ENCLOSURE 4:

Marked-up Copy – BAW-10227P, Revision 2, Draft Safety Evaluation – NONPROPRIETARY

UNITED STATES
NUCLEAR REGULATORY COMMISSION
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DRAFT SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10227P, REVISION 2

"EVALUATION OF ADVANCED CLADDING AND STRUCTURAL MATERIAL (M5)

IN PWR REACTOR FUEL"

FRAMATOME INC.

PROJECT NO. 710; DOCKET NO. 99902041

(EPID: L-2019-TOP-0054)

1.0 INTRODUCTION

By letter dated December 31, 2019 (Ref. [1]), Framatome Inc. submitted Topical Report (TR) BAW-10227, Revision (Rev.) 2, "Evaluation of Advanced Cladding and Structural Material (M5) in [Pressurized Water Reactor] PWR Reactor Fuel" (Ref. [2]), for U.S. Nuclear Regulatory Commission (NRC) review and approval. With this TR, Framatome requests an update of M5 material properties as well as an **[**

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2.0 REGULATORY EVALUATION

Regulatory guidance for the review of fuel system materials and designs and adherence to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Appendix A, General Design Criteria (GDC)--10, "Reactor Design," GDC-27, "Combined Reactivity Control Systems Capability," GDC-28, "Reactivity Limits," and GDC-35, "Emergency Core Cooling," is provided in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants" (SRP), Section 4.2, "Fuel System Design" (Ref. [3]). In accordance with SRP Section 4.2, the objectives of the fuel system safety review are to provide reasonable 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. A "not damaged" fuel system is defined as fuel rods that do not fail, fuel system dimensions that remain within operational tolerances, and functional capabilities that are not reduced below those assumed in the safety analysis. Objective 1, above all, is consistent with GDC-10, and the design limits that accomplish this are called specified acceptable fuel design limits. "Fuel rod failure" means that the fuel rod leaks, and that the first fission product barrier (the cladding) has therefore, been breached. However, the NRC staff recognizes that it is not possible to avoid all fuel rod failures during normal operation, and reactor coolant cleanup systems are installed to deal with a small number of leaking rods.

Fuel rod failures must be accounted for in the dose analysis required by 10 CFR Part 100, "Reactor Site Criteria," and 10 CFR 50.67, "Accident source term," for postulated accidents. "Coolable geometry" means, in general, that the fuel assembly retains its rod bundle geometrical configuration with adequate coolant channels to permit removal of residual heat following a design-basis accident. The general requirements to maintain control rod insertability and core coolability appear repeatedly in the GDC, but are most explicit in GDC-27, GDC-28, and GDC-35. Specific coolability requirements for the loss-of-coolant accident (LOCA) are given in 10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors."

In order to ensure that the above stated objectives are met and follow the format of Section 4.2 of the SRP, Sections 3.2, "Mechanical Properties," 3.3, "Oxidation and Hydrogen Pickup During Normal Operation," and 3.4, "Component Performance," of this safety evaluation (SE) covers the following three major categories: (1) fuel system damage mechanisms, which are most applicable to normal operation and AOOs; (2) fuel rod failure mechanisms, which apply to normal operation, AOOs, and postulated accidents; and (3) fuel coolability, which are applied to postulated accidents. Specific fuel damage or failure mechanisms are identified under each of these categories in Section 4.2 of the SRP.

3.0 TECHNICAL EVALUATION

Framatome is requesting an [ ], as well as some new models that will be used to analyze the cladding. Some of these models have also been approved up to the requested burnup limit by the NRC staff as part of the GALILEO fuel performance code review (Refs. [4] and [5]). Where these models are the same, this SE will not make a finding but instead note the prior approval and defer to the SE for GALILEO. Additionally, some proposed models are the same as previously approved for M5 up to the existing burnup limit (62 GWD/MTU rod average), in Rev. 1 of BAW-10227(P)(A) (Ref. [6]). These are similarly noted in the following sections.

3.1 MATERIAL PROPERTIES

3.1.1 Melting Point

The M5 melting point has been previously approved in the GALILEO TR SE (Refs. [4] and [5]), is unchanged in this proposed TR, and is therefore acceptable.

3.1.2 Density

The M5 density has previously been approved in the GALILEO TR SE (Refs. [4] and [5]), is unchanged in this proposed TR, and is therefore acceptable.

3.1.3 Specific Heat Capacity

The M5 Specific Heat Capacity model has previously been approved for M5 to 62 GWD/MTU (Ref. [6]). As specific heat capacity is a structure insensitive property, which indicates insensitivity to burnup, the NRC staff finds that the Specific Heat Capacity model's use for [ ] in this proposed TR, to be acceptable.

3.1.4 Coefficient of Thermal Expansion

The M5 thermal expansion coefficient model has previously been approved for M5 to 62 GWD/MTU (Ref. [6]). As Young's modulus is a structure insensitive property, which indicates insensitivity to burnup, the NRC staff finds the thermal expansion coefficient model's use [ ] in this proposed TR, to be acceptable.

3.1.5 Thermal Conductivity

The M5 thermal conductivity has previously been approved in the GALILEO TR SE (Refs. [4] and [5]), is unchanged in this proposed TR, and is therefore acceptable.

3.1.6 Young's Modulus

The M5 Young's modulus model has previously been approved for M5 to 62 GWD/MTU (Ref. [6]). As Young's modulus is a structure insensitive property, which indicates insensitivity to burnup, the NRC staff finds the Young's modulus model's use [ ], in this proposed TR, to be acceptable.

3.1.7 Poisson's Ratio

The M5 Poisson's ratio has previously been approved for M5 to 62 GWD/MTU (Ref. [6]). As Poisson's ratio is a structure insensitive property, which indicates insensitivity to burnup, the NRC staff finds the Poisson's model's use [ ], in this proposed TR, to be acceptable.

3.1.8 Emissivity

The M5 emissivity model has previously been approved for M5 to 62 GWD/MTU (Ref. [6]). As specific heat capacity is a structure insensitive property, which indicates insensitivity to burnup, the NRC staff finds the emissivity model's use [ ], in this proposed TR, to be acceptable.

3.1.9 Meyer's Hardness

Section 7.9, "Meyer's Hardness," of BAW-10227P, Rev. 2, describes Framatome's treatment of Meyer's Hardness. Meyer's Hardness influence thermal resistance across the fuel cladding gap once this gap has closed. Framatome [ ]. Meyer's Hardness increases with burnup but saturates [ ].

This model has previously been approved in BAW-10227P, Rev. 1 (Ref. [6]). The NRC staff finds this model to be acceptable, as it has previously been approved and is not expected to change in the [ ] requested.

3.2 MECHANICAL PROPERTIES

This section describes Framatome's treatment of M5 yield strength, ultimate tensile strength, and elongation. These properties [ ].

Yield and tensile strengths are used to calculate fuel rod stress limits, described in Section 10.1, "Fuel Rod Stress Limits," of BAW-10227P, Rev. 2, and addressed in Section 3.5.1, "Irradiation Induced Free Growth and Creep," of this SE.

3.2.1 <u>Unirradiated Yield Strength</u>

Sections 8.1.1.1, "Yield Strength," and 8.1.2.1, "Yield Strength," of BAW-10227P, Rev. 2, describe Framatome's treatment of M5 cladding unirradiated uniaxial and biaxial yield strength, respectively. The NRC staff examined the design limits, presented in Figures 8-1, "Design Uniaxial Yield Strength of Unirradiated M5$_{\text{Framtome}}$ Material as a Function of Temperature," and 8-3, "Design Biaxial Yield Strength of Unirradiated M5$_{\text{Framtome}}$ Material as a Function of Temperature," of BAW-10227P, Rev. 2, and found them to appropriately represent the presented data.

As the design unirradiated yield strength is shown to adequately represent the data, the NRC staff finds Framatome's unirradiated yield strength models to be acceptable.

3.2.2 <u>Unirradiated Ultimate Tensile Strength</u>

Sections 8.1.1.2, "Tensile Strength," and 8.1.2.2, "Tensile Strength," of BAW-10227P, Rev. 2, describe Framatome's treatment of M5 cladding unirradiated uniaxial and biaxial ultimate tensile strength (UTS), respectively. The NRC staff examined the design limits and best estimate models, presented in Figures 8-2, "Design Uniaxial Tensile Strength of Unirradiated M5$_{\text{Framtome}}$ Material as a Function of Temperature," and 8-4, "Best-Estimate Biaxial Tensile Strength of Unirradiated M5$_{\text{Framtome}}$ Material as a Function of Temperature," of BAW-10227P, Rev. 2, and found them to appropriately represent the presented data.

As the design and best estimate unirradiated ultimate tensile strength models are shown to adequately represent the data, the NRC staff finds Framatome's models for unirradiated UTS to be acceptable.

3.2.3 <u>Irradiated Yield Strength</u>

Sections 8.2.1.1, "Yield Strength," and 8.1.2.1, "Yield Strength," of BAW-10227P, Rev. 2, describe Framatome's treatment of M5 cladding irradiated uniaxial and biaxial yield strength, respectively. The [ ] to the requested burnup limit which confirm that the effect of irradiation on yield strength saturates. The NRC staff examined the best estimate models and design limits, presented in Figures 8-5, "Best-Estimate Uniaxial Yield Strength of Irradiated M5$_{\text{Framtome}}$ Material as a Function of Fast Fluence," and 8-7, "Best-Estimate Uniaxial Yield Strength of Irradiated M5$_{\text{Framtome}}$ Material as a Function of Fast Fluence," of BAW-10227P, Rev. 2, and found them to appropriately represent the presented data.

As the design and best estimate irradiated yield strength models are shown to adequately represent the data, the NRC staff finds Framatome's models for irradiated yield strength to be acceptable.

3.2.4 Irradiated Ultimate Tensile Strength

Sections 8.2.1.2, "Tensile Strength," and 8.2.2.2 of BAW-10227P, Rev. 2, describe Framatome's treatment of M5 cladding irradiated uniaxial and biaxial UTS, respectively. The [ ] to the requested burnup limit which confirm that the effect of irradiation on UTS saturates. The NRC staff examined the best estimate models and design limits, presented in Figures 8-6, "Best-Estimate Uniaxial Tensile Strength of Irradiated $M5_{Framtome}$ Material as a Function of Fast Fluence," and 8-8, "Best-Estimate Biaxial Tensile Strength of Irradiated $M5_{Framtome}$ Cladding as a Function of Fast Fluence," of BAW-10227P, Rev. 2, and found them to appropriately represent the presented data.

As the design and best estimate irradiated UTS models are shown to adequately represent the data, the NRC staff finds Framatome's models for irradiated ultimate tensile strength to be acceptable.

3.2.5 Elongation

Section 8.3, "Elongation," of BAW-10227P, Rev. 2, describes the data collected on total elongation of M5 cladding in the unirradiated and irradiated states. Elongation is not used to establish strain limits but provides an indicator that Framatome understands the fuel behavior and that the 1 percent strain limit is acceptable for use with M5 cladding.

Framatome states that the total elongation remains above [ ] up to a fluence representative of the requested burnup limits.

Because the fluence remains above [ ], and the elongation does not play a role in determining design or safety limits, the NRC staff finds Framatome's treatment of elongation to be acceptable.

3.3 OXIDATION AND HYDROGEN PICKUP DURING NORMAL OPERATION

3.3.1 Corrosion Rate

Section 9.1, "Corrosion Rate," of BAW-10227P, Rev. 2, describes the multi-stage corrosion model used to predict oxidation of M5 components. [ ]. The M5 cladding oxidation model and coefficients were previously reviewed and approved up to [ ] as part of the GALILEO TR (Ref. [4]). Figures 9-4, "Comparison of Measured and Predicted Oxide Thickness for Guide Tubes," and 9-6, "Comparison of Measured and Predicted Oxide Thickness for Page Spacer Grids," of BAW-10227P, Rev. 2, provide predicted versus measured oxide thickness for guide tubes and grid straps, respectively. During an audit (Ref. [7]), Framatome representatives and the NRC staff discussed the empirical database supporting the guide tube and grid strap corrosion models. Based upon the extent of the empirical database and good agreement between predicted and measured oxide thickness, the NRC staff finds the guide tube and grid strap oxidation model and coefficients are acceptable up to the [ ].

3.3.2 <u>Hydrogen Pickup</u>

Section 9.1 of BAW-10227P, Rev. 2, describes the multi-stage hydrogen uptake models for fuel rod cladding, guide tubes, and grid straps. During an audit (Ref. [7]), Framatome described how the hydrogen uptake models were being revised as a result of the GALILEO review. In response to an RAI on this topic (RAI #5, Ref. [8]), Framatome provided further information regarding the revised hydrogen uptake model along with change pages for this TR. The M5 cladding hydrogen uptake model was previously reviewed and approved up to [ ] as part of the GALILEO TR (Ref. [4]). With respect to guide tubes and grid straps, [ ]. Figures 9-5, "Comparison of Measured and Predicted Hydrogen Concentration for Guide Tubes," and 9-7, "Comparison of Measured and Predicted Hydrogen Concentration for Spacer Grids," of BAW-10227P, Rev. 2, provide predicted versus measured hydrogen content for guide tubes and grid straps, respectively. Examination of these figures shows good agreement. Note that based on the extent of the hydrogen uptake empirical database (i.e., oxidation rate of samples measured), the proposed changes to the hydrogen uptake models described in response to RAI #5 do not impact the predictions shown on Figures 9-2, "Measured and Predicted Hydrogen Concentration for $M5_{Framatome}$ Cladding," 9-5, and 9-7. Based on the comparison between the predicted to measured hydrogen data, the NRC staff finds the M5 guide tube and grid strap hydrogen uptake models acceptable.

Section 9.4, "Hydride Morphology in Cladding," of BAW-10227P, Rev. 2, describes the hydride morphology in M5 fuel rod cladding. Optical microscopy of irradiated fuel rods [ ]. During the audit, Framatome and NRC discussed hydride orientation as it relates to the PCMI cladding failure threshold curves in Regulatory Guide (RG) 1.236, "Pressurized Water Reactor Control Rod Ejection and Boiling Water Reactor Control Rod Drop Accidents." Framatome confirmed [ ].

Section 9.5, "Limits on Oxidation and Hydriding," of BAW-10227P, Rev. 2, defines an upper bound on cladding oxide thickness of [ ]. A limit on maximum cladding oxide thickness is established to prevent oxide spallation and localized areas on non-uniform mechanical properties. Examination of the fuel cladding oxidation empirical database (Figure 6-4, "$M5_{Framatome}$ Cladding Corrosion Database used for Validation of GALILEO Fuel Rod Performance Code") reveals a [ ]. During the audit and in response to an RAI on this subject (RAI #6, Ref. [8]), Framatome described a more extended operational database which included European experience [ ]. Examination of [ ]. Based on the information provided in the BAW-10227P, Rev. 2, and in response to RAI #6, the NRC staff finds the maximum cladding oxidation limit acceptable.

Section 9.5 of BAW-10227P, Rev. 2, states that hydride limits for $M5_{Framatome}$ cladding are set by the safety criteria affected by hydrogen concentrations, and therefore, no general hydride limit was established. Limits on cladding hydrogen uptake are usually dictated by the empirical database of measured uniform elongation on irradiated cladding segments under biaxial loading.

This data sets the cladding transient strain limit for AOO overpower scenarios (e.g., 1 percent plastic strain). Hydrogen-dependent safety criteria are also being introduced for reactivity insertion accidents and LOCAs.

Section 10.4, "Transient Cladding Strain," of BAW-10227P, Rev. 2, states that mechanical tests and ramp tests have been performed that demonstrate that the 1 percent transient cladding strain criterion is conservative for M5 cladding material [ ]. Based on irradiated mechanical testing on similar RXA cladding, the NRC staff had concerns with the assertion that M5 cladding would be capable of achieving 1 percent transient cladding strain prior to failure at hydrogen levels approaching these elevated hydrogen levels. During the audit and in response to an RAI on this subject (RAI #6, Ref. [8]), Framatome described [ ]. Based upon the information presented in response to RAI #6, the NRC staff finds that M5 cladding is capable of achieving the transient cladding strain criterion without failure at and beyond EOL conditions. Hence, a predefined cladding hydrogen limit is unnecessary. As a result of this discussion, changes to BAW-10227P, Rev. 2, Section 10.4 were proposed, and the NRC staff finds them to be acceptable.

In response to RAI #6, Framatome also describes quality assurance and [ ] in place to ensure that M5 corrosion models remain applicable.

3.4 COMPONENT PERFORMANCE

3.4.1 Fuel Rod Stress Limits

Framatome has requested a change to the value of the design stress intensity (Sm), from [ ]. They present multiple correlations for UTS and yield strength (YS) in Section 8, "Mechanical Properties," of BAW-10227P, Rev. 2. Framatome states that by about [ ].

As the fuel strength described in BAW-10227P, Rev. 2, Section 8, has been found acceptable in Section 3.2 of this SE, and the new limits are still appropriately conservative, the NRC staff finds the proposed fuel rod stress limits to be acceptable.

3.4.2 Fuel Rod Buckling

The fuel rod buckling methodology was previously approved for use with M5 cladding by NRC staff in the SE of BAW-10277P-A, Rev. 1 (Ref. [6]). The [ ]. As the [ ], and the inputs have been found acceptable, the NRC staff finds Framatome's buckling methodology acceptable.

3.4.3 Cladding Creep Collapse

The cladding creep collapse methodology, CROV Rev 3, has previously been approved by NRC staff for use with M5 cladding (Refs. [6] and [9]). Framatome states that they will use approved fuel performance codes to generate inputs to the CROV methods. As Framatome will be using pre-approved methods, and creep collapse is only a concern at BOL [ ], the NRC staff finds the treatment of cladding creep collapse to be acceptable.

3.4.4 Transient Cladding Strain

The NRC staff's review of transient cladding strain is described in Section 3.3.2 of this SE.

3.4.5 Fuel Rod Fatigue

Section 10.5, "Fuel Rod Fatigue," of BAW-10227, Rev. 2, discusses fuel rod fatigue design criteria. These criteria have been slightly modified from BAW-10227, Rev. 1 (Ref. [6]). Previously condition I, II, and a single condition III event were considered; however, in the TR under review only condition I and II events are considered. Because this is consistent with the approach in American Society of Mechanical Engineers *Boiler and Pressure Vessel Code*, the NRC staff finds this change to be acceptable; however, any changes to expected fatigue cycles due to [ ] need to be evaluated when the fatigue analysis is completed for a specific licensee based on their case-specific inputs. This expectation is captured in the limitations and conditions section of this SE.

3.4.6 Fuel Rod Fretting

The NRC staff have previously approved Framatome's design criterion and test methodology for fretting wear. Framatome states that no fretting related failures have occurred in M5 cladding in assemblies with [ ]. Fretting depends largely on spacer grid design. As Framatome has not requested any [ ], the existing approval of Framatome's treatment of fretting is still applicable, and thus the NRC staff finds this treatment to be acceptable.

3.5 GROWTH AND CREEP

3.5.1 Irradiation Induced Free Growth and Creep

The M5 irradiation induced free growth and creep models have previously been approved in the GALILEO TR SE (Ref. [5]), is unchanged in this proposed TR, and is therefore acceptable.

3.5.2 Fuel Rod Axial Growth

Section 11.2, "Fuel Rod Axial Growth," of the BAW-10227, Rev. 2, addresses fuel rod axial growth. Fuel rod axial growth is important to model, as unexpected excessive growth can result in closure of the shoulder gap and subsequent fuel rod damage.

Framatome presents an upper bound model for fuel rod growth in this section. This model is supported with a figure plotting a significant number of data points from multiple assembly designs [ ]. Framatome also states that [ ].

As this model [ ], the NRC staff finds the treatment of fuel rod growth to be acceptable.

3.5.3 Fuel Assembly Growth

Section 11.3, "Fuel Assembly Growth," of BAW-10227, Rev. 2, addresses fuel assembly growth. This model has previously been approved (Ref. [10]) for use up to 62 GWD/MTU. Fuel assembly growth is dependent on the growth of the guide tubes over the life of the fuel assembly. As Framatome is [ ] acceptable.

3.5.4 Fuel Rod Bowing

Section 11.4, "Fuel Rod Bowing," of BAW-10227, Rev. 2, addresses Fuel Rod Bowing. RAI #3 requested additional data to support the handling of rod bow described in the original TR submittal. In response (Ref. [11]), Framatome submitted change pages that replaced the section with a new model. This model is reviewed as follows.

Framatome has proposed a new [ ]. This limit is to be applied to [ ] that meet a list of [ ] key characteristics. These characteristics are:

[ ]

The rod bow design limit is an input to a calculation of a minimum departure from nucleate boiling ratio (MDNBR) penalty. This penalty is applied if [ ].

Framatome has presented data on rod bow from multiple assembly designs that exhibit a variety of these characteristics and shown that the new rod bow design limit conservatively bounds the data. [ ]. For these reasons the NRC staff finds the new rod bow correlation to be acceptable.

Framatome's response also suggests that the rod bow design limit [ ] has a strong impact on rod bow.

Framatome provided data as well as [ ]. Because of this supporting evidence, and the fact that the rod bow MDNBR penalty is only applied when bow exceeds a certain threshold, the NRC staff finds the [ ] to be acceptable.

3.6 NON-LOCA PERFORMANCE

Section 12, "Material Performance in Non-LOCA," of BAW-10227, Rev. 2, states that existing non-LOCA methodologies that have previously been approved by the NRC continue to be valid. The range of applicability of these methodologies, set by burnup or other limits, is not changed by this TR or SE. As these methodologies were previously approved by the NRC, and Framatome [ ], these methodologies were outside the scope of this review.

3.7 CLADDING PERFORMANCE UNDER LOCA CONDITIONS

Section 13.0, "Material Performance in LOCA," of BAW-10227P, Rev. 2 (Ref. [2]), describes proposed updates to LOCA-specific cladding models in two areas: swelling and rupture (Section 13.1) and high-temperature oxidation (Section 13.2). These areas will be addressed in Sections 3.7.1, "Cladding Swelling and Rupture," and 3.7.2, "Cladding Embrittlement Criteria," of this SE.

3.7.1 Cladding Swelling and Rupture

As described in Section 13.1, "Swelling and Rupture," of Rev. 2 of BAW-10227P and supplemented by three responses to RAIs #8-10 (Refs. [12], [13], and [14]), Framatome has proposed to modify certain aspects of its existing, approved material-specific swelling and rupture models for M5 cladding for the proposed application. Framatome's swelling and rupture models for M5 are largely based upon the fundamental modeling approaches contained in NUREG-0630 (Ref. [15]) for Zircaloy cladding, but with adjustments to account for differences in material properties.

Framatome's analytical models address four main phenomena:

- cladding rupture temperature
- cladding pre-rupture strain
- cladding rupture strain
- fuel assembly flow blockage

Framatome's existing swelling and rupture models for M5 cladding are described in Appendix K of BAW-10227P, Rev. 1 (Ref. [6]). Following the approval of these models, Framatome continued to perform testing of M5 cladding in its EDGAR test facility. The EDGAR tests serving as the basis for Framatome's analytical models have been performed in a steam environment using individual sections of cladding tubes that were internally pressurized with argon gas and placed on the desired temperature ramp using direct Joule heating.

~~As discussed in Section 13.1.2 of BAW-10227P, Rev. 2, the Framatome LOCA evaluation models that reference the existing, approved cladding swelling and rupture models are the following:~~

- ~~BAW-10192P-A, Revision 0 and Supplement 1, "BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants" (Refs. [16] and [17]).~~

- ~~EMF-2328, Revision 0 and Supplement 1, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based" (Refs. [18] and [19]).~~

- ~~EMF-2103, Revision 3, "Realistic Large Break LOCA Methodology for Pressurized Water Reactors" (Ref. [20]).~~

~~The first two methodologies listed above (BAW-10192 and EMF-2328) conform to~~ Appendix K to 10 CFR Part 50~~, which~~ requires that the degree of cladding swelling experienced during a LOCA not be underestimated. Satisfaction of Appendix K requirements implies that the analytical model proposed by Framatome would be expected to be bound empirical test data, with the exception of any outlying or non-representative datapoints.

~~The third methodology (EMF-2103) uses realistic modeling with an explicit accounting for uncertainty, as permitted by 10 CFR 50.46(a)(1)(i).~~ For realistic modeling approaches, the NRC staff expects proposed uncertainty distributions to encompass representative test data. Satisfaction of 10 CFR 50.46(a)(1)(i) implies that the analytical models proposed by Framatome would be expected to represent the mean of empirical test data, with uncertainty bands sufficient to encompass the remaining data, with the exception of any outlying or non-representative datapoints.

The present SE considers the information in proposed Revision 2 to BAW-10227P in conjunction with the existing, approved evaluation models listed above. While the modeling approaches described in Revision 2 to BAW-10227P may have broader applicability beyond the specific evaluation models listed above, the NRC staff will determine the acceptability of these modeling approaches for other regulatory applications, as necessary, in future regulatory reviews.

Section 3.7.1.1, "Cladding Rupture Temperature," through 3.7.1.4, "Fuel Assembly Flow Blockage," of this SE describe Framatome's consideration of the new test data from the EDGAR facility with respect to its modeling approaches for each of the four main phenomena listed above that are associated with cladding swelling and rupture.

Subsequently, Section 3.7.1.5, "NRC Staff Evaluation of Swelling and Rupture Model Updates," provides the NRC staff's evaluation of Framatome's proposed models for swelling and rupture.

Finally, Section 3.7.1.6, "NRC Staff Conclusion Regarding Swelling and Rupture Model Updates," provides the NRC staff's conclusion concerning Framatome's updated approach for modeling swelling and rupture for M5 cladding.

3.7.1.1 <u>*Cladding Rupture Temperature*</u>

Determination of the cladding rupture temperature is necessary to calculate cladding strain and flow channel blockage under LOCA conditions. **[**

]

3.7.1.2 <u>*Cladding Pre-Rupture Strain*</u>

Pre-rupture strain refers to plastic deformation of the cladding as it approaches its rupture temperature **[**

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3.7.1.3 <u>*Cladding Rupture Strain*</u>

Should the cladding continue to overheat, a vulnerable region experiencing high temperature and stress conditions would eventually suffer additional deformation and rupture. The impacts of rupture strain are similar to those of pre-rupture strain; however, depending upon conditions, rupture strain can be significantly greater in magnitude.

In BAW-10227P, Rev. 2 (Ref. [2]), Framatome proposed to revise its modeling of rupture strain for M5 cladding. Since the approval of Framatome's existing rupture strain curves, Framatome has gathered additional test data from the EDGAR facility.

[

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The NRC staff's review of Framatome's proposed modifications to its approved rupture strain curves is provided below in Section 3.7.1.5, "NRC Staff Evaluation of Swelling and Rupture Model Updates," of this SE.

3.7.1.4 Fuel Assembly Flow Blockage

Fuel rod cladding that deforms during a LOCA will expand into adjacent coolant channels, creating additional flow resistance and diverting flow away from coolant channels adjacent to the ballooned region. Framatome's LOCA evaluation models incorporate flow blockage modeling to account for the potential reduction in cooling associated with this phenomenon. Framatome stated that no changes to the methodology for determining the amount of assembly flow blockage for a given rupture strain are necessary in light of the new data and proposed no changes to this methodology.

However, cladding rupture strain remains an input to the calculation of fuel assembly flow blockage. In light of the proposed modifications to its rupture strain curves described above, Framatome stated in Section 2.0 of the response to the Follow-up RAI to RAIs #8-10 (Ref. [14]) that corresponding updates to its fuel assembly blockage curves are made.~~2.6, “[ ]” of its second response to RAIs #8-10 (Ref. [13]) that these revised cladding strains will result in corresponding updates to its fuel assembly blockage curves. In its third response to RAIs #8-10 (Ref. [14]),~~ Framatome included updated fuel assembly blockage curves that reflect all proposed changes to its modeling of rupture strain, which are noted in the previous section above. Specifically, the updated blockage curves are depicted in Table 13-3, “$M5_{Framatome}$ SRM Slow and Fast Ramp Rate Assembly Blockage Factors,” and Figure 13-7, “$M5_{Framatome}$ SRM Slow and Fast Ramp Rate Assembly Blockage Curves,” in the section of Ref. [14]~~Framatome’s third response~~ that contains markup pages to BAW-10227P, Rev. 2.

The NRC staff’s review of Framatome’s proposed modifications to its approved flow blockage curves is provided below in Section 3.7.1.5 of this SE.

3.7.1.5 *<u>NRC Staff Evaluation of Swelling and Rupture Model Updates</u>*

The NRC staff’s review of BAW-10227P, Rev. 2, evaluated the acceptability of Framatome’s modeling approaches for (1) cladding rupture temperature, (2) cladding pre-rupture strain, (3) cladding rupture strain, and (4) fuel assembly flow blockage.

In each of these areas, the modeling approaches used by Framatome [ ]. Furthermore, these approaches derive strongly from NUREG-0630-based methods [ ]. Hence, the NRC staff’s review focused upon the implications of the recent data obtained in the EDGAR facility [ ].

As such, the NRC staff’s evaluation of Framatome’s proposed model updates and additional test data associated with cladding swelling and rupture focused on two review criteria:

- Reasonably assuring the acceptability of Framatome’s proposed revisions to its approach for modeling cladding rupture strain, [

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- Reasonably assuring, considering the new swelling and rupture data, the continued acceptability of other aspects of Framatome's swelling and rupture modeling that have not been modified.

The NRC staff continues to find the basic structure of Framatome's modeling approach for swelling and rupture, which derives from the NRC staff-developed NUREG-0630 methodology (Ref. [15]), to be appropriate for assessing the figures of merit associated with its existing, approved LOCA evaluation models. Since the issuance of NUREG-0630 in 1980 through to the present time, modeling approaches based thereon have been widely used by the NRC staff and industry in performing LOCA analyses. ~~to demonstrate that the peak cladding temperature, maximum local oxidation, and core-wide oxidation comply with the acceptance criteria specified in 10 CFR 50.46(b)(1)-(3).~~ However, successful implementation of analytical modeling approaches for cladding alloys not directly considered within NUREG-0630 (e.g., M5) depends upon acceptably addressing material-specific physical behavior and ensuring validation of the resulting modeling approaches against material-specific empirical data.

Returning now to the evaluation of the first two of the four specific areas of Framatome's swelling and rupture modeling, the NRC staff's review of the new EDGAR data found no evidence that revisions to Framatome's existing, approved approaches for determining the cladding rupture temperature and pre-rupture strain are necessary. Hence, the present review finds that the basis for the acceptability of these models discussed in the NRC staff's SEs on Revisions 0 and 1 of BAW-10227P (Refs. [21] and [6]) remains valid.

Next, for the third specific area evaluated in this section of the SE, cladding rupture strain, Framatome proposed modifications to its current modeling approach, including several changes implemented during the NRC staff's review. Therefore, the NRC staff focused its review effort in this area. A main objective of the NRC staff's review was evaluating a number of datapoints from recent EDGAR testing that lay above the proposed rupture strain curves for M5 that were originally included in Rev. 2 of BAW-10227P. To ensure compliance with requirements in 10 CFR 50.46, the NRC staff's review sought to ensure that the presence of these datapoints above the proposed rupture strain curves would not result in the potential to underestimate the range of potential cladding rupture strain values.

In initially assessing the rupture strain curves in BAW-10227P, Rev. 2, which Framatome updated in subsequent responses to RAIs #8-10, the NRC staff evaluated the proportion of datapoints bounded by the proposed rupture strain curves relative to the analogous proportion in the corresponding figures (Figures C6 and C7) in BAW-10227P, Rev.1 (Ref. [6]). **[**

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The proportion of data under the rupture strain curves proposed by Framatome is relevant to the NRC staff's review of LOCA evaluation models because (1) for conservative evaluation models, Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50 requires that the "degree of swelling and incidence of rupture are not underestimated" and (2) for best-estimate-plus-uncertainty evaluation models, 10 CFR 50.46 requires explicit consideration of uncertainty to ensure a high level of probability that the acceptance criteria set forth in 10 CFR 50.46(b) would not be exceeded.

Hence, the NRC staff issued RAIs #8-10 (Ref. [22]), as supplemented (Ref. [23]), to address issues identified concerning Framatome's proposed rupture strain curves and its supporting technical justification, including the following:

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The NRC staff ultimately did not agree that Framatome's response (Ref. [12]) fully justified the rupture strain curves proposed in BAW-10227P, Rev. 2.~~Framatome's first two responses to RAIs #8-10 (Refs. [12] and [13]) include extended discussion of a number of empirical observations and phenomenological insights, as well as a modification to the originally proposed rupture strain curves. The NRC staff's review found that these responses to RAIs #8-10 include a number of insightful observations concerning swelling and rupture behavior during a LOCA, with particular focus on the influence of azimuthal temperature gradient. However, as~~ ~~[~~

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Subsequently, Framatome submitted ~~a third revision to RAIs #8-10 (~~Ref. [14]~~)~~ that proposed to modify the slow temperature ramp rate rupture strain curve (see Figure 2-1 and Table 13-2 therein) [ ]. This proposed modification addressed the NRC staff's remaining concerns with the conservatism of Framatome's proposed rupture strain curves by ensuring that the curves bound an adequate proportion of relevant experimental datapoints. While, even following this modification, some datapoints remain unbounded, the NRC staff observed that (1) the majority of such datapoints indicate large rupture strains that may be difficult to achieve in a rod bundle geometry with prototypical adjacent rod interactions and (2) existing regulatory guidance in NUREG-0630, which reflects a mixture of empiricism and physical insights, establishes rupture strain curves using a similar conservatively representative approach, rather than attempting to bound all rupture strain datapoints.

Finally, with respect to the fourth specific area of Framatome's modeling approach, fuel assembly flow blockage, the NRC staff's review found no evidence that revisions to Framatome's existing, approved approach for calculating flow assembly blockage are warranted. As discussed in Appendix C of Revisions 0 and 1 of BAW-10227P (Refs. [21] and [6]), Framatome's fuel assembly blockage model has been benchmarked against the NUREG-0630 model and compares well against its predictions. Hence, the present review finds

that the basis for the acceptability of the existing approach discussed in the NRC staff's previous SEs on Revisions 0 and 1 of BAW-10227P remains valid.

However, because the calculation of assembly flow blockage depends in part upon the cladding rupture strain, Framatome's proposed revisions to its cladding rupture strain model described above, as summarized in Table 13-2 of ~~Framatome's third response to RAIs #8-10 (~~Ref. [14]~~)~~, resulted in changes to the calculated fuel assembly blockage factors listed in Table 13-3 of the same RAI response. [

]. Based upon its review of Framatome's third response to RAIs #8-10 and consideration of the approved methodology for fuel assembly blockage that is described in Revisions 0 and 1 of BAW-10227P, the NRC staff finds that the calculated changes in the flow blockage values reflected in Table 13-3 of Framatome's third RAI response appear consistent with the modified cladding rupture strain curves.

3.7.1.6 *NRC Staff Conclusion Regarding Swelling and Rupture Model Updates*

Returning to the two review criteria discussed at the beginning of the previous section of this evaluation, the NRC staff made the following conclusions:

- The modifications Framatome proposed to its cladding rupture strain modeling in Revision 2 of BAW-10227P and associated RAI responses are adequate, including

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The NRC staff's review assured Framatome's proposed modifications to its rupture strain curves envelop a sufficient proportion of the available, relevant experimental data. As discussed above, the NRC staff based its judgment in this matter on the standard established by the rupture strain curves in NUREG-0630, which have a long regulatory history of application in approved LOCA evaluation models.

In arriving at its conclusion, the NRC staff further observed that the rupture strains represented by the small proportion of remaining unbounded datapoints from single-rod tests would be difficult to achieve in a prototypical rod geometry given the strong potential for adjacent rod interactions that would tend to limit cladding rupture strain.

- There is reasonable assurance, considering both the proposed fuel burnup increase and the new swelling and rupture data, of the continued acceptability of the aspects of Framatome's approach for modeling cladding swelling and rupture that were not modified in Revision 2 of BAW-10227P, including the rupture temperature, pre-rupture strain, and fuel assembly blockage. Concerning fuel assembly blockage, Framatome updated the fuel assembly blockage factors in Table 13-3 of the third response to RAIs #8-10 to reflect the revised modeling of cladding rupture strain described above but proposed no changes to the approved method for calculating fuel assembly blockage.

The NRC staff's review of BAW-10227P, Revision 2, and associated RAI responses confirmed that the new experimental data and other information considered within the review provides no indication that additional modifications (i.e., beyond those discussed in the bullet above) to Framatome's currently approved analytical models are necessary. The NRC staff continues to find the basic structure of Framatome's modeling approach for swelling and rupture, which derives from the NRC staff-developed NUREG-0630 methodology (Ref. [15]), to be appropriate for assessing the figures of merit associated with its existing, approved LOCA evaluation models. The basis for the acceptability of these models has been documented previously in Revisions 0 and 1 of BAW-10227P (Refs. [21] and [6]) and remains valid.

In conclusion, the NRC staff finds the proposed modeling approach for cladding swelling and rupture described in BAW-10227P, Rev. 2, and its associated RAI responses to be acceptable for determining compliance with 10 CFR 50.46(b) acceptance criteria in conjunction with the [ ]~~10 CFR 50.46(b)(1)-(3), in conjunction with Framatome's existing, approved LOCA evaluation models (Refs. [16] through [20])~~. The NRC staff notes that these swelling and rupture models, as implemented in Framatome's attendant LOCA methodologies, are tailored to the determination of swelling and rupture for a hot rod that is expected to be limiting with respect to the acceptance criteria in 10 CFR 50.46(b) ~~10 CFR 50.46(b)(1)-(3)~~. The NRC staff's approval thereof pertains exclusively to this proposed application. This SE's approval of the proposed swelling and rupture models for the specific applications described in Framatome's approved LOCA evaluation models does not imply acceptance of these modeling approaches for other purposes, such as determining the potential for fuel fragmentation, relocation, and dispersal on a core-wide basis. The applicability of these models for other purposes will be assessed separately, as necessary, in future regulatory reviews.

3.7.2 Cladding Embrittlement Criteria

Section 13.2 of BAW-10227P, Rev. 2, provides results from steam oxidation testing under LOCA conditions. Based on the data provided in this section, the NRC staff finds that the Baker-Just correlation and Cathcart-Pawel correlation are acceptable for calculating the metal-water reaction for M5Framatome cladding. ~~Note that while both correlations are acceptable for predicting the metal-water reaction, only the Baker-Just correlation should be used to integrate time-at-temperature for comparison against the 17 percent equivalent cladding reacted (ECR) criterion.~~

Section 13.3 of BAW-10227P, Rev. 2, provides data from ring compression tests performed on high temperature steam oxidized cladding segments to demonstrate the applicability of the 10 CFR 50.46 criteria, 2200°F and 17 percent Baker-Just (BJ)-ECR.

This section refers to testing protocols and test results within NUREG/CR-7219 and draft RG 1.224. However, this section does not address the three key research findings in these same documents: (1) hydrogen-enhanced beta-layer embrittlement, (2) cladding inner diameter (ID) oxygen ingress, and (3) breakaway oxidation.

With respect to hydrogen-enhanced beta-layer embrittlement, Framatome stated that the combination of the 10 CFR 50.46 criteria, 2200°F and 17 percent BJ-ECR criterion, as adjusted for pre-transient oxidation in accordance with Information Notice (IN) 1998-29, "Predicted Increase in Fuel Rod Cladding Oxidation," remained acceptable for retaining adequate cladding post-quench ductility (PQD). As described in response to an RAI on this subject (RAI #7, Ref. 7), M5 cladding retained acceptable PQD at cladding hydrogen levels beyond expected EOL conditions when compared against the equivalent BJ-ECR criterion. This demonstration was possible due to the favorable M5 cladding corrosion properties. Based on the information presented in response to RAI #7, the NRC staff finds that the application of the existing 10 CFR 50.46 criteria, 2200°F and 17 percent BJ-ECR criterion, as adjusted for pre-transient oxidation in accordance with IN 1998-29, remained acceptable for M5 cladding.

With respect to cladding ID oxygen ingress, **[**

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With respect to breakaway oxidation, Framatome stated that M5 cladding is resistant to breakaway oxidation, and associated hydrogen embrittlement, up to time durations well beyond LOCA scenarios. The NRC staff surveyed the existing PWR fleet and found that the maximum time duration at temperatures where cladding has been found susceptible to breakaway phenomena (i.e., 1472 °F) were well below the measured timing for M5 to experience onset of breakaway oxidation. In response to RAI #7 (Ref. 7), Framatome described additional breakaway oxidation testing conducted at Paimboeuf which confirmed M5 cladding's resistance and showed that the existing time-at-temperature limit, 17 percent BJ-ECR, was sufficient to ensure that breakaway oxidation was not a real concern.

Framatome also described studies to better understand the underlying phenomena and sensitivity of breakaway oxidation to manufacturing process, as well as design and manufacturing process control procedures in place to avoid significant changes in breakaway performance. Based on the information presented in response to RAI #7, the NRC staff finds that existing limitations on time-at-temperature are sufficient to ensure that onset of breakaway oxidation is avoided for the current PWR fleet up to **[** **]** .

3.8 FUEL SURVEILLANCE

In Section 14.0 of the BAW-10227P, Rev. 2, Framatome describes its strategy for fuel surveillance for M5 cladding, and its intent to focus on EOL PIE for high-burnup fuel assemblies if burnup limits are increased. As sufficient fuel surveillance data was presented in this TR, the NRC staff finds this to be acceptable and place no conditions or limitations on fuel surveillance.

4.0 LIMITATION AND CONDITION

As documented in the SE above, the NRC staff's evaluation of BAW-10227P, Rev. 2, found one limitation and condition necessary to assure the acceptability of the methodology:

> When applying the methodology described in BAW-10227P, Rev. 2, [ ] , licensees shall ensure that changes to expected fatigue cycles are appropriately captured in the fatigue evaluation.

5.0 CONCLUSION

Framatome's TR BAW-10227P, Rev. 2, presents a definition and characteristics for M5 material for use as cladding and structural material in PWR fuel assemblies. This revision updates some material properties based on data collected since the prior approval. Additionally, this TR requests approval to change the fuel rod cladding [ ] . Structural component material approval is requested to [ ].

Framatome's description of M5 physical and mechanical properties, oxidation and hydrogen pickup during normal operation, growth and creep, material performance in non-LOCA, and planned surveillance have been reviewed by the NRC staff and found to be acceptable. The NRC staff also found the treatment of component performance to be acceptable, while noting that any changes to expected fatigue cycles due to [ ] need to be evaluated when the fatigue analysis is completed for a specific licensee based on their case-specific inputs, as captured above as a limitation and condition.

The NRC staff's review further found Framatome's methods for determining cladding performance during a LOCA to be acceptable. As described above in Section 3.7, the review addressed Framatome's approach for modeling cladding swelling and rupture behavior and its cladding embrittlement criteria. The NRC staff's acceptance of Framatome's modeling of cladding swelling and rupture behavior was facilitated by modifications Framatome implemented to its approach during the review in response to RAIs #8-10.

The NRC staff's review of BAW-10227P, Rev. 2, resulted in one limitation and condition stated in Section 4.0 of this SE. The NRC staff finds the proposed methodology acceptable contingent upon this limitation and condition being satisfied.

6.0 REFERENCES

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[12] Framatome, "RAI Response Part 2 - #7, #8, #9, #10," December 2020, (ADAMS Accession No. ML20366A115 (Non-Proprietary) ML20366A114 (Proprietary)).

[13] Not Used.~~Framatome, Inc., "Response to Request for Additional Information Regarding BAW-10227P, Revision 2, 'Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel'," November 24, 2021. (ADAMS Accession No. ML21336A457 (Proprietary), ML21136A456 (Non-Proprietary)).~~

[14] Framatome, "Revised Response to Request for Additional Information Regarding BAW-10227P, Revision 2, 'Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel'," August 31, 2022.

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[16] Not Used.~~Framatome Technologies, Inc., "BAW-10192P-A, Revision 0, 'BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants'," June 1998.~~

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