PRESSURIZED WATER REACTOR OWNERS GROUP

PWROG-18034-NP
Revision 0

WESTINGHOUSE NON-PROPRIETARY CLASS 3

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"

Materials Committee

PA-MSC-1519, Revision 1, Task 3

October 2018

Westinghouse

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PA-MSC-1519, Revision 1, Task 3

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October 2018

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	Millstone 3 (W)		X
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Wolf Creek Nuclear Operating Co.	Wolf Creek (W)		X
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Electrabel	Doel 1, 2 & 4 (W)		X
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	Hanbit 1 & 2 (W)		X
	Hanbit 3, 4, 5 & 6 (CE)		X
	Hanul 3, 4 , 5 & 6 (CE)		X
Kyushu	Genkai 2, 3 & 4 (MHI)		X
	Sendai 1 & 2 (MHI)		X
Nuklearna Electrarna KRSKO	Krsko (W)		X
Ringhals AB	Ringhals 2, 3 & 4 (W)		X
Shikoku	Ikata 1, 2 & 3 (MHI)		X
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1 SCOPE OF CHANGES

1.1 BACKGROUND / PURPOSE

WCAP-15030-NP-A [1] was prepared to establish a standard methodology for evaluating the acceptability of baffle-former and barrel-former bolting distributions under Faulted conditions. The Nuclear Regulatory Commission (NRC) issued a Safety Evaluation (SE) for the Topical Report (TR) on November 10, 1998. The NRC approved methodology in the TR was applied to some plants; however, changes to the NRC approved methodology are required in order to obtain acceptable bolt pattern results for other plants. 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 acceptable bolting patterns result from the methodology as defined.

The purpose of this TR is to identify the changes to the NRC approved methodology in WCAP-15030-NP-A [1] that are used to evaluate the baffle-former and barrel-former bolting patterns for Faulted conditions, and obtain NRC review and approval of those changes.

The changes are grouped into the following three categories:

- Modeling – Changes to the material model used to represent the bolting in the finite element model (FEM) of the baffle-former assembly that is discussed in Section 2.1.3.2.1 of [1].
- Acceptance Criteria for Replacement Bolting – Changes to Section 4.3.1 of [1] including the ASME Code version, material, and allowable limits that are used to evaluate replacement bolts.
- Acceptance Criteria for Irradiated Bolting – Changes to Section 4.3.2 of [1], including the stress limits and justification for the irradiated material properties.

Section 1.2 discusses the basis for each change, and Section 2 discusses the NRC approved methodology in WCAP-15030-NP-A [1], and a justification for each change to the NRC approved method.

1.2 BASIS FOR THE CHANGES

The NRC-approved methodology in WCAP-15030-NP-A was developed from WCAP-9401-P-A [2] for the structural evaluation of the fuel assemblies during a Faulted condition event. The WCAP-9401-P-A methodology assumes that both baffle and barrel bolts were in the as-designed condition, i.e., all bolts are installed in all locations. WCAP-15030-NP-A contains a methodology for evaluating the impact on fuel assembly structural integrity associated with reduced numbers of baffle and barrel bolts during Faulted conditions to confirm that core coolability and control rod insertability are maintained.

The WCAP-15030-NP-A methodology is used to determine the acceptable number and distribution of baffle-former and barrel-former bolts, less than the original design of 100%, which is referred to as an Acceptable Bolting Pattern Analysis (ABPA). This methodology utilizes leak-before-break (LBB) to exclude certain pipe breaks, based on the plant specific licensing basis, and break opening times of greater than one millisecond. In addition, this methodology evaluates alternate bolting patterns using the original bolting with irradiated material properties, or replacement bolting with unirradiated material properties.

The FEMs contained in WCAP-15030-NP-A are a one-octant sector representation of the baffle-former assembly, which uses pipe (or beam) elements to represent each baffle and barrel bolt. A sub-modeling technique is used, where each seismic and LOCA transient will be re-run based upon the displacements and equivalent loading from the global system model. This modeling technique utilized in WCAP-15030-NP-A was not available when the original design basis calculations were performed, and often results in higher bolt loading.

Additional conservatisms are introduced when implementing the methodology in WCAP-15030-NP-A, which tend to artificially increase the bolt loads. For example, edge bolts, if present in the design, can be conservatively excluded. The design bolt preload is considered in the analysis; even though the preload will dissipate as the bolts become irradiated. In addition, a linear-elastic material model was initially used for the baffle and barrel bolts.

Finally, conservative acceptance criteria were contained in WCAP-15030-NP-A for replacement bolts and irradiated bolts. These include the linear-elastic limits contained in F-1331 of Appendix F of the ASME Code for the replacement bolts. The acceptance criterion for irradiated bolting at Faulted conditions was based upon a maximum stress equal to 90% of the yield strength, which is consistent with the evaluation of fuel rod cladding per Section 4.2, "Fuel System Design," of the NUREG-0800 Standard Review Plan (SRP) [14].

The WCAP-15030-NP-A methodology was first applied to representative 2-, 3-, and 4-loop Westinghouse Nuclear Steam Supply System (NSSS) plants. It became apparent that the higher bolt loads and conservative acceptance criteria resulted in unacceptable bolting pattern results especially for those plants with a downflow design configuration. Note that the direction of flow refers to the baffle-former cavity, (i.e., downward in downflow design plants versus upward in upflow design plants), where downflow plants are subjected to additional bolt loading.

The use of an elastic-plastic material model was not included in WCAP-15030-NP-A for the evaluation of irradiated bolting; however, Limitation 3 in the NRC SE for WCAP-15030-NP-A stated:

> *"The methodology should not be used to assess existing bolting without demonstration of adequate conservatism in projected bolting material properties (i.e., yield and ultimate strength) to ensure that sufficient ductility is present in existing irradiated stainless steel bolting materials."*

After the NRC SE for WCAP-15030-NP-A was issued, tensile testing of baffle bolts from Farley Unit 1 and Point Beach Unit 2 was performed, which demonstrated that irradiated bolts had increased yield and ultimate strength and still retained substantial ductility. Note that these tensile test results were used to satisfy Limitation 3 in the NRC SE for WCAP-15030-NP-A as discussed in Section 2.1 of this TR.

Based on these factors, an elastic-plastic material model was developed for the evaluation of bolting patterns, especially for the plants with a downflow design configuration. The use of a non-linear material model more accurately represents the behavior of the system response by considering the strain energy dissipated by the ductility of the bolts during a Faulted condition event. The strain energy is proportional to the area under the stress-strain curve, where a representative curve for ductile failure is shown in Figure 1. The relative change in the strain energy is determined by comparing the triangular cross-hatched area for loading to the yield strength relative to the total area under the stress-strain curve up to the point of failure. Therefore, the use of a non-linear material model can provide a substantial increase in margin relative to a linear-elastic model for the evaluation of ductile materials.

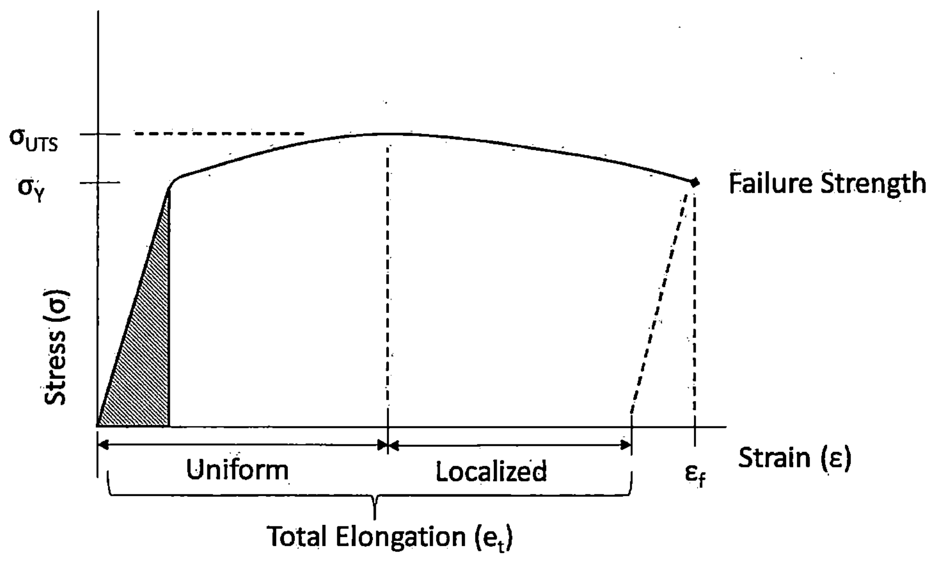

Figure 1 Typical Stress Strain Curve Obtained from Tensile Testing

Elastic-plastic acceptance criteria, as defined in Appendix F of the ASME Code, will be used to evaluate irradiated bolting. This is acceptable due to the similarity between the effect of strain-hardening and irradiation upon stainless steel bolt material. The allowable limits are calculated

from the available material properties as determined from tensile testing of irradiated materials, i.e., the yield strength (σ_y), ultimate strength (σ_{UTS}), and total elongation to failure (e_t) of the failed test specimens. See Section 2.3 for additional justification on this topic.

Sufficient ductility in the material properties of irradiated bolts must be confirmed to use an elastic-plastic material model. The NRC reviewed the tensile test data from irradiated materials that is discussed Section 2.1 of this TR that was provided in response to Part 1 of RAI 33 on WCAP-17096-NP-A [13], "Reactor Internals Acceptance Criteria Methodology and Data Requirements," and concluded that sufficient ductility exists in the material properties of irradiated bolting material, therefore, Limitation 3 in the NRC SE for WCAP-15030-NP-A has been addressed.

Note that the elastic-plastic limits as defined in Appendix F of the ASME Code will be used for the evaluation of replacement bolting. However, replacement bolts use the material properties as defined by the ASME Code, which are based upon the unirradiated condition. The changes to the NRC approved modeling methodology, acceptance criteria for replacement bolting, and acceptance criteria for irradiated bolting in WCAP-15030-NP-A are discussed in Section 2.

1.3 REVIEW OF THE LIMITATIONS IN THE NRC SE FOR WCAP-15030-NP-A

The purpose of this section is to review each of the four Limitations contained in the NRC SE for WCAP-15030-NP-A, to determine if they are applicable to the methodology updates contained in this TR.

The NRC SE for WCAP-15030-NP-A contained the following four Limitations:

> *"1. The bolt loading should be determined by analysis for a class of plants and a specific break;*
>
> *2. The noding to be used in the representation of the loading is demonstrated to be adequate by performing nodalization sensitivity studies or by some other acceptable methodology;*
>
> *3. The methodology should not be used to assess existing bolting without demonstration of adequate conservatism in projected bolting material properties (i.e., yield and ultimate strength) to ensure that sufficient ductility is present in existing irradiated stainless steel bolting materials;.*
>
> *4. The use of the methodology for existing irradiated stainless steel bolting should account for limitations in available ISI methods with regard to the probability of detection characteristics;"*

Limitation 1

The Faulted condition loading will be plant-specific or consistent with a class of plant, (e.g., the number of RCS loops and direction of RCS flow, for example, "4-loop downflow") and will use the break size consistent with the plant specific licensing basis. LBB can be utilized to determine the largest RCS branch line piping to be considered. The updated methodology does not include any changes to the plant's CLB with respect to the break size or break opening times in the evaluation of acceptable bolting patterns. Therefore, this Limitation remains applicable to the development of Faulted condition loading in the NRC approved methodology contained in WCAP-15030-NP-A, and the updated methodology contained in this TR, whichever is implemented.

Limitation 2

The noding used in the Multiflex 3.0 model to develop the LOCA loads must include adequate nodalization for each evaluation performed. Adequate nodalization is included in the WCOBRA/TRAC Code that was used to evaluate two-phase loads as discussed in Step 8 of the NRC SE for WCAP-14449-P-A [15]. The updated methodology does not include any changes that would impact the development of LOCA loads or the NRC SE for WCAP-14449-P-A [15]. Therefore, this Limitation remains applicable to the development of LOCA loads in the NRC approved methodology, as contained in WCAP-15030-NP-A, and the updated methodology, contained in this TR, whichever is implemented.

Limitation 3

This Limitation was satisfied based on the irradiated test data that was provided in response to Part 1 of RAI 33, as discussed in the NRC SE for WCAP-17096-NP-A in [13]. Note that satisfying Limitation 3 allows the use of an elastic-plastic material model for irradiated bolting contained in this TR.

Limitation 4

This Limitation was satisfied based on responses to Part 5 of RAI 32 and Part 2 of RAI 33 as discussed in the NRC SE for WCAP-17096-NP-A in [13]. The updated methodology in this TR does not include any changes that would impact the ISI methods with respect to the probability of detection characteristics. The limitations in ISI methods with respect to the probability of detection characteristics will be addressed as required by the NRC approved methodology contained in WCAP-15030-NP-A, and the updated methodology contained in this TR whichever is implemented.

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 model as shown in Figure 2. This 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. Note that the bilinear model is appropriate for both irradiated and unirradiated materials, and includes the effect of hysteresis (i.e., path dependency in stress and strain).

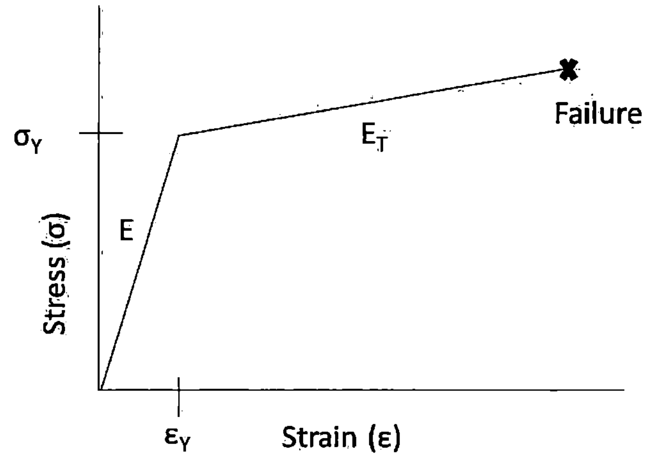

Figure 2 Bilinear Elastic-Plastic Material Model for Irradiated Bolting

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 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.

2.2 ACCEPTANCE CRITERIA FOR REPLACEMENT BOLTS

<u>Acceptance Criteria for Replacement Bolts as Discussed in Section 4.3.1 of WCAP-15030-NP-A:</u>

"4.3.1 Replacement Bolts

The mechanical properties at operating temperatures for SA-193 B8M grade (type 316 CW SS) of the replacement bolts for the baffle-former assembly are provided in Tables A, B, and C of the ASME Code Case N-60-4. Also the mechanical properties for the type 347 SS replacement bolts are provided in Tables I-1.2, I-2.2, and I-3.2 of the 1989 Edition Section III, Division 1 of the ASME Code (Reference 4-4). The ASME code allowables for the replacement bolts are defined as:

Allowable Stress Limits for Normal and Upset Conditions

a. Primary Membrane Stress, P_m

$$P_m = S_m$$

b. Primary Membrane Plus Secondary Membrane, $P_m + Q_m$

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

c. Shearing Stress for Threads, τ

$$\tau = 0.6\ S_y$$

d. Bearing Stress Under Bolt Head σ

$$\sigma = 2.7\ S_y$$

e. Primary Membrane and Bending Plus Secondary Membrane and Bending, $P_m+Q_m+P_b+Q_b$

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

Faulted Conditions

In accordance with F-1331 of Appendix F of the ASME Code:

a. Primary Membrane, P_m

$$P_m = \text{Lesser of } 2.4\ S_m \text{ or } 0.7\ S_u$$

b. Primary Membrane Plus Primary Bending, $P_m + P_b$

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

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.

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

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

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

$$S_{max} = \text{Less than } 0.9\ S_u$$

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

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

Justification for the Changes

The primary focus of WCAP-15030-NP-A is the evaluation of Faulted conditions to confirm that the structural integrity of the fuel assemblies will be maintained with reduced bolting patterns. The objective of the Normal / Upset stress limits is to evaluate potential degradation of the bolting due to the loading at operating conditions, which are classified as Normal / Upset in the ASME Code. The methodology discussed in Section 3 of WCAP-15030-NP-A, as required in Step "m" of the pattern development process in Figure 2-1 of WCAP-15030-NP-A, satisfies this objective. The required evaluations include the assessment of baffle gaps, thermal cycling (low cycle fatigue), flow-induced vibration (high cycle fatigue), baffle jetting (momentum flux), and by-pass flow evaluations. These evaluations are sufficient since these consider each plausible degradation mechanism, and evaluate the reduced bolting patterns. Therefore, 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.

In some cases, compliance with Normal / Upset condition bolt stress Criteria (b) for P_m+Q_m and Criteria (e) for $P_m+Q_m+P_b+Q_b$ using a linear-elastic analysis is difficult to meet due to the large secondary stress due to the bolt preload and the relative thermal expansion between the baffle plate and core barrel. Therefore, an alternative methodology, elastic-plastic shakedown analysis, can be used in lieu of Criteria (b) and Criteria (e). The purpose of a shakedown analysis is to demonstrate that the primary plus secondary stresses are self-limiting, and to confirm that any deformation of the bolts will stabilize to an elastic response when evaluating the cyclic response of consecutive iterations of the limiting transient. Therefore, this evaluation satisfies the intent of the Criteria (b) and Criteria (e), and a shakedown analysis provides an acceptable alternative to Criteria (b) and (e) as identified above.

The following limits as provided herein are used for the allowable stress limits that will be used for ABPAs. These equations are consistent with the limits as defined in the 1989 Edition [3] through the 2013 Edition [4] of the ASME Code, which is the industry standard used to perform structural analysis of reactor vessel internals components. The N-60-4 [5], N-60-5 [6], and N-60-6 [7] versions of N-60 are specifically referenced as they are versions of Code Case N-60 associated with the 1989 Edition [3] through 2013 Editions [4] of the ASME Code. Note that SA-479 Type 316 is an acceptable alternate material to SA-193 B8M, since it is included in N-60-5 [6] and N-60-6 [7], and is used for the bolting material in the reactor vessel internals.

Unirradiated replacement bolts will eventually become irradiated. However, it is not necessary to re-evaluate the replacement bolts as irradiated bolts due to the conservatisms included in the stress limits in an ASME Section III Code evaluation.

2.3 ACCEPTANCE CRITERIA FOR IRRADATED BOLTS

Acceptance Criteria for Irradiated Bolts that is Discussed in Section 4.3.2 of WCAP-15030-NP-A:

"4.3.2 Irradiated Bolts

The ASME Code does not provide allowable stress limits for irradiated materials. Using the interpretation of the ASME code, the allowable limits for the irradiated 316 CW SS and the 347 SS bolting materials are established. The test data which was considered for the 316 CW SS and 347 SS bolting materials had significantly lower fluence levels than those for the bolts in the baffle region (5 to 75.0 E+21 n/cm^2 versus 1.6 E+23 n/cm^2 thereby making them conservative limits since the material yield and ultimate strengths increase with increasing fluence levels.

Based on the ASME Code stress limits, it is seen that the S_m value for 347 SS is approximately 90% of the yield strength at operating temperatures (650 degree F), and approximately 50% of the yield for the 316 CW SS. Since, the ASME Code does not specify S_m value for the irradiated materials, it is conservative to consider that for these irradiated bolting materials $S_m = 0.4 \cdot S_y$. The yield stress, S_y, and the ultimate stress, S_u, for these irradiated materials is obtained from the test data.

Having determined the values of S_m, S_y, and S_u, the allowable stress limits described in Section 4.3.1 can be defined and used for normal/upset conditions. For faulted conditions, the stress allowable for primary membrane and bending of irradiated bolt material is taken to be $0.9 \cdot S_y$. This is consistent with the practice for evaluating fuel rod cladding integrity discussed in Section 4.1.3."

Acceptance Criteria for Irradiated Bolts:

Replacement with the Following:

(a,b,c)

(a,b,c)

<u>Allowable Stress Limits for Normal and Upset Conditions</u>

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]), $P_m + Q_m$

$P_m + Q_m$ =Lesser of 0.9 S_y 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]), $P_m+Q_m+P_b+Q_b$

$P_m+Q_m+P_b+Q_b$ = Lesser of $1.2 \cdot S_y$ 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.

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. 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.

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 would be used by the plants with lower loaded bolts, and either Option 2 or Option 3 would be used by the plants with higher loaded bolts.

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

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

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

$$S_{max} = \text{Less than } 0.9\ S_u$$

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

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

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 short and medium length bolts (i.e., 2.12 inches or less), and a strain limit of [ ]$^{(a,b,c)}$ applies to long bolts of 3.5 inch length.

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 short and medium length bolts (i.e., 2.12 inches or less), and a strain limit of [ ](a,b,c) applies to long bolts of 3.5 inch length.

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 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.

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.

(a,b,c)

(a,b,c)

(a,b,c)

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 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 and a strain limit of [ ]$^{(a,b,c)}$ is defined for long bolts. 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.

4 REFERENCES

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2. Westinghouse Topical Report, WCAP-9401-P-A, Rev. 0, "Verification Testing and Analysis of the 17 x 17 Optimized Fuel Assembly," August 1981. (Westinghouse Proprietary)
3. ASME Boiler and Pressure Vessel Code, 1989 Edition, Section III, Division 1.
4. ASME Boiler and Pressure Vessel Code, 2013 Edition, Section III, Division 1.
5. ASME Code Case N-60-4, "Material for Core Support Structures", Section III, Division 1, May 13, 1991.
6. ASME Code Case N-60-5, "Material for Core Support Structures," Section III, Division 1, February 15, 1994.
7. ASME Code Case N-60-6, "Material for Core Support Structures", Section III, Division 1, December 6, 2011.
8. [

   ](a,b,c)
9. [

   ](a,b,c)
10. [

    ](a,b,c)
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12. ASTM Document, E21-92, "Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials," 1992.
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14. Nuclear Regulatory Commission Document, NUREG-0800, Rev. 2, "Standard Review Plan – 4.2 Fuel System Design," July 1981.

15. Westinghouse Topical Report, WCAP-14449-P-A, Rev. 1, "Application of Best Estimate Large Break LOCA Methodology to Westinghouse PWRs with Upper Plenum Injection," October 1999. (Westinghouse Proprietary)