Westinghouse Non-Proprietary Class 3

WCAP-18869-NP-A
Revision 0

May 2026

High Performance Cladding for use in Boiling Water Reactor Fuel

Westinghouse

WCAP-18869-NP-A
Revision 0

High Performance Cladding for use in Boiling Water Reactor Fuel

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May 2026

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Section A

Final Safety Evaluation

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 9, 2026

Mr. Jerrod Ewing
Manager, Operating Plants Licensing
Westinghouse Electric Company
1000 Westinghouse Drive, Building 1
Cranberry Township PA 16066

SUBJECT: FINAL SAFETY EVALUATION FOR WESTINGHOUSE ELECTRIC COMPANY TOPICAL REPORT WCAP-18869-P/NP, REVISION 0, “HIGH PERFORMANCE CLADDING FOR USE IN BOILING WATER REACTOR FUEL” (EPID L-2024-TOP-0007)

Dear Mr. Ewing,

By letter dated March 8, 2024 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML24072A267), Westinghouse Electric Company (Westinghouse) submitted Topical Report (TR) WCAP-18869-P/NP, Revision 0, “High Performance Cladding for Use in Boiling Water Reactor Fuel” (Proprietary/Non-proprietary), for the U.S. Nuclear Regulatory Commission (NRC) review and approval. By the letter dated December 17, 2025 (ML25253A373), the NRC issued its draft safety evaluation (SE). Based on its review of the information submitted in the TR, the NRC staff finds the TR acceptable for referencing subject to the limitations specified in the TR, and in the NRC safety evaluation (SE).

Please find enclosed proprietary and non-proprietary versions of the NRC staff’s final SE’s for TR WCAP-18869-P/NP, Revision 0, “High Performance Cladding for Use in Boiling Water Reactor Fuel.” The NRC staff has found the TR acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the TR and in the NRC final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the accepted material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plants-specific review in accordance with applicable review standards.

NOTICE: Enclosure 2 to this letter contains Proprietary Information. Upon separation from Enclosure 2, this letter is DECONTROLLED.

In accordance with the guidance provided on the NRC website, we request that Westinghouse publish accepted versions of the proprietary and non-proprietary TR within 20 business days of the receipt of this letter. The accepted proprietary version shall incorporate this letter and the proprietary final SE (Enclosure 2), and the accepted non-proprietary version shall incorporate this letter and the non-proprietary final SE (Enclosure 1) after the title page. Also, the accepted versions must contain historical review information, including NRC requests for additional information (RAIs) and your responses after the title page. The accepted version shall include an "-A" (designating accepted) following the TR identification symbol.

As an alternative to including the RAIs and RAI responses behind the title page, if changes to the TRs were provided to the NRC staff to support the resolution of RAI responses, and the NRC staff reviewed and approved those changes as described in the RAI responses, there are two ways that the accepted version can capture the RAIs:

1. The RAIs and RAI responses can be included as an Appendix to the accepted version.
2. The RAIs and RAI responses can be captured in the form of a table (inserted after the final SE) which summarizes the changes as shown in the approved version of the TR. The table should reference the specific RAIs and RAI responses which resulted in any changes, as shown in the accepted version of the TR.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, Westinghouse will be expected to revise the TR appropriately. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

If you have any questions, please contact Ekaterina Lenning via phone at 301-415-3151 or via email at Ekaterina.Lenning@nrc.gov.

Sincerely,

/RA/

Damaris Marcano, Branch Chief
Licensing Projects Branch
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation

Docket No. 99902038

Enclosures:
1. Final SE (Non-Proprietary)
2. Final SE (Proprietary)

SUBJECT: FINAL SAFETY EVALUATION FOR WESTINGHOUSE ELECTRIC COMPANY TOPICAL REPORT WCAP-18869-P/NP, REVISION 0, "HIGH PERFORMANCE CLADDING FOR USE IN BOILING WATER REACTOR FUEL" (EPID L-2024-TOP-0007) DATED MARCH 9, 2026

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U.S. NUCLEAR REGULATORY COMMISSION

OFFICE OF NUCLEAR REACTOR REGULATION

FINAL SAFETY EVALUATION

TOPICAL REPORT WCAP-18869-P/NP, REVISION 0

“HIGH PERFORMANCE CLADDING FOR USE IN BOILING WATER REACTOR FUEL”

WESTINGHOUSE ELECTRIC COMPANY

DOCKET NO. 99902038; EPID L-2024-TOP-0007

1.0 INTRODUCTION

By letter dated March 8, 2024 (Ref. 1), Westinghouse Electric Company (Westinghouse) submitted Topical Report (TR) WCAP-18869-P/NP, Revision 0, “High Performance Cladding for Use in Boiling Water Reactor Fuel” (Proprietary/Non-proprietary), for the U.S. Nuclear Regulatory Commission (NRC) staff review and approval.

This cladding material is a zirconium (Zr)-based alloy designed to maximize the safety margins for boiling water reactor (BWR) fuel, amid increasing demands for higher fuel duties and burnup, by reducing the hydrogen uptake. Westinghouse stated that it **[**

].

The improved performance of HiFi™ cladding is the result of optimizing the Zr-based alloy dopants of iron (Fe) and chromium (Cr).

The NRC staff conducted a regulatory audit of the WCAP-18869-P/NP, Revision 0, on December 12-13, 2024 (Refs. 2 and 3), to ensure that the NRC staff had proper understanding of the TR, had access to all the information it needed to perform the review, and fully understood the scope of the TR. After the NRC staff’s preliminary review and results of the audit, the NRC staff issued its request for additional information (RAI) (Ref. 4).

2.0 REGULATORY EVALUATION

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic Licensing of Production and Utilization Facilities,” contains the general design criteria (GDC) described in Appendix A to Part 50, including, GDC 10, “Reactor design,” GDC 25, “Protection system requirements for reactivity control malfunctions,” GDC 26, “Reactivity control system redundancy and capability,” GDC 27, “Combined reactivity control systems capability,” GDC 28, “Reactivity limits,” and GDC 35, “Emergency core cooling.”

Enclosure 1

GDC 10 states:

> The reactor core and associated coolant, control, and protection systems shall be designed with the appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

GDC 10 establishes specified acceptable fuel design limits to ensure that the fuel is not damaged. That means that fuel rods do not fail, fuel system dimensions remain within operational tolerances, and functional capabilities are not reduced below those assumed in the safety analysis. NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants – LWR Edition” (SRP), Section 4.2, “Fuel System Design,” acceptance criteria are based on meeting the requirements of GDC 10.

Requirements for analyzing the design-basis loss-of-coolant accident (LOCA) are provided in 10 CFR 50.46, Appendix K to 10 CFR Part 50, and GDC 35. The most relevant regulations to this review are:

- Per 10 CFR 50.46(a)(1)(i), each boiling or pressurized light-water nuclear power reactor fueled with uranium oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with an emergency core cooling system (ECCS) that must be designed so that its calculated cooling performance following postulated LOCAs conforms to the criteria set forth in Section 50.46(b). ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated.

- 10 CFR Part 50, Appendix K, sets forth the documentation requirements for each evaluation model and establishes the required and acceptable features of evaluation models for heat removal by the ECCS.

- GDC 35 requires abundant emergency core cooling sufficient to (1) prevent fuel and cladding damage that could interfere with effective core cooling and (2) limit the metal-water reaction on the fuel cladding to negligible amounts.

Regulatory guidance for the NRC staff review of fuel system designs that shows conformance to these GDC is provided in SRP, specifically, Section 4.2 (Ref. 5). Additionally, SRP Section 4.3, “Nuclear Design” (Ref. 6), and Section 4.4, “Thermal and Hydraulic Design” (Ref. 7), are pertinent to the review of fuel systems.

Consistent with SRP Section 4.2, the objectives of the fuel system safety review are to provide assurance that:

- The fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs),

- Fuel system damage is never so severe as to prevent control rod insertion when it is required,

- The number of fuel rod failures is not underestimated for postulated accidents, and
- Coolability is always maintained.

SRP Chapter 15, “Transient and Accident Analyses” (Ref. 9), including acceptance criteria for AOOs and postulated accidents and their impact on HiFi cladding, is addressed in the TR. The NRC staff’s review of this TR is based on the acceptance criteria for each of the events described in SRP Chapter 15.

3.0 TECHNICAL EVALUATION

3.1 Alloy Definition

The HiFi alloy was developed to reduce the hydrogen uptake to meet evolving requirements imposed on fuel cladding materials for BWR nuclear fuel, in particular, increasing demands for higher fuel duties and burnup. **[**

]. HiFi is a Zr alloy with higher Fe content and **[**
] than that of Zircaloy-2 cladding, the material currently in use in BWR fuel produced by Westinghouse. Table 1-1 in Section 1.3 of the TR WCAP-18869-P/NP, Revision 0, compares the chemical composition of HiFi and Zircaloy-2. HiFi cladding is defined to have a nominal **[**

] specified for Zircaloy-2 cladding in Reference 13. **[**

].

Table 1-1 Chemical composition of new BWR alloy and Zircaloy-2 alloys

[ ]

Element (wt%)	Zircaloy-2 Alloy (Reference 4)
Sn	1.20-1.70
Fe	0.07-0.20
Cr	0.05-0.15
Ni	0.03-0.08
O	0.09-0.16
Zr	Balance

Westinghouse determined the final chemical composition of the HiFi cladding following extensive out-of-core testing, aiming to optimize manufacturability, mechanical properties, corrosion and hydrogen pickup.

3.2 Phase Transformation and Microstructure

For temperatures below about 750 degrees Celsius (°C), Zr is in the so called α phase, and for temperatures above 1000°C, Zr is in the β phase. There is a mixed phase region, which varies depending on the alloy. In the Zircaloy-2, the mixed phase region covers the temperature range from 750 to 1000°C, and the precipitates are dissolved at about 850°C.

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3.3 Properties and Experience

The data for the HiFi alloy has been collected in two separate development programs: (1) a high Fe cladding that was developed by NFI and (2) Westinghouse acquired relevant experience with **[**

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3.3.1 Manufacturing Process

WCAP-18869-P/NP, Revision 0, states that HiFi cladding for Westinghouse nuclear fuel designs is manufactured following the same steps as the current Zircaloy-2 LK3 cladding. Processing of cladding tubes is commonly tailored to the chemical composition and to the equipment capabilities of each manufacturer to optimize the microstructure for robust performance.

In the response to RAI 7 (Ref. 4), Westinghouse states that with the exception of **[**

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In summary, **[** **]**:

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

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Table 3-3 and Table A-1 in TR WCAP-18869-P/NP, Revision 0, demonstrated that the most obvious trend is that [ ]. Typical average SPP sizes vary [ ].

The NRC staff reviewed the information and determined that a very small difference in SPP size between Zircaloy-2 and HiFi is not expected to result in any detrimental effects on performance, as demonstrated by testing results presented in later sections of the TR.

After reviewing the manufacturing process information provided by Westinghouse, the NRC staff concluded that the manufacturing processes used for HiFi cladding show only minimal differences between manufacturers, driven mainly by the capabilities of different manufacturers. These small differences do not result in significant differences in the resulting annealing parameters and associated microstructures, which demonstrate the equivalence of the manufacturing processes for the HiFi new alloy, as well as the closeness to the extensive experience of Zircaloy-2 cladding.

3.3.2 Materials Properties

3.3.2.1 Chemical Composition

WCAP-18869-P/NP, Revision 0, states that for normal production, samples for chemical analysis are taken from the top, middle, and bottom of the ingot. All the results (Table A-2 in the Appendix to the TR WCAP-18869-P/NP, Revision 0) fulfill the requirements of the material specification and the alloy definition in Table 1.1 and demonstrate the consistency of the chemical composition in the different sections of the ingot and throughout the process.

3.3.2.2 Thermal Properties

The TR WCAP-18869-P/NP, Revision 0, states that relevant thermal properties have been measured for HiFi cladding at three different temperatures (25°C, 300°C, and 1000°C). In Section 3.2.2, Table 3-4 of the TR WCAP-18869-P/NP, Revision 0, the thermal properties of HiFi cladding are compared to measured or reference values for Zircaloy-2 cladding, including Table A-3 in the appendix which summarizes additional results on thermal diffusivity, heat capacity, and thermal conductivity at different temperatures. The NRC staff concluded that **[**

].

Emissivity depends strongly on the surface condition and the presence of any oxide. The NRC staff concluded that HiFi cladding has the same emissivity as Zircaloy-2 within the experimental uncertainty since **[**

].

3.3.2.3 Mechanical Properties

Mechanical properties of HiFi cladding with different compositions fabricated for Westinghouse 10x10 fuel and TRITON11 fuel with the standard Westinghouse Zr-tin(Sn) liner have been tested in order to verify that the material meets the specification of Zircaloy-2 cladding. Tensile and burst tests were performed. The results shown in Section 3.2.3, Table 3-5; and Table A-4 and Table A-5 in the appendix to the TR WCAP-18869-P/NP, Revision 0, fulfill the specification requirements with margin and are comparable to the experience of Zircaloy-2. The NRC staff determined that the differences between the two materials are within the variability of the measurements, and the values are well above the minimum specification limits. There is a small difference in yield strength values between the qualified suppliers due to minor differences in conditions for the final cold pilger and the final recrystallization anneal. All suppliers fulfil the specification requirements with margin.

The NRC staff has reviewed the differences in the mechanical properties of HiFi to that of Zircaloy-2 cladding and determined the properties of HiFi to be within those assumed in the safety analysis for Zircaloy-2 cladding. Therefore, the NRC staff concluded that **[**

].

3.3.2.3.1 Thermal Creep

WCAP-18869-P/NP, Revision 0, states that samples of HiFi cladding fabricated for different fuel designs were tested [ ]. The results are shown in Section 3.2.3.1, Table 3-6 of the TR, and are compared with the similar tests performed for Zircaloy-2 LK3 cladding. The NRC staff concludes that the results demonstrate that the thermal creep of HiFi cladding is [ ].

Irradiation creep is discussed in Section 3.4.2.3 of WCAP-18869-P/NP, Revision 0, which states that [ ] regarding irradiation creep.

Westinghouse stated in the response to RAI 4 (Ref. 4) that since the measurements demonstrate that the creep behavior of HiFi cladding [ ].

Figure 10 in the Westinghouse's response to RAI 4 presents results from calculation of the irradiation cladding creep for a TRITON11 fuel rod with the fuel performance code STAV7.2. The irradiation creep is a function of fluence and no pellet cladding mechanical interaction (PCMI) or differential pressure effects are considered.

Figure 11 in Westinghouse's RAI 4 response contains calculations of lift-off pressure for TRITON11 fuel with the BWR fuel performance code described in WCAP-15836-P-A (STAV7.2). Since [ ].

The accuracy of the predicted lift-off pressure will depend on the ability of the fuel performance code and methods to correctly capture the behavior of the specific fuel/cladding materials being used. The NRC staff reviewed Westinghouse's response to RAI 4 and concluded that [ ] applicable to the HiFi

3.3.2.3.2 Texture and Contractile Strain Ratio

The texture of HiFi cladding tubes fabricated in multiple designs and reference Zircaloy-2 tubes produced with the same manufacturing parameters has been evaluated using laboratory X-ray diffraction by Westinghouse. Samples [ ], were also tested for CSR, a bulk

The NRC staff has reviewed the differences in the [ ].
Therefore, the NRC staff concluded that [ ] for HiFi cladding acceptable for use in Westinghouse fuel rod safety analysis evaluation models.

3.3.2.4 Material Properties for Fuel Rod Design Methods

With a change from Zircaloy-2 cladding to HiFi cladding, the properties of interest for fuel rod design are the thermo-mechanical properties of the fuel cladding material. Thermo-mechanical properties of Zr alloys are functions of temperature, burnup and/or fast neutron fluence. The following paragraphs evaluate **[**
] for HiFi cladding.

3.3.2.4.1 Thermal Properties

The thermal conductivity and thermal expansion of Zr alloys are primarily functions of temperature.

The NRC staff reviewed the Table 3.4 results in Section 3.2.2 of WCAP-18869-P/NP, Revision 0, which show **[**
].

Therefore, the NRC staff concluded that **[**
] are applicable to HiFi cladding.

3.3.2.4.2 Elastoplastic Properties

Properties such as elastic moduli, Poisson’s ratio, strength coefficients, strain rate, and strain hardening are functions of temperature, oxygen content, cold work, and fast neutron fluence.

The NRC staff determined that the operational experience and tests on unirradiated and irradiated material, presented in Sections 3.3 and 3.4 of WCAP-18869-P/NP, Revision 0, demonstrate that the mechanical behavior of HiFi cladding **[**
].

3.3.3 Out-Of-Pile Testing

3.3.3.1 Uniform Corrosion and Hydrogen Pickup

HiFi and Zircaloy-2 tubes **[**
]. The results are shown in Section 3.3.1, Figure 3-1 of TR WCAP-18869-P/NP, Revision 0, illustrating that the uniform corrosion resistance of HiFi cladding is very similar to that of Zircaloy-2 cladding. More importantly, the in-reactor experience of HiFi cladding compared to Zircaloy-2 cladding, described in Section 3.4 of the TR, also supports this conclusion.

Figure 3-2 and Figure 3-3 in Section 3.3.1 of TR WCAP-18869-P/NP, Revision 0, demonstrate that the hydrogen content and hydrogen pickup fraction of HiFi cladding behavior observed in autoclave corrosion tests are significantly lower than that of Zircaloy-2 cladding.

WCAP-18869-P/NP, Revision 0, also demonstrated that HiFi cladding with different compositions within the range according to Table 1-1 of the TR, fabricated to the specification for SVEA-96 Optima2 and SVEA-96 Optima3 fuel, **[** **]**. The NRC staff determined that the results shown in Table 3-7 of the TR further demonstrate a lower hydrogen pickup fraction for HiFi cladding with respect to Zircaloy-2 cladding. Westinghouse stated in WCAP-18869-P/NP, Revision 0, that the distribution of hydrides was verified in the outer component. **[** **]**, as illustrated in Figure 3-4 of the TR. The NRC staff concluded that the orientation of the hydrides is consistent with the experience with Zircaloy-2 LK3.

3.3.3.2 Nodular Corrosion

Westinghouse indicated in TR WCAP-18869-P/NP, Revision 0, that the plates of manufactured alloys were evaluated for nodular corrosion resistance by corrosion testing in steam at 525°C for 24 hours. As shown in Section 3.3.2, Figure 3-5 of the TR, the nodular corrosion resistance of Zircaloy-2 material is degraded as the annealing parameter ΣA is increased over 10^{-18}, as illustrated by the scatter in weight gain, while HiFi material maintains nodular corrosion resistance up to 10^{-17}.

Westinghouse demonstrated in TR WCAP-18869-P/NP, Revision 0, that the nodular corrosion tests were performed on **[** **]**. Based on the results of its review, the NRC staff determined that **[** **]**.

3.3.3.3 Loss-of-Coolant Accident Behavior

Westinghouse stated in WCAP-18869-P/NP, Revision 0, that out-of-pile tests were performed using HiFi cladding tubes fabricated for **[** **]** to evaluate the LOCA behavior.

Based on the testing results shown in Figure 3-6 and Figure 3-7 in Section 3.3.3 of the TR, the NRC staff determined that the high temperature corrosion behavior of HiFi cladding is **[** **]**
The NRC-approved corrosion model for the BWR fuel performance code STAV7.2 is found in WCAP-15836-P-A (Ref. 10). Validation was done with the Zircaloy-2 alloys **[** **]** in WCAP-15836-P-A with the aim to have a bounding model **[** **]**. An additional Westinghouse validation of the current STAV7.2 model with **[** **]**. Figure 7 in Westinghouse response to RAI 3 contains the used validation database. The NRC staff concluded that the model in STAV7.2 **[** **]** HiFi cladding corrosion.

High temperature burst tests were performed and confirmed that the burst behavior for HiFi and Zircaloy-2 materials is very similar, as illustrated in Section 3.3.3, Figure 3-8 of WCAP-18869-P/NP, Revision 0. Furthermore, burst testing has been performed **[** **]**. In addition, Westinghouse has performed **[** **]**. The NRC staff determined that **[** **]**.

The NRC staff reviewed WCAP-18869-P/NP, Revision 0, and concluded that the TR demonstrated the **[** **]** of failure thresholds relative to equivalent cladding reacted (ECR) and temperature for HiFi and Zircaloy-2 cladding. **[** **]** based on the tests that were performed in axial non-restrained and fully restrained conditions during quenching in Figure 3-9 of the TR.

3.3.4 Irradiation Experience

The extensive irradiation experience of HiFi cladding in different applications is presented in Section 3.4 of TR WCAP-18869-P/NP, Revision 0, detailing that HiFi cladding has been subjected to irradiation in different forms and in different facilities.

Table 3-9 in Section 3.4 of TR WCAP-18869-P/NP, Revision 0, summarizes the irradiation experience for HiFi cladding, and the following sections of this safety evaluation (SE) describe the results of the irradiation programs that have been already completed. All the irradiation programs and post-irradiation examination (PIE) included both HiFi and Zircaloy-2 cladding to compare the performance side-by-side.

3.3.4.1 Plant A – **[** **]**

Coupons made from prototypic HiFi and Zircaloy-2 alloys were placed in a container loaded into the water channel of 9x9 fuel in **[** **]**.

In the test, coolant was circulated in the container to prevent the coupon surface from reaching boiling temperatures. The coupon temperature was estimated to be 275°C. After undergoing three irradiation cycles (totaling 900 days), **[** **]**, the container holding the coupons was transferred to a PIE facility. Visual inspection, metallographic analysis, hardness analyses, and hydrogen analyses were conducted. **[** **]**

[

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Westinghouse demonstrated in Section 3.3.2 of TR WCAP-18869-P/NP, Revision 0, that the findings on the relationship between the annealing parameter ΣA and nodular corrosion resistance aligned with the ex-core nodular corrosion tests. Specifically, **[**

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3.3.4.2 Kashiwazaki-Kariwa 5

As described in TR WCAP-18869-P/NP, Revision 0, the irradiation program at Kashiwazaki-Kariwa Unit 5 (K5) was developed to **[**

]. This extensive program involved **[**

].

The coupons inside the capsules underwent six irradiation cycles over roughly 2,500 days, achieving an equivalent burnup of 72 GWd/MTU and a fast fluence of 15×10^{25} n/m². Although coolant circulated within the capsules, the coupon surfaces were estimated to be in a boiling state due to γ-heating. TRAC code simulations indicated a void fraction of about 20 percent and a coupon temperature of 285°C. The interior of the capsules remained stable and consistent throughout the six cycles. TEM discs were kept in an inert atmosphere to prevent oxidation.

[

]. Measurements of oxide thickness during irradiation of coupons in K5, along with **[** **]**, showed close proximity of data points, including some overlap, from side-by-side samples of HiFi and Zircaloy-2 tested under the same conditions. This indicates **[**

].

Figure 3-13 in TR WCAP-18869-P/NP, Revision 0, illustrates the hydrogen pickup fraction of the K5 coupons. In alignment with the out-of-pile tests, the uniform corrosion between Zircaloy-2 and HiFi cladding is comparable. However, the hydrogen pickup fraction of HiFi cladding is significantly lower than that of Zircaloy-2 cladding. For both materials, the hydrogen pickup fraction remains **[**

]

3.3.4.2.1 Tensile Test

Tensile tests at 343°C and room temperature (Ref. 23) were performed on both HiFi cladding and reference Zircaloy-2 cladding coupon samples in K5. The results of these tensile tests, which measured yield strength and elongation for both materials as a function of fluence, along with additional results presented in the following sections, are shown alongside **[**

].

3.3.4.2.2 Fatigue Tests

Westinghouse described in WCAP-18869-P/NP, Revision 0, fatigue tests that were carried out on both unirradiated and irradiated K5 coupons at room temperature show that HiFi material has comparable or superior performance, in terms of cycles to failure, compared to the reference Zircaloy-2 at a given stress amplitude. The results for irradiated HiFi material surpass the O'Donnell-Langer best fit for unirradiated Zircaloy-2 (Ref. 32).

3.3.4.2.3 Irradiation Creep

Closed specimens pressurized with noble gas were irradiated in K5 for 1,666 days. As shown in Figure 3-18 of TR WCAP-18869-P/NP, Revision 0, outer diameter (OD) measurements taken on these samples indicate that **[**
].

3.3.4.2.4 Characterization of Second Phase Precipitates

TEM images of HiFi and Zircaloy-2 cladding that were taken after six irradiation cycles revealed that most of the precipitates were amorphous. Irradiation caused a reduction in the Fe content of the precipitates. This is demonstrated in Figure 3-20 of TR WCAP-18869-P/NP, Revision 0, which shows a decrease in the Fe-to-(Fe+Cr) ratio with increasing neutron fluence. The ratio eventually stabilizes, with HiFi material maintaining a slightly higher level than Zircaloy-2, owing to its higher Fe content.

3.3.4.3 Halden BWR

Westinghouse indicated in TR WCAP-18869-P/NP, Revision 0, that fuel rods with HiFi and Zircaloy-2 cladding underwent irradiation testing in a BWR corrosion test loop within the Halden BWR (HBWR). The fuel rods were irradiated successfully, without any failures, achieving a rod average burnup of 60 GWd/MTU.

Intermediate inspections of the fuel rods were carried out after irradiation to fuel rod averages of 20 GWd/MTU and 40 GWd/MTU. Oxide thickness measurements, taken using eddy current at 40 GWd/MTU and 60 GWd/MTU, showed total oxide thicknesses ranging from 20 to 60 μm, with thicker oxides observed on the surface nearer to the stainless-steel flask. HiFi cladding had a thinner oxide layer on the side facing the stainless-steel flask compared to Zircaloy-2 cladding. Additionally, visual inspections revealed that the oxide film on the Zircaloy-2 cladding surface facing the flask had flaked off, whereas HiFi cladding showed minimal flaking. Significant oxide flaking was noted in the non-boiling region upstream of the Zircaloy-2 material. The thicker oxide and the flaking can be attributed to the phenomenon known as “shadow corrosion.” These findings suggest that HiFi cladding may be less prone to shadow corrosion than Zircaloy-2 cladding.

3.3.4.4 Plant B – **[ ]**

[ ] fuel assemblies with HiFi cladding tubes were irradiated for **[ ]**, achieving **[ ]** without any performance issues. Poolside inspections of these assemblies involved visual examinations, fuel rod diameter measurements, oxide thickness measurements using eddy current, and fuel rod growth measurements at various stages. Hot cell examinations included metallography, hydrogen content analysis, hardness tests, and burst tests.

[ ].

The oxide thickness measurements for the rods shown in Figure 3-26 in the TR WCAP-18869-P/NP, Revision 0, confirm that HiFi and Zircaloy-2 cladding **[ ]**. The hydrogen content of the fuel rod, obtained in hot cell, is shown in Figure 3-27 of the TR. **[ ]**. Additionally, the hydrogen content of HiFi is **[ ]**.

3.3.4.4.1 Burst Test

Westinghouse stated in TR WCAP-18869-P/NP, Revision 0, that burst tests were performed to assess the mechanical properties of irradiated HiFi cladding tubes as shown in Figures 3-29 and 3-30 of the TR. **[ ]**.

3.3.4.5 Plant C - **[ ]**

In conjunction with the experience gained by NFI with HiFi cladding in Japan, Westinghouse initiated a development program focused on three different high Fe alloys. **[ ]**.

During the irradiation program, the fuel rods were inspected multiple times. Results from poolside inspections, as shown in Table 3-11 and Figure 3-31 to Figure 3-34 of TR

WCAP-18869-P/NP, Revision 0, indicate that [ ].

[ ]. The NRC staff reviewed these results and concluded that [ ].

3.3.4.6 Plant D – [ ]

WCAP-18869-P/NP, Revision 0, states that [ ] lead use programs for HiFi cladding in Westinghouse fuel are [ ].

[ ] lead use assemblies (LUAs), containing [ ] HiFi cladding, were inserted. [ ].

3.3.4.7 Plant E – [ ]

The [ ] lead use program of HiFi cladding in Westinghouse fuel started in Plant E,].

[ ] pool-side PIE of rods with HiFi cladding in [ ]. The rod growth was [ ]. Inspections conducted in both 2019 and 2022 revealed comparable performance between the cladding materials, including similar outcomes for lift-off. Therefore, the NRC staff determined that the

[

].

3.3.4.8 Overall Operating Experience

Westinghouse stated in WCAP-18869-P/NP, Revision 0, that **[**

].

Westinghouse's response to RAI 2 (Ref. 4) states that **[** **]** operates with ultra-low feedwater Fe, as well as very low levels of other corrosion products, which many of the BWRs operating in the U.S. are transitioning towards. **[** **]** is a General Electric BWR-6 and has many cycles with experience of local fuel rod burnups above 70 MWd/kgU and/or more than six years of operation. **[** **]** has transitioned to HWC and OLNC water chemistry which is the typical operation for the U.S. BWRs.

The response to RAI 2 states that **[**

].

The NRC staff reviewed Westinghouse's response to RAI 2 and concluded that **[**

].

The poolside PIEs of rods with Alloy-2 LTRs and HiFi cladding included **[**

].

WCAP-18869-P/NP, Revision 0, states that **[**

] as shown in Figure 3-37 of the TR. **[**

], as shown in Figure 3-38 and Figure 3-39 of the TR. **[**
]. The NRC staff reviewed the information provided in the TR and determined that the fuel rod growth and lift-off in both mid-span and spacer regions were comparable between HiFi and Zircaloy-2.

Table 1 in Westinghouse's response to RAI 1 shows a compilation of the fuel assemblies/fuel rods that have continued their irradiation since the submittal of TR WCAP-18869-P/NP, Revision 0. **[** **]**

[
].

The Westinghouse response to RAI 1 (Ref. 4) reported that **[**
].

Figure 3 in Westinghouse's response to RAI 1 illustrates that **[**
].

[
].

[
].

The NRC staff reviewed the results and determined that **[**
].

3.4 Fuel Design and Accident Analysis

3.4.1 Fuel Assembly Mechanical Design

The fuel assembly designs can be impacted by changes in unirradiated yield strength and ultimate strength. The mechanical strength for both irradiated and un-irradiated HiFi cladding is **[**
]. Therefore, the NRC staff concluded that the HiFi cladding meets the fuel assembly mechanical design criteria.

3.4.2 Fuel Rod Design

Westinghouse BWR fuel designs are analyzed employing the following fuel rod design criteria by using the NRC-approved BWR methods and methodologies for **[**
]. Each criterion is specified along with the evaluation of the use of HiFi cladding on the specific criterion. Section 4.2 of TR WCAP-18869-P/NP, Revision 0, contains Westinghouse's evaluation of how

the use of HiFi cladding impacts the analysis, results, and margin. Westinghouse provided additional information in response to RAI 8 (Ref. 4). A discussion of the criteria is provided in the following sections of this SE.

3.4.2.1 Rod Internal Pressure

Criterion: The design criterion for rod internal pressure states that the internal pressure of the fuel rod shall not exceed a value which would cause the outward cladding creep to increase the diametrical fuel pellet-cladding gap. This value of fuel rod internal pressure is defined to be that internal pressure which causes the outward cladding creep rate to exceed the fuel effective swelling rate. This requirement is referred to as "the lift-off criterion."

Evaluation: The rod internal pressure and the lift-off pressure are calculated with the NRC-approved BWR fuel performance code. The pressure depends on the cladding creep, which is **[**

].

The NRC staff has reviewed the differences in the **[** **]**.

Therefore, the NRC staff concluded that **[** **]** for HiFi cladding acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.2 Cladding Stresses

Criterion: Fuel rod stresses must be maintained within acceptable limits. This criterion is implemented by establishing design limits for stresses to ensure that failure does not occur and that stresses of the fuel rod remain within acceptable limits.

Evaluation: Cladding stress is evaluated **[**

] is calculated with the NRC-approved fuel performance code and is dependent on **[**

].

The NRC staff has reviewed the differences in the **[** **]**.

Therefore, the NRC staff concluded that **[** **]** HiFi cladding acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.3 Cladding Strain

Criterion: The total transient induced cladding circumferential strain should not exceed 1 percent. In this context, total transient induced strain is the elastic and plastic strain which can occur during normal operation and AOOs excluding the effects of steady-state creep down and irradiation growth.

Evaluation: The criterion is evaluated by calculating the transient induced strain with an NRC-approved BWR fuel performance code. The transient strain depends on **[**
] (see Section 3.2.4.1 and Table 3-4 of TR WCAP-18869-P/NP, Revision 0) and on the strain, which is discussed in Section 3.2.4.2 in WCAP-18869-P/NP, Revision 0. **[**

].

The NRC staff has reviewed the differences in the **[**
].
Therefore, the NRC staff concluded that **[** **]** for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.4 Hydriding

Criterion: Cladding hydriding from waterside and internal sources shall be maintained sufficiently low that premature cladding failure shall not occur due to hydrogen embrittlement.

Evaluation: The LTA data shows evidence of a lower hydrogen pickup fraction in HiFi cladding with respect to Zircaloy-2 cladding. For the purpose of TR WCAP-18869-P/NP, Revision 0, **[**

].

The NRC staff has reviewed the differences in the **[**
]. Therefore, the NRC staff concluded that **[** **]** for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models and current hydriding criterion remains applicable.

3.4.2.5 Cladding Corrosion

Criterion: Cladding corrosion must be limited to assure that excessive cladding corrosion does not lead to premature fuel rod failures due to excessive metal thinning or excessive cladding temperatures. The effect of cladding corrosion shall be included in the thermal-mechanical evaluation of the cladding.

Evaluation: The criterion is evaluated by calculating the oxide thickness with the NRC-approved BWR fuel performance code. Westinghouse's response to RAI 8 stated that **[**

] (see Figure 3-38 in TR WCAP-18869-P/NP, Revision 0).

The NRC staff has reviewed the differences in the **[**

].

Therefore, the NRC staff concluded that **[**
] for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.6 Cladding Collapse

Criterion: Cladding collapse shall not occur during the design life of the fuel rod. Cladding collapse or "elastic and plastic instability" refers to the pressure across the tubing walls at which the cladding will buckle in the elastic and plastic ranges.

Evaluation: The cladding creep collapse is evaluated with the NRC-approved method. The creep collapse depends on the cladding creep, **[**
] (see Section 3.4.2.3 in TR WCAP-18869-P/NP, Revision 0). **[**

].

The NRC staff has reviewed the differences in the **[**

]. Therefore, the NRC staff concluded that **[**
] for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models. The NRC staff's conclusion includes evaluation of and effect on instantaneous collapse at the BOL and creep collapse later during operation.

3.4.2.7 Cladding Fatigue

Criterion: Cladding fatigue shall not cause fatigue damage during normal operation and AOOs. The fatigue evaluation shall account for the effects of cladding corrosion.

Evaluation: The fatigue limits derived by O'Donnell Langer are used for evaluation of cladding fatigue. In Figure 3-17 in TR WCAP-18869-P/NP, Revision 0, it is shown that the O'Donnell Langer curves bound the HiFi cladding fatigue behavior. The evaluation of fatigue is done with the NRC-approved BWR fuel performance code and relies on the mechanical behavior of the cladding (see Section 3.2.4.2 of WCAP-18869-P/NP, Revision 0).

The NRC staff reviewed Westinghouse's evaluation and determined that **[**
]
of HiFi cladding with respect to that of Zircaloy-2 LK3 cladding. Accordingly, the NRC staff determined that **[**

] HiFi cladding.

3.4.2.8 Cladding Temperature

Criterion: Cladding overheating during normal operation and AOOs shall not cause fuel rod failure.

Evaluation: **[** **]**, and there is no adverse effect of HiFi material on the thermal properties of the cladding.

The NRC staff has reviewed the differences in the **[** **]**. Therefore, the NRC staff concluded that **[** **]** for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.9 Fuel Temperature

Criterion: The maximum centerline pellet temperature shall remain below the melting temperature of the fuel during normal operation and AOOs.

Evaluation: The evaluation of fuel temperature is done with an NRC-approved BWR fuel performance code. **[** **]**.

The NRC staff has reviewed the differences in the **[** **]**. Therefore, the NRC staff concluded that **[** **]** for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.2.10 Fuel Rod Bow

Criterion: Excessive fuel rod bowing shall be precluded for the design life of the fuel assembly. Fuel rod bowing shall be evaluated, and any significant impact shall be accounted for in the thermal and mechanical evaluation of the fuel rods and the assembly.

Evaluation: **[** **]**.

The NRC staff has reviewed the differences in the **[** **]**. Therefore, the NRC staff concluded that **[** for HiFi cladding is acceptable for use in Westinghouse's fuel rod safety analysis evaluation models.

3.4.3 Nuclear Design

The NRC staff reviewed the statements in Section 4.3 of the TR WCAP-18869-P/NP, Revision 0, indicating that **[** **]**. The NRC staff has determined that **[** **]** and no other nuclear design inputs result from the HiFi material changes. Based on this determination, the NRC staff concluded that Westinghouse's disposition of Nuclear Design **[** **]** acceptable.

3.4.4 Thermal and Hydraulic Design

Westinghouse states in Section 4.4 of the TR, WCAP-18869-P/NP, Revision 0, that the thermal-hydraulic analysis depends on the fuel assembly geometric conditions, the cladding surface finish, and the heat transferred to the surface of the cladding. The NRC staff has determined that **[** **]**. Based on this determination, the NRC staff concluded that Westinghouse's disposition of **[** **]** is acceptable.

3.4.5 Non-LOCA Accident Design

Westinghouse states in TR WCAP-18869-P/NP, Revision 0, Section 4.5, that in non-LOCA events the cladding temperature remains below the α to α+β phase transition temperature, precluding any significant differences in specific heat. The specific heat, and in general all the thermo-mechanical properties, of Zircaloy-2 and HiFi cladding are **[** **]**. The NRC staff reviewed the statement in the TR and determined that it was acceptable based on the engineering judgement of non-LOCA transient analyses and which parameters affect the results. This is typical of previous fuel rod cladding material changes across the industry.

3.4.6 LOCA Design

Westinghouse states in TR WCAP-18869-P/NP, Revision 0, Section 4.6, that thermal conductivity, specific heat, density, thermal expansion, and emissivity of HiFi material and Zircaloy-2 material are **[** **]**. The NRC staff reviewed the statement in the TR and determined that it was acceptable based on the engineering judgement of LOCA analyses and which parameters affect the results. This is typical of previous fuel rod cladding material changes across the industry.

3.4.7 Pellet-Cladding Interaction and Reactivity-Initiated Accident

The susceptibility to pellet-cladding interaction (PCI) is determined by the properties of the inner wall (i.e., the liner). Westinghouse states in TR WCAP-18869-P/NP, Revision 0, Section 4.7, that **[**

].

The susceptibility of cladding to reactivity-initiated accident (RIA) is determined by a combination of materials microstructure and the hydrogen content. **[**

].

Therefore, the NRC staff reviewed HiFi material behaviors described in the TR and determined that the PCI and RIA methods and evaluations are acceptable, as discussed above.

3.4.8 Hydrogen Pickup

Figure 4-1 in TR WCAP-18869-P/NP, Revision 0, summarizes hydrogen data from both unirradiated and irradiated programs. The TR states that the benefit of a lower hydrogen pickup with HiFi cladding **[**

]. Based on the NRC staff's review of the hydrogen complete data set from both unirradiated and irradiated programs presented in Figure 4-1 of the TR, the NRC staff concluded **[**

].

4.0 LIMITATIONS AND CONDITIONS

HiFi cladding as described in TR WCAP-18869-P/NP, Revision 0, is intended for use within the following limitations and conditions:

1. The fuel rod burnup limit for this approval shall remain at currently established limits as specified in the SEs for the following TRs:

   CENPD-287-P-A, “Fuel Assembly Mechanical Design Methodology for Boiling Water Reactors” (Ref. 11),

   WCAP-15942-P-A, “Fuel Assembly Mechanical Design Methodology for Boiling Water Reactors Supplement 1 to CENP-287” (Ref. 12), and

   WCAP-15836-P-A, Revision 0, “Fuel Rod Design Methods for Boiling Water Reactors - Supplement 1,” Volumes I & II (Ref. 10).

2. All the Limitations & Conditions listed in NRC final SEs for the NRC-approved TRs in References 10, 11, and 12 for methodologies used for Zircaloy-2 fuel analysis shall continue to be met, except that the use of HiFi cladding in addition to or in place of Zircaloy-2 cladding is now approved. Those include Oxide Thickness < 100 μm, Hydrogen Pickup ≤ **[ ]**.

5.0 CONCLUSION

The NRC staff reviewed TR WCAP-18869-P/NP, Revision 0 (Ref. 1), to ensure that all applicable NRC regulations and requirements for fuel rod cladding material would be able to be met. Based on its evaluation discussed above, the NRC staff has determined that Westinghouse demonstrated that it has up to date evaluation models and methods to evaluate HiFi cladding performance in plant specific license amendment requests to support establishing compliance with all applicable NRC regulations and requirements for plant licensees.

The NRC staff reviewed TR WCAP-18869-P/NP, Revision 0, and determined that Westinghouse has demonstrated acceptable performance of HiFi cladding material using its currently approved methodology for evaluation when done in accordance with the limitations and conditions in Section 4.0 of this SE. Westinghouse has demonstrated that **[ ]** to HiFi cladding

The NRC staff reviewed all the information and data provided in Reference 1 and the RAI responses regarding HiFi performance beyond the current fuel burnup limits and has determined that Westinghouse can acceptably analyze HiFi cladding operation up to **[ ]** with respect to cladding material figures of merit only. This acceptability determination does not raise the current burnup operating limit in References 10 and 12.

6.0 REFERENCES

1. Letter from Z. Harper, Westinghouse, to NRC Document Control Desk (DCD), "Submittal of Westinghouse Topical Report WCAP-18869-P/NP, Revision 0, 'High Performance Cladding for Use in Boiling Water Reactor Fuel' (Proprietary/Non-Proprietary)," March 8, 2024 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML24072A267).

2. NRC, "U. S. NRC Regulatory Audit Plan of Westinghouse Topical Report WCAP-18869-P/NP, Revision 0, 'High Performance Cladding for Use in Boiling Water Reactor Fuel,'" November 25, 2024 (ML24324A166).

3. NRC, "U. S. NRC Report for Regulatory Audit of Westinghouse Topical Report WCAP 18869-P/NP, Revision 0, 'High Performance Cladding for Use in Boiling Water Reactor Fuel,'" April 30, 2025 (ML25108A038).

4. NRC, "U. S. NRC Report for Regulatory Audit of Westinghouse Topical Report WCAP18869-P/NP, Revision 0, 'High Performance Cladding for Use in Boiling Water Reactor Fuel,'" April 30, 2025 (ML25108A038).

5. Letter from J. Ewing, Westinghouse, to NRC DCD, LTRNRC2523, "Submittal of Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18869-P/NP, 'High Performance Cladding for Use in Boiling Water Reactor Fuel,'" April 21, 2025 (ML25112A272).

6. NRC, SRP, NUREG-0800, Section 4.2, "Fuel System Design," Revision 3, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition - Reactor (NUREG-0800, Chapter 4)," March 2007 (ML070740002).

7. NRC, SRP, NUREG-0800, Section 4.3, "Nuclear Design," Revision 3, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition - Reactor (NUREG-0800, Chapter 4)," March 2007 (ML070740003).

8. NRC, SRP, NUREG-0800, Section 4.4, "Thermal and Hydraulic Design," Revision 2, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition - Reactor (NUREG-0800, Chapter 4)," March 2007 (ML070550060).

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10. WCAP-15836-P-A, Revision 0, "Fuel Rod Design Methods for Boiling Water Reactors - Supplement 1," Volumes I & II, April 2006 (ML061220485 (Proprietary/Non-publicly available)).

11. CENPD-287-P-A, "Fuel Assembly Mechanical Design Methodology for Boiling Water Reactors," July 1996 (ML19353D872 (Proprietary/Non-publicly available)).

12. WCAP-15942-P-A, “Fuel Assembly Mechanical Design Methodology for Boiling Water Reactors Supplement 1 to CENP-287,” March 31, 2006 (ML061110351 (Proprietary/Non-publicly available)).

13. Letter from K. Hosack, Westinghouse, to NRC DCD, “Submittal of WCAP17769PA and WCAP-17769-NP-A, Revision 0, “Reference Fuel Design SVEA-96 Optima3” (Proprietary/Non-Proprietary), LTR-NRC-20-38, May 27, 2020 (ML20150A239).

14. “Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding,” ASTM B811, 2013.

15. C. Lemaignan, and A.T. Motta, “Zirconium Alloys in Nuclear Applications,” in “Materials Science and Technology – A Comprehensive Treatment,” Volume 10B, Nuclear Materials, Part II, Edited by R.W. Cahn, P. Haasen & E.J. Kramer, Volume Editor Brian R.T. Frost, VCH Verlagsgesellschaft mbH, Weinheim (Germany), VCH Publisher Inc., New York, NY (USA), 1994.

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18. P. Tägtström, M. Limbäck, M. Dahlbäck, T. Andersson, and H. Pettersson, “Effects of Hydrogen Pickup and Second-Phase Particle Dissolution on the In-Reactor Corrosion Performance of BWR Claddings,” Zirconium in the Nuclear Industry: Thirteenth International Symposium, ASTM STP 1423, 2002, pp. 96118.

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22. N. Itagak, et al., “Development of New High Corrosion Resistance Zr Alloy ‘HiFi’ for High Burnup Fuel,” Proceedings European Nuclear Society TopFuel, Wüstzburg, 2003.

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Principal Contributors: R. Fu, NRR
J. Dean, NRR

Date: March 9, 2026

NRC Resolution to Westinghouse Proprietary Markings and Voluntary Comments

By letter dated February 2, 2026 (ML26034C024), Westinghouse submitted the proprietary markup and voluntary comments. The NRC staff reviewed and incorporated Westinghouse’s proprietary markings requests (including Westinghouse’s requests for removal of some proprietary markings) and voluntary minor editorial comments into the final SE.

Section B

List of Changes

List of Changes

No.	Sections(s)	Description
1	Entire Document	Minor editorial and formatting changes.
2	4.2	Based on RAI #8, changes to the evaluation portions of Section 4.2 were made to provide detailed data for the fuel rod design criteria along with the evaluations of the use of **HiFi** cladding on the specific criteria.
3	Section D	Clarified markings for proprietary information in the original submittal of LTR-NRC-25-13.

Section C

Submittal of Topical Report

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LTR-NRC-24-7

March 8, 2024

Subject: Submittal of Westinghouse Topical Report WCAP-18869-P/-NP, "High Performance Cladding for Use in Boiling Water Reactor Fuel." (Proprietary/Non-Proprietary)

Enclosed are proprietary and non-proprietary versions of Westinghouse Electric Company LLC ("Westinghouse") topical report WCAP-18869-P/-NP, "High Performance Cladding for Use in Boiling Water Reactor Fuel." for United States Nuclear Regulatory Commission ("Commission") review and approval. Westinghouse respectfully requests the Commission complete its review of the enclosed topical report by March 2025.

This submittal contains proprietary information of Westinghouse. In conformance with the requirements of 10 CFR Section 2.390, as amended, of the Commission's regulations, we are enclosing with this submittal an Affidavit. The Affidavit sets forth the basis on which the information identified as proprietary may be withheld from public disclosure by the Commission.

Correspondence with respect to the proprietary aspects of this submittal or the Westinghouse Affidavit should reference AW-24-012 and should be addressed to Camille T. Zozula, Manager, Global Nuclear Regulatory Affairs, Westinghouse Electric Company, 1000 Westinghouse Drive, Building 1, Cranberry Township, PA 16066.

Zachary S. Harper

Zachary S. Harper, Senior Manager
Licensing Engineering

cc: Ekaterina Lenning
Gerond George

Enclosures:

1. Affidavit, AW-24-012
2. Westinghouse Topical Report WCAP-18869-P, "High Performance Cladding for Use in Boiling Water Reactor Fuel." (Proprietary)
3. Westinghouse Topical Report WCAP-18869-NP, "High Performance Cladding for Use in Boiling Water Reactor Fuel." (Non-Proprietary)

AFFIDAVIT AW-24-012

Commonwealth of Pennsylvania:
County of Butler:

(1) I, Zachary Harper, Senior Manager, Licensing, have been specifically delegated and authorized to apply for withholding and execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse).

(2) I am requesting the proprietary portions of WCAP-18869-P, Revision 0 be withheld from public disclosure under 10 CFR 2.390.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged, or as confidential commercial or financial information.

(4) Pursuant to 10 CFR 2.390, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

   (i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse and is not customarily disclosed to the public.

   (ii) The information sought to be withheld is being transmitted to the Commission in confidence and, to Westinghouse's knowledge, is not available in public sources.

   (iii) Westinghouse notes that a showing of substantial harm is no longer an applicable criterion for analyzing whether a document should be withheld from public disclosure. Nevertheless, public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

(5) Westinghouse has policies in place to identify proprietary information. Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

   (a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.
   (b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage (e.g., by optimization or improved marketability).
   (c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.
   (d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.
   (e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.
   (f) It contains patentable ideas, for which patent protection may be desirable.

(6) The attached documents are bracketed and marked to indicate the bases for withholding. The justification for withholding is indicated in both versions by means of lower-case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower-case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (5)(a) through (f) of this Affidavit.

I declare that the averments of fact set forth in this Affidavit are true and correct to the best of my knowledge, information, and belief. I declare under penalty of perjury that the foregoing is true and correct.

Executed on: 3/8/2024

Signed electronically by
Zachary Harper

EXECUTIVE SUMMARY

This document is the licensing topical report for application of fuel cladding material with increased Fe content compared to Zircaloy-2 in boiling water reactor (BWR) nuclear fuel. This cladding will be applied to all Westinghouse licensed BWR fuel design.

This cladding material is a zirconium-based alloy designed to maximize the safety margins for BWR fuel, amid increasing demands for higher fuel duties and burnup, by reducing the hydrogen uptake. **[**

]^{a,c} In this report, **HiFi^{TM}** cladding is defined to have a nominal **[** **]^{a,c}** specified for Zircaloy-2 cladding in Reference 4. **[** **]^{a,c}**

HiFi cladding refers to the outer component of the fuel cladding. **[**

]^{a,c}

HiFi cladding is manufactured following the same steps as the current BWR Zircaloy-2 fuel cladding material used by Westinghouse, referred to as LK3. Processing of **HiFi** **[** **]^{a,c}** which are tailored to the modification in chemical composition and to the equipment capabilities of the manufacturers, in order to optimize the microstructure for robust performance. The similar fabrication processes have **[** **]^{a,c}**

Characterization has demonstrated that the as-fabricated microstructure is almost identical between Zircaloy-2 and **HiFi** cladding, **[**

]^{a,c} This is the origin of the main benefit of **HiFi** cladding, which follows the trend of the industry to maximize the benefit of iron as an alloying element, to **[** **]^{a,c}**

Side-by-side out-of-pile testing comparing **HiFi** and Zircaloy-2 cladding demonstrates that **[** **]^{a,c}** This includes thermal properties, mechanical properties, corrosion properties, and **[** **]^{a,c}** The exception in equivalence between Zircaloy-2 and **HiFi** cladding is the hydrogen pickup fraction observed in **HiFi** cladding, being significantly lower than that of Zircaloy-2 cladding.

Table 0-1 summarizes the extensive irradiation testing performed **[** **]^{a,c}** In addition to the experience acquired by NFI, Westinghouse acquired relevant experience with **[**

]^{a,c}

Table 0-1 Summary of irradiation experience of *HiFi* cladding

a,c

All the post irradiation examinations (PIE) have demonstrated that the performance of **HiFi** cladding is equivalent or superior to that of Zircaloy-2 cladding. This includes in-reactor corrosion, hydrogen pickup, creep and growth. Post-irradiation mechanical (yield strength, elongation, fatigue) and **[**

]^{a,c}

In particular, current approved models for **[**

]^{a,c} Experience has indicated that the benefit of lower hydrogen uptake with **HiFi** cladding becomes apparent in demanding conditions where **[**

]^{a,c}

Extensive testing performed on Zircaloy-2 and **HiFi** cladding demonstrates that **[**

]^{a,c} This precludes any impact on current approved analysis models and methods.

Having concluded that there are no changes in safety compliance, Westinghouse is seeking NRC approval for the use of **HiFi** cladding with an iron content range of 0.25-0.50 wt% and a chromium content range of

0.05-0.20 wt% **[**

]^{a,c} in all approved Westinghouse BWR fuel designs.

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ACRONYMNS AND ABBREVIATIONS

AOO	anticipated operational occurrence
BCC	body-centered cubic
BWR	boiling water reactor
CSR	contractile strain ratio
DHC	delayed hydride cracking
ECR	equivalent cladding reacted
EDS	energy dispersive (X-ray) spectroscopy
EOL	end-of-life
FCC	face-centered cubic
[ ]^{a,c}	[ ]^{a,c}
[ ]^{a,c}	[ ]^{a,c}
[ ]^{a,c}	[ ]^{a,c}
HBWR	Halden boiling water reactor
HCP	hexagonal close-packed
HWC	hydrogen water chemistry
K5	Kashiwazaki-Kariwa 5
[ ]^{a,c}	[ ]^{a,c}
[ ]^{a,c}	]^{a,c}
LOCA	loss of coolant accident
LTR	lead test rod
LUA	lead use assembly
NFI	Nuclear Fuel Industries Ltd.
NRC	Nuclear Regulatory Commission
NWC	normal water chemistry
[ ]^{a,c}	[ ]^{a,c}
OLNC	online noble chemistry
PCI	pellet-cladding interaction
PIE	post irradiation examination
PWR	pressurized water reactor
RIA	reactivity-initiated accident
RXA	recrystallization anneal
SCC	stress corrosion cracking
SMP	Special Metals Plant
[ ]^{a,c}	[ ]^{a,c}
SPP	second phase particle
SRP	standard review plan
TEM	transmission electron microscope (or microscopy)
TREX	tube reduced extrusion
WZ	Western Zirconium

1 INTRODUCTION

In order to meet evolving requirements imposed on fuel cladding materials for boiling water reactor (BWR) nuclear fuel, in particular increasing demands for higher fuel duties and burnup, Nuclear Fuel Industries Ltd. (NFI), developed the **HiFi** alloy**.** The **HiFi** alloy is a zirconium-based cladding material that builds on the extensive performance experience acquired with Zircaloy-2 cladding, but with a relatively minor change of the chemical composition. Particularly, **HiFi** cladding was designed to improve resistance to hydrogen uptake, intended to maintain and increase safety margin compared to Zircaloy-2 cladding that is currently the standard for BWR fuel in Westinghouse. **[**

]^{a,c} BWR cladding alloy definition **[**

]^{a,c}

1.1 PURPOSE

This licensing topical report contains information supporting the application of **HiFi** cladding alloy as fuel cladding in BWR nuclear fuel **[**

]^{a,c} Results of extensive testing reported in this document demonstrate that the properties of **HiFi** cladding are equivalent or superior to those of Zircaloy-2 cladding. The purpose is to obtain Nuclear Regulatory Commission (NRC) approval for the application of the alloy as fuel cladding material in BWR fuel, **[**

]^{a,c}

1.2 APPLICABILITY

HiFi cladding refers to the outer component of the fuel cladding and will be applied to all Westinghouse licensed BWR fuel design. **[**

]^{a,c}

1.3 ALLOY DEFINITION

HiFi is a zirconium alloy with higher iron content than that specified for Zircaloy-2 cladding and **[**

]^{a,c} than that of Zircaloy-2 cladding, the material currently in use in BWR fuel produced by Westinghouse. Table 1-1 compares the chemical composition of **HiFi** and Zircaloy-2. The composition of **HiFi** as defined in this report **[**

]^{a,c} The selected composition ranges are based on the alloy development and testing performed by NFI and Westinghouse. The final chemical composition of cladding was determined following extensive out-of-core testing, aiming to optimize manufacturability, mechanical properties, corrosion and hydrogen pickup.

Starting in the mid-1980s, NFI developed an advanced cladding material with high corrosion resistance and low hydrogen pickup for next generation high burnup BWR fuel, with discharged average batch burnup greater than 60 GWd/MTU / maximum assembly burnup greater than 70 GWd/MTU. This advanced cladding material has a nominal iron content of **[** **]**^{a,c} the ASTM specification for Zircaloy-2 cladding (Reference 4). This material was called **HiFi**.

In addition to higher iron, other variants considered during development of cladding included **[** **]** ^{a,c} All the variants demonstrated good fabricability, without significant differences observed during processing.

Modified Zircaloy-2 claddings with **[** **]**^{a,c} were developed and tested in a high burnup program by Westinghouse. The results of that program have allowed the extension of the definition of the composition of **HiFi**. The composition finally chosen is that listed in Table 1-1, **[** **]** ^{a,c}

Table 1-1 Chemical composition of new BWR alloy and Zircaloy-2 alloys

[ ]^{a,c}

Element (wt%)	Zircaloy-2 Alloy (Reference 4)
Sn	1.20-1.70
Fe	0.07-0.20
Cr	0.05-0.15
Ni	0.03-0.08
O	0.09-0.16
Zr	Balance

The final heat treatment of cladding is **[** **]**^{a,c} . **HiFi** cladding is manufactured following the same steps as the current Zircaloy-2 cladding used in Westinghouse BWR fuel designs, referred to interchangeably throughout this report as LK3. Processing of **HiFi** cladding has been tailored to optimize the microstructure for robust performance. **HiFi** cladding is manufactured following the same quality control and testing standards as the current Zircaloy-2 cladding, which exceed stipulations of industry standards such as ASTM B811 (Reference 4). Details of the manufacturing process for cladding can be found in Section 3.1.

1.4 LICENSING BASIS

HiFi cladding is a modification of Zircaloy-2 cladding, which has been achieved by increasing the iron content. The content of this report demonstrates that the properties and performance of **HiFi** are equal to or exceed those of Zircaloy-2. **[** **]**^{a,c} **HiFi** complies with all design methods and safety analyses that have been approved for Zircaloy-2, and can be employed acceptably in any of the Westinghouse BWR fuel designs in the United States without changes.

Having concluded that there are no changes in safety compliance, Westinghouse is seeking NRC approval for the use of **HiFi** cladding **[**

]^{a,c} in all approved Westinghouse BWR fuel designs.

1.5 LIMITATIONS AND CONDITIONS FOR APPLICATION

HiFi cladding as described in this topical report is intended for use within the following constraints:

1. **[**
   ]^{a,c}
2. Oxide Thickness < 100 µm
3. Hydrogen Pickup ≤ **[ ]^{a,c}**

2 BACKGROUND

This section provides perspective and background on the evolution from Zircaloy-2 cladding to **HiFi** cladding, and analyzes the impact of the differences in composition between the two alloys framed in a discussion of basic properties and metallurgy of zirconium based alloys. General metallurgy information in this section comes from References 5 and 6.

2.1 PHASE TRANSFORMATIONS AND MICROSTRUCTURE

For temperatures below about 750°C zirconium is in the so called α phase, and for temperatures above 1000°C zirconium is in the β phase. There is a mixed phase region between 750 and 1000°C, which varies depending on the alloy. The α and β phases have hexagonal close-packed (HCP) and body-centered cubic (BCC) crystal structures, respectively. The phase transformation temperatures and the melting point change with variations in alloying composition. These changes depend on the fact that different alloying elements stabilize different phases. For example, in zirconium based alloys tin and oxygen are α-phase stabilizers, while niobium is a β phase stabilizer. Meaning that, additions of tin and oxygen tend to raise the α to α+β phase transformation temperature, while addition of niobium tends to lower the α to α+β phase transformation temperature. In the Zircaloys the mixed phase region covers the temperature range 750 to 1000°C, and the precipitates are dissolved at about 850°C. **[**

]^{a,c}

2.2 ALLOYING ELEMENTS

The most common alloying elements used in zirconium-based alloys, relevant for the development of the cladding, are briefly discussed in the following subsections.

2.2.1 Oxygen

Oxygen is to be considered as an alloying element, rather than as an impurity. It is added before melting as small additions of ZrO_2 powder. Oxygen is an α-stabilizer, expanding the α region of the phase diagram by formation of an interstitial solid solution. The usual oxygen content in zirconium alloys is in the range of 900-1600 ppm (0.09 to 0.16 wt%) and its purpose is to increase the yield strength by solution strengthening: a 1000 ppm oxygen addition increases the yield strength by 150 MPa at room temperature. The effect is less pronounced above 250°C.

At high concentrations, oxygen stabilizes the α phase up to liquid temperatures. During high temperature oxidation, simulating a reactor accident, a layer of oxygen-stabilized α-zirconium is found between the β-quenched structure and the Zirconium oxide layer. At normal operating temperatures the oxygen diffusion layer ahead of the oxide front is very limited in thickness, e.g., below 1 μm at 400°C. **[**

]^{a,c}

2.2.2 Tin

Tin is an α stabilizer. It forms, in the α and β phases, a substitutional solid solution. Tin, at a concentration of 1.2-1.7 wt%, was originally added to increase the corrosion resistance, especially by mitigating the deleterious effects of nitrogen in deteriorating the corrosion resistance. Through a better control of processing parameters, and consequently of nitrogen content, it is now possible to reduce the tin content in the current alloys. Tin, however, also has an impact on the mechanical strength of the material and therefore its concentration should not be excessively reduced, without specific consideration of this effect. **[**

]^{a,c}

2.2.3 Iron, Chromium, and Nickel

Since iron, chromium and nickel in their phase diagrams give eutectoid decomposition of the β phase they are considered as β-eutectoids.

All three elements have an impact on the alpha to beta transformation in the zirconium binary systems, **[**

]^{a,c} phase transformation temperatures.

At the concentrations used in Zircaloy-2 and high iron cladding materials, these elements are fully soluble in the β phase. This temperature of dissolution is in the range of 835-845°C, i.e., in the α+β range. In the α phase their solubility is very low, in the region of 120 ppm for iron and 200 ppm for chromium at the maximum solubility temperature. For the Zr-Cr and Zr-Ni binary alloys, the stable forms of the second phases are Zr_2Ni or $ZrCr_2$. In the Zircaloys, iron substitutes for the corresponding transition metal and the intermetallic compounds found in Zircaloy are $Zr_2(Ni,Fe)$ and $Zr(Cr,Fe)_2$. In Zircaloy-4 alloy, the iron/chromium ratio of those precipitates is the same as the nominal composition of the alloy. In **HiFi**, as it occurs for Zircaloy-2, the partitioning of iron between the two types of intermetallic phases leads to a more complex relationship between nominal composition and precipitate composition, giving a broad range of iron/chromium ratios in $Zr(Cr,Fe)_2$ and iron/nickel ratios in $Zr_2(Ni,Fe)$.

The size of the precipitates is of importance for the properties of the alloys, especially the corrosion rate. Better uniform corrosion resistance is obtained for Zircaloys used in pressurized water reactors (PWRs) if they contain large precipitates, while better resistance to localized forms of corrosion is seen in boiling water reactors (BWRs) in materials that have finely distributed small precipitates. Further discussions regarding the effect of second phase particles (SPPs) on corrosion properties are presented in Section 2.3 below.

[

]^{a,c}

2.3 INCREASING IRON CONTENT – SECOND PHASE PARTICLES

Pure zirconium cannot be used in reactor systems due to its mechanical softness and low corrosion resistance in water environments. Present day commercial alloys in general are based on binary, ternary or quaternary alloy systems.

Up to the mid-to-late eighties, to a large extent, only four alloys were used commercially in nuclear systems. Two of these, Zircaloy-2 and Zircaloy-4 alloys, were established by a military program, around 1950. The compositions of these standard Zircaloys, are defined in ASTM standards for nuclear fuel cladding applications (Reference 4). These compositions have remained unchanged for many years. Zircaloy-2 and Zircaloy-4 alloys have been used for cladding and structural materials, such as guide tubes in fuel assemblies and spacers.

Table 2-1 ASTM requirements for contents of alloying elements and some impurities (Reference 4)

	Zircaloy-2	**Zircaloy-4**
ASTM Grade	**R 60802**	**R 60804**
Sn (wt%)	1.20-1.70	1.20-1.70
Nb (wt%)	-	-
Fe (wt%)	0.07-0.20	0.18-0.24
Cr (wt%)	0.05-0.15	0.07-0.13
Ni (wt%)	0.03-0.08	≤0.0070
Fe+Cr+Ni (wt%)	0.18-0.38	-
Fe+Cr (wt%)	-	0.28-0.37
C (ppm)	≤270	≤270
H (ppm)	≤25	≤25
N (ppm)	≤80	≤80
Si (ppm)	≤120	≤120

The differences between the alloying elements used in the different types of zirconium-based alloys result in different SPPs, or precipitates, or intermetallics. As stated above, SPPs of only the type $Zr(Cr,Fe)_2$ are observed in Zircaloy-4 alloy, while the alloying elements in Zircaloy-2 alloy result in two types of precipitates, $Zr(Cr,Fe)_2$ and $Zr_2(Ni,Fe)$.

The effects of the size distribution of the SPPs on the corrosion properties of the Zircaloy materials have been studied extensively, and it has been concluded that the size distribution has an important influence on corrosion behavior. The size of the SPPs depends on the chemical composition and the processing. The alloying elements that form SPPs in Zircaloy-2 and **HiFi** cladding are iron, chromium and nickel. The processing parameters that determine the SPP size distribution are the quenching rate from the β phase, where these elements are in solid solution, and the subsequent annealing temperatures and times in the α phase during fabrication.

In BWR conditions, the rate of uniform corrosion is higher when the size of the SPPs is very small. In reactor this effect can be seen at burnups above 20 GWd/MTU (References 7 and 8). Coarse SPPs may, on the other hand, lead to nodular corrosion in BWRs. **[**

]^{a,c} The continuous refinement of Zircaloy-2 has, consequently, led to an iron concentration in the upper range of the ASTM specification in modern BWR applications, **[** **]**^{a,c} **HiFi** cladding increases the iron concentration even further, resulting in **[** **]**^{a,c}

[

]^{a,c}

In addition to the increase in iron content [

]^{a,c} For in-reactor corrosion, it has been shown that the size distribution of the SPPs can be influenced by the fast neutron flux through the acceleration of dissolution processes as well as through the acceleration of alloying elements diffusion within the zirconium lattice (References 7 and 8).

Extensive studies of the effect of SPP size distribution and chemical composition on corrosion and hydriding performance of claddings in BWRs were reported in Reference 8. It was demonstrated that increasing the annealing parameter as well as increasing the iron content resulted in increased mean SPP diameter. The difference in SPP distribution affected both the corrosion and hydriding behavior of the materials. Claddings with smaller initial SPPs showed a higher hydrogen uptake and a lower corrosion resistance than claddings with initially larger SPPs (Reference 8). [

]^{a,c}

Electrochemistry research work on the role of iron on hydrogen pickup mechanisms on zirconium alloys conducted by NFI (Reference 9), has demonstrated that iron addition modifies the surface potential of the material during corrosion, which is an indication of changes in the potential gradient in the oxide film. The potential gradient and differing hydrogen absorption in $Zr(Cr,Fe)_2$ and $Zr_2(Ni,Fe)$ SPPs are theorized to influence the hydrogen (proton) diffusion through the oxide film. Similar modeling and experimental work has proposed a mechanism where the resistivity of the oxide is proportional to the transport of protons, with oxidized alloying elements in the oxide reducing or increasing space charge effects in the oxide, thereby modifying the hydrogen pickup fraction (Reference 10).

The Westinghouse/NFI observations are in line with the results presented in Reference 11, where Zircaloy-2 is compared with materials similar to Zircaloy-2 but with iron and nickel slightly above the ASTM specified values for Zircaloy-2. The results agree with the Westinghouse/NFI experience, and consequently further confirm the advantages gained through the evolution from Zircaloy-2 to **HiFi** cladding.

Variation within the specification range of **HiFi** cladding, as defined in Table 1-1, is expected to have very limited impact on mechanical or physical properties and the properties will vary within the same range as for Zircaloy-2 . The main impact of variation in [ ]^{a,c} is the detailed distribution of SPP sizes. This will impact hydriding resistance and potentially corrosion resistance at very high burnup.

3 PROPERTIES AND EXPERIENCE

The data for the **HiFi** alloy has been collected in two separate development programs:

A high iron cladding was developed by NFI. Out-of-pile testing was performed during development of **HiFi** cladding, **[** **]**^{a,c} Selected candidates were included in irradiation programs in commercial and experimental BWR plants. Irradiation data has been accumulated up to **[**

]^{a,c} (see Sections 3.4.1 to 3.4.4). The development program by NFI has also been documented in several publications (References 12 to 16).

In addition to the development program for **HiFi** cladding led by NFI, Westinghouse acquired relevant experience with **[**

]^{a,c}

Westinghouse has qualified **[**

]^{a,c}

Out-of-pile testing results from **[** **]**^{a,c} are presented in Section 3.3, together with the combined irradiation experience, demonstrating that the properties and performance of the cladding are equal to or exceed those of Zircaloy-2 cladding.

3.1 MANUFACTURING PROCESS

HiFi cladding for Westinghouse nuclear fuel designs is manufactured following the same steps as the current Zircaloy-2 LK3 cladding. Processing of cladding tubes is commonly tailored to the chemical composition and to the equipment capabilities of each manufacturer, in order to optimize the microstructure for robust performance. Table 3-1 lists the basic manufacturing steps for the cladding (the same as Zircaloy-2 LK3 cladding). Inspection and intermediate conditioning steps (straightening, cleaning, polishing) are not included in the table, as they are adjusted by each manufacturer to fulfill the material specifications. **[**

]^{a,c}

Table 3-1 cladding manufacturing steps (same steps as Zircaloy-2 LK3 cladding)

[ ]^{a,c}

HiFi ingots, for the outer component of the lined BWR cladding, are melted using **[** **]**^{a,c} **HiFi** alloy is melted **[** **]**^{a,c} times to homogenize the distribution of alloying elements. Ingots are forged at high temperature into bars and subsequently β-quenched. For the current cladding designs, **[** **]**^{a,c} Following the final pilgering, the tubes undergo **[** **]**^{a,c} For surface finishing, the surface of the inner diameter **[** **]**^{a,c}

Following melting of the ingots, including control of the chemical composition, a β-quenching operation is performed to homogenize the distribution of alloying elements. The β-quenched microstructure is effectively the starting point for optimization of the SPP size distribution during the subsequent thermo-mechanical processing. The total time at temperature during thermo-mechanical processing following β-quenching is commonly expressed as an annealing parameter, which is defined as (Reference 17):

$$\sum A_i = t_i \, e^{\left(-\frac{Q}{RT_i}\right)}$$

Where t_i represents annealing time (in hours) for annealing step i after β-quenching, T_i is the annealing temperature (K) and Q/R used for calculations in this report is 40,000 K, see Reference 12. It has been demonstrated (Reference 18) that there is a clear correlation between the accumulated annealing parameter and the corrosion behavior of zirconium-based materials, more specifically Zircaloy-2 and Zircaloy-4 alloys. There is also a strong correlation between the size of SPPs and the annealing parameter, independent of the number and the sequence of annealing steps in the α range, which is also not affected by intermediate cold-working steps.

The annealing parameter of **HiFi** cladding **[**

]^{a,c}

HiFi cladding for Japanese BWR fuel has **[**

]^{a,c} **HiFi** cladding introduced by Westinghouse in Europe was **[**

]^{a,c} Table 3-2 shows a comparison of the manufacturing parameters after β-quenching for the different applications of **HiFi** cladding included in this report. **[**

]^{a,c}

The only significant difference between **HiFi** cladding for Japan and for Westinghouse in Europe and the US is that **[**

]^{a,c} Table 3-2 shows how the resulting annealing parameter is **[**

]^{a,b,c}

Table 3-2 Comparison of nominal annealing parameters for the manufacturing of *HiFi* cladding

a,b,c

[

]

Measurements of SPP size distributions have been performed in cladding manufactured using the different processes described. The majority of examinations characterized the total SPP size distributions, but a separate study has also been performed to independently measure the distributions of $Zr(Fe,Cr)_2$ and $Zr_2(Fe,Ni)$.

HiFi with different compositions and reference Zircaloy-2 materials **[** **]**^{a,c} has been examined. The detailed data is found in Table A-1. Average SPP sizes **[**

]^{a,c} In order to reduce the impact of experimental differences, a comparative study of **[** **]**^{a,c} was performed for **[**

]^{a,c}

The data shown in Table 3-3 differentiates between the two main types of SPP:s. All the data in Table 3-3 was collected using the same sample preparation and evaluation techniques to eliminate systematic differences between different examinations.

The most obvious trend is that **[**

]^{a,c} Typical average SPP sizes vary **[**

]^{a,b,c}

The very small difference in SPP size between Zircaloy-2 and **HiFi** is not expected to result in any detrimental effects on performance, as demonstrated by testing results presented in later sections.

Table 3-3. Results of SPP measurements of HiFi and Zircaloy-2

[ ]^{a,b,c}

In-reactor verification of **HiFi** cladding to high burnup has been performed in Europe, **[**

]^{a,b,c} The inner diameter liner of this **HiFi** cladding **[**

]^{a,c}

This section has demonstrated that the manufacturing processes used for **HiFi** cladding presented in this document show only minimal differences, driven mainly by the capabilities of different manufacturers. These small differences do not result in significant differences in the resulting annealing parameters and associated microstructures, which demonstrate the equivalence of the manufacturing processes for the new alloy, as well as the closeness to the extensive experience of Zircaloy-2 cladding.

3.2 MATERIAL PROPERTIES

3.2.1 Chemical Composition

For normal production, samples for chemical analysis are taken from the top, middle and bottom of the ingot. The composition of different batches of **[**

]^{a,c} are found in Table A-2 in the Appendix. All the results fulfill the requirements of the material specification and the alloy definition in Section 1.3, and demonstrate the consistency of the chemical composition in the different sections of the ingot and throughout the process.

3.2.2 Thermal Properties

Relevant thermal properties have been measured for **HiFi** cladding at three different temperatures. In Table 3-4 the thermal properties of **HiFi** cladding are compared to measured or reference values for Zircaloy-2 cladding. The thermal conductivity (λ) of **HiFi** cladding was calculated from measured values of thermal diffusivity (α) and heat capacity (Cp), which were measured using the laser flash method. The thermal conductivity is calculated as $\lambda = \alpha \, Cp \, \rho$, where the density ρ at temperature is calculated from measured thermal expansion.

Reference values for Zircaloy-2 cladding properties were obtained from Reference 19. **[**

]^{a,c} Table A-3 in the Appendix summarizes the results. **[**

]^{a,c}

Emissivity depends strongly on the surface condition and the presence of any oxide. A suggested value for standard error of emissivity of 0.1 is found in Reference 20. **[**

]^{a,c}

Table 3-4 Thermal properties of *HiFi* cladding compared to reference values

[ ]^{a,b,c}

3.2.3 Mechanical Properties

Mechanical properties of **HiFi** cladding with different compositions within the range defined in Table 1-1, fabricated for Westinghouse 10x10 fuel and **TRITON11** fuel with the standard Westinghouse zirconium-tin liner, have been tested in order to verify that the material meets the specification of Zircaloy-2 cladding. Tensile and burst tests were performed. The results shown in Table 3-5 fulfill the specification requirements with margin and are comparable to the experience of Zircaloy-2. Expanded results can be found in Table A-4 and Table A-5 in the Appendix. The reference values in the table correspond to **[** **]**^{a,c} The differences between the two materials are within the variability of the measurements and the values are well above the minimum specification limits. There is a small difference in yield strength values between the qualified suppliers due to minor differences in conditions for the final cold pilger and the final recrystallization anneal. All suppliers fulfil the specification requirements with margin.

Table 3-5 Mechanical properties of *HiFi* and Zircaloy-2 LK3 cladding

a,b,c

3.2.3.1 Thermal Creep

Samples of **HiFi** cladding fabricated for different fuel designs were tested **[**

]^{a,c} For each sample, the diameter was measured before and after each testing time. An average transversal creep strain was then calculated. The results are shown in Table 3-6, and are compared with a similar tests performed for Zircaloy-2 LK3 cladding. The results demonstrate that the thermal creep of **HiFi** cladding is **[** **]**^{a,c}

Table 3-6 Average thermal creep testing results of *HiFi* cladding [
]^{a,c}

a,c

3.2.3.2 Texture and Contractile Strain Ratio

The texture of **HiFi** cladding tubes fabricated in multiple designs and reference Zircaloy-2 tubes produced with the same manufacturing parameters has been evaluated using laboratory X-ray diffraction. Samples **[** **]**^{a,c} were also tested for contractile strain ratio (CSR), a bulk mechanical parameter related to texture. The CSR obtained for **HiFi** and Zircaloy-2 cladding was **[**

]^{a,b,c} Typical pole figures from **HiFi** cladding can be found in Figure A-1 in the Appendix.

3.2.4 Material Properties for Fuel Rod Design Methods

With a change from Zircaloy-2 cladding to **HiFi** cladding, the properties of interest for fuel rod design are the thermo-mechanical properties of the fuel cladding material. Thermo-mechanical properties of zirconium alloys are functions of temperature, burnup and/or fast neutron fluence. The following paragraphs evaluate the applicability of NRC-approved BWR Zircaloy-2 cladding models for **HiFi** cladding, based on the data presented above.

3.2.4.1 Thermal Properties

The thermal conductivity and thermal expansion of zirconium alloys are primarily functions of temperature. Previous work using Zircaloy-2 and Zircaloy-4 materials shows that the difference between these materials appears to be of the same magnitude as the statistical scatter in the data.

Heat capacity is an auxiliary calculation used for input into transient analysis. For fuel rod design the heat capacity is only modeled in the α phase.

The results in Section 3.2.2 above show **[**

]^{a,c}

3.2.4.2 Elastoplastic Properties

Properties such as elastic moduli, Poisson's ratio, strength coefficients, strain rate, and strain hardening are functions of temperature, oxygen content, cold work and fast neutron fluence.

Operational experience and tests on unirradiated and irradiated material, presented in Sections 3.3 and 3.4 below, demonstrate that the mechanical behavior of **HiFi** cladding **[**

]^{a,c}

3.3 OUT-OF-PILE TESTING

3.3.1 Uniform Corrosion and Hydrogen Pickup

HiFi and Zircaloy-2 tubes **[**

]^{a,c} The results are shown in Figure 3-1, illustrating that the uniform corrosion resistance of **HiFi** cladding is very similar to that of Zircaloy-2 cladding. More importantly, the in-reactor experience of **HiFi** cladding compared to Zircaloy-2 cladding, presented in Section 3.4, also supports this conclusion.

Figure 3-1 Out-of-pile uniform corrosion testing at 400°C

a,b,c

Figure 3-2 and Figure 3-3 show the results of hydrogen content and hydrogen pickup fraction after this long term corrosion test. The hydrogen pickup fraction of **HiFi** cladding in autoclave corrosion tests is significantly lower than that of Zircaloy-2 cladding.

Figure 3-2 Out-of-pile hydrogen content

a,b,c

Figure 3-3 Out-of-pile hydrogen pickup fraction

[$]^{a,b,c}$

HiFi cladding with different compositions within the range according to Table 1-1, fabricated to the specification for SVEA-96 Optima2 and SVEA-96 **Optima3** fuel **[** $]^{a,c}$ The results shown in Table 3-7 further exemplify a lower hydrogen pickup fraction for **HiFi** cladding with respect to Zircaloy-2 cladding. The distribution of hydrides was verified in the outer component. **[** $]^{a,c}$ as illustrated in Figure 3-4. The orientation of the hydrides matches the experience with Zircaloy-2 LK3.

Table 3-7 Long-term corrosion results for *HiFi* and Zircaloy-2 cladding

[$]^{a,c}$

Figure 3-4 Hydride orientation and distribution after long term out-of-pile corrosion testing of *HiFi* cladding

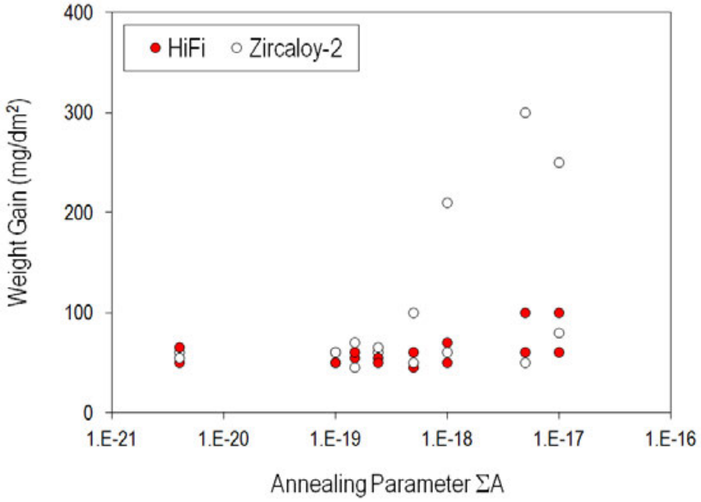
[ ]^{a,b,c}

3.3.2 Nodular Corrosion

During early development of manufacturing processes for **HiFi** cladding by NFI, the effects of accumulated annealing parameter on nodular corrosion resistance were estimated by ex-core nodular corrosion testing on **HiFi** alloy plates annealed under various conditions. The intermediate anneal after the final solution heat treatment was varied to achieve different accumulated annealing parameters. Coupons made with different annealing parameters were tested in-reactor **[ ]^{a,c}** for selection of the annealing parameter for **HiFi** cladding.

Plates of manufactured alloys were evaluated for nodular corrosion resistance, by corrosion testing in steam at 525°C for 24 hours. Figure 3-5 shows the results. The nodular corrosion resistance of Zircaloy-2 material is degraded as the annealing parameter ∑A is increased over 10^{-18}, as illustrated by the scatter in weight gain, while **HiFi** material maintains nodular corrosion resistance up to 10^{-17}. **[ ]^{a,b,c}**

Figure 3-5 Nodular corrosion vs. annealing parameter



Nodular corrosion tests were performed on **[**

]^{a,b,c}

Table 3-8 Nodular corrosion test results

a,b,c

3.3.3 Loss of Coolant Accident Behavior

Out-of-pile tests were performed using **HiFi** cladding tubes fabricated for **[ ]**^{a,c} to evaluate the loss of coolant accident (LOCA) behavior. Figure 3-6 shows the weight gain as a function of the square root of corrosion time, while Figure 3-7 shows the Arrhenius plot of the parabolic rate law constants determined by high temperature steam oxidation tests. From these results, it was confirmed that the high temperature corrosion behavior of **HiFi** cladding is **[**

]^{a,c} High temperature burst tests were also performed, and confirmed that the burst behavior for **HiFi** and Zircaloy-2 materials is very similar, as illustrated in Figure 3-8.

Figure 3-6 High temperature steam oxidation

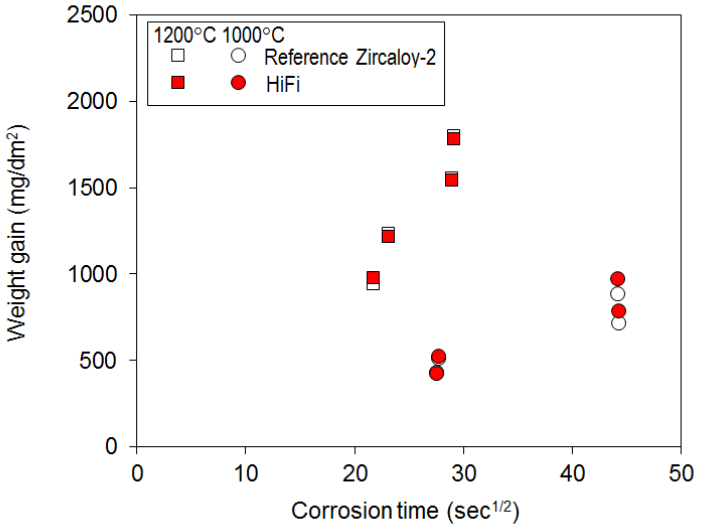


Figure 3-7 High temperature oxidation reaction rate constant (from Reference 16)

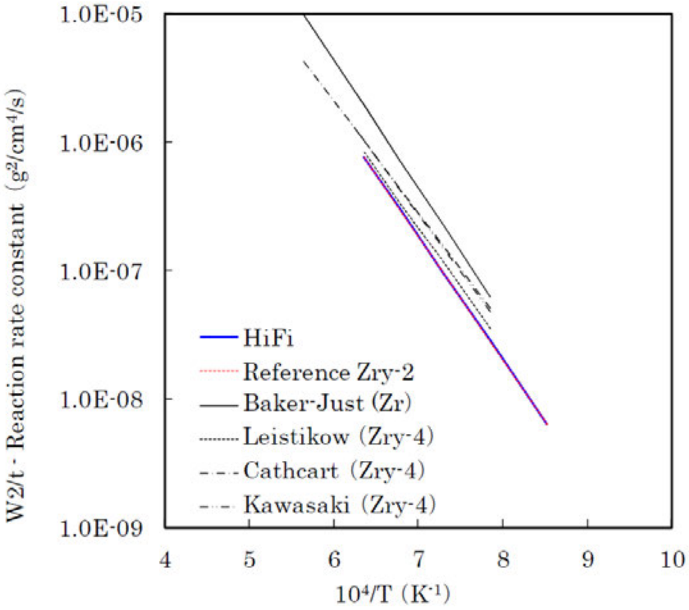
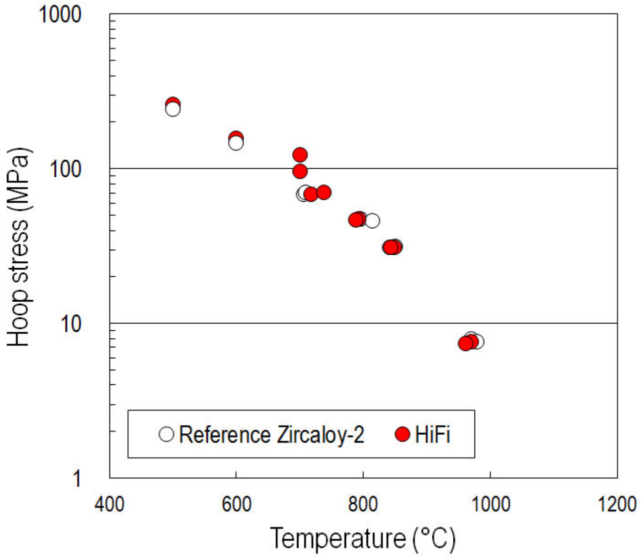


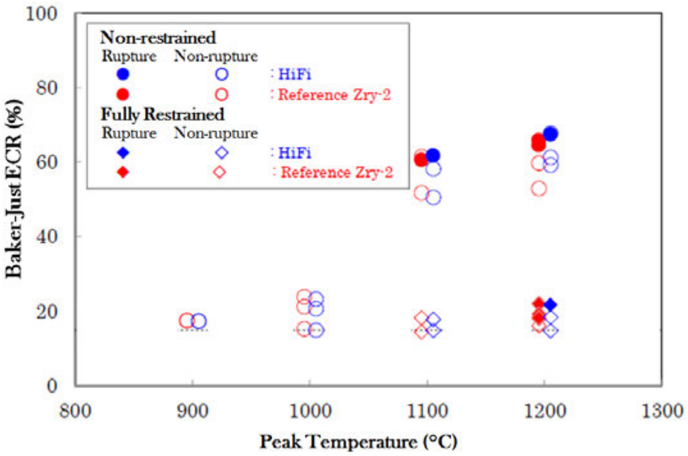
Figure 3-8 Correlation of burst hoop stress and cladding temperature



Integral tests simulating LOCA transient conditions and consisting of rod burst, oxidation and re-flooding thermal shock testing of the material were conducted to confirm that the equivalent cladding reacted (ECR) criteria are met (15% in Japan). To address the possible restriction of the cladding shrinkage and the consequent tensile loading, the tests were performed in axial non-restrained and fully restrained conditions during quenching. Figure 3-9 shows the failure map relative to ECR and temperature for **HiFi** and Zircaloy-2 cladding. **[**

]^{a,c}

Figure 3-9 ECR value measured by quench tests



3.4 IRRADIATION EXPERIENCE

In this section, the extensive irradiation experience of **HiFi** cladding in different applications is presented. The purpose is to demonstrate that the in-reactor performance of **HiFi** cladding is equivalent or superior to that of Zircaloy-2 cladding. **HiFi** cladding has been subjected to irradiation in different forms and in different facilities. Irradiation started with coupons in the Kashiwasaki-Kariwa 5 reactor in Japan **[** **]**^{a,c} The completed irradiation campaigns, **[** **]**^{a,c} were conducted in **[** **]**^{a,c}

More recently, Westinghouse SVEA-96 Optima2 fuel rods with **HiFi** cladding were inserted in **[** **]**^{a,c} Table 3-9 summarizes the irradiation experience for **HiFi** cladding, while the following sections describe the results of the irradiation programs already completed. In all the irradiation programs PIE included both **HiFi** and Zircaloy-2 cladding, in order to compare the performance side-by-side.

Table 3-9 Summary of irradiation experience of *HiFi* cladding

[ ]a,c

As described in Section 3.1, **HiFi** material has been manufactured **[**

]a,c

3.4.1 Plant A - [ ]a,c

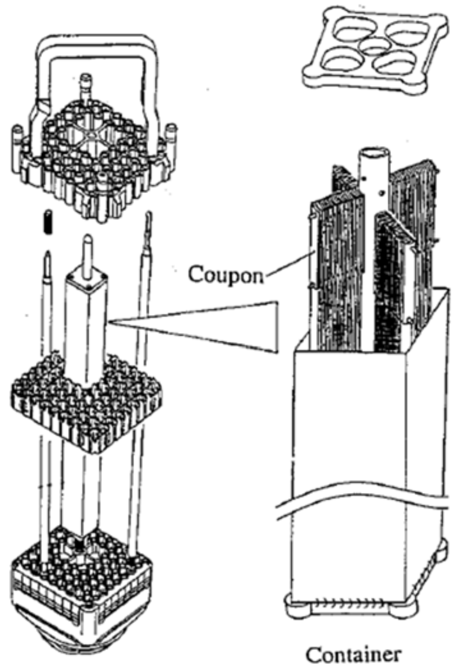
Coupons made from prototypic **HiFi** and Zircaloy-2 alloys were placed in a container loaded into the water channel of 9x9 fuel in **[** **]a,c** using the setup illustrated in Figure 3-10. **[**

]a,c

Coolant was flowed in the container to prevent the coupon surface from boiling. The coupon temperature was estimated as 275°C. The container including the coupons was transported to a PIE facility after three cycles (900 days) irradiation, **[** **]a,c** Visual inspection, metallographic analysis, hardness and hydrogen analyses were performed. Results show that **[**

]^{a,b,c}

Figure 3-10 Configuration for irradiation in [ ]^{a,c}



Regarding the relationship between the annealing parameter ∑A and the nodular corrosion resistance, the results were consistent with the ex-core nodular corrosion tests reported in Section 3.3.2. **[**

]^{a,b,c}

3.4.2 Kashiwazaki-Kariwa 5

The irradiation program in Kashiwazaki-Kariwa 5 (K5) was designed to **[**

]^{a,c} This large scale program included **[**

]^{a,c}

Coupons were placed in Zircaloy-2 capsules of 13 mm outer diameter. Capsules were loaded into dummy neutron source holders. Figure 3-11 shows the configuration of the capsules and the corrosion samples as an example. The capsules were irradiated during six irradiation cycles, approximately 2,500 days amounting to an equivalent burnup of 72 GWd/MTU and fast fluence of $15x10^{25}n/m^2$. Coolant flowed within the capsules; however, coupons surfaces were estimated to be in boiling condition because of γ-heating. According to computer calculations using TRAC code, the void fraction was approximately 20% and the temperature of the coupons was 285°C. The capsule interior was stable and maintained a similar condition during the six cycles. TEM discs were located in an inert atmosphere to avoid oxidation.

The holders containing the coupons were unloaded from the core after **[**

]^{a,c} They were transported to a post irradiation examination (PIE) facility to perform visual inspection, weight measurement, metallographic examination, hydrogen analysis, mechanical testing and TEM analysis. **[**

]^{a,c} Figure 3-12 shows the measurements of oxide thickness during irradiation of coupons in K5, together with **[**

]^{a,c} The proximity of points, even with some overlapping, taken from the side-by-side samples of **HiFi** and Zircaloy-2 tested under the same conditions demonstrates **[**

]^{a,c}

Figure 3-11 Holder irradiated in K5 and configuration of corrosion sample

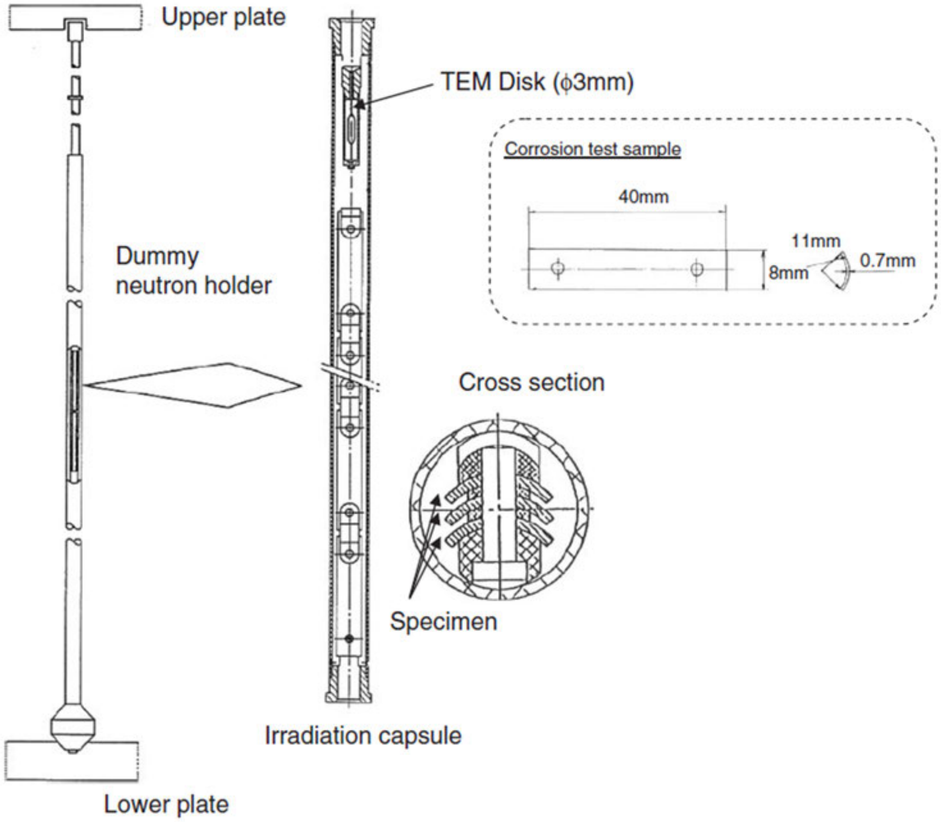


Figure 3-12 Corrosion of K5 coupons and [ ]^{a,c}

[ ]^{a,b,c}

The hydrogen pickup fraction of the K5 coupons is shown in Figure 3-13. Consistent with the out-of-pile tests, the uniform corrosion is comparable between Zircaloy-2 and **HiFi** cladding, but the hydrogen pickup fraction of **HiFi** cladding is significantly lower than that of Zircaloy-2 cladding. Images of hydride precipitation after four cycles of irradiation (47 GWd/MTU burnup) are shown in Figure 3-14, including the hydrogen content which, given the similar total corrosion, results in an improved hydrogen pickup fraction for **HiFi** cladding. The hydrogen pickup fraction is [

]^{a,c}

Figure 3-13 Hydrogen pickup fraction in K5 coupons

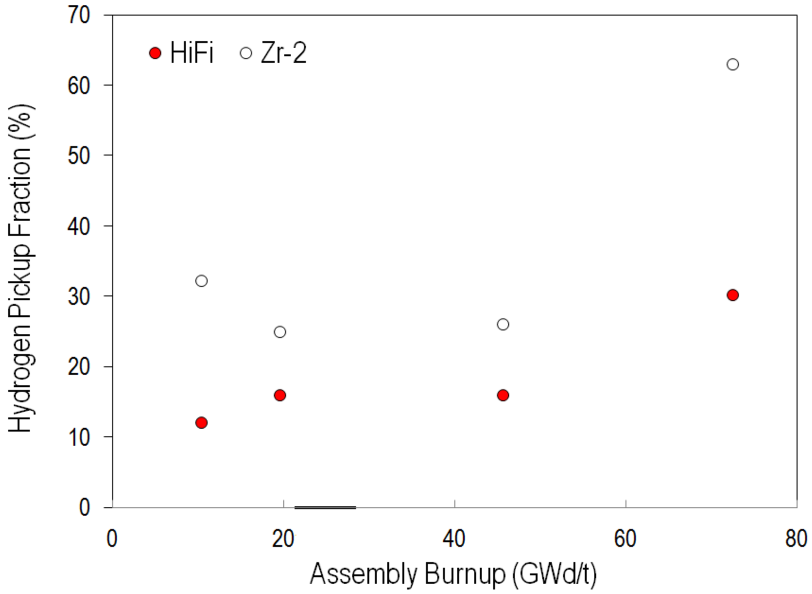
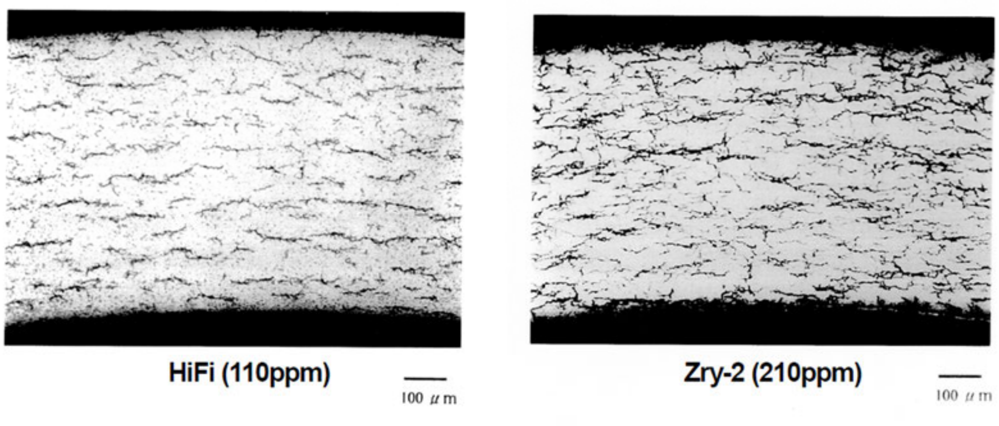


Figure 3-14 Hydride precipitation



HiFi (110ppm)

Zry-2 (210ppm)

3.4.2.1 Tensile Tests

Tensile tests at 343°C and room temperature (see reference 16) were conducted on the **HiFi** cladding and reference Zircaloy-2 cladding coupon samples in K5. The mechanical strength of the **HiFi** coupons showed **[** **]^{a,c}** which is similar to the experience database illustrating the similarities with Zircaloy-2. Figure 3-15 and Figure 3-16 show the results of yield strength and elongation in K5 for both materials as a function of fluence. The tensile test results, as well as other results in the following sections, are shown together with **[** **]^{a,c}**

Figure 3-15 Yield strength (343°C) of K5 coupons

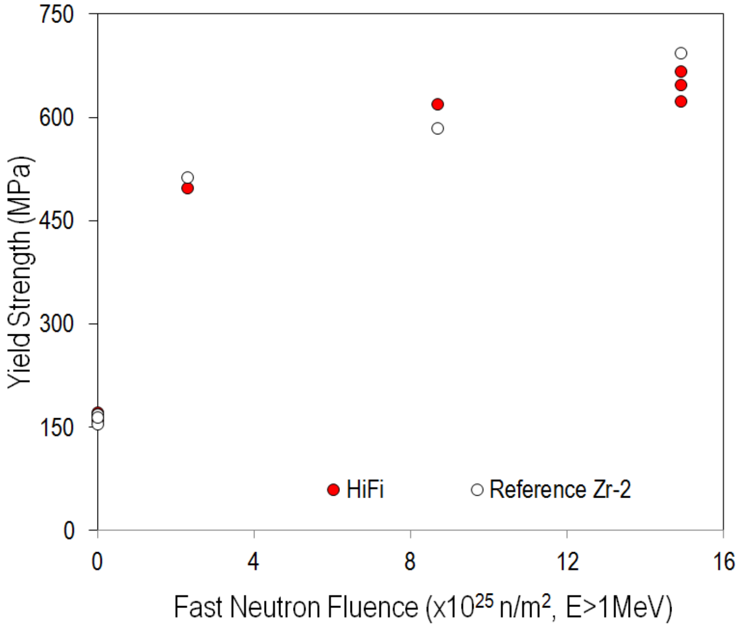
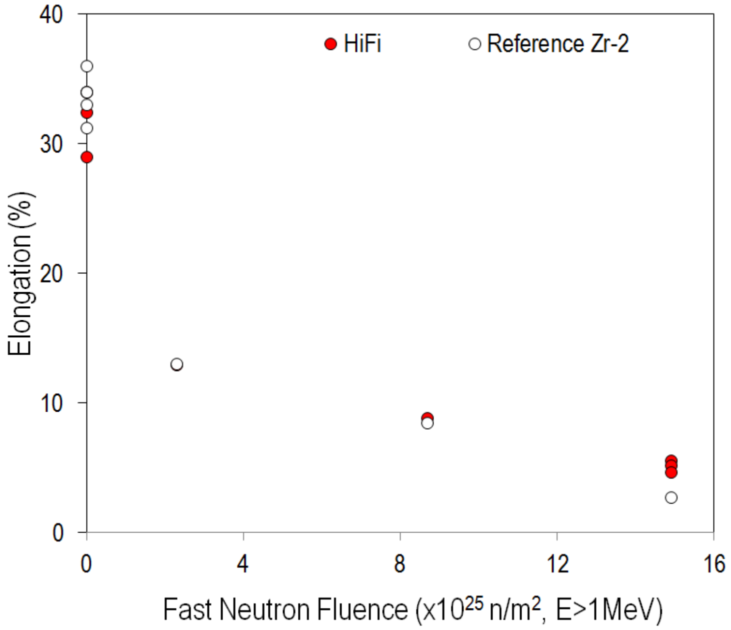


Figure 3-16 Elongation (343°C) of K5 coupons

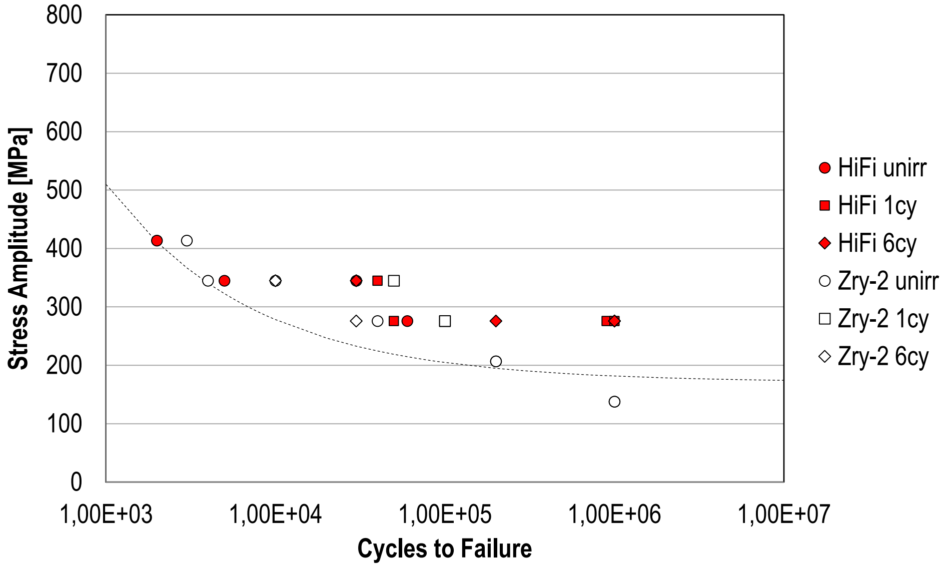


3.4.2.2 Fatigue Tests

Figure 3-17 shows results of fatigue tests performed on unirradiated and irradiated K5 coupons conducted at room temperature, which demonstrate comparable or superior performance, i.e. cycles to failure, of **HiFi** material with respect to the reference Zircaloy-2, for a given stress amplitude. The results for irradiated **HiFi** material exceed the O'Donnell-Langer best fit of unirradiated Zircaloy-2 (Reference 21).

Figure 3-17 Fatigue results of K5 coupons at room temperature.

The curve shows the O'Donnell-Langer best fit of unirradiated Zircaloy-2 (Reference 21)

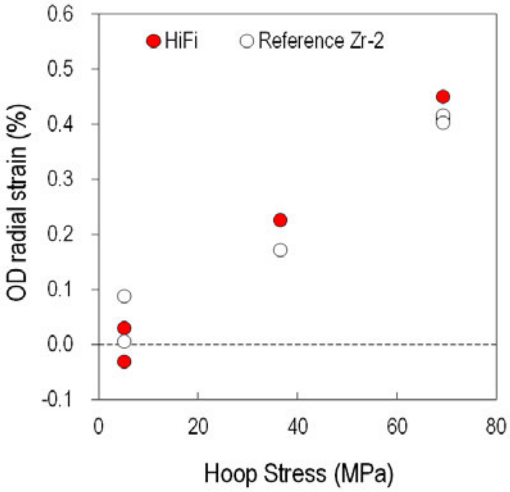


3.4.2.3 Irradiation Creep

Closed specimens pressurized with a noble gas were irradiated in **[ ]**^{a,c} for 1666 days. Figure 3-18 shows outer diameter (OD) measurements performed on these samples, demonstrating **[**

]^{a,c}

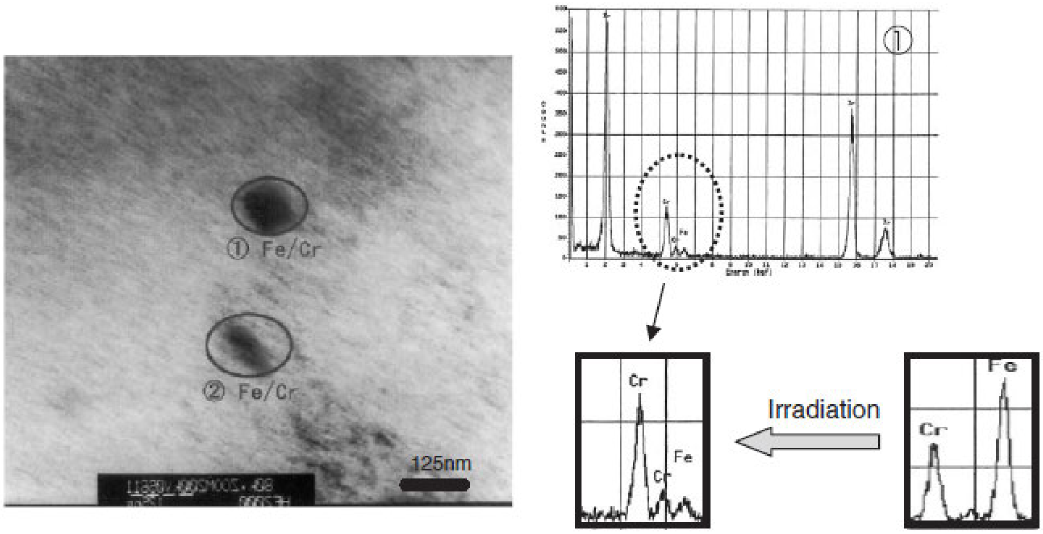
Figure 3-18 OD measurements in pressurized [ ]^{a,c} samples



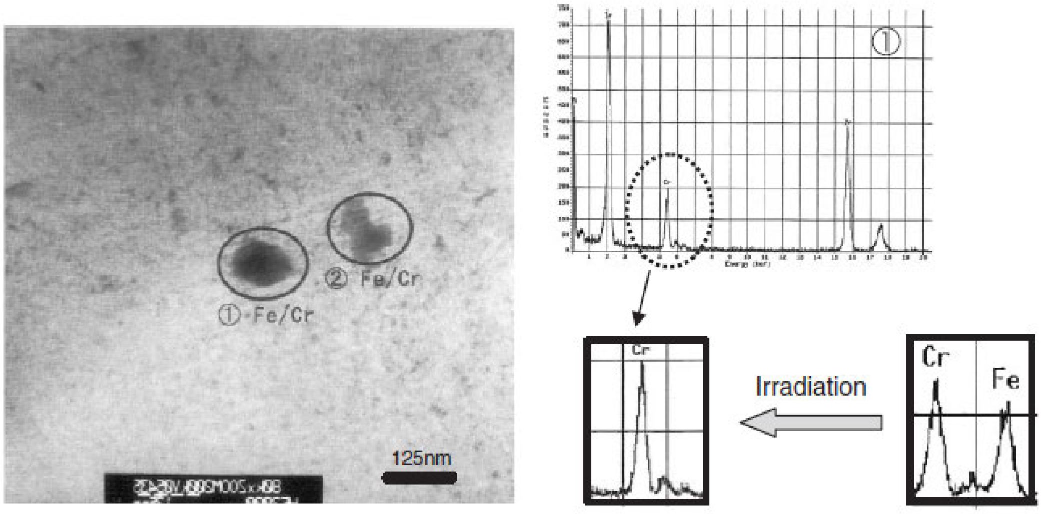
3.4.2.4 Characterization of Second Phase Precipitates

TEM characterization, including energy-dispersive X-ray spectroscopy (EDS) was conducted on **HiFi** and Zircaloy-2 cladding specimens to study the evolution of second phase precipitates. Figure 3-19 shows TEM images of **HiFi** and Zircaloy-2 cladding after six cycles of irradiation. The majority of the precipitates studied appeared amorphous. The presence of iron in the precipitates decreases with irradiation. This is illustrated in Figure 3-20, which shows that the iron/(iron+chromium) ratio decreased with neutron fluence. The ratio reaches a stable level, which is slightly higher for **HiFi** material than for Zircaloy-2 material due to the higher iron content.

Figure 3-19 TEM images of precipitates observed in Zircaloy-2 and *HiFi* alloys

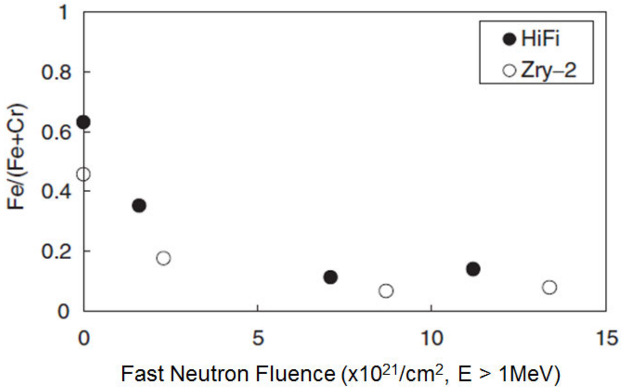


(HiFi alloy)



(Zry–2)

Figure 3-20 Fe/(Fe+Cr) ratio of precipitates as a function of fast neutron fluence



3.4.3 Halden BWR

Irradiation testing of fuel rods with **HiFi** and Zircaloy-2 cladding was performed in a BWR corrosion test loop in the Halden boiling water reactor (HBWR). The fuel rods were irradiated without failure reaching a rod average burnup of 60 GWd/MTU. The active length of the fuel rods was 40 cm with an outer diameter of 11 mm. Rods were placed in a stainless steel flask as illustrated schematically in Figure 3-21. System pressure of the loop was 7 MPa, coolant inlet temperature was 280°C and the average linear heat generation of the fuel rods was constant, approximately 40 kW/m up to 25 GWd/MTU and was gradually reduced to 25 kW/m up to 40 GWd/MTU. Boiling started at 15-20 cm elevation from the bottom of the active length.

Intermediate inspection of the fuel rods was conducted after irradiation to 20 GWd/MTU and 40 GWd/MTU fuel rod average. Oxide thickness was measured using eddy current at 40 GWd/MTU and 60 GWd/MTU. Results are shown in Figure 3-22 and Figure 3-12. The total oxide thickness observed was between 20 and 60 µm, with thicker oxide observed on the surface oriented closer to the stainless steel flask. Compared to Zircaloy-2 cladding, **HiFi** cladding had a thinner oxide on the surface towards the stainless steel flask. Furthermore, visual inspection showed that the oxide film of the Zircaloy-2 cladding material towards the flask had flaked off, with minimal flaking observed in **HiFi** cladding. Oxide flaking in the Zircaloy-2 material was significant in the non-boiling region of the upstream. The thicker oxide and the flaking can be attributed to the phenomenon known as “shadow corrosion”, observed at contact points and/or close proximity regions between zirconium alloy components and other materials such as nickel-based alloy spacers or stainless steel control rods. These results indicate that **HiFi** cladding may be less susceptible to shadow corrosion than Zircaloy-2 cladding.

Figure 3-21 Schematic drawing of Halden BWR corrosion loop test

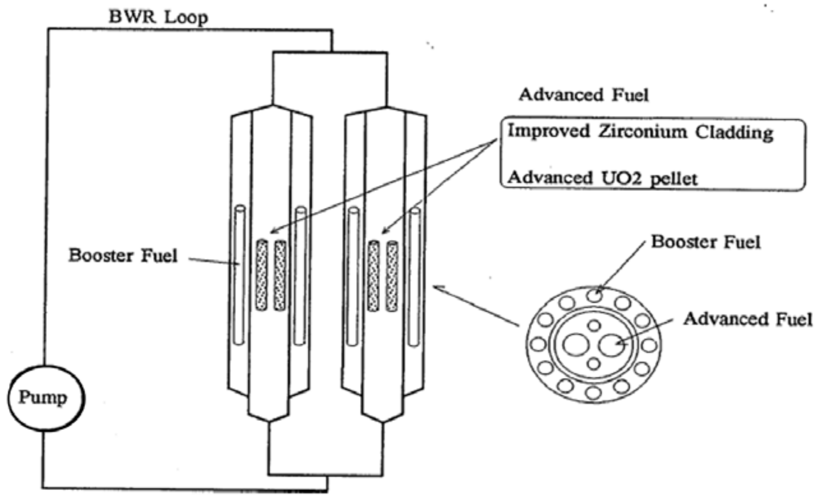
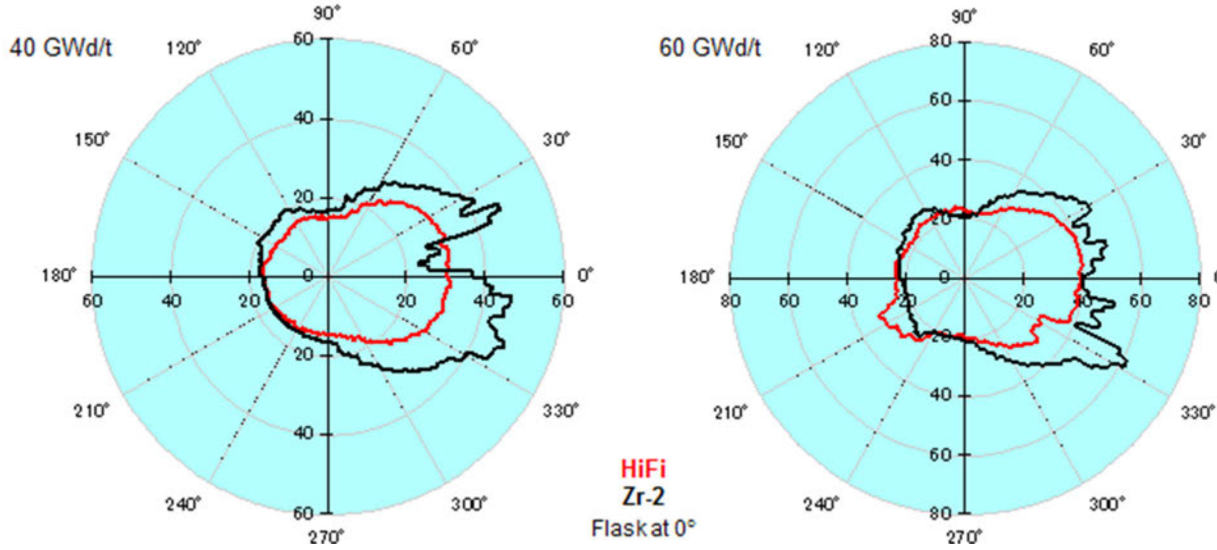


Figure 3-22 Oxide thickness around the circumference of BWR fuel rodlets irradiated in Halden



3.4.4 Plant B - [ ]a,c

[ ]a,c fuel assemblies with **HiFi** cladding tubes were irradiated for [ ]a,c reaching [ ]a,c without any issues in performance. In total there were [ ]a,c Six assemblies were discharged after [ ]a,c Two assemblies were irradiated for [ ]a,c The pool-side inspection of these assemblies included visual inspection, fuel rod diameter measurements, oxide thickness measurements using eddy current, and fuel rod growth measurements at different points in life. Hot cell examinations included metallography, hydrogen content, hardness, and burst tests.

HiFi cladding tubes were confirmed to be sound by the visual inspection after [ ]a,c as illustrated in Figure 3-23. Average results of measurements of outer diameter of the fuel rods, performed pool-side at two azimuthal positions and along the full length, are shown in Figure 3-24. [ ]a,c Results of fuel rod growth measurements are shown in Figure 3-25, [ ]a,c It is important to note that the [ ]a,c

The oxide thickness of the rods examined is shown in Figure 3-26, [ ]a,c The hydrogen content of the fuel rods, obtained in hot cell, is shown in Figure 3-27. The hydrogen content for [ ]a,c

[

]^{a,c} which is combined in the figure. For example, after **[**

]^{a,c}

Figure 3-23 Visual inspection results on [ ]^{a,c} fuel rods after [ ]^{a,c} of irradiation

[ ]^{a,b,c}

Figure 3-24 OD measurements on [ ]^{a,c} fuel rods

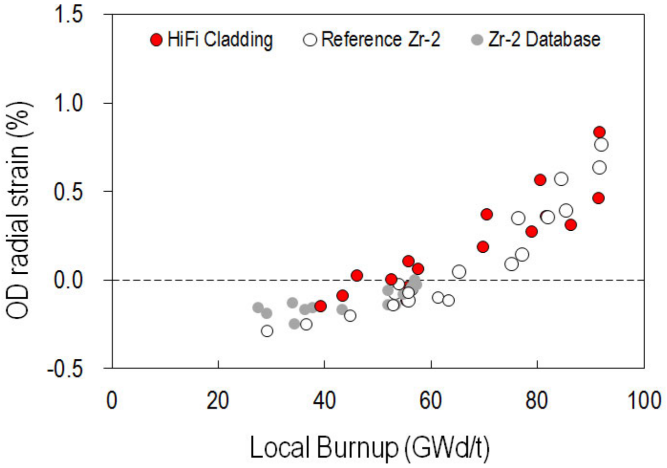


Figure 3-25 Growth of [ ]^{a,c} fuel rods

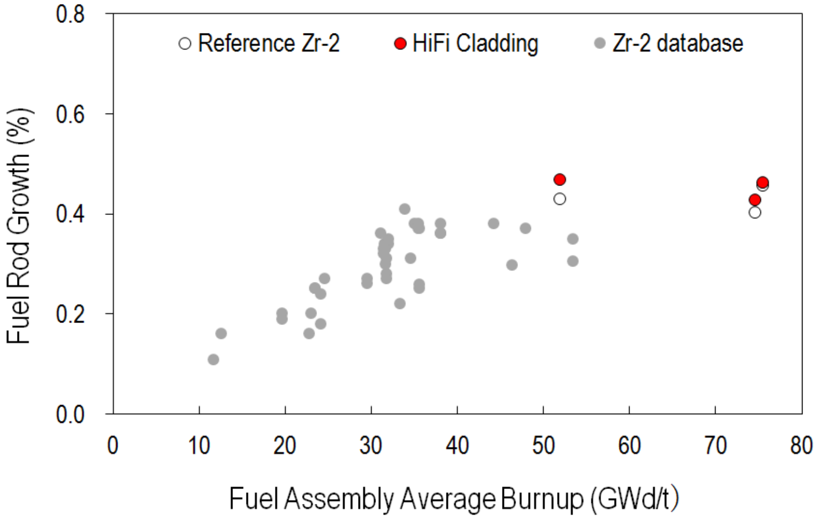


Figure 3-26 Corrosion of [ ]^{a,c} fuel rods

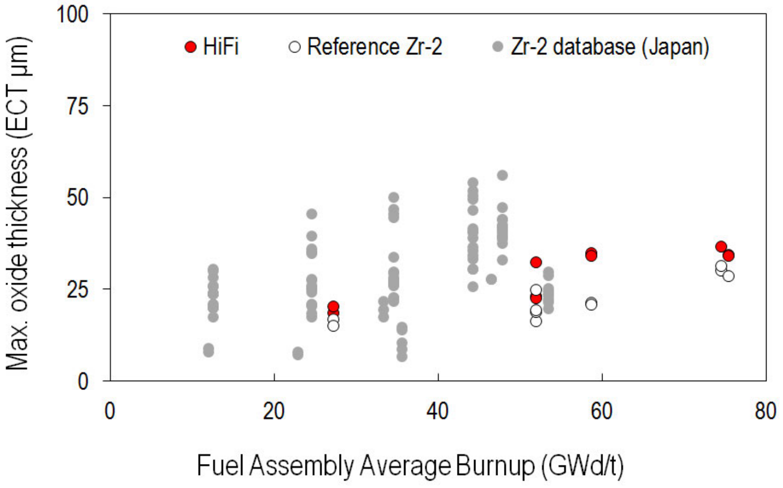


Figure 3-27 Hydrogen uptake of [ ]^{a,c} fuel rods

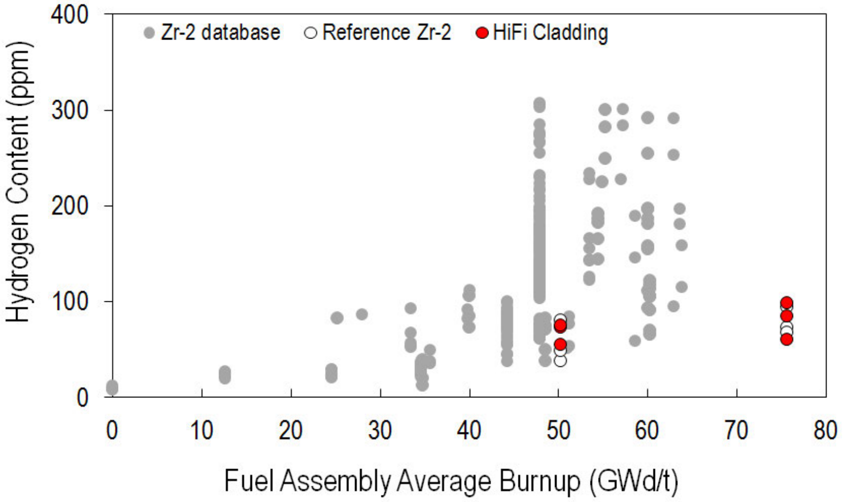
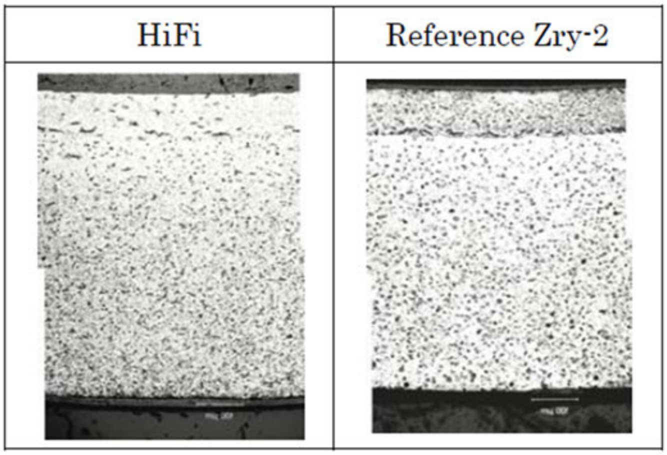


Figure 3-28 Hydride distribution of irradiated cladding tubes from [ ]^{a,c} (4 cycles)



3.4.4.1 Burst Test

Burst tests were conducted to determine the mechanical properties of irradiated **HiFi** cladding tubes. Figure 3-29 and Figure 3-30 show respectively the burst stress and circumference elongation of the cladding tubes at 343°C, showing minimal differences between the **HiFi** cladding and Zircaloy-2. **[**

]^{a,c}

Figure 3-29 Burst stress of cladding tubes irradiated in [ ]^{a,c}

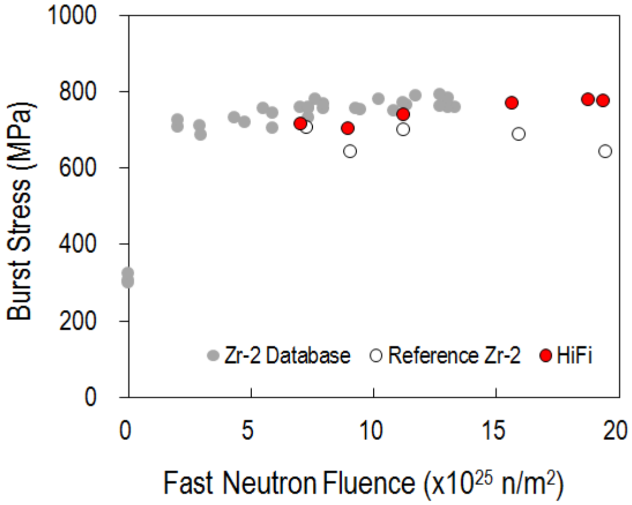
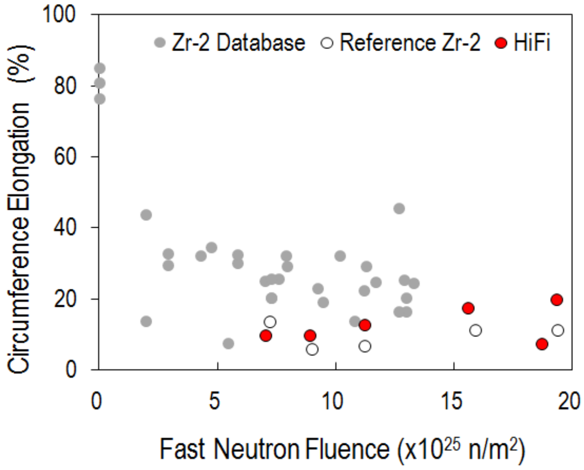


Figure 3-30 Circumference elongation after burst testing of cladding tubes irradiated in [ ]^{a,c}



3.4.5 Plant C - [ ]^{a,c}

In parallel to the experience acquired by NFI with **HiFi** cladding in Japan, Westinghouse had started a development program including three different high iron alloys. [

]^{a,c}

Table 3-10 Main alloying elements of [ ]^{a,c}

[ ]a,c

In 2001, one fuel assembly was loaded in [

]^{a,c} The fuel assembly was irradiated for [

]^{a,c} Throughout the irradiation program, the fuel rods have been inspected on several occasions, as shown in Table 3-11 below. Results from the pool-side inspections can be found in Figure 3-31 to Figure 3-34. [ ]^{a,c}

[

]^{a,c}

Table 3-11 Pool-side examinations performed on [ ]^{a,c}

a,c

Figure 3-31 Pool-side rod growth measurements of [ ]^{a,c}

a,b,c

Figure 3-32 Pool-side fuel rod average lift-off of [ ]^{a,c}

a,b,c

Figure 3-33 Pool-side maximum lift-off measured on [ ]^{a,c}

[ ]^{a,b,c}

Figure 3-34 EOL visual pool-side inspection results of [ ]^{a,c}

[ ]^{a,b,c}

In 2012, a rod **[** **]**^{a,c} This demonstrates that **[** **]**^{a,c}

Figure 3-35 Comparison of hydride orientation of [ ]^{a,c}

]^{a,b,c}

3.4.6 Plant D - [ ]^{a,c}

[**]**^{a,c} lead use programs of **HiFi** cladding in Westinghouse fuel are **[**

]^{a,c}

[**]**^{a,c} lead use assemblies (LUAs) with **[** **]**^{a,c} **HiFi** cladding were inserted. **[**

]^{a,c}

3.4.7 Plant E – [ ]^{a,c}

The **[** **]**^{a,c} lead use program of **HiFi** cladding in Westinghouse fuel started in Plant E, **[**

]^{a,c} which broadens the experience window for the exposed materials. In Plant E **[** **]**^{a,c} fuel assemblies with a total of **[**

]^{a,c}

[**]**^{a,c} pool-side PIE of rods with **HiFi** cladding in **[** **]**^{a,c}

[

]^{a,c} Rod growth was **[** **]**^{a,c} Inspections have thereafter been performed both in 2019 and 2022, showing a comparable experience between cladding materials also for lift-off.

3.4.8 Overall Operating Experience

[

]^{a,c}

Table 3-12 In-reactor test experience (coolant chemistry*)

a,b,c

Figure 3-36 Power history for *HiFi* fuel rods

[ ]^{a,b,c}

The pool-side PIEs of rods with Alloy-2 LTRs and **HiFi** cladding have included **[** **]**^{a,c} as illustrated in Figure 3-37. **[** **]**^{a,c} as illustrated in Figure 3-38 and Figure 3-39 respectively. **[** **]**^{a,c}

Figure 3-37 Fuel rod growth of rods with *HiFi, Alloy-2* LTRs and LK3 cladding

a,b,c

Figure 3-38 Fuel rod lift-off of rods with *HiFi, Alloy-2* LTRs and LK3 cladding

a,b,c

Figure 3-39 Fuel rod lift-off in spacer regions of rods with *HiFi* and LK3 cladding

a,b,c

4 FUEL DESIGN AND ACCIDENT ANALYSIS

This section discusses fuel design and accident analysis for application of **HiFi** cladding, assessing its effect on NRC-approved methods, to verify compliance with 10 CFR Part 50. The Westinghouse methodologies for conducting fuel assembly and fuel rod mechanical evaluations for the current licensed BWR fuel designs, prescribed in Section 4.2 of the Standard Review Plan (SRP) in Reference 22, are detailed in References 1 to 3. This section discusses the different acceptance criteria, concluding that **HiFi** cladding is compliant with NRC-approved BWR methods and has acceptable performance in Westinghouse BWR fuel designs. Compliance to NRC-approved methods is demonstrated by evaluating the test data.

4.1 FUEL ASSEMBLY MECHANICAL DESIGN

The fuel assembly designs can be impacted by changes in unirradiated yield strength and ultimate strength. The mechanical strength for both irradiated and un-irradiated **HiFi** cladding is **[**

]^{a,c} Therefore, **HiFi** cladding will meet fuel assembly design criteria.

4.2 FUEL ROD DESIGN

Westinghouse BWR fuel designs are analyzed employing the following fuel rod design criteria by using NRC-approved BWR methods and methodologies for Zircaloy-2 (reference 3). Each criterion is specified along with the evaluation of the use of **HiFi** cladding on the specific criterion.

4.2.1 Rod Internal Pressure

Criterion: The design criterion for rod internal pressure states that the internal pressure of the fuel rod shall not exceed a value which would cause the outward cladding creep to increase the diametrical fuel pellet-cladding gap. This value of fuel rod internal pressure is defined to be that internal pressure which causes the outward cladding creep rate to exceed the fuel effective swelling rate. This requirement is referred to as “the lift-off criterion”.

Evaluation: The rod internal pressure and the lift-off pressure are calculated with an NRC-approved BWR fuel performance code. The pressure depends on the cladding creep, which is **[**

]^{a,c} (see Section 3.2.4.1 and Table 3-4). There is no adverse effect of **HiFi** cladding on the rod internal pressure, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluating the lift-off criterion.

4.2.2 Cladding Stresses

Criterion: Fuel rod stresses must be maintained within acceptable limits. This criterion is implemented by establishing design limits for stresses to assure that failure does not occur and that stresses of the fuel rod remain within acceptable limits.

Evaluation: Cladding stress is evaluated **[**

]^{a,c} is calculated with an NRC-approved fuel performance code and is dependent on **[**

]^{a,c} (see Section 3.2.4.1 and Table 3-4). There is no **[** **]^{a,c}** adverse effect of **HiFi** material on unirradiated or irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluating the cladding stresses.

4.2.3 Cladding Strain

Criterion: The total transient induced elastic and plastic cladding circumferential strain should not exceed 1%. In this context, total transient induced strain is the elastic and plastic strain which can occur during normal operation and anticipated operational occurrences (AOOs) excluding the effects of steady-state creep down and irradiation growth.

Evaluation: The criterion is evaluated by calculating the transient induced strain with an NRC-approved BWR fuel performance code. The transient strain depends on **[** **]^{a,c}** (see Section 3.2.4.1 and Table 3-4) and on the strain, which is discussed in Section 3.2.4.2. There is no adverse effect of **HiFi** cladding on the rod internal pressure, unirradiated or irradiated mechanical properties, compared to Zircaloy-2 cladding. Therefore, there will be no effect on the mechanical response for evaluation of the cladding strain.

4.2.4 Hydriding

Criterion: Cladding hydriding from waterside and internal sources shall be maintained sufficiently low that premature cladding failure shall not occur due to hydrogen embrittlement.

Evaluation: There is evidence of the lower hydrogen pickup fraction in **HiFi** cladding with respect to Zircaloy-2 cladding. For the purpose of this Topical Report **[**

]^{a,c}

4.2.5 Cladding Corrosion

Criterion: Cladding corrosion must be limited to assure that excessive cladding corrosion does not lead to premature fuel rod failures due to excessive metal thinning or excessive cladding temperatures. The effect of cladding corrosion shall be included in the thermal-mechanical evaluation of the cladding.

Evaluation: The criterion is evaluated by calculating the oxide thickness with an NRC-approved BWR fuel performance code. There is no adverse effect of **HiFi** material on corrosion, as corrosion of **HiFi** cladding has been demonstrated to be **[** **]^{a,c}** (see Figure 3-38). Therefore, there will be no impact on evaluating the cladding corrosion criterion.

4.2.6 Cladding Collapse

Criterion: Cladding collapse shall not occur during the design life of the fuel rod. Cladding collapse or "elastic and plastic instability" refers to the pressure across the tubing walls at which the cladding will buckle in the elastic and plastic ranges.

Evaluation: The cladding creep collapse is evaluated with an NRC-approved method. The creep collapse depends on the cladding creep, **[** **]^{a,c}** (see Section 3.4.2.3). There is no adverse effect of **HiFi** material on unirradiated or irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluation of cladding collapse. This includes instantaneous collapse at the beginning of life and creep collapse later during operation.

4.2.7 Cladding Fatigue

Criterion: Cladding fatigue shall not cause fatigue damage during normal operation and AOOs. The fatigue evaluation shall account for the effects of cladding corrosion.

Evaluation: The fatigue limits derived by O'Donnell Langer are used for evaluation of cladding fatigue. In Figure 3-17, it is shown that **[** **]^{a,c}** The evaluation of fatigue is done with an NRC-approved BWR fuel performance code and relies on the mechanical behavior of the cladding (see Section 3.2.4.2). **[** **]^{a,c}** Therefore, there will be no effect of **HiFi** material on the cladding fatigue evaluation.

4.2.8 Cladding Temperature

Criterion: Cladding overheating during normal operation and AOOs shall not cause fuel rod failure.

Evaluation: **[** **]^{a,c}**, and there is no adverse effect of **HiFi** material on the thermal properties of the cladding. Therefore, there will be no effect on evaluation of cladding temperature.

4.2.9 Fuel Temperature

Criterion: The maximum centerline pellet temperature shall remain below the melting temperature of the fuel during normal operation and AOOs.

Evaluation: The evaluation of fuel temperature is done with an NRC-approved BWR fuel performance code. **[** **]^{a,c}**

[**]^{a,c}** Therefore, there will be no effect of **HiFi** material on the fuel temperature criterion evaluation.

4.2.10 Fuel Rod Bow

Criterion: Excessive fuel rod bowing shall be precluded for the design life of the fuel assembly. Fuel rod bowing shall be evaluated, and any significant impact shall be accounted for in the thermal and mechanical evaluation of the fuel rods and the assembly.

Evaluation: There is no adverse effect of **HiFi** material on irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluation of fuel rod bow.

4.3 NUCLEAR DESIGN

There is no effect of **HiFi** alloy on the nuclear design analytical models and methods. **[** **]^{a,c}**

4.4 THERMAL AND HYDRAULIC DESIGN

The thermal-hydraulic analysis depends on the fuel assembly geometric conditions, the cladding surface finish and the heat transferred to the surface of the cladding. Since the heat transferred to the surface of the cladding remains unchanged, the cladding surface conditions are unaltered, and the fuel assembly geometry remains unchanged, the increase in iron content in the **HiFi** alloy will have no effect on the thermal-hydraulic analysis.

4.5 NON-LOCA ACCIDENT DESIGN

In non-LOCA events the cladding temperature remains below the α to α+β phase transition temperature, precluding any significant differences in specific heat. The specific heat, and in general all the thermo-mechanical properties, of Zircaloy-2 and **HiFi** cladding are **[** **]^{a,c}**

4.6 LOCA DESIGN

Thermal conductivity, specific heat, density, thermal expansion and emissivity of **HiFi** material and Zircaloy-2 material are **[** **]^{a,c}**

4.7 PELLET-CLADDING INTERACTION AND REACTIVITY-INITIATED ACCIDENT

Pellet-cladding interaction (PCI) is a stress-corrosion cracking (SCC) phenomenon where an incipient crack is formed at the cladding inner wall, due to high stress combined with the presence of chemically aggressive fission products, and given the right conditions, propagates to the outer wall. The later stages of propagation, where the stress intensity at the crack tip may be very high, can involve other phenomena, e.g., delayed hydride cracking (DHC) or other hydrogen-assisted mechanisms.

The susceptibility to PCI is therefore determined by the properties of the inner wall, i.e., the liner. **[**

]^{a,c}

The susceptibility of cladding to RIA (reactivity-initiated accident) is determined by a combination of materials microstructure and the hydrogen content. **[**

]^{a,c}

4.8 HYDROGEN PICKUP

Throughout this report hydrogen data from both unirradiated and irradiated programs have been presented. The complete data set is summarized in Figure 4-1. **[**

]^{a,c}

Figure 4-1 Summary of hydrogen pickup on *HiFi* and reference Zircaloy-2 cladding

[ ]^{a,b,c}

The benefit of a lower hydrogen pickup with **HiFi** cladding **[**

]^{a,c}

5 CONCLUSION

Extensive characterization tests performed on Zircaloy-2 and **HiFi** cladding demonstrate that the differences in chemical composition between the materials **[**

]^{a,c} The results presented in this document **[**

]^{a,c} Therefore, the use of **HiFi** cladding in BWR fuel **[**

]^{a,c}

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APPENDIX

Table A-1. Summary of SPP measurements.

a,b,c

Table A-2 Chemical composition of full size ingots for *HiFi* and Zircaloy-2 cladding

a,b,c

Table A-3 Thermo-physical Properties of *HiFi* and Zircaloy-2 cladding

a,b,c

Table A-4 Tensile testing results for *HiFi* and Zircaloy-2 LK3 cladding in 10x10 dimensions and 11x11 dimension

a,b,c

Table A-5 Burst testing results for *HiFi* and Zircaloy-2 LK3 cladding

a,b,c

Table A-6 Corrosion testing results for *HiFi* and Zircaloy-2 LK3 cladding

a,b,c

Figure A-1 Representative pole figures from *HiFi* cladding

a,b,c

Section D

Submittal of Responses to Request for Additional Information

Westinghouse Electric Company
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Cranberry Township, Pennsylvania 16066
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LTR-NRC-25-23

April 21, 2025

Subject: Submittal of Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18869-P/NP, “High Performance Cladding for Use in Boiling Water Reactor Fuel.” (Proprietary/Non-Proprietary)

Enclosed are proprietary and non-proprietary responses to the requests for additional information (RAIs) on the Westinghouse Topical Report WCAP-18869-P/NP, “High Performance Cladding for Use in Boiling Water Reactor Fuel.”

This submittal contains proprietary information of Westinghouse Electric Company LLC (“Westinghouse”). In conformance with the requirements of 10 CFR Section 2.390, as amended, of the Nuclear Regulatory Commission’s (“Commission’s”) regulations, we have enclosed with this submittal an Affidavit. The Affidavit sets forth the basis on which the information identified as proprietary may be withheld from public disclosure by the Commission.

Correspondence with respect to the proprietary aspects of this submittal or the Westinghouse Affidavit should reference AW-25-027 and should be addressed to Jerrod A. Ewing, Manager, Operating Plants Licensing, Westinghouse Electric Company, 1000 Westinghouse Drive, Building 1, Cranberry Township, PA 16066.

Jerrod Ewing

Jerrod A. Ewing, Manager
Operating Plants Licensing

cc: Ekaterina Lenning
Gerond George

Enclosures:
(1) Affidavit, AW-25-027
(2) Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18869-P/NP, “High Performance Cladding for Use in Boiling Water Reactor Fuel.” (Proprietary)
(3) Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18869-P/NP, “High Performance Cladding for Use in Boiling Water Reactor Fuel.” (Non-Proprietary)

AFFIDAVIT AW-25-027

Commonwealth of Pennsylvania:
County of Butler:

(1) I, Jerrod Ewing, Manager, Operating Plants Licensing, have been specifically delegated and authorized to apply for withholding and execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse).

(2) I am requesting the proprietary portions of LTR-NRC-25-23 be withheld from public disclosure under 10 CFR 2.390.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged, or as confidential commercial or financial information.

(4) Pursuant to 10 CFR 2.390, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

- (i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse and is not customarily disclosed to the public.
- (ii) The information sought to be withheld is being transmitted to the Commission in confidence and, to Westinghouse's knowledge, is not available in public sources.
- (iii) Westinghouse notes that a showing of substantial harm is no longer an applicable criterion for analyzing whether a document should be withheld from public disclosure. Nevertheless, public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

(5) Westinghouse has policies in place to identify proprietary information. Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage (e.g., by optimization or improved marketability).

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

(6) The attached documents are bracketed and marked to indicate the bases for withholding. The justification for withholding is indicated in both versions by means of lower-case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower-case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (5)(a) through (f) of this Affidavit.

I declare that the averments of fact set forth in this Affidavit are true and correct to the best of my knowledge, information, and belief. I declare under penalty of perjury that the foregoing is true and correct.

Jerrod Ewing

Executed on: 4/21/2025

Signed electronically by
Jerrod Ewing

Enclosure 3

Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18869-P/NP, "High Performance Cladding for Use in Boiling Water Reactor Fuel."

(Non-Proprietary)

April 2025

**Westinghouse Electric Company
1000 Westinghouse Drive
Cranberry Township, PA 16066**

Request for Additional Information (RAI) 1

Please provide any additional data that was collected since publication of the submitted TR for all lead test rod (LTR)/post irradiation examination programs for **HiFi™** cladding.

Response to RAI 1

Table 1 shows a compilation of the fuel assemblies/fuel rods that have continued their irradiation since the publication of the submitted Topical Report. **[**

]^{a,c}

Table 1 Summary of the **[**

]^{a,c}

a,c

a,c

[

]^{a,c}

a,c

Figure 1 [

]^{a,c}

a,c

Figure 2 **[**

]^{a,c}

Figure 3 illustrates **[**

]^{a,c}

a,c

Figure 3 **[**

]^{a,c}

Figure 4 illustrates **[**

]^{a,c}

Figure 5 illustrates **[**

]^{a,c}

a,c

Figure 4 **[**

]^{a,c}

a,c

Figure 5 **[**

]^{a,c}

In summary, **[**

]^{a,c}

RAI 2

For the BWR reactor coolant chemistry control programs in the U.S. that are not a part of the Westinghouse LTR program, or not specifically tested for this study, please justify why those chemistry control programs are not expected to have a negative effect on the performance of **HiFi** cladding (cladding corrosion, hydrogen pickup, etc.). If possible, please provide response in a format which lists the program vs. the effect on **HiFi** cladding.

Response to RAI 2

[**]**^{a,c}
Forsmark 2, a known plant for high hydrogen uptake, and Kernkraftwerk Leibstadt. Forsmark 2 operates with ultra-low feedwater iron, as well as very low levels of other corrosion products, which many of the BWRs operating in the US are transitioning towards. Leibstadt is a GE BWR-6 and has many cycles with experience of local fuel rod burnups above 70 MWd/kgU and/or more than 6 years of operation. Leibstadt has transitioned to HWC and OLNC water chemistry which is the typical operation for the US BWRs.

[

]^{a,c}

RAI 3

What is the models' uncertainty of **HiFi** cladding predicted oxide thickness that justifies using **[ ]^{a,c}**

Conversely, if this data and discussion are to be included in the specific fuel bundle design reports, please clarify this method of inclusion.

Response to RAI 3

The currently NRC approved corrosion model for the BWR fuel performance code STAV7.2 is found in WCAP-15836-P-A. Validation was done with the Zircaloy-2 alloys **[ ]^{a,c}** in WCAP-15836-P-A with the aim to have a bounding model **[ ]^{a,c}**

a,c

Figure 6 Corrosion model for **[ ]^{a,c}** *alloys in STAV7.2, from WCAP-15836-P-A*

An additional validation of the STAV7.2 model with **[ ]^{a,c}** The used validation database is seen in Figure 7.

The validation of the best estimate model shows that it bounds more than **[ ]^{a,c}** see Figure 9.

a,c

Figure 7 **[** **]**^{a,c} *validation of the oxide model in STAV7.2*

a,c

Figure 8 *Results from the validation of the STAV7.2* **[** **]**^{a,c} *oxide model*

a,c

Figure 9 Results from the validation of the STAV7.2 **[ ]**^{a,c}

The data (and spread) for **HiFi** cladding **[ ]**^{a,c}, see answer to comment 1.

The model in STAV7.2 is conservative and **[ ]**^{a,c} bounds **HiFi** cladding corrosion.

Any new model approved by the NRC that **[ ]**^{a,c} be applicable for **HiFi** cladding.

The cladding corrosion criterion will be verified in the fuel bundle design reports based both on the actual corrosion database which includes **[ ]**^{a,c} and **HiFi** cladding and based on calculations with an NRC-approved **[ ]**^{a,c} or **HiFi** cladding.

RAI 4

Please provide detailed model and data analysis to justify the use of **[ ]**^{a,c} including the data discussed during the NRC regulatory audit of TR WCAP-18869-P/NP, “High Performance Cladding for Use in Boiling Water Reactor Fuel,” conducted by the NRC staff on December 12-13, 2024.

Response to RAI 4

Creep measurements are presented in WCAP-18869-P, Revision 0. Thermal creep measurements on unirradiated material are found in Section 3.2.3.1 and Table 3-6 and the measurements demonstrate that **[**
]^{a,c}

Irradiation creep is found in Section 3.4.2.3 where **[**

]^{a,c} regarding in-reactor creep.

Since the measurements demonstrate that the creep behavior of **HiFi** cladding **[**
]^{a,c}
The currently NRC-approved cladding creep model **[**

]^{a,c}

When a new cladding creep model is approved by the NRC **[**
]^{a,c} based on the measurement results presented in WCAP-18869-P, Revision 0.

Since **[**
]^{a,c} A calculation of the irradiation cladding creep is done for a **TRITON11** fuel rod with the fuel performance code STAV7.2 and presented in Figure 10. The irradiation creep is a function of fluence and no pellet cladding mechanical interaction (PCMI) or differential pressure effects are considered.

a,c

*Figure 10 Cladding irradiation creep for a **TRITON11** fuel rod with* **[**

]^{a,c}

Calculations of lift-off pressure for **TRITON11** fuel with the BWR fuel performance code described in WCAP-15836-P-A (STAV7.2) are found in Figure 11. Since **[**

]^{a,c}

Note that the lift-off pressure depends on the fuel, fuel performance code, and connected methodology/model used. As discussed above, **[**

]^{a,c} applicable for **HiFi** cladding.

a,c

*Figure 11 Lift-off pressure for **TRITON11** fuel calculated with STAV7.2. The results are* **[**

]^{a,c}

RAI 5

The following are related to the impact of high-performance cladding response to LOCA and associated analyses:

a) Please provide the detailed data and analysis of the impact of iron on the α → α + β transformation temperature that justifies **[** **]**^{a,c} including the data discussed during the NRC regulatory audit.

b) Please provide a **[**

]^{a,c} Also, please describe how flow blockage is determined from predicted burst strains for **HiFi** cladding. Conversely, if this data and discussion are to be outside this TR, then please clarify how this information will be addressed.

Response to RAI 5a

Dilatometry was performed **[** **]**^{a,c}; see *Figure 12* and *Figure 13*.

- Thermal expansion measurements (by dilatometry) show **[** **]**^{a,c}; see *Figure 13*.
- The temperature for the initial reaction is **[** **]**^{a,c}

a,c

Figure 12 **[** **]**^{a,c}

a,c

Figure 13 **[**

]^{a,c}

Response to RAI 5b

Burst testing has been performed **[**

]^{a,c}

a,c

Figure 14 **[**
]^{a,c}

In addition, Westinghouse has performed **[**

]^{a,c}

[

]^{a,c}

Regarding flow blockage determined from predicted burst strains, the burst **[**

]^{a,c}

RAI 6

What are the textures and second phase particle (SPP) size distributions for the different lead use assembly's (LUA's) cladding with **HiFi**?

Response to RAI 6

The leading **HiFi** rods in the LUAs **[**

]^{a,c}

Table 2 **[** **]**^{a,c}

a,c

Pole figures for **[** **]**^{a,c}

SPP data for **[ ]^{a,c}** is found in the TR in Table A-1. The specific section is copied below (see highlight):

[ ]a,c

With more detail found in Table 3-3 of the TR copied below (see highlighted cells):

Table 3-3. Results of SPP measurements of HiFi and Zircaloy-2

[ ]a,b,c

RAI 7

What fabrication specifications will be applied to texture and SPPs for **HiFi** cladding in production and how do these compare to current generation Zr-2 specifications for the fuel rods?

Other than the material composition, **[ ]^{a,c}** If yes, what are they and what **[ ]^{a,c}**

Response to RAI 7

With the exception of **[ ]^{a,c}**

As stated in Section 3-1 of the TR:

“This section has demonstrated that the manufacturing processes used for **HiFi** cladding presented in this document show only minimal differences, driven mainly by the capabilities of different manufacturers.

These small differences do not result in significant differences in the resulting annealing parameters and associated microstructures, which demonstrate the equivalence of the manufacturing processes for the new alloy, as well as the closeness to the extensive experience of Zircaloy-2 cladding.”

[

]^{a,c}

- **[**

]^{a,c}

Any changes to products and processes will be managed through Westinghouse's 10CFR50 Appendix B program.

RAI 8

Please provide detailed data for the fuel rod design (FRD) criteria along with the evaluations of the use of **HiFi** cladding on the specific criteria (Section 4.2 of TR WCAP-18869-P/NP, Revision 0). This should also include all discussions of Westinghouse acceptance criteria for FRD.

Response to RAI 8

Evaluation of how the use of **HiFi** cladding impacts the analysis, results, and margin is found in WCAP-18869-P, Section 4.2. An example of an analysis is the sample calculations for the **TRITON11** fuel in WCAP-18951-P/NP, "TRITON11® Reference Fuel Design" in Section 4.3.

Section 4.2 of WCAP-18869-P can be clarified as follows (clarification in **bold**):

> 4.2 FUEL ROD DESIGN
>
> Westinghouse BWR fuel designs are analyzed employing the following fuel rod design criteria by using NRC-approved BWR methods and methodologies for **[**
> **]^{a,c}** Each criterion is specified along with the evaluation of the use of **HiFi** cladding on the specific criterion.
>
> 4.2.1 Rod Internal Pressure
>
> Criterion: The design criterion for rod internal pressure states that the internal pressure of the fuel rod shall not exceed a value which would cause the outward cladding creep to

increase the diametrical fuel pellet-cladding gap. This value of fuel rod internal pressure is defined to be that internal pressure which causes the outward cladding creep rate to exceed the fuel effective swelling rate. This requirement is referred to as “the lift-off criterion”.

Evaluation: **The rod internal pressure and the lift-lift off pressure are calculated with an NRC-approved BWR fuel performance code. The pressure depends on the cladding creep, which is [**

]^{a,c} (see Section 3.2.4.1 and Table 3-4). There is no adverse effect of **HiFi** cladding on the rod internal pressure, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluating the lift-off criterion.

4.2.2 Cladding Stresses

Criterion: Fuel rod stresses must be maintained within acceptable limits. This criterion is implemented by establishing design limits for stresses to assure that failure does not occur and that stresses of the fuel rod remain within acceptable limits.

Evaluation: **Cladding stress is evaluated [**

]^{a,c} is calculated with an NRC-approved fuel performance code and is dependent on [

]^{a,c} (see Section 3.2.4.1 and Table 3-4). There is no **[** **]^{a,c}** adverse effect of **HiFi** material on unirradiated or irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluating the cladding stresses.

4.2.3 Cladding Strain

Criterion: The total transient induced elastic and plastic cladding circumferential strain should not exceed 1%. In this context, total transient induced strain is the elastic and plastic strain which can occur during normal operation and anticipated operational occurrences (AOOs) excluding the effects of steady-state creep down and irradiation growth.

Evaluation: **The criterion is evaluated by calculating the transient induced strain with an NRC-approved BWR fuel performance code. The transient strain depends on [** **]^{a,c} (see Section 3.2.4.1 and Table 3-4) and on the**

strain, which is discussed in Section 3.2.4.2. There is no adverse effect of **HiFi** cladding on the rod internal pressure, unirradiated or irradiated mechanical properties, compared to Zircaloy-2 cladding. Therefore, there will be no effect on the mechanical response for evaluation of the cladding strain.

4.2.4 Hydriding

Criterion: Cladding hydriding from waterside and internal sources shall be maintained sufficiently low that premature cladding failure shall not occur due to hydrogen embrittlement.

Evaluation: There is evidence of the lower hydrogen pickup fraction in **HiFi** cladding with respect to Zircaloy-2 cladding. For the purpose of this Topical Report **[**

]^{a,c}

4.2.5 Cladding Corrosion

Criterion: Cladding corrosion must be limited to assure that excessive cladding corrosion does not lead to premature fuel rod failures due to excessive metal thinning or excessive cladding temperatures. The effect of cladding corrosion shall be included in the thermal-mechanical evaluation of the cladding.

Evaluation: **The criterion is evaluated by calculating the oxide thickness with an NRC-approved BWR fuel performance code.** There is no adverse effect of **HiFi** material on corrosion, as corrosion of **HiFi** cladding has been demonstrated to be **[** **]**^{a,c} **(see Figure 3-38)**. Therefore, there will be no impact on evaluating the cladding corrosion criterion.

4.2.6 Cladding Collapse

Criterion: Cladding collapse shall not occur during the design life of the fuel rod. Cladding collapse or “elastic and plastic instability” refers to the pressure across the tubing walls at which the cladding will buckle in the elastic and plastic ranges.

Evaluation**: The cladding creep collapse is evaluated with an NRC-approved method. The creep collapse depends on the cladding creep, [** **]**^{a,c} **(see Section 3.4.2.3).** There is no adverse effect of **HiFi** material on unirradiated or irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluation of cladding collapse. This includes instantaneous collapse at the beginning of life and creep collapse later during operation.

4.2.7 Cladding Fatigue

Criterion: Cladding fatigue shall not cause fatigue damage during normal operation and AOOs. The fatigue evaluation shall account for the effects of cladding corrosion.

Evaluation: **The fatigue limits derived by O'Donnell Langer are used for evaluation of cladding fatigue. In Figure 3-17, it is shown that [ ]^{a,c} The evaluation of fatigue is done with an NRC-approved BWR fuel performance code and relies on the mechanical behavior of the cladding (see Section 3.2.4.2). [ ]^{a,c}**

Therefore, there will be no effect of **HiFi** material on the cladding fatigue evaluation.

4.2.8 Cladding Temperature

Criterion: Cladding overheating during normal operation and AOOs shall not cause fuel rod failure.

Evaluation: **[ ]^{a,c}**, and there is no adverse effect of **HiFi** material on the thermal properties of the cladding. Therefore, there will be no effect on evaluation of cladding temperature.

4.2.9 Fuel Temperature

Criterion: The maximum centerline pellet temperature shall remain below the melting temperature of the fuel during normal operation and AOOs.

Evaluation: **The evaluation of fuel temperature is done with an NRC-approved BWR fuel performance code. [ ]^{a,c}**

Therefore, there will be no effect of **HiFi** material on the fuel temperature criterion evaluation.

4.2.10 Fuel Rod Bow

Criterion: Excessive fuel rod bowing shall be precluded for the design life of the fuel assembly. Fuel rod bowing shall be evaluated, and any significant impact shall be accounted for in the thermal and mechanical evaluation of the fuel rods and the assembly.

Evaluation: There is no adverse effect of **HiFi** material on irradiated mechanical properties, irradiation growth, creep or corrosion, compared to Zircaloy-2 cladding. Therefore, there will be no effect on evaluation of fuel rod bow.

RAI 9

Please confirm that all the performance acceptance criteria and material limits **[**

]^{a,c} and identify where they are addressed.

Response to RAI 9

The fuel rod design acceptance criteria are **[**

]^{a,c} are found in WCAP-17769-P-A "Reference Fuel Design SVEA-96 Optima3" in Section 3.3 and 4.3. The fuel rod design acceptance criteria applied for **HiFi** cladding are the ones applicable for the **TRITON11** fuel described in WCAP-18951-P, "TRITON11® Reference Fuel Design" in Section 3.3 and 4.3.