AUDIT REPORT

BAW-10227P, REVISION 1, SUPPLEMENT 1P

"EVALUATION OF ADVANCED CLADDING AND STRUCTURAL MATERIAL (M5) IN PRESSURIZED WATER REACTOR REACTOR FUEL"

1.0 BACKGROUND

By letter dated May 4, 2017, Framatome Inc. (Framatome, formerly AREVA Inc.) submitted Topical Report (TR) BAW-10227P, Revision 1, Supplement 1P, "Evaluation of Advanced Cladding and Structural Material (M5) in Pressurized Water Reactor (PWR) Reactor Fuel" (BAW-10227 R1, S1), for the U.S. Nuclear Regulatory Commission (NRC) review and approval (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17130A708). Framatome explained its intent for the supplement is to re-establish the iron impurity concentration limit without a need to change any application methods or licensee Technical Specifications methodology references based on its evaluation.

2.0 REGULATORY AUDIT OBJECTIVES

The NRC staff completed its acceptance review on October 18, 2017, and found that the material presented was sufficient to begin its review (ADAMS Accession No. ML17283A261). After an initial review, the NRC staff identified some areas requiring further discussion. The NRC staff determined it necessary to review documents supporting BAW-10227 R1, S1, analyses to resolve the NRC staff concerns. The scope and objectives were defined in an audit plan (ADAMS Package Accession No. ML18355A977).

An audit was conducted at the Framatome offices in Lynchburg, VA on January 30-31, 2019. Participants in the audit are listed in Table 1.

Table 1: List of Attendees

Name	Organization
Amrit Patel	NRC
Paul Clifford	NRC
Jonathan Rowley	NRC
Jerald Holm	Framatome
Gary Williams	Framatome
Kevin McCoy	Framatome
Jim Hoerner	Framatome
Julie O'Shaughnessy	Framatome
Jacki Stevens	Framatome

3.0 AUDITED MATERIAL AND DISCUSSIONS

The eight open items identified in the audit plan are discussed below. All of the open items were closed with no need for further information.

Item #1

Sections 3 and 4 of BAW-10227 R1, S1, reference a technical paper (Impact of Iron in M5™) presented at the American Society for Testing and Materials B10 Zirconium in the Nuclear Industry Symposium (i.e., BAW-10227 R1, S1, Reference 2) for a vast amount of data and analysis to support this TR supplement. The technical paper is cited 31 times. The technical paper was authored by representatives from several different Framatome organizations in France, Germany, and the United States. This technical paper lacks the pedigree necessary to support an NRC safety finding. The NRC staff requests an audit of the underlying Framatome testing and research reports and requests that Framatome affirm that the information cited from the technical paper is accurate and was processed under the Framatome quality assurance program.

<u>Disposition</u>

Quality Assurance Procedures

Regarding the quality assurance aspect of design analyses, the Framatome technical staff discussed the use of Document FSOP-07, Revision 7, "Fuel Operating Procedure: Design Analysis," as a standard procedure in the preparation of BAW-10227 R1, S1. During the review of FSOP-07, the NRC staff observed on page 8 of Section 6.3.4 the following internal requirements regarding establishment of design analysis technical bases:

> Reviewers shall perform the technical review of the Design Analysis and its Documentation addressing the following list:
> Inputs are correctly selected, referenced as described by Appendix 5, and verified...Reference source materials and inputs are valid for and applicable to the Design Analysis.

Upon further review of Appendix 5 (Referencing Design Information), the NRC staff observed a specific requirement related to incorporation of experimental data from company-generated documents (i.e., reference of BAW-10227 R1, S1, Reference 2 for several technical bases) into a design analysis:

> In addition, references shall meet the following requirements:
> [Reference documents are] generated according to quality assurance procedures.

The NRC staff observed that Framatome used a procedure with clear quality assurance requirements in the preparation of BAW-10227 R1, S1 – specifically in the use of design information from BAW-10227 R1, S1, Reference 2. Furthermore, the NRC staff observed that the incorporation of findings and conclusions from BAW-10227 R1, S1, Reference 2 were all tied to company-generated internal documentation, which the NRC staff independently confirmed during the audit. Consequently, use of information from

BAW-10227 R1, S1, Reference 2 was found to be acceptable. This issue is closed with no need for additional information. The following subsection contains a summary of this internal documentation review along with the NRC staff's observations.

Audit Document Review Summary

The "Reference No." column in Table 2 below corresponds to the relative location of BAW-10227 R1, S1, Reference 2 citations in order of appearance in the TR. Note that 28 references to BAW-10227 R1, S1, Reference 2 were reviewed. Based on discussions with Framatome staff during the audit, the remaining 3 BAW-10227 R1, S1, Reference 2 citations were incidental and were not used as original sources to independently establish technical bases in BAW-10227 R1, S1 (i.e., in these cases, the technical bases originated from BAW-10227 R1, S1 rather than BAW-10227 R1, S1, Reference 2) and were therefore not reviewed in the context of the audit. The NRC staff also observed that Reference Nos. 27 and 28 were administrative citations and not technical in nature.

Table 2: BAW-10227 R1, S1, Reference 2 Citations Reviewed

Reference No.	**BAW-10227 R1, S1 Section**	**Audit Document**	**Observations**
1	3.1, "Microstructure and Texture"	**[ ]**	Photomicrographs translated correctly in the journal article.
2	3.1, "Microstructure and Texture"	**[ ]**	BAW-10227 R1, S1, states no trend on kearns factors observed between samples. Review of clad mid-point location values supports claim of no apparent effect due to iron content range of 240-970 parts per million (ppm).
3	4.6.1, "Aqueous Corrosion"	**[ ]**	Data reviewed supports BAW-10227 R1, S1, statement that "only a small effect of iron was seen, which was that the oxide thickness at intermediate times was slightly lower for alloys with high iron concentrations."

Reference No.	BAW-10227 R1, S1 Section	Audit Document	Observations
4	4.6.1, "Aqueous Corrosion"	[ ]	After conversion from areal density to thickness (by multiplying by ~15 microns/mg/dm^2 as provided by Jacki Stevens of Framatome) for the 625 ppm iron (Fe) case, the figure was confirmed to have been translated correctly in the journal article. The BAW-10227 R1, S1, claim that corrosion performance for the 285-1330 ppm Fe cases was improved relative to the 273 ppm Fe case was confirmed.
5	4.6.1, "Aqueous Corrosion"	[ ]	Data reviewed supports BAW-10227 R1, S1, statement regarding five M5-Fe[1] alloys at increasing concentrations of Fe tested at 360°C in water with 70 ppm Lithium for up to 300 days: "Increasing the iron concentration provided progressive improvements in resistance to acceleration of corrosion." Figure appears to be translated correctly in the journal article.

[1] "M5-Fe" here refers to the currently approved specification of M5, but with a higher Fe concentration (as is being proposed in BAW-10227 R1, S1, including Fe concentrations up to approximately 1000 ppm).

Reference No.	BAW-10227 R1, S1 Section	Audit Document	Observations
6	4.6.1, "Aqueous Corrosion"	[ ]	Data reviewed supports BAW-10227 R1, S1, statement that M5-Fe with 1000 ppm of Fe had measured oxide thicknesses consistently in the lower range of data typical of current M5 over a range of burnup up to 66 gigawatt days per metric ton of uranium (GWd/MTU) for French and German operating reactors.
7	4.6.1, "Aqueous Corrosion"	[ ]	Data reviewed supports the BAW-10227 R1, S1, statement that "the cladding with the higher Fe concentration had a smaller maximum oxide thickness and less variation in oxide thickness with elevation." Figures appear to be translated correctly in the journal article.
8	4.6.2, "High Temperature Oxidation"	[ ]	Data reviewed supports the BAW-10227 R1, S1 statement that "performance was variable after breakaway, but the results for an iron concentration of 715 ppm were similar to those for concentrations of 195 and 350 ppm." Figures appear to be translated correctly in the journal article.

Reference No.	BAW-10227 R1, S1 Section	Audit Document	Observations
9	4.7, "Ultimate Tensile Strength"	[ ]	Data reviewed supports the BAW-10227 R1, S1, statement that current M5 and M5-Fe with 1000 ppm Fe "show a slight trend toward increased ultimate tensile strength as the iron concentration increases. The increase was seen at both room temperature and 400°C."
10	"	"	Same as Number 9.
11	"	"	Same as Number 9 except for yield strength instead of ultimate tensile strength.
12	"	"	Same as Number 11.
13	4.9, "Ductility"	[ ]	Data not exactly the same, but appears consistent with corresponding journal article figure.[2] Data reviewed supports the BAW-10227 R1, S1, statement that there is little difference between current M5 and M5-Fe with up to 1000 ppm of Fe (for both room temperature and at 400°C). The M5-Fe with up to 1000 ppm of Fe falls within the range of scatter for current M5.

[2] Observed *minor* differences in data were not investigated further. Most of the audit documents were written in French or German, and Framatome staff noted that translations to English can sometimes cause minor differences.

Reference No.	BAW-10227 R1, S1 Section	Audit Document	Observations
14	"	"	Same as Number 13.
15	4.10.1, "Fuel Rod Cladding"	**[ ]**	Data reviewed supports the BAW-10227 R1, S1, statement that "a slight trend of increasing strains was observed with increasing iron concentration" -- the NRC staff notes that in the audit document the **[ ]** for the 130 megapascal (MPa) and 160 MPa datasets, respectively, indicating slight and potentially statistically insignificant trends. Data reviewed confirmed to be consistent with corresponding journal article figures. Figures appear to be translated correctly in the journal article.
16	4.10.1, "Fuel Rod Cladding"	**[ ]**	Data reviewed supports the BAW-10227 R1, S1, statement that "samples with 310 ppm Fe were found to creep at a rate that was similar to that for samples with 935 ppm Fe." Figures appear to be translated correctly in the journal article.
17	"	"	Same as Number 16

Reference No.	**BAW-10227 R1, S1 Section**	**Audit Document**	**Observations**
18	4.10.1, “Fuel Rod Cladding”	**[ ]**	The data supports the BAW-10227 R1, S1, conclusion that the diametral creep rate is similar between M5 and M5-Fe with higher Fe concentrations. Data from figure (German data) and table (French data) appear to be translated correctly in the journal article.
19	4.14.1, “Free Growth”	**[ ]**	Data reviewed confirmed to be mostly consistent with corresponding journal article figures.
20	"	"	Concluding statement in BAW-10227 R1, S1, not the same as in journal article -- i.e., presence of “slightly more growth for the variant with 1000 ppm Fe” versus “no significant effect of iron content”, respectively. Based on the audit document reviewed, there is more data with more scatter so it is difficult to say either way. Regardless, the effect of Fe content on free growth does not appear to be very significant.

Reference No.	**BAW-10227 R1, S1 Section**	**Audit Document**	**Observations**
21	4.14.2, "Growth of Fuel Assembly Components"	**[ ]**	Confirmed that fuel rods with M5-Fe with 1000 ppm Fe have fuel rod growth within the scatter of the current M5 database, but on the low side on an individual reactor basis.
22	4.14.2, "Growth of Fuel Assembly Components"	**[ ]**	Confirmed BAW-10227 R1, S1 statement that samples from commercial reactors show that M5-Fe with 1000 ppm Fe may produce an increase in assembly growth by up to 0.1 percent (absolute strain) at high fluences. Figure data points appear to be translated correctly in the journal article.
23	4.15, "Resistance to Hydriding"	**[ ]**	Confirmed hydrogen pickup at 53.9 GWd/MTU within range (lower part) expected of current M5 for M5 with up to **[ ]** ppm Fe. Figure M5-Fe data points appear to be translated correctly in the journal article.
24	"	"	Same as Number 23.

Reference No.	BAW-10227 R1, S1 Section	Audit Document	Observations
25	4.15, “Resistance to Hydriding”	[ ]	Photomicrographs translated correctly in the journal article.
26	4.16, “Stress Corrosion Cracking Resistance”	[ ]	Confirmed that number of Laves phase precipitates remain small compared to beta-Niobium (Nb) precipitates; 970 ppm Fe case: 1741/1770 beta-Nb versus 29/1770 hexagonal intermetallics.
27	5.0, “Irradiation Experience”	[ ]	Documentation describing Reactor D40 labeling as Reactor C in journal article.
28	5.0, “Irradiation Experience”	[ ]	Documentation describing Reactor D71 labeling as Reactor Q in journal article.

Item #2

Section 4 of BAW-10227 R1, S1, describes various material properties. Discuss why material properties aren’t updated based on the current state-of-knowledge. For example, M5 density reported in the base TR from 2003 is an extrapolation between pure zirconium (Zr) and a CANDU Zr-2.5 Niobium alloy.

<u>Disposition</u>

The goal of this TR was to demonstrate that the increase in Fe content has no impact on M5’s material properties or performance. As such, no model changes are necessary. During the audit, Framatome identified that there are plans to submit a full revision to

BAW-10227 (Revision 2) which will update databases, properties, and models to capture the current state-of-knowledge. As such, the NRC staff's concerns regarding updated material properties will be addressed in this future revision. This issue is closed with no need for additional information.

Item #3

The various subsections of BAW-10227 R1, S1, Section 4 refer to "reported uncertainties." Provide a reference for the reported uncertainties for the structure-insensitive properties as they are not located with M5 material properties in Appendix A of the base TR.

<u>Disposition</u>

Framatome provided references for the "reported uncertainties" cited within BAW-10227 R1, S1. During the audit, the NRC staff reviewed these references and performed the following tasks:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

The magnitude of uncertainty seems reasonable, especially given the usage in this TR, which is solely to describe the minimal impact of raising iron content by a small amount. This issue is closed with no need for additional information.

Item #4

Section 4.10.2 of BAW-10227 R1, S1 describes the evaluation for guide tube creep. What is the basis for not providing data **[ ]**?

<u>Disposition</u>

For guide tubes, axial creep is of primary importance because it effects fuel assembly growth. Growth reflects both free growth, which is induced by fluence and hydrogen, and creep, which relates to the stress state. Framatome has developed design-specific assembly growth models based on measured data.

During the audit, Framatome described creep tests which addressed forms, stress states, and compositions as individual effects to determine the performance of high-iron guide tubes under uniaxial stress. Tests on cladding at **[ ]** MPa and variable stress cover iron content up to **[ ]** ppm. From these tests, it was concluded that free growth measurements do not indicate a significant change in growth with higher Fe content. Furthermore, the results do not indicate a significant change in creep rate with higher Fe content. As a result, existing fuel assembly growth models remain applicable.

The NRC staff reviewed Framatome calculation **[**

] This calculation described the various tests conducted in the BOR-60 test reactor including:

- Tests on M5 with **[** **]**
- Tests on M5 with **[**
  ].

The NRC staff also reviewed Framatome calculation **[**
] This calculation evaluates the impact of an increase in Fe content on M5 properties and performance. Highlights from this calculation include:

- The calculation was reviewed by all functional disciplines.

- The calculations were completed in accordance with the Framatome QA program.

- Figure 1 plots the average Fe content in M5 ingots over time (1997-2014). **[**
  ]

- From Section 3, **[**

  ]

- **[**
  ]

Based upon discussions during the audit, supporting audit documents reviewed, and the material described in the TR, the NRC staff considers this issue resolved.

Item #5

Section 4.14.2 of BAW-10227 R1, S1, describes the evaluation of fuel rod and guide tube growth. Based on observations and growth measurement, Framatome states, "The slight reduction in fuel rod growth will result in a slightly larger shoulder gap, which is not detrimental to fuel performance. Therefore, models of fuel rod growth for M5 remain applicable." A decrease in fuel rod growth would have a negative impact on predicted void volume and rod internal pressure, therefore the impact of the re-defined M5 depends on whether the application methods credit fuel rod growth in those predictions. Discuss the impacts of the re-defined M5 on previously approved application methods.

Disposition

The Framatome fuel rod growth models are based on an extensive database. The empirical database is shown (gray dots) in Figure 17 of Reference 2 of the TR. Examination of this figure reveals a large spread in the data attributed to different designs and operating histories. The high iron fuel rod growth measurements on the 72 fuel rods at 1000 ppm are shown, along with data from the same reactors. The measurements of the high iron fuel rods tend to fall at the lower end of the data for the same fuel assembly designs. The high iron measurements remain within the scatter of the entire database. Furthermore, at the target iron content (**[ ]** ppm maximum) the expected impact should be less than observed at the 1000 ppm level. Based on these observations, the NRC staff considers this issue closed.

Item #6

Discuss how differences between COPERNIC models and methods and those of GALILEO were considered in the development of BAW-10227 R1, S1.

Disposition

This TR demonstrates that existing material properties and performance of M5 remain applicable up to the higher Fe content. Based on the NRC staff's review, we accept this conclusion. There are differences between COPERNIC and GALILEO mostly due to the evolving databases and changes in application methods (e.g., sampling). The higher Fe content does not influence these existing differences. The NRC staff considers this issue closed.

Item #7

Section 4.14.2 of BAW-10227 R1, S1, describes the evaluation on fuel rod and guide tube growth. Guide tube measurements suggest a slight increase in growth at higher Fe concentrations. Framatome concludes that existing models remain applicable. Framatome has an NRC-approved process for measuring guide tube growth and updating design-specific models without prior NRC review. Why doesn't BAW-10227 R1, S1, acknowledge this process and commit to follow it in the future should significant growth differences be observed?

Disposition

The update process mentioned above applies to Q12 guide tubes and was clearly defined in the NRC staff's approval of Q12. It includes data collection and model confirmation. The original M5 approval of BAW-10227 discussed continued growth measurement and model updates, but not to the same level of detail and requirements. During the audit, Framatome mentioned that their M5 growth models have been refined and updated as more data is collected. The NRC staff supports these continued improvements and data collection. BAW-10227 R1, S1, does not need to further define an update process. The NRC staff considers this issue closed.

Item #8

Section 4.17 of BAW-10227 R1, S1, describes the evaluation of phase transition temperature. Fe has been identified as a beta-stabilizer in Zr alloys. As such, the NRC staff expects the alpha-Zr to alpha-Zr plus beta-Zr phase transition temperature should be slightly reduced at the higher Fe concentrations. Discuss the basis for assuming the phase transition temperature remains the same for the re-defined M5 considering other factors besides iron may impact the phase transition temperature.

Disposition

During the audit, Framatome presented the Zr-Fe phase diagram. The beta phase transition temperature initially decreases with increasing Fe. It drops from approximately **[**

]

The NRC staff considers this issue closed.

4.0 REGULATORY AUDIT CONCLUSIONS AND FINDINGS

All of the regulatory audit objectives listed in Section 2 were covered and all audit items were closed. No errors or negative findings were identified during the audit. No requests for additional information were needed to provide further information.