Enclosure 2:

BAW-10227 Revision 2, Q4NP Revision 1, “Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel”

Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel

BAW-10227
Revision 2, Q4NP
Revision 1

Topical Report

August 2022

FRAMATOME TRADEMARKS

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	Section 2.0	The RAI response is completely revised as a result of technical discussions with the NRC.
2	Section 3.0	Added to discuss topical report changed pages.

Contents

List of Tables

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Nomenclature

Acronym	Definition
ECCS	Emergency Core Cooling System
EM	Evaluation Model
LOCA	Loss of Coolant Accident
NRC	Nuclear Regulatory Commission
RAI	Request for Additional Information
SRM	Swelling and Rupture Model
W&CE	Westinghouse and Combustion Engineering

INTRODUCTION

The United States Nuclear Regulatory Commission (NRC) provided a request for additional information (RAI) regarding the topical report BAW-10227P, Revision 2 (Reference 2-4). The original response to RAI questions 8, 9, and 10 was previously sent in Reference 2-5. The RAI requesting additional information regarding RAI questions 8, 9, and 10 (Reference 2-4) is duplicated in its entirety in Section 1.0 of this document.

Section 2.0 of this document provides the response to this follow-up RAI to NRC questions 8, 9, and 10. Section 3.0 provides the topical report markups.

1.0 RAI 8, 9, AND 10 FOLLOW-UP RAI

1.1 *Background*

On August 21, 2020 (ADAMS Package Accession No. ML20223A229), the NRC staff issued a request for additional information (RAI) to Framatome concerning our ongoing review of Revision 2 to BAW-10227P, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel." In a combined response, Framatome replied to RAIs 8-10 in a submittal dated December 18, 2020 (ADAMS Package Accession No. ML20366A127). In a closed, proprietary teleconference dated March 19, 2021, the NRC staff discussed several issues with Framatome's RAI response. This RAI serves as follow-up for Framatome to respond to the NRC staff's issues regarding the response to RAIs 8, 9, and 10. These issues, include the following, and are discussed in detail below:

- Applicability of Framatome's arguments to ruptures occurring in both the alpha and beta phases of zirconium.

Framatome requested an opportunity to address these issues, and an audit was subsequently arranged for June 3, 2021 (ADAMS Package Accession No. ML21223A278). In the audit, Framatome discussed the general development of rupture strain curves, conservatisms of the EDGAR test facility, and insights drawn from tests performed at various facilities concerning [

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On June 24, 2021 (ADAMS Accession No. ML21183A056), the NRC staff held a follow up closed teleconference meeting with Framatome to discuss the June 3, 2021 audit topics. The NRC staff (1) stated that the information discussed by Framatome appears primarily relevant to ruptures occurring in the alpha phase of zirconium and (2) identified areas where the audited information did not appear fully to address the NRC staff's concerns about ruptures occurring in the beta phase or the transitional alpha plus beta region. Further discussion of these topics occurred in a closed teleconference meeting on September 17, 2021 (Reference 1-2).

1.2 *Regulatory Basis*

In accordance with 10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," realistic evaluation models for analysis of the LOCA event must include sufficient justification to show the analytical technique realistically describes event behavior with an explicit accounting for uncertainty such that there is a high level of probability that the criteria in 50.46(b) would not be exceeded. To support the acceptability of evaluation models conforming to Appendix K, "ECCS Evaluation Models," to 10 CFR 50, Appendix K states that swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated.

1.3 *Request for Additional Information*

The following RAI requests additional information to address the NRC staff's remaining issues with Framatome's response to RAIs 8-10 and the information presented during the audit on June 3, 2021.

(a) Please submit for review an appropriately detailed summary of the information presented during the audit held on June 3, 2021.

(b) To support completion of the NRC staff's review of Revision 2 of BAW-10227P, please further address either item i. or ii. below:

i. As discussed in further detail below, conclusions made by Framatome concerning the rupture strain behavior of zirconium in its beta phase and in the alpha plus beta region appear not fully supported by, and in some cases contrary to, references cited by Framatome in response to RAIs 8-10 and in audit materials reviewed by the NRC staff. Please provide additional evidence and justification that the arguments presented during the June 3, 2021, audit apply to cladding ruptures that occur in the beta phase and alpha plus beta region with sufficient confidence to satisfy the regulatory requirements of 10 CFR 50.46 and Appendix K. The response should address the following specific concerns discussed during the June audit and subsequent teleconferences:

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ii. Alternatively, please modify the existing rupture strain curves [

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1.4 *References*

1-1. Powers, D. A., and Meyer, R. O., "NUREG-0630, 'Cladding Swelling and Rupture Models for LOCA Analysis'," 1980.

1-2. NRC Staff, "NRC Staff Slide Presentation on RAIs 8-10," September 17, 2021 (ADAMS Accession No. ML21272A088).

1-3. Chung, H. and Kassner, T., "NUREG/CR-0344, 'Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam Under Transient-Heating Conditions: Summary Report'," 1978.

1-4. Grandjean, C., "A State-of-the-Art Review of Past Programs Devoted to Fuel Behavior Under LOCA Conditions. Part One. Clad Swelling and Rupture Assembly Flow Blockage (Technical Report SEMCA-2005-313)," 2005.

1-5. Erbacher, F. and Leistikow, S., "KfK-3973, 'A Review of Zircaloy Fuel Cladding Behavior in a Loss-of-Coolant Accident'," Kernforschungzentrum Karlsruhe, 1985.

1-6. Narukawa, T., and Amaya, M., "The Effect of Azimuthal Temperature Distribution on the Ballooning and Rupture Behavior of Zircaloy-4 Cladding Tube Under Transient-Heating Conditions," Journal of Nuclear Science and Technology, 2016.

1-7. Markiewicz, M.E. and Erbacher, F.J., "KfK 4343, 'Experiments on Ballooning in Pressurized and Transiently Heated Zircaloy-4 Tubes," Kernforschungszentrum Karlsruhe, 1988.

2.0 FOLLOW-UP RAI RESPONSE

NUREG-0800, Section 4.2 describes NUREG-0630 as the NRC-standard for acceptably modeling bursting (Reference 2-1: Section 1.B.vii) and rupture and flow blockage/ballooning (Reference 2-1: Section 3.C.vi). [

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The slow and fast ramp rupture strain curves for BAW-10227 Rev. 2 applications are shown in Figure 2-1 and Figure 2-2. The datapoints of these curves are shown in Table 2-1. Corresponding to those curves and the pre-rupture strain curves in Table 13-1 of Reference 2-3, the assembly blockage factors to be used in BAW-10227 Rev. 2 applications are supplied in Table 2-2.

2.1 *References*

2-1. NUREG-0800 Revision 3, “Chapter 4, Section 4.2, Fuel System Design” U.S. NRC Standard Review Plan, March 2007.

2-2. BAW-10227P-A Revision 1, “Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel,” June 2003.

2-3. BAW-10227P Revision 2, “Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel,” December 2019.

2-4. Letter, Ngola Otto (NRC) to Gary Peters (Framatome Inc.), “Request for Additional Information Regarding Framatome Inc. Topical Report, BAW-10227, Revision 2, ‘Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel’ (EPID L-2019-TOP-0054),” October 6, 2021.

2-5. Letter, Gary Peters (Framatome Inc.) to Document Control Desk (NRC), “Response to Request for Additional Information Regarding BAW-10227P, Revision 2, ‘Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel’,” NRC:20:032, December 18, 2020.

Table 2-1: M5Framatome Rev. 2 SRM Slow and Fast Ramp Rate Rupture Strains

Table 2-2: M5$_{\text{Framatome}}$ Rev. 2 SRM Slow and Fast Ramp Rate Assembly Blockage Factors

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Figure 2-1: M5$_{\text{Framatome}}$ Rev. 2 SRM Slow Ramp Rate Rupture Strain Curve [

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Figure 2-2: M5$_{\text{Framatome}}$ Rev. 2 SRM Fast Ramp Rate Rupture Strain Curve [ ]

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3.0 TOPICAL REPORT MARKUPS

The following sections of the as submitted Topical Report will be changed in the approved version of the topical report. Change pages are presented in Attachment A.

- Within the Abstract, Section 2.0, Section 13.1.2, Section 13.1.3, Section 13.1.4.3, Section 13.1.4.4, Table 13-1 through Table 13-3 titles and headings, and Figure 13-3 title, general text modifications are made for clarification, consistency, and to reflect the RAI response.
- [ ]
- Figure 13-4 is deleted.
- Figure 13-5 is replaced.
- Figure 13-6 is deleted.
- Figure 13-7 is replaced.
- Table 13-2 is updated.
- Table 13-3 is updated.
- References [26] through [29] are deleted with subsequent references renumbered.

Attachment A

BAW-10227NP Revision 2
Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel

Topical Report
Markups

ABSTRACT

The purpose of this topical report is to present the definition and characteristics for M5$_{\text{Framatome}}$ material as an advanced cladding and structural material for use in pressurized water reactor (PWR) fuel assemblies. This report provides updates to the M5$_{\text{Framatome}}$ material characteristics based on data collected since the approval of BAW-10227P-A Revision 1 (Reference [1]). The iron content of M5$_{\text{Framatome}}$ material was previously updated in Reference [2]. NRC approval for M5$_{\text{Framatome}}$ material as a fuel rod cladding material is requested to [

] The M5$_{\text{Framatome}}$ material is a proprietary variant of Zr - 1 wt. % Nb.

A discussion is presented of the current regulatory guidance related to cladding as well as structural material. This guidance is found primarily in NUREG-0800 Section 4.2 (Reference [3]). A comparison of applicable NUREG-0800 Section 4.2 criteria and the design evaluation input for the M5$_{\text{Framatome}}$ material is provided.

The composition of M5$_{\text{Framatome}}$ material is defined. The M5$_{\text{Framatome}}$ microstructure and manufacturing process is described. The irradiation experience with M5$_{\text{Framatome}}$ material to-date is summarized. Fuel assemblies with M5$_{\text{Framatome}}$ cladding, guide tubes, instrument tubes, and spacer grids have been irradiated and provide information about the material behavior.

The physical properties, mechanical behavior, oxidation and hydrogen pick-up fractions, irradiation growth and creep are defined. The application of these properties to design evaluations is summarized and the impact on component performance is discussed. An updated model for fuel rod growth is provided, and the fuel assembly growth correlation is confirmed. [

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1.0 INTRODUCTION

The purpose of this topical report is to present the definition and characteristics for $M5_{Framatome}$ (also referred to as M5) material as an advanced cladding and structural material for use in PWR fuel assemblies. $M5_{Framatome}$ material is a proprietary variant of Zr - 1 wt. % Nb. This report provides updates to the material characteristics based on data collected since the approval of BAW-10227P-A Revision 1 (Reference [1]),

[

] The iron content was previously updated in Reference [2]. This revision does not invalidate models approved in previous revisions for application in various methods~~ except as identified in Section 13.1.2~~.

NRC approval for $M5_{Framatome}$ material as a fuel rod cladding material is requested [

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Section 3.0 discusses the regulatory requirements of the Standard Review Plan, and Section 4.0 defines the requested range of applicability. Section 5.0 provides a definition of $M5_{Framatome}$ material including its composition and microstructural state. Framatome's operating experience with $M5_{Framatome}$ components is described in Section 6.0. The physical and mechanical properties are provided in Sections 7.0 and 8.0, respectively. Section 9.0 presents the oxidation and hydrogen pickup models. Section 10.0 discusses various aspects of performance that are relevant to fuel system damage and fuel rod failure. Creep and free growth are discussed in Section 11.0. Material performance in non-LOCA accidents is discussed in Section 12.0 and the material performance in LOCA is presented in Section 13.0. Framatome's planned ongoing surveillance is covered in Section 14.0. Future data may require updates to models in this report. Section 15.0 describes a process for updating the report.

2.0 SUMMARY

This topical report describes operating experience, reactor performance, and models needed to design and analyze $M5_{Framatome}$ cladding and structural components. An update process is defined that facilitates Framatome's ability to monitor future performance of $M5_{Framatome}$ material and to update the models as necessary.

The following approach is used to demonstrate that $M5_{Framatome}$ material is suitable for use in fuel assemblies:

- The Standard Review Plan (Reference [3]) is reviewed to determine the criteria that apply to cladding, guide tubes, instrument tubes, and spacer grids.
- A definition of $M5_{Framatome}$ material is provided, in terms of both composition and manufacturing processes. The definition provides confidence that the material will retain its distinctive characteristics and that future performance will be consistent with the available experience.
- The materials-related input for design evaluations of these components is identified. Some of the input, such as density and the coefficients of thermal expansion, are used directly in analytical models. Values or equations for the input, based on laboratory measurements, are provided. Other input, such as corrosion rate and fuel assembly growth, can only be determined by irradiation tests. Empirical correlations based on irradiation experience are provided. All of the materials-related input needed to show compliance with the Standard Review Plan is discussed.
- Performance under Loss of Cooling Accident (LOCA) conditions is discussed, including a concise summary of the swelling and rupture model, high temperature oxidation, and applicability of the 10 CFR 50.46 criteria. [

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4.0 RANGE OF APPLICABILITY

$M5_{Framatome}$ material is an advanced cladding and structural material used in pressurized water reactor fuel. Material properties and performance models are updated in this revision, based on the expanded test database since the approval of BAW-10227P-A Revision 1 (Reference [1]). $M5_{Framatome}$ material limits are [

] This revision is consistent with the $M5_{Framatome}$ cladding models applied in Framatome's advanced fuel rod performance code (Reference [4]).

The updated models in this revision are intended for [

] The range of applicability is addressed with each model. This revision does not invalidate models approved in previous revisions for application in various methods ~~except as identified in Section 13.1.4~~.

13.1.2 Swelling and Rupture Database Updates

Following NRC approval of the swelling and rupture model in Appendix K of Reference [1], EDGAR testing of M5$_{Framatome}$ cladding continued. [

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~~Three LOCA methods utilize the swelling and rupture model approved in Reference [1]. Reference [1] directly addressed the incorporation of the M5~~$\cancel{_{Framatome}}$ ~~cladding properties into the B&W LOCA methodology (Reference [26], as amended by Reference [27]) through user inputs. The M5~~$\cancel{_{Framatome}}$ ~~material properties in the W&CE plant type Small Break LOCA methodology (Reference [28]) were incorporated by Reference [8]. The Realistic Large Break LOCA (RLBLOCA) Revision 0 methodology (Reference [29]) did not include the swelling and rupture model. The swelling and rupture model is part of the RLBLOCA Revision 3 methodology (Reference [10]).~~

~~The approval of Revision 2 of this topical report updates the approved swelling and rupture model to be used in those methodologies that incorporate the model, including the following:~~

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13.1.3 Description of EDGAR Tests

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13.1.4 Swelling and Rupture Model

The M5Framatome swelling and rupture model was developed in a similar manner to the NUREG-0630 (Reference [25]) Zircaloy models, and accordingly has the same general features. [ ]

13.1.4.4 Assembly Blockage Factors

It is important to characterize assembly blockage so that effects of clad swelling, such as flow diversion, can be simulated. [

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4. The core geometry remains amenable to cooling - The implication of this criterion is that the core shall remain in a condition that can be readily cooled by the type of short- and long-term cooling mechanisms provided by the plant ECCS. While the calculated core geometry can be dependent on the cladding, the criterion itself is not related to nor affected by the cladding material. This 10 CFR 50.46 criterion is therefore applicable to fuel with $M5_{Framatome}$ cladding.

5. Long-term core cooling is maintained - Maintaining long-term ECCS recirculation coolant delivery provides assurance that core geometry remains stable and further fuel cladding damage (beyond that experienced during the initial period of accident) would be minimal. This is a plant system requirement and the criterion itself is not related to nor affected by the cladding material. This 10 CFR 50.46 criterion is therefore applicable to fuel with $M5_{Framatome}$ cladding.

The high temperature metal-water reaction results in oxidation of the cladding (Section 13.2). The oxidation results in the development of an outer surface Zr-oxide layer and diffusion of oxygen in solid solution into the metal substrate, forming an oxygen-stabilized α-Zr layer, and a β-Zr layer with low oxygen content. With increasing time, diffusion of oxygen into the metal will convert more and more of the beta phase to the oxygen-stabilized alpha phase– the alpha layer grows and the beta region shrinks. Following quench, three distinct regions remain, as shown in Figure 13-12 (Reference ~~[30]~~[26]), the ZrO_2 layer, the oxygen stabilized alpha layer, and the prior-beta layer. The ZrO_2 layer and oxygen stabilized alpha phase are brittle at low temperature and therefore do not contribute to the cladding integrity. The prior-beta phase ductility and mechanical resistance depend on the oxygen concentration. With sufficiently low oxygen concentrations, the prior-beta region can remain ductile.

Mechanical tests were performed on samples oxidized at high temperatures (Section 13.2) to study the post-quench performance of $M5_{Framatome}$ cladding. [

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The results of the RCT tests on samples oxidized at 1200 °C are shown in Figure 13-13. The residual ductility is shown as a function of the calculated Baker-Just ECR (% BJ ECR). [

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These RCT results demonstrate the comparable performance of Zr-4 and M5$_{\text{Framatome}}$ cladding and clearly show that M5$_{\text{Framatome}}$ samples were not brittle below the 17% BJ ECR limit (13% CP ECR). This conclusion is further strengthened by Figure 13-14 which presents the same information, but for all four oxidation temperatures. These results are also in line with the results in Reference ~~[30]~~[26], summarized by Figure 24, and the proposed NRC-acceptable PQD limit in Figure 2 of Reference ~~[31]~~[27] that show that unirradiated M5$_{\text{Framatome}}$ cladding retains ductility to at least 18% CP ECR and 2200 °F.

Section 13.2 demonstrated that there is no increase in the oxidation kinetics as compared to Zr-4 below 1250 °C (2282 °F) and that the Baker-Just correlation is applicable. In combination with the RCT results demonstrated in this section, it is concluded that the 2200 °F and 17% ECR limit are applicable to M5$_{\text{Framatome}}$ cladding.

Table 13-1: M5Framatome SRM Slow and Fast Ramp Rate Pre-Rupture Strains ~~Model for M5Framatome Cladding~~

Table 13-2: M5Framatome SRM Slow and Fast Ramp Rate Rupture Strains ~~Model for M5Framatome Cladding~~

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Table 13-3: M5$_{Framatome}$ SRM Slow and Fast Ramp Rate Assembly Blockage Factors~~Model with M5$_{Framatome}$ Cladding~~

Figure 13-3: $M5_{Framatome}$ SRM Slow and Fast ~~Heating~~ Ramp Rate Pre-Rupture Strain Curves ~~for $M5_{Framatome}$ Cladding~~

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Figure 13-4: Deleted~~Fast Heating Ramp Rate Rupture Strain Curves and EDGAR Rupture Strain Data for M5$_{Framatome}$ Cladding~~

Figure 13-5: M5$_{Framatome}$ SRM Slow and Fast ~~Heating~~ Ramp Rate Rupture Strain Curves ~~for M5$_{Framatome}$ Cladding~~

[ ]

Figure 13-6: Deleted~~Fast Heating Ramp Rate Assembly Blockage Curves with M5~~~~Framatome~~ ~~Cladding~~

Figure 13-7: M5$_{\text{Framatome}}$ SRM Slow and Fast ~~Heating~~ Ramp Rate Assembly Blockage Curves ~~with M5$_{\text{Framatome}}$ Cladding~~

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[18] ANP-10337P-A Revision 0, "PWR Fuel Assembly Structural Response to Externally Applied Dynamic Excitations," April 2018.

[19] BAW-10084P-A, Revision 3.0, "Program to determine in-reactor performance of BWFC fuel cladding creep collapse".

[20] EMF-92-116(P)(A) Revision 0, "Generic Mechanical Design Criteria for PWR Fuel Designs," February 1999.

[21] ANP-10342PA, Revision 0, GAIA Fuel Assembly Mechanical Design, September 2019.

[22] BAW-10179P-A Revision 3, "Safety Criteria and Methodology for Acceptable Cycle Reload Analyses," October 1999.

[23] BAW-10179P-A Revision 9, "Safety Criteria and Methodology for Acceptable Cycle Reload Analyses," November 2017.

[24] XN-75-32(P)(A) Supplements 1, 2, 3, and 4, "Computational Procedure for Evaluating Fuel Rod Bowing," October 1983.

[25] D.A. Powers and R.O. Meyer, NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis," April 1980.

~~[26] BAW-10192P-A Revision 0, "BWNT LOCA – BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants," June 1998.~~

~~[27] BAW-10192P-A Revision 0 Supplement 1P-A Revision 0, "BWNT LOCA – BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Stream Generator Plants," November 2017.~~

~~[28] EMF-2328(P)(A) Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," March 2001.~~

~~[29] EMF-2103(P)(A) Revision 0, "Realistic Large Break LOCA Methodology for Pressurized Water Reactors," April 2003.~~

~~[30]~~[26] NUREG/CR-7219, "Cladding Behavior During Postulated Loss-of-Coolant Accidents," NRC ADAMS Accession Number ML16211A004, July 2016.

~~[31]~~[27] Pre-Decisional Regulatory Guide 1.224, "Establishing Analytical Limits for Zirconium-Alloy Cladding Material," NRC ADAMS Accession Number ML16005A133.

~~[32]~~[28] BAW-10164P-A Revision 6, "RELAP5/MOD2-B&W – An Advanced Computer Program for Light Water Reactor LOCA and Non-LOCA Transient Analysis," June 2007.