sensitivity study was a small change in bolt stress at the limiting baffle-former bolt location regardless of whether an irradiated or unirradiated material model was used for the top row baffle-former or for the barrel-former bolts. When the limiting bolt is below the yield point, the change in maximum bolt stress is within 10%, and when the limiting bolt is above the yield point, the change in the limiting bolt stress is less than 2%. Considering bolts above the yield point, increases in strain of up to 15% were found; however, the magnitude of the maximum strain for any bolt was within 5%, which is well below the applicable strain limit of [ ]$^{(a,b,c)}$ for bolts of 2.12 inch or less.

As expected, consideration of the top row baffle-former bolts and barrel-former bolts as unirradiated reduces the stress margin at these bolt locations relative to considering these bolts to be irradiated. However, both the top row baffle-former bolts and barrel-former showed considerable stress margin (typically 50%) regardless of the selected material model. Therefore, it was concluded that there is no significant impact to the limiting stress margins in the baffle-former bolts as a result of modeling of the top row baffle-former bolts or barrel-former bolts as irradiated versus unirradiated.

The TR will be revised based on the discussion above, to acknowledge that the modeling of the barrel-former bolts as irradiated versus unirradiated was included in the scope of the sensitivity study, and that the sensitivity study concludes that the impact of the modeling of top row baffle former bolts and barrel-former bolts as irradiated versus unirradiated is a small change (i.e., less than 2% for bolts above the yield point) in the limiting baffle-former stress margins. These changes, as shown in the redline markup of PWROG-18034-P on pages 5 and 12 of Attachment 2, will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

It was noted that the strains in the unirradiated baffle-former bolts were generally higher than in the irradiated bolts. This is expected due to the lower yield strength for the unirradiated bolts. Therefore, a strain limit should be added regarding the use of elastic-plastic Option 1 in order to conclude that Option 1 is conservative relative to Option 2. Therefore, the strain limits developed for irradiated bolts as shown in Table 2 of the TR will also be used for elastic-plastic Option 1. Note that it is conservative to apply strain limits developed from testing of irradiated bolts to unirradiated bolts due to the loss of ductility that occurs due to irradiation. This change, as shown in the redline markup of PWROG-18034-P on page 8 of Attachment 2, will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

While the sensitivity study was performed using the elastic-plastic material model, the same conclusion would be expected for a linear-elastic material model as discussed below. Irradiation does not affect the elastic modulus when a linear-elastic model is considered; therefore, the response of the model is the same. The stress limits are lower for an unirradiated linear-elastic model, which would reduce margin relative to the use of an irradiated model; however, the baffle-former bolts on the top former row and barrel-former bolts are not limiting with respect to the stress limits. Therefore, the bolting pattern acceptability would not be affected by modeling the top row baffle-former bolts or barrel-former bolts as unirradiated versus irradiated when using a linear-elastic model.

2. The use of the material properties in this TR should be limited to within the fluence range of the tested material. The test data utilized in this TR show saturated properties in the 5 to 15 dpa for the Type 347 SS material and 10 to 65 dpa for the Type 316 SS material. Therefore, the use of the material properties shown in Table 2 of the TR should be limited to [ ](a,b,c) or greater. These trends are in agreement with the tensile test data in Section 2.12 of MRP-211 [5], which discusses a saturated strength of 5 to 20 dpa for irradiated austenitic stainless steel and approximately 5 dpa for total elongation.

The TR will be revised to identify that the properties shown in Table 2 will only be used for applications with an estimated dose of [ ](a,b,c) or greater. This change, as shown in the redline markup of PWROG-18034-P on page 5 of Attachment 2 and in the title of Table 2 for PWROG-18034-P as shown on page 6 of Attachment 2 will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

The use of irradiated material properties with regard to the evaluation of reduced patterns of barrel-former bolts will also result in a revision to the TR. Note that barrel-former bolts are located at a sufficient distance from the reactor core such that saturated irradiated properties as shown in RAI Table 2 will not be achieved through 60-years of plant operation. The plant-specific dose, in conjunction with the unirradiated limits as discussed in Option 1 will be used. This is conservative, since the use of an irradiated material model for the bolts based upon plant-specific irradiation will produce higher stress results relative to an unirradiated material model, which are then compared to the lower stress limits for unirradiated materials. The use of unirradiated limits to evaluate reduced patterns of barrel-former bolts is reflected in the redline markup of PWROG-18034-P on page 12 of Attachment 2.

The FE model that will be used for reduced barrel-former bolt patterns is a multilinear material model, which includes additional piecewise linear representation of the tangent modulus to approximate non-linear behavior. The allowance for use of a multilinear material model is reflected in the redline markup of PWROG-18034-P as shown on page 2 of Attachment 2. Likewise, the nomenclature to define the elastic-plastic material model has been revised to "Bilinear / Multilinear," as shown in the title of Figure 2 on page 2 of Attachment 2, on page 3 of Attachment 2, and in the summary on page 13 of Attachment 2. These changes will be incorporated in NRC approved version of the TR after the Final Safety Evaluation is issued.

An editorial change was made to the strain limits to clarify how to apply these limits to evaluate barrel-former bolts. As discussed in the last paragraph on page 21 of PWROG-18034-P, the strain limits were developed from testing of medium length baffle-former bolts of 2.12 inch and 2.0 inches. The TR reduced the strain limit to [ ] (a,b,c) for long (3.5 inch baffle-former bolts). However, Westinghouse barrel-former bolts have different lengths than baffle-former bolts in some plant designs. Therefore, the use of the [ ] (a,b,c) strain limit will be conservatively applied to any bolt length greater than 2.12 inches. These clarifications have been added to the last paragraph shown on page 5 of Attachment 2, Note 1 of Table 2 on page 6 of Attachment 2, the strain limit for Options 1 and 2 on page 8 of Attachment 2, the strain limit for Option 3 as shown on page 9 of Attachment 2, the discussion in the 2nd paragraph of page 11 of Attachment 2, and the summary shown on page 13 of Attachment 2. These changes will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

NRC RAI 3

NRC Question

Background

The TR (Section 2.3, p.26) describes the procedure by which [[ ]] It appears that the [[ ]]

Issue

It is not clear that determining [[ ]] is appropriate given the difference in specimen geometries.

Request

1. [[ ]]

2. Identify whether the determination of the scale factors was performed in accordance with any industry standards, such as American Society of Testing and Materials (ASTM) standards.

3. Provide the calculation and values of the [[ ]].

Response to RAI 3:

1. A comparison of the specimen tests and full bolt tests shows numerous similarities between the two tests including the material composition, cold work, and level of level of irradiation. Furthermore, the full bolt tests resulted in a ductile failure mode within the bolt shank, which will result in a general state of uniaxial tension within the bolt shank that is very similar to that from the design of a tensile specimen. With similarities in the variables discussed above, the remaining independent variables are geometry and temperature. Therefore, it is appropriate to develop scale factors to characterize these independent variables from the tests.

The scale factors are used to normalize the average full bolt test strength value to match the average value from the specimen tests, which provides the more accurate measure of material strength. As stated in the first paragraph on page 26 of PWROG-18034-P: "Specimen tests were performed in accordance with ASTM E8 [11] at room temperature and E21 [21] at elevated temperature and provide a reliable indicator of the material strengths." This is appropriate, because the specimen tests were performed in a laboratory using calibrated equipment and controlled specimen geometry to provide the most reliable indicator of the material strength. The full bolt test results are used to establish the statistical distribution in the strength values.

This process allows for the statistical distribution from the large number of full bolt tests to be included in the development of the material properties in Table 2 of the TR. Since full bolt testing was not conducted in accordance with recognized test standards, there is a potential that this statistical distribution could also contain additional bolt-to-bolt variation. Any test setup with bolt-to-bolt variability would have a tendency to broaden the distribution of the results, which would be conservative for the purposes of developing minimum allowables for use in evaluating structural acceptability of baffle-former bolts.

2. No explicit standard was used for developing the scale factors. Please see the responses to Parts 1 and 3 of this RAI for the basis and determination of the scale factors.

3. The scale factors were determined from the average material property values after compiling the available data into appropriate groups. The scale factors for the yield and ultimate strength of Type 347 SS material are provided in RAI 3 Table 1, and for the yield and ultimate strength of Type 316 SS in RAI 3 Table 2. The factors in RAI 3 Table 3 and RAI 3 Table 4 were applied to all of the 287 full bolt test data points (i.e, 122 for Type 347 SS and 165 for Type 316 SS) at room temperature during the statistical analysis.

Note that the scale factors were separated into temperature and geometry components such that each contribution can be differentiated. The temperature factor is based upon the ratio of the "Specimen – Group 1" strength values versus the "Specimen – Group 2" results, and the geometry factor is based upon the ratio of the "Specimen – Group 2" values with the "Bolt – Group 1" results. The combined temperature and geometry factor is based upon the ratio of the "Specimen – Group 1" values relative to the "Bolt – Group 1" values.

For the Type 347 SS material, the effects of temperature and geometry on the yield and ultimate strength were determined to be small for material in the irradiated condition. The yield strength is about 4% lower at operating temperature relative to room temperature (i.e., [ ] (a,b,c) versus [ ] (a,b,c)), and the ultimate strength decreases about 6% at operating temperature (i.e., [ ] (a,b,c) versus [ ] (a,b,c)). The effect of geometry varies, with an increase of 5% for yield strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)), and a decrease of 1% for ultimate strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)). Therefore, the combined effect of temperature and geometry are a 1% overall increase for yield strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)) and a 7% decrease for ultimate strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)).

For the Type 316 SS material, the effects of temperature and geometry were determined to be more significant in the irradiated condition. The yield strength is approximately 8% lower at operating temperature relative to room temperature (i.e., [ ] (a,b,c) versus [ ] (a,b,c)), and the ultimate strength is approximately 17% lower at operating temperature ([ ] (a,b,c) versus [ ] (a,b,c)). The geometry effect results in a19% increase on yield strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)), and a 26% increase on ultimate strength (i.e., [ ] (a,b,c) versus [ ] (a,b,c)). Therefore, the combined effect of temperature and geometry is a 9% increase on yield strength ([ ] (a,b,c) versus [ ] (a,b,c)), and a 5% increase in ultimate strength ([ ] (a,b,c) versus [ ] (a,b,c)). As such, the application of the combined temperature and geometry factors to the full bolt test results in a net overall increase in strength. This trend is explained because the geometry effect is found to more than offset the decrease in strength with temperature.

RAI 3 Table 1: Scale Factors for Yield and Ultimate Strength for Type 347 SS Material

[ ] (a,b,c)

RAI 3 Table 2: Scale Factors for Yield and Ultimate Strength for Type 316 SS Material

[ ] (a,b,c)

The scale factors for the total elongation for Type 347 SS material are provided in RAI 3 Table 3, and for the total elongation of Type 316 SS in RAI 3 Table 4. A substantial reduction (approximately 60% reduction for Type 347 SS and 50% for Type 316 SS) in total elongation was determined at operating temperature relative to room temperature. The scale factors in RAI Tables 3 and 4 were applied to all of the 287 full bolt test data points (i.e, 122 for Type 347 SS and 165 for Type 316 SS) at room temperature during the statistical analysis.

RAI 3 Table 3: Scale Factors for Total Elongation for Type 347 SS Material.

[ ] (a,b,c)

RAI 3 Table 4: Scale Factors for Total Elongation for Type 316 SS Material

[ ] (a,b,c)

NRC RAI 4

NRC Question

Background

The TR states that the acceptance criteria for an elastic-system analysis from F-1331 of Appendix F of the ASME Code are applied to evaluate irradiated bolting when a linear-elastic material model is used. The TR also states that the following acceptance criteria will be applied to evaluate irradiated bolting, which are consistent with the F-1331 of Appendix F limits of the ASME Code, as applicable. The TR states that two acceptance criteria options will be used. Option 1 would be used by the plants with lower loaded bolts, and Option 2 would be used by the plants with higher loaded bolts.

Similarly, for elastic-plastic analysis of bolts under faulted conditions, the TR states that Option 1 (use of unirradiated bolt material properties) would be used for plants with lower-loaded bolts, while either Option 2 or Option 3 would be used for plants with higher-loaded bolts.

The TR states under the justification for the changes that a sensitivity study has been performed to confirm that using Option 1 provides conservative results relative to the other options that consider the bolts to be irradiated, and that, therefore, the use of Option 1 is a conservative approach for the evaluation of irradiated bolts. This statement appears to be applicable to both elastic analysis and elastic-plastic analysis. The TR further states that this criterion will only be applied to the plants with lower loaded baffle bolts with an upflow design configuration.

Issue

It is not clear whether it is the intent of the TR that for elastic analysis, that either Option 1 or Option 2 could be used if acceptable stresses resulted regardless of load level. It is not clear whether for elastic-plastic analysis, it is the intent of the TR that either Option 1, Option 2, or Option 3 could be used for any plant design, provided that acceptable stresses could be demonstrated regardless of load level.

Request

1. Clarify whether Option 1 for both elastic and elastic-plastic analysis is restricted only to plants operating in an upflow configuration, or if any plant may use Option 1 provided it meets the applicable stress limits.

2. Clarify whether it is the intent of the TR that any plant could use either Option 1 or Option 2 for elastic analysis, or Option 1, Option 2, or Option 3 for elastic-plastic analysis.

3. Summarize the sensitivity study that demonstrated Option 1 provided conservative results relative to the other options.

Response to RAI 4:

1. It was not intended to limit the use of Option 1 to plants operating in an upflow configuration. Rather, either linear-elastic or elastic-plastic Option 1 can be used by any plant provided it meets the applicable stress limits. Therefore, the statement, "This criterion will only be applied to plants with lower loaded

baffle bolts with an upflow design configuration," will be deleted from the TR. This change, as shown on page 11 of the Attachment 2, will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

2. There was no intention to limit the use of certain options that are defined in the TR to certain plant types; all options are acceptable for use in evaluating the acceptability of a bolting pattern at any plant. The different options have varying levels of simplicity and associated conservatism. Multiple options are provided to allow the application of refined approaches if required, based on plant specific loadings, to show acceptable margin.

To provide further clarification on this topic, the statement in the 2nd paragraph of page 23 of PWROG-18034-P for linear-elastic analysis will be revised. Therefore, the statement, "Two acceptance criteria options will be used. Option 1 would be used by plants with lower loaded bolts, and Option 2 would be used by plants with higher loaded bolts," will be revised. This statement will be revised to: "Two acceptance criteria options will be used where Option 1 includes additional conservatism relative to Option 2." This change as shown in the redline markup as shown on page 7 of Attachment 2, will be incorporated into the NRC approved version of the TR after the Final Safety Evaluation is issued. The same change will also be made to the statement regarding elastic-plastic analysis on the first paragraph of page 24 in PWROG-18034. This change as shown in the redline markup on page 8 of Attachment 2, will be incorporated into the NRC approved version of the TR after the Final Safety Evaluation is issued.

3. Sensitivity studies have been performed by changing the material from elastic-plastic Option 1 to elastic-plastic Option 2 for a representative plant, and these results demonstrate that Option 1 is conservative relative to Option 2. For the linear-elastic material model, the conservative use of Option 1 versus Option 2 is justified by considering that the stress limits for Option 1 are lower for common bolting materials than Option 2. For example, consider the material properties for SA-193 B8M from Code Case N-60-5 [9], a common replacement bolt material, which has an S_m of 16.6 ksi, a yield strength of 50.9 ksi (a specified minimum of 65 ksi), and ultimate strength of 81.6 ksi (a specified minimum of 90 ksi).

This material would have a linear-elastic P_m limit of:

$$P_m = \text{Lesser of } (2.4 \cdot S_m \text{ or } 0.7 \cdot S_u) = \text{Lesser of } [2.4 \cdot (16.6\text{ksi}) \text{ or } 0.7 \cdot (50.9\text{ksi})] = 35.6 \text{ ksi}$$

The P_m+P_b limit is determined from:

$$P_m + P_b = \text{Lesser of } (3.6 \cdot S_m \text{ or } 1.05 \cdot S_u) = \text{Lesser of } [3.6 \cdot (16.6\text{ksi}) \text{ or } 1.05 \cdot (50.9\text{ksi})] = 53.4 \text{ ksi}$$

The P_m of 35.6 ksi and P_m+P_b of 53.4 ksi from linear-elastic Option 1 are significantly less than those that result from linear-elastic Option 2, which based upon the properties in Table 2 of PWROG-18034-P, are [ ](a,b,c) and [ ](a,b,c), as discussed in RAI 5. Therefore, it is demonstrated that linear-elastic Option 1, for a typical bolting material, is conservative relative to linear-elastic Option 2.

A similar example is provided to compare elastic-plastic Option 1 to Option 2. Based upon the preceding material properties for SA-193 B8M, the P_m limit is determined:

$$P_m = \text{Greater of } 0.7S_u \text{ and } S_y + 1/3 \cdot (S_u - S_y)$$

$$P_m = \text{Greater of } 0.7 \cdot (81.6\text{ksi}) \text{ and } (50.9\text{ksi}) + \frac{1}{3} \cdot (81.6\text{ksi} - 50.9\text{ksi}) = 61.1 \text{ ksi}$$

The P_m+P_b limit is determined from:

$$P_m + P_b = 0.9S_u = 0.9 \cdot (81.6\text{ksi}) = 73.4\ ksi$$

The P_m of 61.1 ksi and P_m+P_b of 73.4 ksi from elastic-plastic Option 1 are significantly less than those that result from elastic-plastic Option 2, which, based upon the properties in Table 2 of PWROG-18034-P, are [ ] (a,b,c) and [ ] (a,b,c), as discussed in RAI 5. Therefore, it is demonstrated that the stress limits for Option 1, for a typical bolting material, are conservative relative to Option 2. Note that Option 1 is conservative relative to Option 3, since Option 3 results in bolting patterns that are essentially the same as Option 2. As discussed in the Response Part 2 of RAI 2, an additional limitation will be added to elastic-plastic Option 1 to also apply the strain limit from Table 2 of PWROG-18034-P for irradiated bolts. Therefore, it has also been confirmed that elastic-plastic Option 1 is conservative relative to Option 2.

NRC RAI 5

NRC Question

Background

Under Option 2 for elastic analysis in the TR, the allowable primary membrane (P_m) stress plus bending stress (P_b) is determined per F-1440(c)(1) of the ASME Code, Section III, as follows:

$P_m+P_b = 3 \cdot S_m = S_u$

Where S_u is the ultimate strength

S_m is normally the allowable stress intensity for the material from the ASME Code Section II. The TR states the following definition of S_m is applicable to the evaluation of irradiated bolting:

$S_m = (1/3) \cdot S_u$

Issue

The staff notes that the bounding irradiated bolt properties of [[ ]], when used with Option 2 for elastic analysis, result in a higher allowable total primary stress (primary membrane stress (P_m) + primary bending stress (P_b) than either Option 2 or Option 3 for elastic-plastic analysis, as shown in the table below:

[[

]]

It seems that elastic-plastic analysis should result in higher allowable $P_m + P_b$ than elastic analysis.

Request

Justify why the $P_m + P_b$ equation from F-1440 c(1) can be used for irradiated bolts with the bounding material properties; e.g., why is it acceptable for elastic analysis to result in a higher allowable $P_m + P_b$ than elastic-plastic analysis?

Response to RAI 5:

It is agreed that the allowable stress is higher for linear-elastic Option 2 relative to elastic-plastic Option 2. However, the strain energy, as determined from the area under the stress strain curve, for linear-elastic Option 2 is a small fraction of that for elastic-plastic Option 2. Therefore, linear-elastic Option 2 is significantly bounding.

For example, consider a material model for stainless steel with an elastic modulus of 25,300 ksi at 600°F, a yield strength of [ ] (a,b,c), an ultimate strength of [ ] (a,b,c), and a failure strain of [ ] (a,b,c) (consistent with the material properties in Table 2 of PWROG-18034-P) where the applicable stress strain curve for the linear-elastic and elastic-plastic material models are shown in RAI 5 Figure 1.

Consider that the maximum strain in the linear-elastic model is determined from the ultimate strength (σ_{UTS}) and the elastic modulus (E):

$$\varepsilon_{L-E,max} = \frac{\sigma_{UTS}}{E} = \Big[\qquad \qquad \Big]^{(a,b,c)}$$

The strain energy for a linear-elastic material model corresponding to the P_m+P_b limit in Option 2 is determined from the area under the stress-strain curve (A_{L-E}):

$$A_{L-E} = \frac{1}{2} \cdot \epsilon_{L-E,max} \cdot \sigma_{UTS} = \Big[\qquad \qquad \Big]^{(a,b,c)}$$

Likewise, the strain at the yield strength (ε_y) is determined from the yield strength (σ_y), and E:

$$\varepsilon_y = \frac{\sigma_y}{E} = \Big[\qquad \qquad \Big]^{(a,b,c)}$$

The strain energy for an elastic-plastic material model corresponding to the P_m+P_b limit in Option 2 is determined from the area under the stress-strain curve (A_{E-P}):

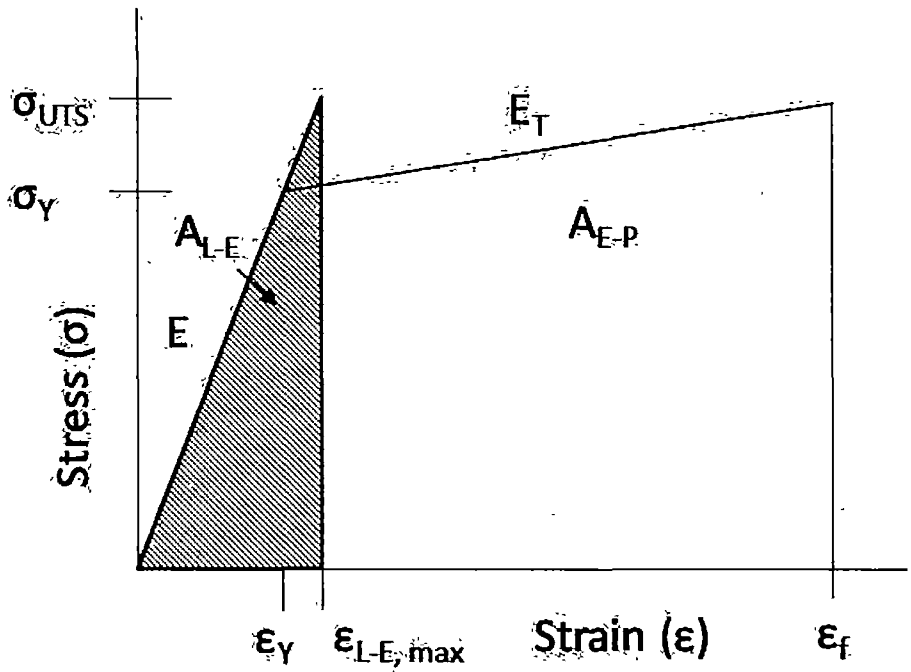
$$A_{E-P} = \frac{1}{2} \cdot \epsilon_y \cdot \sigma_y + \frac{1}{2} \cdot (\varepsilon_f - \varepsilon_y) \cdot (\sigma_y + \sigma_{UTS})$$

$$A_{E-P} = \Big[\qquad \qquad \qquad \qquad \Big]^{(a,b,c)}$$

The ratio of the area for the linear-elastic versus the elastic-plastic material model can be used to compare the strain energy:

$$A_{ratio} = \frac{A_{L-E}}{A_{E-P}} = \Big[\qquad \Big]^{(a,b,c)} = 0.0273$$

The area under the stress-strain curve for the linear-elastic material model is less than 3% of the elastic-plastic material model. Therefore, it is demonstrated that the strain energy for the elastic-plastic material model substantially bounds the linear-elastic material model.



RAI 5 Figure 1: Comparison of Strain Energy for Linear-Elastic and Elastic-Plastic Material Models

NRC RAI 6

NRC Question

Background

In the TR, Option 2 for elastic-plastic analysis of BFBs under faulted conditions is based on the stress limits for high strength threaded structural fasteners from F-1440(c)(2) in Appendix F of the ASME Code (i.e., with an S_u> 100 ksi at operating temperature) using the material properties in Table 2 for the evaluation of irradiated bolting.

TR Option 3 for elastic-plastic analysis of BFBs under faulted conditions uses the limits of F-1341.2(a) for maximum primary membrane stress, and the limits of F-1440(c)(2) for maximum primary stress ($P_m + P_b$).

The ASME Code, Section III, Nonmandatory Appendix F, F-1440, provides allowable stress criteria for Level D Service Loadings of core support structures. F-1440 states that the procedures of F-1300 may be used except as stipulated in [F-1440] (a) through (d).

F-1440(a) states that the specified dynamic or equivalent static loads shall not exceed 80% of the ultimate collapse load as obtained from test P_t, where P_t is defined as the load at which the horizontal tangent to the load deformation curve occurs, or 80% of a load combination used in the test of a prototype or model. F-1440(a) further states that in using this method, account shall be taken of the size effect and dimensional tolerances as well as differences which may exist in the ultimate strength or other governing material properties of the actual part and the tested parts to assure that the loads obtained from the test are a conservative representation of the load carrying capability of the actual component under postulated loading conditions for which Level D Service Limits apply.

F-1440 (b) states in part that component inelastic analysis may be combined with elastic system analysis (F-1331).

The procedures of F-1440 (c) are specified for fasteners with a minimum ultimate strength greater than 100 ksi.

F-1440 (d) addresses the stress limits for threaded structural fasteners having ultimate strength less than or equal to 100 ksi (690 MPa) at operating temperatures, and, therefore, does not apply to irradiated BFBs.

Issue

1) It is not clear if F-1440(a) is met with respect to the allowable stress criteria of the TR, for Option 2 and Option 3 for elastic-plastic analysis of BFBs under faulted conditions.

2) Contrary to F-1440 (c), Option 3 for elastic-plastic analysis in the TR uses the criteria of F-1341.2(a) for the allowable primary membrane stress intensity, P_m, which is:

P_m= Greater of 0.7 S_u and S_y+ 1/3 (S_u - S_y)

This criterion results in a higher allowable P_m for Option 3 versus Option 2 when using the bounding irradiated material properties given in the TR. Since the irradiated BFBs are assumed to have ultimate

strengths greater than 100 ksi, F-1440 (c) in Option 2 seems to be the applicable method. F-1341.2 is for plastic analysis of components, but it is not clear that it was intended to apply to high strength fasteners

Request

The staff requests the PWROG:

a) Discuss whether the TR methodology meets F-1440(a) for Option 2 and Option 3. If not met, discuss why this criterion does not need to be met.

b) Justify how the use of F-1341.2(a) allowable stresses for the primary membrane stress intensity in Option 3 is consistent with F-1440. If the use of F-1341.2(a) is not consistent with F-1440, provide a technical justification for use of these stress criteria for the primary membrane stress.

Response to RAI 6:

a) The intent of Subsection F-1440 of Appendix F of the ASME Code is to establish limitations to the methods in F-1300 for the evaluation of core support structures. The purpose of the criteria in F-1440(a) is to restrict the load used in an evaluation of collapse such that, "The specified dynamic or equivalent static loads shall not exceed 80% of the ultimate collapse load as obtained from test..." Therefore, this criterion supersedes that in F-1341.3 for the evaluation of collapse using a plastic system analysis, which specified that the, "Static or equivalent static loads shall not exceed 90% of the limit load collapse load..." However, note that Subsection F-1341 (Criteria for Components) clarifies that:

> "Acceptability of components may be demonstrated using any one of the following methods:
>
> a) Elastic analysis
> b) Plastic analysis
> c) Collapse load analysis
> d) Plastic instability analysis
> e) Interaction methods"

The methods of either "elastic analysis" or "plastic analysis" are used to demonstrate the structural integrity of the bolting. Since "collapse load analysis" was not invoked to evaluate bolting in this TR; the criterion in F-1440(a) is not applicable.

b) It is agreed that combining the P_m from F-1341.2(a) and P_m+P_b limit from F-1440(c) is not consistent. The justification for including Option 3 is discussed on page 27 of Section 2.3 in the TR as follows:

> "Option 3 is an alternative criterion for the elastic-plastic analysis of irradiated bolting. This option was selected since the corresponding P_m limit is not a function of S_m, and it was not necessary to define S_m and apply it to these limits. However, Option 3 also considers the more limiting criteria of F-1440(c)(2) for the evaluation of the P_m+P_b limit used in Option 2. The P_m+P_b limit is considered to be more limiting than the P_m limit for the development of bolting patterns. Therefore, the bolting patterns developed with Option 3 will be equivalent to those developed using Option 2. As a result, the use of Option 3 is an acceptable alternative for the development of bolting patterns for elastic-plastic analysis of irradiated bolting."

NRC RAI 7

NRC Question

Background

For replacement bolts under normal or upset conditions, the TR proposes to allow demonstration of shakedown in lieu of meeting the following allowable stress criteria from WCAP-15029-P-A: The TR states that:

> The demonstration of shakedown (NG-3213.17 of [ASME Boiler and Pressure Vessel Code, 1989 Edition, Section III, Division 1]) can be used in lieu of Normal/ Upset Criterion (b) for P_m+Q_m and Normal / Upset Criterion (e) for $P_m+Q_m+P_b+Q_b$. A shakedown analysis evaluates the cyclic response from a limiting Normal / Upset transient using an elastic-plastic material model. Shakedown is demonstrated when the deformation stabilizes and the subsequent structural response is elastic.

Issue

The TR references NG-3213.17, which provides a definition of shakedown. However, Subsection NG does not provide a methodology for determining if shakedown occurs.

Request

The staff requests that the PWROG describe the methodology for determining if shakedown occurs.

Response to RAI 7:

The NRC TR will be revised to include the following process steps to implement an elastic-plastic shakedown analysis:

1. Identify the limiting transient pairing at Normal / Upset conditions that represent the maximum and minimum primary plus secondary stress conditions.
2. Develop a finite element model of the baffle-former assembly, and include an elastic-plastic material model of the bolts as appropriate.
3. The loading is cycled from the maximum to the minimum condition until either the deflections stabilize or otherwise continue to accumulate.
4. Shakedown is demonstrated if the deformation stabilizes and subsequent structural response is linear-elastic.

This change, as shown in the redline markup on page 4 of Attachment 2 for a linear-elastic analysis, and also on page 7 of Attachment 2 for an elastic-plastic analysis, and will be incorporated in the NRC approved version of the TR after the Final Safety Evaluation is issued.

References

1. U.S. Nuclear Regulatory Commission Letter, "Request for Additional Information by the Office of Nuclear Reactor Regulation Pressurized Water Reactor Owner's Group Topical Reports PWROG-18034-P, Revision 0, PWROG-18034-NP, Revision 0 Updates to the Methodology in WCAP-15029-P-A, Rev. 1, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," April 9, 2019.
2. U.S. Nuclear Regulatory Commission Letter, "Acceptance for Review of the Pressurized Water Reactor Owners Group Topical Report PWROG-18034-P and PWROG-18034-NP, Revision 0, 'Updates to the Methodology in WCAP-15029-P-A, Rev. 1'," March 26, 2019 (ADAMS Accession No. ML19073A216).
3. PWROG-18034-NP, "Updates to the Methodology in WCAP-15030-NP-A, Rev. 0, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," October 31, 2018 (ADAMS Accession No. ML18306A491).
4. PWROG-18034-P, "Updates to the Methodology in WCAP-15029-P-A, Rev. 1, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," October 31, 2018.
5. *Materials Reliability Program: PWR Internals Age-Related Material Properties, Degradation, Mechanisms, Models, and Basis Data – State of Knowledge (MRP-211). EPRI, Palo Alto, CA: 2007. 1015013.*
6. *Materials Reliability Program: Hot Cell Testing of Baffle/Former Bolts Removed From Two Lead PWR Plants (MRP-51), EPRI, Palo Alto, CA: 2001. 1003069.*
7. *Materials Reliability Program: Characterizations of Type 316 Cold Worked Stainless Steel Highly Irradiated Under PWR Operating Conditions (MRP-73), EPRI, Palo Alto, CA and MRP/International IASCC Committee: 2002. 1003525.*
8. Framatome Technologies Incorporated Report, 51-5003385, "Evaluation of Point Beach Unit 2 Baffle Bolt Tensile Test Result," September 9, 1999.
9. ASME Code Case N-60-5, "Material for Core Support Structures," Section III, Division 1, February 15, 1994.

ATTACHMENT 2

Markups to PWROG-18034-P / PWROG-18034-NP that Reflect the Changes Discussed in the RAI Responses (Non-Proprietary Version)

Purpose

This attachment contains the redline markups of the changes to PWROG-18034-P [3] or PWROG-18034-NP [2] that are discussed in the responses to the U.S. Nuclear Regulatory Commission (NRC) Requests for Additional Information (RAIs) [1].

References

1. U.S. Nuclear Regulatory Commission Letter, "Request for Additional Information by the Office of Nuclear Reactor Regulation Pressurized Water Reactor Owner's Group Topical Reports PWROG-18034-P, Revision 0, PWROG-18034-NP, Revision 0 Updates to the Methodology in WCAP-15029-P-A, Rev. 1, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," April 9, 2019.
2. PWROG-18034-NP, "Updates to the Methodology in WCAP-15030-NP-A, Rev. 0, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," October 31, 2018.
3. PWROG-18034-P, "Updates to the Methodology in WCAP-15029-P-A, Rev. 1, 'Westinghouse Methodology for Evaluating the Acceptability of Baffle-Former-Barrel Bolting Distributions Under Faulted Load Conditions'," October 31, 2018.

2 METHODOLOGY CHANGES

2.1 FINITE ELEMENT MODELING OF THE BAFFLE-FORMER-BARREL REGION

FEM Discussion in Section 2.1.3.2.1 of WCAP-15030-NP-A:

"A single octant model of the baffle-former-barrel region is used in this analysis. Figure 2.1.3.2.1-1 shows a typical model for a two loop plant. The baffles and formers are represented as elastic plate elements. The core barrel is modeled only as an external boundary. Baffle-former, barrel-former, and edge bolts are represented as pipe elements (beam elements can also be used). Baffle-former and barrel-former bolts attach the baffle and barrel to the former plates, as shown in Figure 2.1.3.2.1-2. Edge bolts are non-structural and are installed to maintain a sufficiently small gap between adjacent baffle plates to preclude baffle-jetting. In the finite element model, sufficient nodalization is provided to permit representation of all baffle-former, barrel-former, and edge bolts in the simulated octant. Candidate "acceptable" bolting distributions are analyzed by putting the appropriate bolt elements in only at predefined locations."

Revised FEM Discussion:

Addition of the Following:

Either a linear-elastic or elastic-plastic material model for the bolting (i.e., baffle-former, barrel-former, and edge bolts) can be used. However, the use of a linear-elastic material model for bolting must apply linear-elastic acceptance criteria, and use of an elastic-plastic material model must apply elastic-plastic acceptance criteria.

When an elastic-plastic material model is used, the stress-strain behavior will be determined using a bilinear or multilinear model as shown in Figure 2. The bilinear material model considers the elastic modulus (E) from initial load through the yield point, and a tangent modulus (E_T) from the yield point through the point of failure. The multilinear model considers additional piecewise linear refinement of the tangent modulus ($E_{T,1}$, $E_{T,2}$, ... $E_{T,N}$) to approximate non-linear material behavior. Note that the bilinear / multilinear model is appropriate for both irradiated and unirradiated materials, and includes the effect of hysteresis (i.e., path dependency in stress and strain).

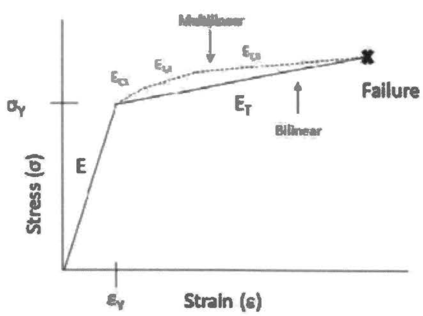


Figure 2 Bilinear / Multilinear Elastic-Plastic Material Model for Irradiated Bolting

Justification for the Changes

The properties of stainless steel from irradiated bolting have been demonstrated to remain ductile; therefore the use of an elastic-plastic material model is appropriate. Recall that EPRI's response to Limitation 3 was reviewed and approved by the NRC in Part 1 of RAI 33 in WCAP-17096-NP-A [13]. The NRC acknowledged EPRI's response in the SE for WCAP-17096-NP-A [13]:

> *"EPRI's response to RAI 33, Part 1, indicated testing of irradiated bolts have shown sufficient ductility such that ASME allowables can still be used. EPRI cited testing of bolts reviewed from Farley that demonstrated good ductility. EPRI indicated that the maximum fluence value of the Farley baffle-former bolts was approximately 10 dpa ($7x10^{21}$ n/cm^2, E > 1MeV), approximately 20 percent of the anticipated end-of-life fluence of the bolts, but changes in the mechanical and fracture properties occur most rapidly between 1 and 5 dpa and saturate by 10 dpa. Therefore, the Farley bolt tensile results can be considered representative with respect to end-of-life properties. EPRI cited test data presented in MRP-175 (Ref. 23) and "Materials Reliability Program: PWR Internals Age-Related Material Properties, Degradation Mechanisms, Models, and Basis Data - State of Knowledge," dated December 31, 2007 (MRP-211) (proprietary report – non-publically available) to support this response."*

Therefore, Limitation 3 has been addressed with the resolution of RAI 33, Part 1 as discussed in the NRC SE for WCAP-17096-NP-A [13]:

> *"The NRC staff reviewed the referenced test data and agrees with EPRI's conclusion. RAI 33, Part 1 is thus resolved."*

A statistical evaluation was performed to account for all the relevant parameters applicable to irradiated bolting [ ](a,b,c), which demonstrate that a strain limit of [ ](a,b,c) is applicable to the bolts that were tested. Therefore, it is appropriate to consider elastic-plastic behavior for irradiated bolting.

The use of a bilinear / multilinear material model to represent elastic-plastic behavior addresses a limitation in finite element models. The beam elements used to represent bolting are based upon engineering stress, which assumes the area of the cross-section remains constant. Tensile testing of irradiated materials demonstrated that localized elongation as shown in Figure 1 (i.e., reduction in the cross-sectional area in the necked region) is a significant contributor to the total elongation. Therefore, it is appropriate to consider the tangent modulus to be a function of material data that characterize the point of failure.

The use of an elastic-plastic material model will result in a significant reduction in individual bolt stiffness once yield is reached as shown in Figure 2. This reduction in stiffness after bolt yielding will result in increased baffle plate displacements, which is conservative. The baffle plate displacements are inputs that are used to evaluate the structural integrity of the fuel assemblies, and increased baffle plate displacements are conservative for that evaluation.

Revised Replacement Bolt Discussion:

Addition of the Following:

The allowable stress limits defined herein will be used for the evaluation of the alternate bolting patterns. These stress limits are consistent with the 1989 Edition [3] through the 2013 Edition [4] of the ASME Code when noted as such. The N-60-4 [5], N-60-5 [6], or N-60-6 [7] versions of Code Case N-60, "Material for Core Support Structures," will be used for replacement bolting. Note that SA-479 Type 316 can be used as an alternate material.

Allowable Stress Limits for Normal and Upset Conditions

The Normal / Upset bolt stress limits will only be evaluated for the plants with reactor vessel internals that are designed to Section III of the ASME Code.

Alternative Secondary Stress Evaluation Criteria for Normal and Upset Conditions

The demonstration of shakedown (NG-3213.17 of [3,4]) can be used in lieu of Normal / Upset Criterion (b) for P_m+Q_m and Normal / Upset Criterion (e) for $P_m+Q_m+P_b+Q_b$. A shakedown analysis evaluates the cyclic response from a limiting Normal / Upset transient using an elastic-plastic material model. Shakedown is demonstrated when the deformation stabilizes and the subsequent structural response is elastic.

The follow process steps are included in an elastic-plastic shakedown analysis:

1. Identify the limiting transient pairing at Normal / Upset conditions that represent the maximum and minimum primary plus secondary stress conditions.
2. Develop a finite element model of the baffle-former assembly, and include an elastic-plastic material model of the bolts as appropriate.
3. The loading is cycled from the maximum to the minimum condition until either the deflections stabilize or otherwise continue to accumulate.
4. Shakedown is demonstrated if the deformation stabilizes and the subsequent structural response is linear-elastic.

Allowable Stress Limits for Faulted Conditions

The use of a non-linear bolt model considers the elastic-plastic stress limits in accordance with F-1341 of Appendix F of the ASME Code:

c. Primary Membrane (per F-1341.2(a) of [3,4]), P_m

P_m = Greater of $0.7 \cdot S_u$ and $S_y + 1/3 \cdot (S_u - S_y)$

d. Maximum Primary Stress Intensity (per F-1341.2(b) of [3,4]), S_{max}

S_{max} = Less than 0.9 S_u

The maximum primary stress intensity limit is applicable to P_m+P_b.

$P_m+P_b = S_{max}$ = Less than 0.9 S_u

Acceptance Criteria for Irradiated Bolts:

Replacement with the Following:

[ ] (a,b,c)

Table 1: 95/95 Lower Bound Limits from Statistical Evaluation for Type 316 SS and Type 347 SS at Operating Temperature

[ ] (a,b,c)

Table 2: Material Property Limits Applied to Evaluate Irradiated Bolting at Operating Temperature and Estimated Dose of [ ] (a,b,c) or Greater

[ ] (a,b,c)

Allowable Stress Limits for Normal and Upset Conditions

The Normal / Upset bolt stress limits will only be evaluated for the plants with reactor vessel internals that are designed to Section III of the ASME Code.

The following definition of S_m is applicable to the evaluation of irradiated bolting:

$$S_m = (1/3) \cdot S_u$$

a. Primary Membrane Stress (per NG-3232.1(d) of [3,4]), P_m

$$P_m = S_m$$

b. Primary Membrane Plus Secondary Membrane (per NG-3232.1(a) of [3,4]), $P_m + Q_m$

$$P_m + Q_m = \text{Lesser of } 0.9\ S_y \text{ or } 2/3\ S_u$$

c. Average Shearing Stress for Threads (per NG-3232.1(b) of [3,4]), τ

$$\tau = 0.6 \cdot S_y$$

d. Average Bearing Stress Under Bolt Head (per NG-3232.1(c) of [3,4]), σ

$$\sigma = 2.7 \cdot S_y$$

e. Primary Membrane and Bending Plus Secondary Membrane and Bending, (per NG-3232.2(a) of [3,4]), $P_m+Q_m+P_b+Q_b$

$$P_m+Q_m+P_b+Q_b = \text{Lesser of } 1.2 \cdot S_y \text{ or } (8/9) \cdot S_u$$

Alternative Secondary Stress Evaluation Criteria for Normal and Upset Conditions

Demonstration of shakedown (NG-3213.17 of [3,4]) can be used in lieu of Normal / Upset Criterion (b) for P_m+Q_m and Normal / Upset Criterion (e) for $P_m+Q_m+P_b+Q_b$. A shakedown analysis evaluates the cyclic response from a limiting Normal / Upset transient using an elastic-plastic material model. Shakedown is demonstrated when the deformation stabilizes and the subsequent structural response is elastic.

The follow process steps are included in an elastic-plastic shakedown analysis:

1. Identify the limiting transient pairing at Normal / Upset conditions that represent the maximum and minimum primary plus secondary stress conditions.
2. Develop a finite element model of the baffle-former assembly, and include an elastic-plastic material model of the bolts as appropriate.
3. The loading is cycled from the maximum to the minimum condition until either the deflections stabilize or otherwise continue to accumulate.
4. Shakedown is demonstrated if the deformation stabilizes and the subsequent structural response is linear-elastic.

Acceptance Criteria for Faulted Conditions – Elastic Analysis

The acceptance criteria for an elastic-system analysis from F-1331 of Appendix F of the ASME Code [3] are applied to evaluate irradiated bolting when a linear-elastic material model is used. The following acceptance criteria will be applied to evaluate irradiated bolting, which are consistent with the F-1331 of Appendix F limits of the ASME Code [3], as applicable. Two acceptance criteria options will be used where Option 1 includes additional conservatism relative to Option 2.

Option 1: Consider Unirradiated Limits

Irradiated bolting will be evaluated in accordance with F-1331 of Appendix F of the ASME Code considering non-irradiated properties. Material properties as defined in Section III of the ASME Code, which best represent the original condition of Type 316 SS and Type 347 SS material properties will be used in the evaluation.

Primary Membrane (per F-1331.1(a) of [3,4]), P_m

P_m = Lesser of 2.4 S_m or 0.7 S_u

Primary Membrane Plus Primary Bending (per F-1331.1(b) of [3,4]), $P_m + P_b$

Allowable primary membrane plus primary bending, $P_m + P_b$, shall not exceed 150% of P_m limit:

P_m+P_b = Lesser of 3.6 S_m or 1.05 S_u

Option 2: Irradiated Limits

The stress limits for high strength threaded structural fasteners in F-1440(c)(1) of Appendix F of the ASME Code are used along with the irradiated material properties shown in Table 2 for the evaluation of irradiated bolting.

The following definition of S_m is applicable to the evaluation of irradiated bolting:

$S_m = (1/3) \cdot S_u$

Primary Membrane (per F-1440(c)(1) of [3,4]), P_m

$P_m = 2 \cdot S_m = (2/3) \cdot S_u$

Primary Membrane Plus Primary Bending (per F-1440(c)(1) of [3,4]), $P_m + P_b$,

$P_m + P_b = 3 \cdot S_m = S_u$

Acceptance Criteria for Faulted Conditions – Elastic-Plastic Analysis

The following three options will be used to evaluate irradiated bolting, where Option 1 includes additional conservatism relative to Option 2 or Option 3.

Option 1: Consider Unirradiated Limits

Irradiated bolting will be evaluated in accordance with F-1341 of Appendix F of the ASME Code [3] considering non-irradiated properties. The material properties as defined in Section III of the ASME Code, which best represent the original condition of Type 316 SS and Type 347 SS material properties, are used in the evaluation.

Primary Membrane Stress Intensity (per F-1341.2(a) of [3,4]), P_m

P_m = Greater of 0.7 S_u and $S_y + 1/3\ (S_u - S_y)$

Maximum Primary Membrane Stress Intensity (per F-1341.2(b) of [3,4]), S_{max}

S_{max} = Less than 0.9 S_u

The Maximum Primary Stress Intensity limit (S_{max}) is applied for the Primary Membrane Plus Bending (P_m+P_b) limit

$P_m + P_b = S_{max}$ = Less than 0.9 S_u

A strain limit of [ ] (a,b,c) is applicable to bolts less than or equal to 2.12 inches long, and a strain limit of [ ] (a,b,c) applies to bolts greater than 2.12 inches long.

Option 2: Irradiated Limits

The stress limits for high strength threaded structural fasteners from F-1440(c)(2) in Appendix F of the ASME Code (i.e., with an S_u > 100 ksi at operating temperature) have been considered using the irradiated material properties in Table 2 for the evaluation of irradiated bolting.

The following definition of S_m is applied for the evaluation of irradiated bolting:

$S_m = (1/3) \cdot S_u$

Primary Membrane (per F-1440(c)(2) of [3,4]), P_m

$P_m = 2 \cdot S_m = (2/3) \cdot S_u$

Maximum Primary Stress Intensity (per F-1440(c)(2) of [3,4]),S_{max}

$S_{max} = \min\{0.9 \cdot S_u, \max[0.67 \cdot S_u, S_y + ⅓ \cdot (S_u - S_y)]\}$

The Maximum Primary Stress Intensity limit (S_{max}) is applied for the Primary Membrane Plus Bending (P_m+P_b) limit

$P_m + P_b = S_{max} = \min\{0.9 \cdot S_u, \max[0.67 \cdot S_u, S_y + ⅓ \cdot (S_u - S_y)]\}$

A strain limit of [ ](a,b,c) is applicable to bolts less than or equal to 2.12 inches long, and a strain limit of [ ](a,b,c) applies to long bolts greater than 2.12 inches long.

Option 3: Alternate Irradiated Limits

The following limits are applied to evaluate irradiated bolting using the material properties in Table 2:

Primary Membrane Stress Intensity (per F-1341.2(a) of [3,4]), P_m

$$P_m = \text{Greater of } 0.7\ S_u \text{ and } S_y + 1/3\ (S_u - S_y)$$

The Maximum Primary Stress Intensity as defined in F-1440(c)(2) is applied to determine the P_m+P_b limit.

Maximum Primary Stress Intensity (per F-1440(c)(2) of [3,4]), S_{max}

$$S_{max} = \min \{0.9 \cdot S_u,\ \max [0.67 \cdot S_u,\ S_y + ⅓ \cdot (S_u - S_y)]\}$$

The Maximum Primary Stress Intensity limit (S_{max}) is applied for the Primary Membrane Plus Bending (P_m+P_b) limit

$$P_m + P_b = S_{max} = \min \{0.9 \cdot S_u,\ \max [0.67 \cdot S_u,\ S_y + ⅓ \cdot (S_u - S_y)]\}$$

A strain limit of [ ](a,b,c) is applicable to bolts less than or equal to 2.12 inches long, and a strain limit of [ ](a,b,c) applies to bolts greater than 2.12 inches long.

Justification for Changes

[ ](a,b,c)

[ ] (a,b,c)

(a,b,c)

Acceptance Criteria

Several conservatisms are included in the development of ASME Code material properties as previously discussed. Therefore, it is appropriate and conservative to consider the acceptance criteria of F-1331 for a linear-elastic analysis and F-1341 for an elastic-plastic analysis along with the unirradiated material that is applicable to the Type 316 SS and Type 347 SS bolting materials as defined by Section III of the ASME Code. A sensitivity study has been performed to confirm that using Option 1 provides conservative results relative to the other options that consider the bolts to be irradiated. Therefore, the use of Option 1 is a conservative approach for the evaluation of irradiated bolts. ~~This criterion will only be applied to the plants with lower loaded baffle bolts with an upflow design configuration.~~

Option 2 applies the Appendix F limits of the ASME Code that would be applicable to high strength threaded structural fasters per F-1440(c)(1) for a linear-elastic analysis and F-1440(c)(2) for an elastic-plastic analysis. These are the appropriate Code limits that would be used for highly strain-hardened SA-193 B8M with a specified ultimate strength of 110 ksi at room temperature, per ASME Code Case N-60-6 [7]. This approach is acceptable due to the similarity in the properties of highly strain-hardened ASME Code bolting material and those determined from testing of irradiated stainless steel bolt material. However, these equations are a function of S_m, where the value of $(1/3)\cdot S_u$ is justified by the following.

The values of S_m are typically determined as the more limiting fraction of the yield or ultimate strengths. Therefore, the properties defined in Code Case N-60-4 [5] for SA-193 B8M are considered to determine S_m as a fraction of the yield and ultimate strengths. The most highly strain-hardened form of SA-193 B8M as defined in Code Case N-60-4 [5] has an S_m of 33.3 ksi, an S_y of 74.4 ksi, and an S_u of 99.9 ksi at 650°F. Based on these properties, S_m is $0.45\cdot S_y$ and $(1/3)\cdot S_u$. The limiting applied yield strength is $0.85\cdot S_u$ for irradiated bolting based upon the applied limits shown in Table 2. As such, the limiting equation for S_m is $(1/3)\cdot S_u$ since this is more limiting than the limit based upon yield strength of $0.38\cdot S_u$ ($0.45\ S_y = 0.45 \times 0.85\cdot S_u$). The acceptance criteria in F-1440(c)(1) for a linear-elastic analysis and F-1440(c)(2) for an elastic-plastic analysis are determined based upon the adopted value of S_m.

Option 3 is an alternative criterion for the elastic-plastic analysis of irradiated bolting. This option was selected since the corresponding P_m limit is not a function of S_m, and it

was not necessary to define S_m and apply it to these limits. However, Option 3 also considers the more limiting criteria of F-1440(c)(2) for the evaluation of the P_m+P_b limit used in Option 2. The P_m+P_b limit is considered to be more limiting than the P_m limit for the development of bolting patterns. Therefore, the bolting patterns developed with Option 3 will be equivalent to those developed using Option 2. As a result, the use of Option 3 is an acceptable alternative for the development of bolting patterns for elastic-plastic analysis of irradiated bolting.

The material properties developed in Table 1 excluded the material data from baffle bolts located at the top former. This was done because the yield strength, ultimate strength, and total elongation values indicate that saturated fluence has not been achieved. However, a sensitivity study was performed considering the top former bolts and also the barrel-former bolts to be irradiated or unirradiated, which indicated small changes to the limiting baffle bolt stress margins. Therefore, it is acceptable to model the top row former bolts and barrel-former bolts as either irradiated or unirradiated when evaluating reduced baffle-former bolt patterns. When evaluating reduced patterns of barrel-former bolts, for doses of less than 10 dpa, the limits defined in Option 1 will be conservatively applied.

The evaluation of the bolt stress limits at Normal / Upset conditions is only required to be performed for those plants that were designed to Section III of the ASME Code, and include Normal / Upset stress limits in the design basis. The same justification as provided in Section 2.2 for replacement bolting also applies to the evaluation of irradiated bolting.

3 SUMMARY / CONCLUSIONS

The changes made to the material model are discussed in Section 2.1 of this TR. The use of either a linear-elastic or an elastic-plastic material model is acceptable; however, the acceptance criteria (i.e, elastic or elastic-plastic) must be consistent with the selected material model. A bilinear / multilinear model that includes hysteresis is used to represent non-linear behavior.

As discussed in Section 2.2 of this TR, the evaluation of Normal / Upset condition bolt stress limits for replacement bolts will only be evaluated for the plants with reactor vessel internals that are designed to Section III of the ASME Code; however, demonstration of shakedown can be used in lieu of primary plus secondary linear-elastic stress limits. Replacement bolts can be evaluated using either a linear-elastic or elastic-plastic material model, as well as acceptance criteria as defined in Section 2.2 of the TR. Replacement bolts will use material properties as defined by the versions of ASME Code Case N-60 that are identified in this TR. An additional alternate material (SA-479 Type 316) is available for replacement bolting.

As discussed in Section 2.3, the evaluation of Normal / Upset condition stress limits for irradiated bolting will only be evaluated for the plants with reactor vessel internals that are designed to the Section III of the ASME Code; however, demonstration of shakedown is allowed in lieu of primary plus secondary linear-elastic stress limits. Either a linear-elastic or elastic-plastic material model can be used to evaluate irradiated bolting. Several additional options are provided for acceptance criteria for the evaluation of irradiated bolting as discussed in Section 2.3. Option 1 conservatively applied the acceptance criteria for unirradiated bolts. Option 2 applies the acceptance criteria for high strength structural fasteners from F-1440 to evaluate irradiated bolting. Option 3 provides acceptance criteria for elastic-plastic analysis, which are not a function of S_m, and determines equivalent bolting patterns as Option 2. The use of Appendix F limits for irradiated bolting is acceptable based upon the similarity between highly strain-hardened ASME Code materials and the properties obtained from the tensile testing of irradiated bolting materials.

A set of bounding material properties (i.e. yield strength, ultimate strength, and strain limit) are provided for the evaluation of irradiated Type 316 SS and Type 347 SS bolting materials. A strain limit of [ ]^{a,b,c} is applicable to short and medium length bolts less than or equal to 2.12 inches long, and a strain limit of [ ]^{a,b,c} is defined for bolts greater than 2.12 inches long. The value of the irradiated material properties is supported by a statistical analysis of the testing that was performed on the irradiated materials (bolts) that account for the relevant parameters [ ]^{a,b,c}.

The NRC approved methodology in WCAP-15030-NP-A [1] is not impacted by these changes, and can still be applied to those plants where it is appropriate to use, i.e. for those plants with an upflow design configuration.

ATTACHMENT 3

Irradiated Material Property Data as Applied in PWROG-18034-P (Non-Proprietary Version)

Purpose

The attachment contains the tensile test data that was as requested in Part 1 of RAI 1 in [1]:

> "Provide a list of all tests included in the database for each material, including material grade, source (component, product form), where irradiated, specimen type, cold work %, neutron fluence or dpa, temperature, yield strength, ultimate strength, uniform elongation, total elongation."

The material data includes 23 specimen tests from MRP-211 [2], MRP-51 [3], and MRP-73 [4]. The data also includes full bolt testing including 122 tests for 347 SS material in 51-5003385 [5], and 165 full bolt tests from a Westinghouse test report.

Discussion

Information about the "material form" such as the: material, material grade, source, where irradiated, specimen type, and cold work %," and "form category" is discussed below. The "material property data" such as the: neutron fluence or dpa, test temperature, yield strength, ultimate strength, uniform elongation, and total elongation, are determined directly from the applicable test report. A total of 27 specimen test data points, as shown in Attachment 3, Table 1 were considered. A total of 287 full bolt tensile test results were considered, as shown in Attachment 3, Table 2, which includes 122 tensile test results from Point Beach Unit 2 and 165 tensile test results from Farley Unit 1.

The material form is one of three categories:

1. Point Beach Unit 2 baffle-former bolts
2. Farley Unit 1 Baffle-former bolts
3. Ringhals Unit 2 flux thimble tubes

<u>Point Beach Unit 2 Baffle-former Bolts</u>

The Point Beach Unit 2 baffle-former bolts were manufactured to the applicable Westinghouse process specification. The material is annealed AISI 347 stainless steel. These were irradiated in an operating plant environment. The bolts were tested in the full bolt condition as documented in 51-5003385 [5], or cut into small tensile specimens and tested to conform to ASTM E8 or E21 as discussed in MRP-51 [3].

These bolts were manufactured from solution-annealed bar stock where no cold working was performed. Therefore, the degree of cold work does not apply, and will be indicated as "N/A."

Farley Unit 1 Baffle-former Bolts

The Farley Unit 1 baffle-former bolts were manufactured to the applicable Westinghouse process specification. The material is carbide solution treated and strain hardened AISI 316 stainless steel. These specimens were irradiated in the plant operating plant environment. The bolts were tested in the full bolt condition, or made into small tensile specimens and tested to conform to ASTM E8 or E21 as discussed in MRP-51 [3]. These bolts were made from strain hardened bars, and the degree of cold work is estimated to be less than 20%.

Ringhals Unit 2 Flux Thimble Tubes

The Ringhals Unit 2 flux thimble tubes were manufactured to the applicable Westinghouse process specification. The material is cold worked, 316 stainless steel. These specimens were irradiated in the plant operating plant environment. The flux thimble tubes were or manufactured into curved "dog bone" specimens and tested as discussed in MRP-73 [4]. MRP-73 reports that the process specification for this material required "~ 10% to 12% cold work after the final anneal."

Attachment 3 Table 1. Irradiated Specimen Test Data Applied in PWROG-18034-P

[ ]

(a,b,c)

Attachment 3 Table 2. Irradiated Full Bolt Test Data Applied in PWROG-18034-P

(a,b,c)

(a,b,c)

[ ] (a,b,c)

[ ](a,b,c)

(a,b,c)

[ ](a,b,c)

[ ]$^{(a,b,c)}$

(a,b,c)

[ ] (a,b,c)

[ ] (a,b,c)

[ ]$^{(a,b,c)}$

[ ] (a,b,c)

References

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2. *Materials Reliability Program: PWR Internals Age-Related Material Properties, Degradation, Mechanisms, Models, and Basis Data – State of Knowledge (MRP-211). EPRI, Palo Alto, CA: 2007. 1015013.*
3. *Materials Reliability Program: Hot Cell Testing of Baffle/Former Bolts Removed From Two Lead PWR Plants (MRP-51), EPRI, Palo Alto, CA: 2001. 1003069.*
4. *Materials Reliability Program: Characterizations of Type 316 Cold Worked Stainless Steel Highly Irradiated Under PWR Operating Conditions (MRP-73), EPRI, Palo Alto, CA and MRP/International IASCC Committee: 2002. 1003525.*
5. Framatome Technologies Incorporated Report, 51-5003385, "Evaluation of Point Beach Unit 2 Baffle Bolt Tensile Test Result," September 9, 1999.