FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10247P-A, SUPPLEMENT 2P, REVISION 0,

"REALISTIC THERMAL-MECHANICAL FUEL ROD METHODOLOGY FOR BOILING WATER REACTORS SUPPLEMENT 2: MECHANICAL METHODS"

PROJECT NO. 728/DOCKET NO. 99902014

1.0 INTRODUCTION

By letter dated April 29, 2016, Framatome Inc. (Framatome, formerly AREVA Inc.) submitted Topical Report (TR) BAW-10247P-A, Supplement 2P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors Supplement 2: Mechanical Methods," (Supplement 2P) for U.S. Nuclear Regulatory Commission (NRC) review and approval (Reference 6). The intent of this supplement is to replace the following legacy TRs:

- EMF-85-74(P), Revision 0, Supplement 1(P)(A) and Supplement 2(P)(A), "RODEX2A (BWR) Fuel Rod Thermal-Mechanical Evaluation Model" (Reference 3) (clarification of exposure limit)

- XN-NF-32(P)(A), Supplements 1, 2, 3, & 4, "Computational Procedure for Evaluating Fuel Rod Bowing" (Reference 5)

Approval of this supplement allows Framatome to remove these legacy TRs when RODEX4 methods, described in BAW-10247P-A, Revision 0, are used for licensing in applications with Framatome boiling water reactor (BWR) fuel designs (Reference 1). Framatome further explains that "the [Supplement 2P] methodology includes peripheral mechanical methods which do not use any thermal-mechanical code such as RODEX4." That is, the mechanical methods described in Supplement 2P have no connection to the thermal-mechanical models previously approved in the base TR as implemented via the RODEX4 fuel performance code. As explained by Framatome, Supplement 2P is meant to provide "a well-defined licensing basis for BWR nuclear plants which have moved to AREVA's realistic fuel rod methodology."

Framatome also notes that "this supplement does not introduce any changes to AREVA's existing BWR methodology other than updates to correlations derived from operating experience data."

By letter dated February 23, 2018 (Reference 8), Framatome provided additional information, with appropriate TR updates (Reference 9), to provide the following:

- Clarification regarding the use of the mechanical models for re-crystallized annealed (RXA) Zircaloy-2 (Zry-2) cladding.

- A description of the material properties of Z4B™ and the mechanical analysis performed for the Z4B™ internal water channel assembly, and

Enclosure

- Additional Z4B™ water channel growth data to support extension of the fuel assembly growth correlation to a burnup of **[ ]**.

Consequently, the NRC staff's review, discussed in detail in Section 3.0 below, is focused on ensuring the acceptability of:

- Updated correlations based on updated databases,

- The applicability of updated correlations to Framatome BWR fuel designs,

- The material properties of Z4B™ and mechanical analysis performed for the Z4B™ internal water channel assembly, and

- Updated mechanical methods compatibility with downstream safety analyses.

2.0 <u>REGULATORY EVALUATION</u>

The fuel system consists of arrays of fuel rods, including fuel pellets and tubular cladding, spacer grids, end plates, and reactivity control rods. The objectives of the fuel system safety review are to provide assurance that (1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), (2) fuel system damage is never so severe as to prevent control rod insertion when it is required, (3) the number of fuel rod failures is not underestimated for postulated accidents, and (4) coolability is always maintained. The NRC staff acceptance criteria are based on the NUREG-0800, Standard Review Plan (SRP), Section 4.2, "Fuel System Design." These criteria include three parts: (1) design bases that describe specified acceptable fuel design limits (SAFDLs) as depicted in General Design Criterion (GDC) 10 to Appendix A of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, (2) design evaluation that demonstrates that the design bases are met, and (3) testing, inspection, and surveillance plans that show that there are adequate monitoring and surveillance of irradiated fuel. The design bases include fuel system damage, fuel rod failure, and fuel coolability.

Framatome states that "the mechanical methods covered in this supplement will be limited to those that establish the design bases for the acceptance criteria as provided in SRP Section 4.2, II.1.A, ''Fuel System Damage.''"

Furthermore, Supplement 2P, Section 1.0, "Introduction," states that the "[Supplement 2P] methods are consistent with the underlying methods supporting the design criteria approved for generic application in Reference 3." Reference 3 of Supplement 2P is ANF-89-98(P)(A) Revision 1 and Supplement 1, "Generic Mechanical Design Criteria for BWR Fuel Designs" (Reference 2), which describes BWR thermal-mechanical, thermal-hydraulic, accident analysis, and nuclear licensing criteria. The purpose of the Framatome BWR licensing criteria or limits is to provide limiting values that prevent fuel damage or failure with respect to each damage mechanism. These previously approved licensing criteria or limits, along with certain definitions for fuel failure, constitute the SAFDLs required by GDC 10.

3.0 TECHNICAL EVALUATION

Since only correlations supporting the fuel rod bow, fuel rod axial growth, and fuel assembly axial growth methods have changed from the previously approved methodologies, these specific correlations were the focus of the NRC staff's review. Z4B™ material properties and the Z4B™ internal water channel mechanical analysis are also reviewed to confirm consistency with previously approved mechanical design criteria for Framatome BWR fuel designs as documented in Reference 2.

BWR Fuel Rod Bow Correlation

The applicable BWR thermal-hydraulic design criterion that is relevant to Supplement 2P is thermal margin performance (Reference 2), which is affected by fuel rod bowing.

The updated rod bow correlation provided in Supplement 2P, Appendix A, represents a deviation from the previously approved rod bow gap closure model documented in XN-75-32(P)(A), Supplement 1, Section 3.0, "Rod Bow Measurements." The updated correlation is now based on post-irradiation examination (PIE) measurements of rod-to-rod spacing from both legacy fuel designs (e.g., 7x7, 8x8, and 9x9) as well as the ATRIUM 10 fuel design, whereas the previous model **[ ]**[1]. This is acceptable as there is **[ ]** based on the data presented in Figure A-1.

The statistical methodology for determining the **[ ]** is mostly consistent with what was previously approved in XN-75-32(P)(A), Supplement 1, Section 3.0. That is, gap closure measurements are first taken for each grid-to-grid span. Then, **[ ]**. As was previously approved, the correlation is based on **[ ]**, which is conservative. Request for additional information (RAI) Question #2 (RAI 2, Reference 7) discussed concerns with rod growth data dependence based on the observation of distinct clusters in the data presented in Figure A-1 of Supplement 2P. However, Framatome clarified that the data shown in Figure A-1 is not representative of the data used to generate the correlation, which again, is based on **[ ]**. Therefore, data dependence is not an issue.

Differences in the new correlation compared to the old correlation include: (1) Fitting the data **[ ]** and (2) removal of the "1.5 multiplier to account for batch-batch variations." The NRC staff notes that the fuel rod data fit change reflects the preferable functional form at the time of XN-NF-32(P)(A), Supplements 1-4, approval. Removal of the 1.5 multiplier is also acceptable as batch-batch variability is already accounted for by basing the new methodology for correlation development on measurement data from several different BWR fuel designs with data from different reactors for a given fuel design.

The NRC staff documented the issues with the **[ ]** in RAI 2. However, based on the response to RAI 3 highlighting the conservatism of the fuel rod bow penalty, it is apparent that

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[1] The spacing measurements are translated into relative gap closure in percent.

substantial conservatism exists in downstream safety analyses to offset any potential issues identified in developing the fuel rod bow correlation **[ ]**.

Framatome states that "when fuel rod-to-rod gap measurements are not taken, fuel rods are typically visually inspected for any signs of abnormal bow behavior." Framatome discusses how ATRIUM 11 lead test assemblies (LTAs) have shown to be "well-represented by the database as shown in recent examinations" for various assembly-average burnups ranging from **[ ]**. Visual inspections over a sufficient range of assembly-average burnups are acceptable to confirm that abnormal bow behavior is not occurring in LTAs; however, measurement data should be added to the database, and evaluated based on the specified surveillance frequency as discussed in the RAI 10c response to determine whether or not the **[ ]** needs to be updated.

Based on its review above, the NRC staff has reasonable assurance that the updated rod-to-rod gap closure correlation will provide an appropriate estimation of fuel rod-to-rod gap closure to be used as an input to minimum critical power ratio evaluations for all current and future Framatome BWR fuel designs up to an **[ ]** provided that the change process[2] described in Supplement 2P, Section 5.0, "Change Process," is followed.

Axial Irradiation Growth Correlations

The applicable BWR thermal-mechanical design criterion that is relevant to Supplement 2P relates to axial irradiation growth (Reference 2)[3]. The previously approved BWR fuel design licensing criteria requires that the fuel rods and other assembly components maintain clearances and engagements in the fuel assembly structure throughout the lifetime of the fuel up to currently approved burnup levels. As stated by Framatome, "the loss of clearance between the fuel rod and the upper tie plate has the potential to affect safety margins since interference may cause additional rod bow and lead to fuel failures."

During its review, the NRC staff noted that the analysis previously performed in EMF-85-74(P)(A), Supplement 2, Revision 0, evaluating the loss of lower tie plate (LTP) seal spring engagement with the channel was based on an upper limit of fuel assembly growth, which was not included as part of Supplement 2P. The NRC staff issued RAI 9 requesting an explanation for why the upper limit fuel assembly growth curve was not provided in Supplement 2P. The safety concern was with respect to the loss of engagement of the LTP seal spring, which limits the bypass coolant leakage rate between the LTP and fuel channel, potentially affecting thermal-hydraulic performance. The response to RAI 9 clarifies that loss of LTP seal spring engagement with the channel is still considered during design; however, it has been shown that additional leakage from losing seal spring engagement at end-of-life (EOL) is not enough to affect safety margins (Reference 4).

[2] Additional clarification regarding the change process is provided in the responses to RAI 10.

[3] Supplement 2P describes both fuel rod and assembly internal water channel growth.

Framatome also clarifies in Reference 13 that:

> Per ANF-89-98(P)(A) Revision 1, external interfaces, including channel spacer/springs, are evaluated for all new fuel designs and for compatibility with co-resident fuel assemblies. When verifying channel spacer/spring engagement, the EOL upper tolerance value is derived from the nominal fuel assembly growth correlation presented in [Supplement 2P] Table C-1 by adding the tolerance value, T. This methodology confirms engagement between adjacent fuel assemblies considering [beginning-of-life] and EOL axial growth conditions.

Consequently, the NRC staff finds it acceptable to use and maintain the upper limit fuel assembly growth curve to support external water channel spacer/spring engagement determination (i.e., by ensuring that the distance to loss of engagement is greater than or equal to T)[4], as part of the revised mechanical methods in Supplement 2P.

Regarding the remaining axial irradiation growth models, Framatome explains:

> To evaluate the minimum EOL clearance between the fuel rod and tie plates it is necessary to determine correlations for the fuel rod growth and the fuel assembly growth derived from post-irradiation length measurements. The initial nominal clearance between the fuel rod and upper tie plate can then be reduced by an accounting of fabrication tolerances and uncertainty in the growth correlations. This determines the design margin for growth.

Hence, the two correlations that have been developed to calculate the minimum EOL clearance between fuel rods and tie plates is a **[ ]** for fuel rod growth and a **[ ]** for fuel assembly growth. This is appropriate because the maximum fuel rod growth is subtracted from the minimum fuel assembly growth, thus ensuring that a clearance is maintained between the fuel rods and the assembly upper tie plate (UTP) at EOL.[5]

BWR Fuel Rod Growth Correlation

The original stress relief annealed (SRA) Zry-2 fuel rod growth correlation was based on data available up to 1998. The correlation has been updated in Supplement 2P and is now based on a more comprehensive database including PIE data since 1998. Comparing the pre-1998 data with the post-1998 data, the post-1998 data is within the scatter of the pre-1998 data.

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[4] This is equivalent to ensuring that the distance to loss of engagement is greater than or equal to the difference between the **[ ]** for the fuel assembly growth curve (or internal water channel growth curve) and the nominal fuel assembly growth curve.

[5] Note that the **[ ]** However, the Supplement 2P update to the fuel assembly growth correlation does not apply to ATRIUM type fuel assemblies where assembly growth is controlled by tie-rods.

Data includes fuel rods from 7x7, 8x8, 9x9, and 10x10 arrays. Framatome notes that **[**

]. Framatome explains that "these **[** **]**." Framatome further states that "this **[**

]." Although the Supplement 2P data appears to be predictable based on burnup alone, growth of SRA Zry-2 depends on factors such as the amount of cold work (i.e., manufacturing process) and the presence of hydrogen or hydrides due to corrosion. Consequently, RAI 10a was issued to understand why the Supplement 2P correlation will be adequate to bound future fuel rod designs that may have different manufacturing processes, plant water chemistry, etc. The RAI 10a response clarifies that the fuel rod growth correlations are adequate to bound future fuel rod designs that are within the range of parameters defined by the existing database supporting the fuel rod growth correlations. Framatome states that any significant deviations in manufacturing processes, plant water chemistry, fuel designs, or the addition of new materials will require out of pile testing and lead test programs to acquire the necessary data to support evaluation methods. These types of changes would need to be submitted to the NRC for review and approval. Any performance drift caused by the accumulation of small changes in design or operation will be captured by Framatome's ongoing surveillance program by the continual collection of PIE data for assessment of growth correlation validity.

A **[** **]** model is used to estimate the best fit of the data; based on the observed fit in Figures B-1 and B-2, this functional form is appropriate and is consistent with the previously approved model in EMF-85-74(P)(A), Supplement 2, Revision 0 (Reference 3). The Siemens Power Corporation 7x7, 8x8, and 9x9 data is still used and is justified since **[**

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The new **[** **]** was initially found to be inappropriate based on the issues identified in RAI 2.[6] The main issue not clearly addressed in the RAI 2 response was why the current correlation remains valid in light of the strong data dependence. Framatome explains that there is conservatism in the correlation based on **[** **]**; however, the NRC staff does not agree that this treatment is completely conservative given that **[** **]**, which would be non-conservative. Additionally, this does not address the data dependence concern, which if unaccounted for could manifest as an under prediction of the proposed **[** **]** due to underestimation of the uncertainty about the regression fit.

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[6] The data also appears to be **[** **]**, which can also invalidate uncertainty estimates. The NRC staff thought this was possibly due to biased sampling. That is, undersampling lower burnup assemblies as evidenced by the number of points per assembly in Figure B-1 at higher burnup compared to lower burnup. This undersampling was also confirmed in the Appendix (see "Average samples per burnup bin"), but the NRC staff found that Framatome's proposed **[** **]** remained valid nonetheless.

To address the above concerns, the NRC staff performed a confirmatory analysis[7] using only the median value of the assembly-wise rod growth data to remove dependency amongst measurements from the same assembly at a given burnup, and to remove the non-conservative bias from assigning a higher burnup to lower burnup rods for a given fuel assembly.[8]

Based on the response to RAI 2, regarding development of a **[ ]** versus a **[ ]**, and the NRC confirmatory analysis using the rod growth data supplied in the response to RAI 2f, the NRC staff has determined that the **[ ]** used, and subsequent correlation developed, is acceptable to be used for fuel rod to UTP clearance determination.

Regarding the possibility of a non-conservatively biased fuel rod growth database, Framatome explains in the RAI 4a response that:

> Generally, fuel assemblies are not necessarily chosen for the expressed purpose of taking fuel rod growth measurements. Fuel assemblies are generally chosen for a number of reasons. For example, assemblies could be chosen because they are limiting for corrosion after water chemistry changes, or because they are useful to explore the boundary of operating experience (e.g., burnup, time, fluence, etc.) in healthy fuel exams, or just because they are lead assemblies. Therefore, any bias would be conservative, i.e., toward the measurement of assemblies viewed as limiting in some aspect.

The RAI 4a response also states that all fuel rods in a fuel assembly are not always measured. Based on the fuel rod growth data provided in the RAI 2f response, it appears that **[ ]**.

To assess the impact of a potential bias in the proposed correlation, potentially caused by not sampling all fuel rods in a given assembly, the NRC staff performed a series of calculations whereby **[ ]** were generated and then compared for a series of cases where successively more assembly-wise data was removed starting with those data from fuel assemblies **[ ]**. By removing assembly-wise data with fewer measurements, this allows for a measure of **[ ]** sensitivity to potentially biased datasets. If there is a large **[ ]** sensitivity, then this may be indicative of a bias in Framatome's proposed **[ ]**; however, if little or no sensitivity is observed, this would provide reasonable assurance that there is no bias due to taking an insufficient number of samples from the population.

The cases analyzed were with **[ ]**.

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7 See "Using the median value of the assembly-wise data" in the Appendix.

8 Note that there are a few assemblies included in the fuel rod growth dataset that were measured at more than one fuel assembly average burnup – an attempt to treat this dependency was not considered.

There was minor variation in the **[ ]** when comparing these sets, and all were bounded by the **[ ]** proposed by Framatome. The minor variation between **[ ]** is a strong indicator that any bias that may exist is not likely to affect the proposed **[ ]** for rod growth, therefore the NRC staff finds the proposed **[ ]** for rod growth acceptable.

Framatome is also requesting approval of this updated correlation for **[ ]** fuel pellets with an **[ ]** applied to cover the **[ ]**. Framatome provides a mechanism for the **[ ]**." However, without data similar to that in Figure B-2 of Supplement 2P for **[ ]**, this claim can't be quantitatively validated. In the response to RAI 6, Framatome explains that **[ ]**.

Based on its review above, the NRC staff has reasonable assurance that the updated fuel rod growth correlation will provide an appropriate estimation of fuel rod growth to be used in determining a clearance between the fuel rod and UTP for all current and future Framatome BWR fuel designs that use Zry-2 cladding material up to an **[ ]** provided that the change process[9] described in Supplement 2P, Section 5.0, "Change Process," is followed.

BWR Fuel Assembly Growth Correlations

An updated assembly growth correlation is proposed:

> ...to be applied for the evaluation of AREVA BWR fuel assemblies where the axial growth is controlled by a central water channel made from a zirconium alloy. The new correlation is based on ATRIUM type fuel assembly growth data only, and excludes designs with load bearing tie rods as well as the European bundle in basket designs. The database includes water channels made from both Zircaloy-4 (Zry-4) and Z4B™ materials.

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[9] Additional clarification regarding the change process is provided in the responses to RAI 10.

The measurement database only contains growth data from ATRIUM 10 and ATRIUM 11 internal water channels, therefore it is directly applicable to the intended application. Framatome states that they have not observed a **[** **]**.

A **[** **]** model is used to estimate the best fit of the data; based on the observed fit in Figure C-1 of Supplement 2P, this functional form appears to be appropriate; however, it differs from the functional form of the previously approved model in Reference A.2 of EMF-85-74(P)(A), Supplement 2, Revision 0, which used a **[** **]** (Reference 3). The updated model only contains data from ATRIUM-10 and ATRIUM-11 fuel designs and no longer contains any data based on older SPC fuel channel designs, therefore the influence of tie rod fuel designs has been removed. The updated model is also more conservative compared to the previous model as seen by the **[** **]**, which is **[** **]**.

Additionally, the new **[** **]** was initially found to be inappropriate based on the issues identified in RAI 2. However, based on the response to RAI 2, regarding development of a **[** **]**[10] versus a **[** **]**, and a NRC staff confirmatory analysis, the NRC staff determined that the tolerance factor used and subsequent correlations developed are acceptable.

Based on its review above, the NRC staff has reasonable assurance that the updated fuel assembly growth correlations will provide for an appropriate estimation of fuel assembly growth to be used in determining: (1) external water channel spacer/spring engagement, and (2) clearances between fuel rods and UTPs for all ATRIUM type fuel designs up to ATRIUM 11 with Zry-4 or Z4B™ internal water channels up to an **[** **]** MWd/kgU provided that the change process[11] described in Supplement 2P, Section 5.0, "Change Process," is followed.

Z4B™ Material Properties

Framatome states that "a proprietary zirconium alloy has been developed, Z4B™, which optimizes the alloying element concentrations for improved corrosion and hydrogen pickup when used for a BWR fuel structural component." Framatome further states that: (1) Z4B™ is similar to Zircaloy-4 (Zry-4) except that Z4B™ has a slightly higher iron and chromium content, and (2) "the small differences in composition between Z4B™ and Zry-4 do not result in any significant differences in fabrication methods or processes."

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[10] **[** **]**. The NRC staff confirmatory analysis in the Appendix, based on the assembly growth data supplied in RAI Response 2f, also provides additional confidence in the validity of the proposed correlation.

[11] Additional clarification regarding the change process is provided in the responses to RAI 10.

Operating experience in the open literature (Reference 10) supports Framatome's claim that increasing the iron and chromium content of niobium-free alloys such as Zry-4 by the amount specified in Supplement 2P, Appendix D, "Z4B™ Water Channel Assembly," has a corrosion rate reducing effect. Framatome also states that the improved corrosion and hydrogen uptake performance of Z4B™ relative to Zry-4 has been demonstrated through the Z4B™ spacer grid material test program and recent Z4B™ lead use fuel channel measurements (Reference 11). Based on past operating experience, as supported by the open literature, which shows improved corrosion and hydrogen pickup performance, the NRC staff finds the use of the Z4B™ acceptable for use as the internal water channel assembly material for Framatome BWR fuel assembly designs.

Z4B™ Internal Water Channel Assembly Mechanical Analysis

Supplement 2P, Appendix D, summarizes the relevant BWR design criteria applicable to the internal water channel assembly tie structure. The previously approved criteria in Reference 2 apply to:

- Stress, strain, or loading limits,
- Axial irradiation growth, and
- Fuel assembly handling.

The NRC staff confirmed that the criteria remain unchanged to those previously approved and therefore remain acceptable. Axial irradiation growth, or fuel assembly growth in this case, was discussed in detail in "Axial Irradiation Growth Correlations" above.

Framatome explains that due to the similarity of Zry-4 and Z4B™, differences in material properties such as elastic modulus, heat capacity, thermal expansion, thermal conductivity, density, etc., are negligible, therefore additional considerations with respect to these parameters are not taken into account. The NRC staff finds this explanation acceptable because the relatively small magnitude of the differences in material composition between Zry-4 and Z4B™ as provided in Supplement 2P, Appendix D, Table D-1, "Alloy Composition," are not expected to impact any of the relevant SRP acceptance criteria related to fuel system damage.

Framatome also explains that the minimum mechanical property requirements for Z4B™ as provided in Supplement 2P, Appendix D, Table D-4, "Unirradiated Strength Specifications for Zry-4 and Z4B™," are the same as or higher than those for Zry-4. Additionally, since it has been demonstrated that irradiated Z4B™ has higher corrosion resistance and lower hydrogen uptake relative to Zry-4, Framatome expects any strength reduction due to these factors to be bounded by what has been seen operationally with Zry-4 components. Consequently, the NRC staff confirms that Z4B™ unirradiated and irradiated strength specifications do not introduce any adverse change to the current analytical methods used to satisfy the mechanical design criteria approved in Reference 2.

Regarding material strain, Framatome compares unirradiated Zry-2, Zry-4, and Z4B™ strain test data and shows that **[**

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Framatome implies that Zry-2 and Zry-4 strain test data would bound Z4B™ strain test data under irradiated conditions because the qualified fuel channel bulge analysis model described in

Reference 12 was found to be acceptable for irradiated external fuel assembly channels made of Zry-2 and Zry-4. Consequently, Framatome assumes the creep rate already defined for Zry-2 and Zry-4 channel material in Reference 12 will be representative of Z4B™. In consideration of the unirradiated Zry-2, Zry-4, and Z4B™ strain test data indicating comparable creep resistance, and the qualified fuel channel bulge analysis model described in Reference 12, the NRC staff finds that using the Zry-2 and Zry-4 channel material creep rate defined in Reference 12 for Z4B™ channel material is appropriate and therefore acceptable to demonstrate that the Z4B™ internal water channel assembly will meet the applicable design criteria in Reference 2.

In summary, Framatome evaluated the Z4B™ internal water channel mechanical design in Appendix D to Supplement 2P with respect to the generic BWR fuel design criteria applicable to the internal water channel tie structure during handling, normal operation, and anticipated operational occurrences (AOOs) as identified in Reference 2. All mechanical design analytical methods are described in Supplement 2P, Section 4, “Analytical Methodology.” Supplement 2P, Section 4.1.1, “Stress, strain or loading limits,” describes the general strength evaluations, including those performed for the internal water channel assembly to demonstrate that the stress, strain, and loading limit criteria (e.g., fuel handling) defined in Supplement 2P, Appendix D, Table D-3, “Generic BWR Design Criteria Applicable to the Tie Structure During Handling, Normal Operation, and AOO,” are met. The results of the internal water channel mechanical design evaluations demonstrate that previously calculated design margins are maintained, therefore the internal water channel mechanical design evaluations are acceptable.

4.0 LIMITATIONS AND CONDITIONS

1. Approval of the updated correlations is limited to Framatome BWR fuel designs with Zry-2 cladding up to **[ ]**.

2. The updated fuel rod growth correlation only applies to: (1) standard (i.e, non-additive) fuel and (2) **[ ]** fuel when **[ ]**.

3. The updated fuel assembly growth correlation only applies to fuel designs with Zry-4 or Z4B™ internal water channels and does not apply to load bearing tie rod designs or the European bundle in basket design.

4. The RAI 10a response clarifies that the fuel rod growth correlations are adequate to bound future fuel rod designs that are within the range of parameters defined by the existing database supporting the fuel rod growth correlations. Any significant deviations in manufacturing processes, plant water chemistry, fuel designs, or the addition of new materials will require out of pile testing and lead test programs to acquire the necessary data to support evaluation methods, which will require NRC review and approval before use.

5. All post-irradiation data must be added to the measurement database supporting the respective correlation as it is acquired, and it must be evaluated as discussed in the RAI 10c response to determine whether or not limits need to be updated.

6. Using the same method as described in the response to RAI 2, new upper or lower limits supported by database updates must be calculated. If the new limits are outside the

envelope defined by the approved limits plus or minus one standard deviation, a new correlation must be submitted to the NRC for review and approval.

5.0 CONCLUSION

The NRC staff has reviewed the updated realistic thermal-mechanical fuel rod methodology for BWRs as described in Supplement 2 and concludes the following to the extent specified under the limitations and conditions delineated in Section 4.0 of this safety evaluation:

1. The fuel rod bow model is acceptable for Framatome BWR fuel designs with Zry-2 cladding up to **[ ]**,

2. The fuel rod growth model is acceptable for Framatome BWR fuel rod designs with Zry-2 cladding up to **[ ]**, and

3. The fuel assembly growth model is acceptable for fuel assembly designs with internal water channels made from Zry-4 and Z4B™ up to **[ ]**.

6.0 REFERENCES

1. BAW-10247PA, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors," AREVA Inc., April 2008 (Agencywide Documents Access and Management System (ADAMS) Accession Number ML081340220).

2. ANF-89-98(P)(A) Revision 1 and Supplement 1, "Generic Mechanical Design Criteria for BWR Fuel Designs," Advanced Nuclear Fuels Corporation, May 1995 (ADAMS Accession Number ML081350281).

3. EMF-85-74(P) Revision 0, Supplement 1(P)(A) and Supplement 2(P)(A), "RODEX2A (BWR) Fuel Rod Thermal-Mechanical Evaluation Models," Siemens Power Corporation, 1998. (ADAMS Accession Number ML15295A333).

4. Curet, H. D.,"NRC Request for Safety Assessment Related to Failed Seal Springs," Siemens Power Corporation, 1997.

5. XN-75-32(P)(A), Supplements 1, 2, 3, & 4, "Computational Procedure for Evaluating Fuel Rod Bowing," Exxon Nuclear Company Inc., 1983 (ADAMS Accession Number ML081710709).

6. BAW-10247P-A, Supplement 2P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors Supplement 2: Mechanical Methods," AREVA Inc., April 2016 (ADAMS Accession Number ML16125A033).

7. Peters, G., Response to Request for Additional Information Regarding AREVA Inc. Topical Report BAW-10247P-A, Supplement 2P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors Supplement 2: Mechanical Methods," April 2017 (ADAMS Accession No. ML17125A141).

8. Framatome, Inc., Additional Information Regarding BAW-10247P-A, Supplement 2P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology For Boiling Water Reactors Supplement 2: Mechanical Methods," February 2018 (ADAMS Accession Number ML18058A781).

9. Framatome, Inc., BAW-10247NP-A, Suppl. 2Q2NP, Rev. 0, "Realistic Thermal-Mechanical Fuel Rod Methodology For Boiling Water Reactors Supplement 2: Mechanical Methods Additional Information," February 2018 (ADAMS Accession Number ML18058A782).

10. Rudling, P., "Zr Alloy Corrosion and Hydrogen Pickup," A.N.T. International, December 2013 (ADAMS Accession Number ML15253A227).

11. ANP-10336P-A, Rev. 0, Z4B™ Fuel Channel Irradiation Program, AREVA Inc., June 2015 (ADAMS Accession Number ML17298A159).

12. EMF-93-177P-A, Rev. 1 Supplement 1P-A Rev. 0, "Mechanical Design for BWR Fuel Channels Supplement 1: Advanced Methods for New Channel Designs," AREVA Inc., September 2013 (ADAMS Accession Number ML14198A133).

13. Framatome, Inc., Additional Information Regarding BAW-10247P-A, Supplement 2P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology For Boiling Water Reactors Supplement 2: Mechanical Methods," July 2018 (ADAMS Accession Number ML18193A453).

Attachment: Appendix

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Date: August 15, 2018

APPENDIX: BAW-10247P-A, SUPPLEMENT 2P CONFIRMATORY DATA ANALYSIS USING NON-PARAMETRIC REGRESSION TOLERANCE INTERVALS

Non-parametric tolerance intervals require less strict assumptions about the underlying data and are generally more conservative than **[ ]**, therefore they have been used as an appropriate and independent means to confirm the validity of the 3 semi-empirical design limits proposed in BAW-10247P-A, Supplement 2P.

The tolerance package (Version 1.2.0) as part of the R statistical computing language (Reference Version 3.3.1) was used to support the confirmatory analysis.

Rod Bow Data

If the **[ ]** is used in the confirmatory UTL (designated as the upper bound curve of the darker grey area in the plot directly below)[1], as previously suggested to account for **[ ]**, the confirmatory UTL remains in reasonable agreement with Framatome's proposed upper design limit (the red curve in the plot directly below)[2] despite it being somewhat above Framatome's limit for average assembly burnups in the range of approximately **[ ]** GWd/MTU.

Framatome's upper design limit is in reasonable agreement with the UTL determined in the NRC staff's confirmatory analysis, therefore it is acceptable.

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[1] All lower/upper bound curves of darker grey areas in plots in this appendix correspond with the NRC staff's respective confirmatory limits.

[2] All red curves in plots in this appendix correspond with Framatome's respective design limits.

Rod Growth Data

<u>Exploratory analysis</u>

Data distributions and ranges

Comparison of assembly-wise burnup data can be made by creating a histogram of the rod growth measurements. The variation between assembly-wise data appears to be mostly normal; the quantiles of the data were also inspected to get a feel for the range of expected rod growth data for a specified burnup range. A summary table with the average measurement sample size is also provided at the end of this section to aid in understanding potential undersampling concerns as discussed in Footnote 5 of the SE.

There are some questionable groups of growth measurements, like those from Assembly 32B082 (see plot below with data from assembly burnups between **[ ]**, which is clearly separated from the rest of the data in the respective group. Assembly 32B082 contains **[ ]** from what appears to be a 10x10 fuel assembly. **[ ]**. In this case, the data would not be expected to have a bias introduced from assembly undersampling, **[ ]** is questionable. However, because this is the only assembly-wise data set that appears to be questionable from a non-conservative standpoint, and since it is still within the range of the rest of data, there is no general concern.

Average sample size

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[
]
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Quantiles

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[
]
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[ ]

Average sample size

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[
]
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Quantiles

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[
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[ ]

Average sample size

[ ]

Quantiles

[ ]

[

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Average sample size

[
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Quantiles

[
]

[ ]

Average sample size

[ ]

Quantiles

[ ]

Average samples per burnup bin

[ ]

Assembly-wise data sample sizes

From the RAI 4a response, Framatome states that all fuel rods in a fuel assembly are not always measured. This could lead to a biased formulation of the **[ ]** if data sampling isn't close to random and/or if there are too few sampled data per assembly. The plot directly below shows the fuel rod growth data with the number of measured fuel rods per assembly indicated with red text directly above the corresponding assembly-wise data to provide additional information where data is densely packed.

[ ]

Based on the fuel rod growth data provided in the RAI 2f response, as plotted directly above, it appears that for approximately half of the data, **[ ].**[1]

[1] Since fuel assembly design types were not indicated in the dataset, the fraction of fuel rods sampled was estimated by assuming each assembly had the average number of fuel rods across the various assembly design types in the dataset.

Below a histogram of rod sampling fraction is shown along with sample quantiles and the data range in terms of number of rods sampled. This data supports the observations in the preceding paragraph.

[ ]

Quantiles

[ ]

Data range

[ ]

<u>Using the median value of the assembly-wise data</u>

Using the median value from the fuel-rod-wise data for a given fuel assembly will most likely produce the most reliable **[ ]**[2]. This is because Framatome has **[ ]** as discussed in the RAI 2 response. This means that fuel rods **[ ]**. Removing both the **[ ]** allows for an unbiased **[ ]** assessment. Additionally, using only a single

[2] This is not necessarily the most desirable **[ ]** because it removes the influence of the higher growth data. However, the influence of the lower growth data is also removed.

assembly-wise data point has the effect of reducing the effective sample size for the **[ ]** computation, increasing the tolerance factor, and adding conservatism.

Framatome's upper design limit was confirmed to be more conservative than the **[ ]** determined in the NRC staff's confirmatory analysis, therefore it is appropriate.

[ ]

<u>Bias assessment</u>

To assess the impact of a potential bias in the proposed correlation, potentially caused by not sampling all fuel rods in a given assembly, the NRC staff performed a series of calculations whereby **[ ]** were generated and then compared for a series of cases where successively more assembly-wise data was removed **[ ]**. By removing assembly-wise data with fewer measurements, this allows for a measure of **[ ]** sensitivity to potentially biased datasets. If there is a large **[ ]** sensitivity, then this may be indicative of a bias in Framatome's proposed **[ ]**. However, if little or no sensitivity is observed, this would provide reasonable assurance that there is no bias due to undersampling.

The cases analyzed were **[ ]**.

There was minor variation in the **[ ]** when comparing these sets, and all were bounded by the **[ ]** proposed by Framatome. The minor variation between **[ ]** is a strong indicator that any bias that may exist is not likely to affect the proposed **[ ]** for rod growth, therefore the NRC staff finds the proposed **[ ]** for rod growth acceptable.

[ ]

Fuel Assembly Growth Data

The response to RAI 4b, regarding fuel assembly growth data collection, states the same basis for data sampling as that in RAI 4a. The NRC staff doesn't have a concern regarding a potential bias in the fuel assembly growth data **[** **]**. Furthermore, the fuel assembly growth correlation is supported by data from applicable fuel assemblies operating in the burnup range of interest.

Framatome's fuel assembly growth design limit is in close agreement with the **[** **]** determined by the NRC staff, therefore the fuel assembly growth design limit is acceptable.