U. S. NUCLEAR REGULATORY COMMISSION

FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

FOR THE WESTINGHOUSE ELECTRIC COMPANY TOPICAL REPORT

WCAP-18546-P/NP, "WESTINGHOUSE AXIOM® CLADDING

FOR USE IN PRESSURIZED WATER REACTOR FUEL"

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1.0 INTRODUCTION AND BACKGROUND

By letter dated March 31, 2021 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21090A110), Westinghouse Electric Company (Westinghouse), submitted for U.S. Nuclear Regulatory Commission (NRC) staff review of Topical Report (TR), WCAP-18546-P/NP, "Westinghouse AXIOM® Cladding for Use in Pressurized Water Reactor Fuel" (Proprietary/Non-Proprietary) (Ref. 1). By letter dated February 17, 2022, Westinghouse submitted responses to the NRC staff's requests for additional information (RAIs) (Ref. 2). By letter dated December 17, 2021, Westinghouse submitted a supplement to WCAP-18546-P/NP to extend the TR's applicability to include Westinghouse Advanced Doped Pellet Technology (ADOPT™) fuel (Ref. 3). AXIOM cladding is a niobium-bearing zirconium alloy like the ZIRLO® alloy, with reduced tin content to increase corrosion resistance like the Optimized ZIRLO™ alloy (Ref. 4), and with added vanadium and copper to improve hydrogen pickup (HPU) property. The AXIOM alloy is processed to be partially recrystallized annealed (pRXA), similar to the Optimized ZIRLO cladding. AXIOM cladded fuel had been in commercial reactor test programs since 2002 domestically and in Europe with burnups reaching 75 gigawatt-days per metric ton of uranium (GWd/MTU). The AXIOM alloy has demonstrated better in-reactor performance compared to the Optimized ZIRLO alloy, especially in high duty operating environments. Thus far, the AXIOM alloy has shown excellent in-reactor dimensional stability.

Westinghouse intends to use the AXIOM alloy as fuel cladding material in all Westinghouse and Combustion Engineering (CE) pressurized water reactor (PWR) fuel assemblies with existing NRC-approved cladding dimensions, fuel structures, fuel assembly components, and fuel materials. WCAP-18546-P/NP TR describes the fuel performance model for AXIOM cladding in the areas of cladding strength, fuel rod growth, cladding creep, and fuel rod corrosion.

This review was focused on the following major areas of the AXIOM materials properties described in Section 3 of WCAP-18546-P/NP: microstructure, specific heat, thermal expansion, thermal diffusivity and conductivity, phase transition temperatures, modulus of elasticity, Poisson's ratio, microhardness, tensile properties, thermal creep, corrosion, high temperature metal-water reaction, emissivity, hydride orientation, breakaway oxidation, and post quench ductility (PQD). The review also covered the irradiation programs and experience of AXIOM cladding and post irradiation examination (PIE) of specimens (Section 4 of the TR). The NRC staff also reviewed the in-reactor behavior of AXIOM cladding (Section 5 of the TR): corrosion models, HPU, fuel rod growth, cladding creep, and irradiated mechanical properties. In addition, the NRC staff reviewed Section 6 of the TR including fuel design criteria, safety analyses that covers both best-estimate loss-of-coolant accident (LOCA) and Appendix K LOCA, Non-LOCA analyses, containment integrity analyses, and fuel assembly seismic and LOCA evaluation.

Section 2.0 of this safety evaluation (SE) describes the regulatory basis for the SE. Section 3.0 and its sub-sections contain the NRC staff's technical evaluation of the AXIOM cladding: Section 3.1 of the SE focuses on AXIOM cladding definition; Section 3.2 describes the characterization of AXIOM cladding properties; Section 3.3 and Section 3.4 describe AXIOM cladding thermal and mechanical properties, respectively; Section 3.5 describes irradiation programs and experience with AXIOM cladding; Section 3.6 discusses characterization of AXIOM cladding behavior; Section 3.7 discusses the AXIOM cladding licensing criteria assessment; Section 3.8 contains safety analyses; Section 3.9 describes impact on nuclear design requirements; Section 3.10 describes thermal hydraulic design methods; Section 3.11 provides licensing criteria conclusion; and Section 4.0 of this SE lists the limitations and conditions.

2.0 REGULATORY EVALUATION

2.1 Applicable Regulations and Review Guidance

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 General Design Criteria (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." Regulatory guidance for the review of fuel system designs and adherence to these GDCs is provided in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants – LWR Edition" (SRP) (Ref. 5). Specifically, Section 4.2, "Fuel System Design (Ref. 6)." Additionally, SRP Section 4.3, "Nuclear Design" (Ref. 7), and Section 4.4, "Thermal and Hydraulic Design" (Ref. 8), are pertinent to the review of fuel systems.

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. SRP Section 4.2 acceptance criteria are based on meeting the requirements of GDC 10.

Requirements for analyzing the design-basis 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 required and acceptable features of evaluation models for heat removal by the ECCS.

- GDC 35 requires abundant 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. GDC 35 further requires suitable redundancy of the ECCS, such that it can accomplish its design functions, assuming a single failure, irrespective of whether its electrical power is supplied from offsite or onsite sources.

In accordance with SRP Section 4.2, “Fuel System Design” (Ref. 6), the objectives of the fuel system safety review are to provide assurance that:

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

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

c. The number of fuel rod failures is not underestimated for postulated accidents, and

d. Coolability is always maintained.

SRP Section 6.2.1, “Containment Functional Design” (Ref. 9), presents information related to containment integrity following postulated LOCA, steam line, or feedline break accidents as impacted by the AXIOM cladding on the above analyses.

SRP Chapter 15, “Transient and Accident Analyses” (Ref. 10), including acceptance criteria for AOOs and postulated accidents and their impact on AXIOM cladding, is addressed in the TR. The review of this TR is based on the acceptance criteria for each of the events described in SRP Chapter 15.

2.2 Application to the NRC-Approved TRs

Section 2.2 of WCAP-18546-P/NP TR describes how Westinghouse plans to expand the limits of applicability for existing NRC-approved fuel rod design TRs to include AXIOM cladding properties and performance and defines how licensees would apply these expanded TRs.

- WCAP-12610-P-A, “VANTAGE+ Fuel Assembly Reference Core Report” (Ref. 14), WCAP-12610-P-A & CENPD-404-P-A, Addendum 1-A (Proprietary) and WCAP-14342-A & CENPD-404-NP-A, Addendum 1-A (Non-Proprietary), “Optimized ZIRLO™” (Ref. 4), and WCAP-12610-P-A & CENPD-404-P-A Addendum 2-A, Revision 0, and WCAP-14342-A & CENPD-404-NP-A Addendum 2-A, Revision 0, “Westinghouse Clad Corrosion Model for ZIRLO and Optimized ZIRLO” (Ref. 47). Because of the functional similarities between AXIOM and ZIRLO/Optimized ZIRLO cladding materials that are discussed in this SE, AXIOM cladding will be considered appropriate for use in place of all existing zirconium-based Westinghouse alloys as a fuel rod cladding for use in PWRs.

- WCAP-16500-P-A, “CE 16x16 Next Generation Fuel Core Reference Report” (Ref. 11) describes the reload methodology for CE-designed PWR plants. WCAP-9272-P-A, “Westinghouse Reload Safety Evaluation Methodology” (Ref. 12), defines the methodology that is used for plants that have contractual arrangements with Westinghouse for reload designs. Upon approval of WCAP-18546-P/NP TR, these methodologies will be used for evaluation of reloads containing AXIOM cladded fuel.

- WCAP-12488-A and WCAP-12488-A, Addendum 1-A (Ref. 13). This TR describes the fuel criteria evaluation process (FCEP) for Westinghouse designed PWR plants. FCEP is the NRC-approved methodology for assessing fuel design changes to determine whether prior NRC approval is needed before implementation of the changes. Based on the similarities between AXIOM cladding and other Westinghouse’s approved zirconium-based cladding materials, the FCEP process is appropriate for assessing design changes when material changes for AXIOM cladding defined in this TR are incorporated.

- WCAP-12610-P-A, “VANTAGE+ Fuel Assembly Reference Core Report” (Ref. 14) TR describes the VANTAGE+ fuel design, and WCAP-16500-P-A, Revision 0, “CE 16x16 Next Generation Fuel Core Reference Report” (Ref. 11) TR describes the CE 16x16 Next Generation of Fuel (NGF™) fuel design. Westinghouse is capable of analyzing the AXIOM cladding with all existing fuel designs, such as VANTAGE+ and CE 16x16 NGF.

- WCAP-17642-P-A, Revision 1, “Westinghouse Performance Analysis and Design Model (PAD5).” The NRC-approved fuel performance and design methodology in PAD5 TR will be expanded to include AXIOM cladding material and will be included in the plant’s licensing basis.

3.0 TECHNICAL EVALUATION

Westinghouse developed AXIOM fuel rod cladding material to provide improved corrosion resistance, lower HPU, and lower creep and growth compared to current zirconium-based fuel cladding materials. AXIOM has reduced tin content (Table 1 in Section 3.1 of this SE) which improves the corrosion resistance. To compensate for creep strength loss caused by the reduced tin content, AXIOM alloy has been processed to be in the pRXA condition similar to the Optimized ZIRLO cladding. Westinghouse initiated its material research and optimization for AXIOM cladding development in 2000, which was followed by the initial alloy testing. In 2005, lead test rod (LTR) irradiation programs started at a variety of research and commercial power reactors worldwide with four major variants with AXIOM cladded fuel being irradiated to burnups over 70 GWd/MTU. Pool side and hotcell PIEs were conducted on these irradiated rods and the process and results were documented. After a detailed evaluation among the candidate alloys, the final AXIOM composition was selected in 2015.

3.1 AXIOM Cladding Definition

AXIOM cladding is a niobium-bearing zirconium alloy like ZIRLO alloy, with reduced tin content to increase corrosion resistance. Adding vanadium and copper improves this specific property. AXIOM is processed to be partially recrystallized annealed (pRXA) condition as opposed to stress-relief annealed (SRA) condition in the ZIRLO cladding. Table 1 lists a comparison of the chemical composition of AXIOM, ZIRLO, and Optimized ZIRLO alloys.

Table 1. Chemical Composition (%) of AXIOM, ZIRLO, and Optimized ZIRLO Cladding

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In the RAI 2 (Ref. 2), the NRC staff asked Westinghouse to describe the impact of adding copper and vanadium to AXIOM cladding. Westinghouse responded that the material properties of AXIOM differ from the Optimized ZIRLO and ZIRLO in the following properties during normal operation:

- Reduced waterside corrosion at high levels of accumulated thermal reactive duty (TRD)
- Reduced HPU
- Reduced axial growth
- Reduced diametrical creep strain
- **[ ]**
- **[ ]**

During accident conditions, AXIOM exhibits the following properties:

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

- **[ ]**

These performance differences for AXIOM cladding are due to the combined effects of differences in chemical composition and microstructure including the addition of vanadium and copper (Table 1).

The NRC staff reviewed the RAI response and determined that the above properties during normal operation and accident condition are true and acceptable for AXIOM cladding.

3.2 Density and Microstructure

Density of AXIOM cladding material was measured geometrically on bulk material. The density of AXIOM was found to be **[ ]** at 22°C or 71.6°F. In comparison, the density of Optimized ZIRLO and ZIRLO are **[ ]**

The microstructure of AXIOM cladding consists of second phase particles (SPP) of combinations of **[ ]** are homogeneously distributed in the Zr matrix. Westinghouse reported that these precipitates are present in a range of sizes up to **[ ]** with an average particle size in the **[ ]** range. The heat treatment yields a partially recrystallized microstructure with **[ ]**

3.3 Thermal Properties

Westinghouse conducted tests to characterize the thermal properties (i.e., specific heat, thermal expansion, phase transition temperature, thermal diffusivity, and thermal conductivity) of AXIOM cladding. The AXIOM samples that were tested experimentally for the determination of thermal properties were **[ ]**

As a result, the NRC staff finds the use of **[ ]** for the experimental determination of the specific heat, phase transformation, thermal diffusivity, and axial thermal expansion of AXIOM cladding to be acceptable.

3.3.1. Specific Heat

Section 3.2.1 of WCAP-18546-P/NP describes measurements for specific heat of AXIOM cladding. Specific heat was measured using a differential scanning calorimeter following the ASTM E1269 standard. The tests were performed from room temperature to 1200°C (2192°F) with a temperature ramp rate of 10°C/min (18°F/min) in flowing argon gas. Measurements were conducted on four AXIOM samples and compared to the specific heat of Optimized ZIRLO and ZIRLO in Figure 3.2-1 in the TR. In response to RAI 17 (Ref. 2), Westinghouse provided the composition of the four samples, as well as other samples used in thermal and mechanical property testing. Samples 1-3 in the specific heat tests were of one composition and Sample 4 was of a slightly different composition. The alloy compositions of all four samples tested lie within the specifications of AXIOM cladding and thus, the NRC staff find the use of these AXIOM cladding samples to be acceptable for thermal and mechanical property testing.

The NRC staff reviewed the specific heat measurements and concluded that there is no appreciable difference between the specific heats of AXIOM, Optimized ZIRLO, and ZIRLO cladding.

3.3.2 Thermal Expansion

Thermal expansion is used in stored energy estimates, LOCA, rod pressure, fuel temperature, and cladding stress strain analyses. Section 3.2.2 of WCAP-18546-P/NP TR describes the measurements and models for thermal expansion of AXIOM cladding. Thermal expansion was measured using a differential dilatometer in argon gas from room temperature to 1000°C (1832°F) with a heating rate of 3°C/min (5.4°F/min), except for at 550°C (1022°F), where it was held for one hour. Thermal expansion results from three AXIOM samples are reported in the TR. In the response to RAI 17, Westinghouse states that the three AXIOM samples were of the same compositions. The axial thermal expansion results from the heating tests of the three AXIOM samples are plotted with the Optimized ZIRLO, ZIRLO, and PAD5.0 results in Figure 3.2-3 of the TR. This figure shows **[ ]** behavior of the AXIOM samples with the Optimized ZIRLO and ZIRLO samples. As a result, Westinghouse states that the Optimized ZIRLO thermal expansion models in PAD5 **[ ]** for AXIOM.

Since there is **[ ]** between the PAD5 Optimized ZIRLO thermal expansion models and the AXIOM data in Figure 3.2-3 of the TR, the NRC staff finds the application of the PAD5 (Ref. 16) Optimized ZIRLO models up to the current licensed temperature of **[ ]** to be acceptable for AXIOM.

3.3.3 Phase Transition Temperature

The $\alpha \leftrightarrow \alpha + \beta$ and $\alpha + \beta \leftrightarrow \beta$ transition temperatures are important for those accidents where the cladding temperatures exceed the transition temperatures. Some zirconium-based cladding properties that may be affected by the phase transition temperatures are thermal expansion, heat capacity, rupture, and ballooning. Section 3.2.3 of WCAP-18546-P/NP describes the measurements to determine the phase transition temperatures. The phase transition temperatures were determined from two different methods, differential scanning calorimetry (DSC) specific heat testing and dilatometer thermal expansion testing. In the response to RAI 16 (Ref. 2), Westinghouse provided additional information about the differences in the two testing methods and the differences in the results from the methods. Both tests do not produce identical results due to the differences in the techniques, but both produce a general estimated range for the temperatures where the phase transition occurs. The DSC specific heat tests measure thermal energy input using a small disk **[ ]** with a heating rate of 10°C/min (18°F/min), while the dilatometer thermal expansion tests measure dimensional changes of a slightly different size AXIOM **[ ]** at a lower heating rate of 3°C/min (5.4°F/min). Four AXIOM samples were tested using each method, one sample of one AXIOM composition and three samples of a slightly different AXIOM composition; and all four of which lie within the specifications stated for AXIOM, as described in the response to RAI 17 (Ref. 2). Overall, the $\alpha + \beta$ region for AXIOM cladding was estimated to occur in the temperature range of **[ ]** The lowest $\alpha \leftrightarrow \alpha + \beta$ temperature and the highest $\alpha + \beta \leftrightarrow \beta$ temperature found in the eight trials are reported for this range. Based on the review of testing techniques and experimental data, the NRC staff finds these estimated phase transition temperatures to be acceptable.

The NRC staff notes that the AXIOM phase transition temperatures are **[ ]** that of Optimized ZIRLO. The reported α ↔ α + β for AXIOM, **[ ]** is approximately **[ ]** than the reported for Optimized ZIRLO in WCAP-12610-P-A & CENPD-404-P-A, Addendum 1-A (Ref. 4). The NRC staff finds that the impact of the **[ ]** phase transition temperatures on other AXIOM properties (e.g., thermal expansion, heat capacity, rupture, and ballooning) has been adequately captured through the characterization of those other properties throughout WCAP-18546-P/NP.

3.3.4 Thermal Diffusivity and Thermal Conductivity

Thermal conductivity of the cladding is an important material property that is used to determine the temperature distribution in the fuel rod. Section 3.2.4 of WCAP-18546-P/NP describes the measurements of thermal diffusivity on AXIOM cladding. Thermal conductivity is determined indirectly by measuring the thermal diffusivity using the laser flash methods of ASTM E1461. The laser flash method for measuring thermal diffusivity consists of irradiating the sample material surface with a laser pulse and monitoring the temperature rise of the material using a photovoltaic infrared detector. The thermal conductivity, λ, is then calculated using the following equation:

$$\lambda = D \times \rho \times C_p$$

where D is the thermal diffusivity, ρ is the density, and C_p is the specific heat.

Figure 3.2-6 of the TR compares the thermal conductivity of AXIOM cladding, Optimized ZIRLO, and ZIRLO. The differences between the thermal conductivity of the three AXIOM samples and Optimized ZIRLO from room temperature to 1200°C (2192°F) are within approximately **[ ]**

The NRC staff finds the experimental data and models for AXIOM thermal conductivity to be acceptable.

3.4 Mechanical Properties

3.4.1 Young’s (Elastic) Modulus

Young’s modulus is used to determine the elastic strain experienced by the cladding and, therefore, also impacts the amount of plastic deformation experienced. Westinghouse stated that the Young’s modulus is determined by interatomic forces and crystal structure, so the presence of less than 3 percent alloying elements in zirconium alloys will not have an effect when compared to the previous Westinghouse cladding alloys. As a result, Westinghouse stated that the AXIOM Young’s modulus lies within the experimental error or is consistent with Zircaloy-4, ZIRLO, and Optimized ZIRLO. The NRC staff noted that the experimental data presented in WCAP-12610-P-A & CENPD-404-P-A, Addendum 1-A (Ref. 4), showed that there was no appreciable difference between the unirradiated or irradiated Young’s modulus for Optimized ZIRLO and ZIRLO. Westinghouse currently uses the same correlation for the Young’s modulus for Zircaloy-4, ZIRLO, Optimized ZIRLO, and AXIOM.

The NRC staff concludes that the Westinghouse treatment of AXIOM Young's modulus is acceptable.

3.4.2 Poisson's Ratio

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force. The Poisson's ratio is dependent on the crystallographic state and texture of the material. **[** **]** which are evaluated in more detail in Section 3.5.3 of this SE, the NRC staff concludes that the Westinghouse treatment of the AXIOM Poisson's ratio is acceptable.

3.4.3 Microhardness

Microhardness is used in calculating the contact conductance between the fuel and cladding when the fuel-to-cladding gap is closed, and this may impact fuel rod fretting wear resistance. It should be noted that a large change in hardness is required to make a significant effect on calculated fuel temperatures. Section 3.3.3 of WCAP-18546-P/NP describes the measurements for Vickers microhardness. The Vickers microhardness was determined by pressing an indenter into AXIOM specimens with a known force and measuring the size of the resulting indentation. Seven AXIOM samples were tested, and five measurements were taken on each sample. It was found that the Vickers transverse microhardness was approximately **[** **]** than that of Optimized ZIRLO. This change in hardness is **[** **]** This difference in microhardness is not expected to have a significant impact on fuel temperature calculations. The NRC staff finds the AXIOM transverse microhardness to be acceptable.

3.4.4 Texture and Contractile Strain Ratio

Crystallographic texture may impact the mechanical properties of the cladding, including the creep, irradiation growth, and Poisson's ratio, among other properties. Section 3.3.4 of WCAP-18546-P/NP describes the measurements for texture and contractile strain ratio (CSR). The texture of AXIOM was quantified using Kearns' basal pole texture parameters, which were determined from x-ray pole measurements. The AXIOM Kearns' texture parameters are **[** **]**

The CSR is defined as the ratio of the circumferential plastic strain to the radial plastic strain. CSR helps to describe how a tube will deform and is another way to characterize the texture. Table 8.1-2 in the Appendix of WCAP-18546-P/NP details 19 CSR measurements on AXIOM cladding samples. The CSR values are within the CSR product specification limits for Optimized ZIRLO and ZIRLO. And the CSR values conform to the values stated in Table 2.D.2 of WCAP-12610-P-A & CENPD-404-P-A, Addendum 1-A (Ref. 4).

The NRC staff concludes that the Kearns' texture parameters and CSR for AXIOM cladding are acceptable.

3.4.5 Unirradiated Tensile Properties (Yield Strength and Ultimate Tensile Strength)

Section 3.3.5 of WCAP-18546-P/NP describes the measurements and models for the unirradiated tensile properties of AXIOM, i.e., the unirradiated yield strength and unirradiated ultimate tensile strength. Experimentation was performed at room temperature and elevated temperatures according to ASTM E8/E8M and ASTM E21 standards. Best estimate and 95/95 UB and lower bound (LB) models were fit to the stress versus temperature data.

The data and models presented indicate that the AXIOM cladding possesses an unirradiated yield strength and ultimate tensile strength that is **[ ]** compared to Optimized ZIRLO and ZIRLO, likely due to the reduced tin content of AXIOM. The largest relative difference between the best estimate AXIOM and Optimized ZIRLO unirradiated yield strength occurs at **[ ]** where the yield strength of AXIOM is **[ ]** than that of Optimized ZIRLO. Similarly, the largest relative difference between the best estimate AXIOM and Optimized ZIRLO unirradiated ultimate tensile strength models occurs at **[ ]** where the ultimate tensile strength of AXIOM is **[ ]** than that of Optimized ZIRLO.

The differences in unirradiated yield strength and ultimate tensile strength will impact beginning of life (BOL) stress analyses and criterion. Section 6.1.2.1 of the TR and Section 3.7.2.1 below discusses this impact.

The NRC staff concludes that the unirradiated yield strength and unirradiated ultimate tensile strength models adequately capture the behavior of unirradiated AXIOM cladding and are therefore acceptable.

3.4.6 Thermal Creep

Section 3.3.6 of WCAP-18546-P/NP describes the measurements for thermal creep. Out-of-reactor thermal creep measurements were performed at 725°F (385°C) at an effective stress of 15.6 kilo pound per square inch (ksi) (107.6 megapascal (mPa)) for durations in the range of 10 and 30 days.

This is similar to the thermal creep tests previously performed for Optimized ZIRLO and ZIRLO. **[**
] Though only ZIRLO data was provided for comparison with AXIOM in Figure 3.3-3 of the TR, the data in WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A (Ref. 4) indicate that there is not an appreciable difference between the thermal creep of Optimized ZIRLO and ZIRLO. Therefore, **[**
] Westinghouse used the AXIOM thermal creep data to confirm that the functional form of their Optimized ZIRLO and ZIRLO thermal creep models are applicable to AXIOM. The calibration of the creep model is based on irradiation data and will be evaluated in Section 3.6.5 of this SE.

High Temperature Creep

Section 3.7 of the TR (Ref. 1) provides information on AXIOM creep phenomena at temperatures greater than **[**

] Table 3.7-1

of the TR presents results of coaxial creep tests for outer diameter (OD) measurements, the corresponding OD strain, and the strain rate. Table 3.7-1 of the TR provides **[**

] in Ref. 4. **[**

]

It should be noted that thermal creep makes up less than 5 percent of the total cladding creep in-reactor. Irradiation-induced creep makes up greater than 95 percent cladding creep.

The NRC staff reviewed the thermal creep and high temperature creep of AXIOM cladding and find the AXIOM creep behavior acceptable.

3.4.7 Fatigue

AXIOM and Optimized ZIRLO cladding were fatigue tested in accordance with International Standards Organization (ISO) 17025 at the Dirats Laboratories using **[** **]** Both AXIOM and Optimized ZIRLO claddings were tested at the same range of stress levels, namely, **[** **]** The results of the tests concludes that the design fatigue curve as shown in Figure 3.4-1 of Ref. 1 is consistent with ZIRLO and Optimized ZIRLO material. The NRC staff has verified the results of fatigue tests and confirmed that the results are consistent with Langer O'Donnell model.

3.4.8 High Temperature Cladding Burst Testing

Cladding burst testing performed at the Westinghouse Columbia Fuel Fabrication Facility was conducted **[**

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Figure 3.6-1 in the TR shows comparison of ZIRLO, Optimized ZIRLO, and AXIOM cladding results. **[**

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The NRC staff reviewed the results of burst temperature and burst pressure tests and determined that the AXIOM cladding data for burst temperature is **[** **]** ZIRLO and Optimized ZIRLO.

3.4.9 Emissivity

Emissivity is important when high cladding temperatures are experienced in certain accidents, such as LOCAs. Westinghouse uses the same emissivity values for Zircaloy-4, ZIRLO, Optimized ZIRLO, and AXIOM. Previous Westinghouse experimental data reported in WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A (Ref. 4) showed that Zircaloy-4, ZIRLO, and Optimized ZIRLO had emissivity values within **[ ]** of each other in steam. The NRC staff finds this treatment of AXIOM emissivity to be acceptable because in-reactor emissivity of zirconium claddings is dominated by the emissivity of the zirconium oxide on the cladding and AXIOM cladding possesses an identical surface finish as Optimized ZIRLO and ZIRLO, which were previously evaluated to have very similar values for emissivity.

3.4.10 High Temperature Metal Water Reaction

AXIOM samples were cleaned and weighed to obtain pre-oxidized masses. Each sample was then exposed to steam at temperatures of **[**

] The parabolic metal-water reaction rate is listed in Table 3.8-2 and plotted in Figure 3.8-2 in WCAP-18546-P/NP.

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The NRC staff reviewed the metal-water reaction tests for AXIOM and determined that the metal-water reaction models are acceptable for AXIOM cladding.

3.4.11 Hydride Reorientation

Characterization of hydrided AXIOM tubing containing about **[ ]** hydrogen was performed before and after hydride reorientation heat treatment which consisted of heating the clad to 752°C pressurizing the cladding with 11.6 ksi internal hoop stress and furnace cooling to room temperature while maintaining pressure. Image analysis was performed on the metallographically prepared cross-sections of the specimens. Fraction of radial (± 30^{o} of vertical) and circumferential (± 30^{o} of horizontal) before and after heat treatment was measured and compared with each other. A summary of the hydride reorientation results is provided in the Table 3.10-1 of the TR (Ref. 1).

Results indicate that the AXIOM cladding average percent radial hydride reorientation fall midway between that of ZIRLO and Low Tin ZIRLO™ cladding materials. A graphical representation of the hydride orientation measured for one of the AXIOM samples tested is depicted in Figure 3.10-1 of the TR.

The NRC staff reviewed the hydride reorientation tests for AXIOM and determined that the hydride reorientation model is acceptable for AXIOM cladding.

3.4.12 Impact on REA Limits

Regulatory Guide (RG) 1.236 (Ref. 20) describes methods and procedures that the NRC staff considers acceptable when analyzing the nuclear reactor's initial response to a postulated control rod ejection accident for PWRs. The REA pellet-cladding mechanical interaction (PCMI) limit for AXIOM cladding is based on interpolation of SRA and RXA PCMI limits provided in RG 1.236 based on a comparison of radial hydride fractions between SRA ZIRLO cladding, pRXA AXIOM cladding and RXA Low Tin ZIRLO cladding.

RG 1.236 provides the PCMI failure thresholds, peak radial average fuel enthalpy (Cal/g) vs. excess cladding hydrogen at PWR temperatures above 500°F. Figures 1 and 2 (Ref. 20, RG 1.236) show the empirically based PCMI cladding failure thresholds for RXA and SRA cladding materials.

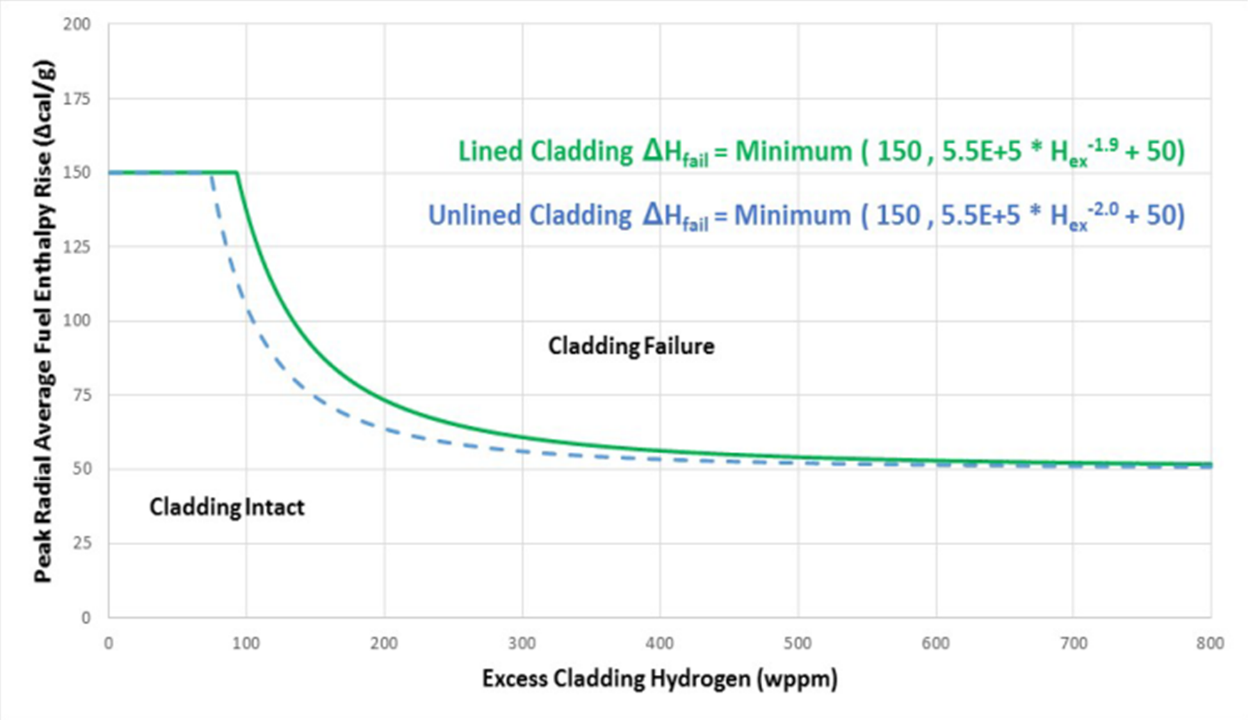

Figure 1: PCMI Cladding Failure (Threshold – RXA Cladding at or above 500°F (Ref. 20, RG 1.236))

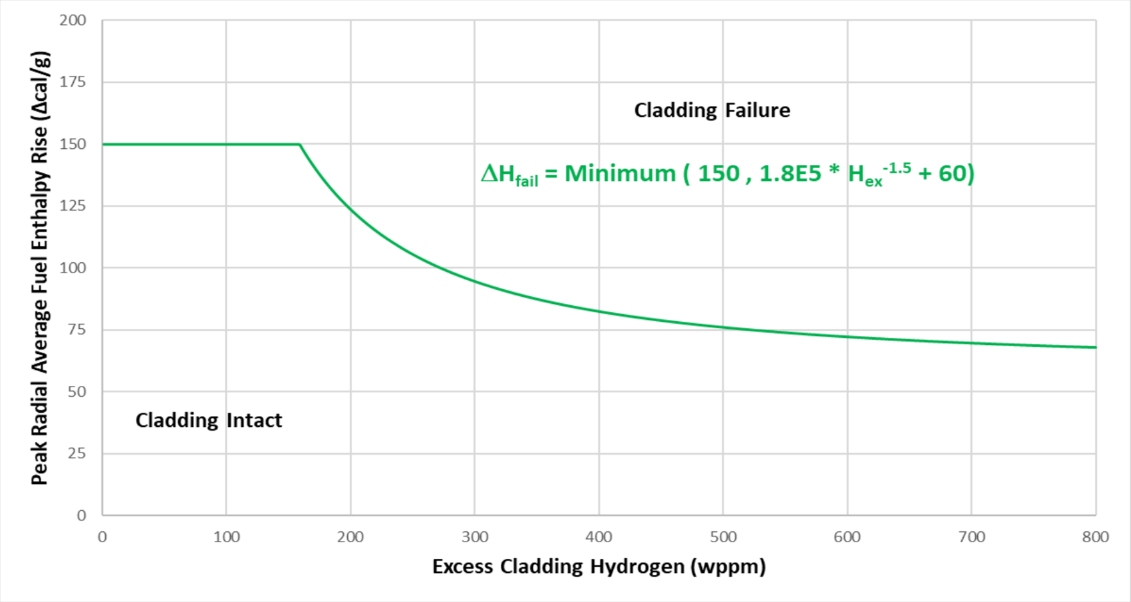

Figure 2: PCMI (Cladding Failure Threshold – SRA Cladding at or above 500°F (Ref. 20, RG 1.236))

Measurements of radial hydride fraction before and after reorientation treatment from Section 3.10 of the TR were used as input. **[**

] The average of the two values was chosen to represent AXIOM cladding to interpolate the AXIOM cladding value. Measurements of the radial hydride fraction before and after reorientation treatment from Section 3.10 of the TR were used as input. Figure 3 shows enthalpy increase limit vs. excess hydrogen for SRA cladding pXRA AXIOM cladding and RXA cladding.

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Figure 3 **Enthalpy increase limit vs. excess hydrogen for SRA cladding pXRA AXIOM cladding and RXA cladding (Ref. 1)**

The NRC staff reviewed Westinghouse's approach to calculate the input to REA for AXIOM and determined that the approach is acceptable because the REA analysis conforms with the applicable RG 1.236 guidance.

3.5 Irradiation Programs and Experience

Irradiation experience provides confidence in the behavior of the material under irradiation. Section 4.0 of WCAP-18546-P/NP describes long-term irradiation programs and subsequent hot cell examinations to characterize the irradiated properties and performance of AXIOM cladding. Many of the measurements obtained in these programs were used to justify materials properties, performance, and analytical models that are discussed in other sections of the TR (and subsequent sections of this SE).

Overall, Westinghouse obtained data for over **[ ]** AXIOM rods across seven commercial nuclear power plants, including **[ ]** The database includes fueled AXIOM rods from burnups ranging from approximately **[ ]** The unfueled rods reached burnups exceeding **[ ]** Standard visual inspections were conducted after each cycle of irradiation. Measurements used for model development were also taken from many rods.

Some of the primary measurements that were taken on many of the irradiated AXIOM rods include:

- fuel rod length (to quantify fuel rod axial irradiation growth),
- fuel rod diameter (to quantify cladding creep), and
- oxide thickness (to quantify cladding corrosion).

It is noted that there was a total of **[ ]** Measurements from these rods were important in developing the fuel rod growth models for AXIOM with ADOPT fuel, which differs from the growth model for AXIOM with standard UO_2 fuel.

Additionally, one commercial plant placed **[ ]** of the AXIOM rods, or eight full AXIOM lead test assemblies (LTAs) in its core. According to Westinghouse, these LTAs are used as a production demonstration for AXIOM and a verification of the irradiation performance. Based on the visual inspections of AXIOM LTAs after the first and second cycles of irradiation, Westinghouse stated that they have performed as expected; no crud deposition or mechanical integrity anomalies were observed.

Another important irradiation and testing campaign included the irradiation of AXIOM rods that had burnups reach approximately **[ ]** and the subsequent comprehensive hot cell PIE of **[ ]** such rods at Studsvik. From the Studsvik tests, Westinghouse retrieved hydrogen analysis results, which were the basis for the AXIOM HPU model. Other notable data retrieved at Studsvik included rod measurements on internal pressure, fission gas release, mechanical properties of the high burnup rods, as well as optical and scanning electron microscopy images.

Furthermore, Sections 4.2.6 and 5.1.2 of WCAP-18546-P/NP describe the testing on AXIOM that was performed at the Halden reactor. Westinghouse participated in the IFA-708 and IFA-785 tests, the purposes of which were to evaluate the performance of cladding alloys at conditions more aggressive than allowed in operating PWRs. The conditions included elevated pH, high heat flux, and significant subcooled boiling. The tests included **[ ]** In the harsh conditions of the Halden tests, the six-inch AXIOM section on the segmented rod exhibited less corrosion than ZIRLO and Optimized ZIRLO in the tests at burnups at and above 38 GWd/MTU and the AXIOM section had better or nearly identical oxide thicknesses at burnups below 38 GWd/MTU as well. This data was not used in model development because of the atypical conditions compared to operating reactors, but the data confirms that the AXIOM oxidation performance is superior relative to ZIRLO and Optimized ZIRLO, even in harsh conditions.

Table 2 lists the test facility, testing method, and a brief summary of results and discussion from the testing for each testing facility.

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The NRC staff reviewed the Westinghouse's extensive irradiation experience of AXIOM cladding in different testing facilities and nuclear plants summarized above. The NRC staff determined that Westinghouse demonstrated that the in-reactor performance of AXIOM cladding is superior or equivalent to that of approved ZIRLO and/or Optimized ZIRLO cladding.

3.6 CHARACTERIZATION OF AXIOM CLADDING BEHAVIOR

3.6.1 Corrosion Model

Section 5.1 of the TR describes irradiation program for AXIOM corrosion model development, HPU model, and the corrosion limits for normal operation and accident conditions. **[**

] HPU data was obtained from hot cell examination of the lead test assembly from Plant B, using a correction for hydrogen in oxide and also without hydrogen correction based on the RG 1.236 guidance.

The integral form of the accumulated TRD term that was developed increases with time and temperature, thus accounting for fluctuations in conditions throughout the operating history. The AXIOM corrosion model was developed by the steps listed in Section 5.1.3.4 of the TR. For AXIOM cladding **[** **]** between measured oxide and TRD was found to be the best overall model (Figure 5.1-4 of Ref. 1). This data was transformed to measured – predicted (M-P) and is presented in Figures 5.1-5 and 5.1-6 as M-P vs. TRD and M-P vs. axial position, respectively in the TR (Ref. 1). This model applied to the validation dataset is presented in Figures 5.1-7 and 5.1-8 as M-P vs. TRD and Measured vs Predicted (M-P) vs. axial position, respectively. The overall statistics for calibration and validation datasets (as listed in Table 5.1-3 in Ref. 1) indicates the same statistical trend.

Corrosion model uncertainties were determined as a function of predicted oxide thickness and **[**

] as given in Equation 5.1-3 of Ref. 1 as AXIOM cladding upper bound (UB) oxide in micrometer. The UB uncertainty in oxide is provided in Figures 5.1-4 through 5.1-8 of Ref. 1.

The NRC staff reviewed the testing data and data processing and the calculations for uncertainty in oxide thickness and determined that the AXIOM corrosion model and uncertainties are acceptable.

3.6.2 HPU

Section 5.2 of the TR provide details of HPU in reactor, model development, and model uncertainty for HPU for AXIOM cladding. The data for HPU is obtained from Plant B for rods that were irradiated up to 70 GWD/MT burnup at different elevations. HPU data were collected from irradiated fuel rods **[** **]** elevation. The net hydrogen absorbed by cladding was calculated using Westinghouse developed empirical model based on test data. This model is documented in Ref. 47.

The corrosion process is characterized by the following chemical reaction of cladding with the coolant:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

An oxide layer, ZrO_2 is formed on the outside of the cladding as the metal wall thickness is reduced. The net amount of hydrogen absorbed by the metal is obtained by subtracting the amount of hydrogen absorbed by the oxide layer from the hydrogen content measured from the cladding. The presence of hydrogen in the cladding can impact the cladding properties, such as ductility.

The overall hydrogen level is characterized by the HPU and is expressed as fraction or a percent. The existing Westinghouse data on HPU fraction for ZIRLO and Optimized ZIRLO cladding is essentially the same as that of Zircaloy-4. Evaluation of the cladding hydrogen data for AXIOM cladding was found to be a lower HPU fraction **[** **]** for ZIRLO and Optimized ZIRLO claddings. The procedure and the theory for determining the cladding hydrogen absorption fraction is listed in Section 5.2.1 of the TR.

The HPU model uncertainties are determined as one-sided UB to cover at the 95/95 (95 percent uncertainty/95 percent confidence) with a linearly increasing uncertainty up to a TRD of 4000 with a constant value after that. The UB uncertainty for the upper 95 percent bound curve and uncertainty for the REA are provided in Equations 5.2-10 and 5.2-11 of the TR, respectively. Figure 5.2-1 in the TR gives the calculated hydrogen content in the metal for the three alloys (AXIOM, ZIRLO, and Optimized ZIRLO) vs. oxide thickness. Figure 5.2-3 provides HPU vs. oxide thickness for AXIOM cladding along with the UB for ZIRLO and Optimized ZIRLO cladding.

The NRC confirmatory fuel performance code, FAST (Ref. 17) was used to confirm the HPU calculations performed for Ref. 1 with AXIOM cladding. The NRC staff selected the 17x17 Next Generation Fuel (17x17 NGF) fuel assembly design (Ref. 18) power history for the confirmatory calculations. The power distribution provided to FAST begins at zero ft and ends at the length of the fuel rod (in this case 12 ft). Therefore, in order to use the provided power shapes, the relative power at zero ft and 12 ft were extrapolated using the first two and the last two relative powers in the distributions, respectively. The confirmatory FAST calculations show that the AXIOM cladding has a lower HPU than Optimized ZIRLO for the range of burnup from 10 to 60 GWd/MTU.

The NRC staff reviewed the data collection process, the HPU model development, and the HPU UB and uncertainty calculations and the results of the calculations. The NRC staff reviewed the results that show that Optimized ZIRLO cladding has a higher HPU ratio than the AXIOM cladding. The NRC staff confirmed that the lower maximum hydrogen content for any AXIOM alloy is due to the combination of low maximum oxide thickness and low HPU pickup ratio. Therefore, the NRC staff determined that the data, model, and uncertainty of AXIOM cladding HPU are acceptable.

3.6.3 AXIOM Cladding Corrosion and Hydrogen Limits for Normal Operation and Accident Conditions

The AXIOM cladding corrosion and HPU models are used with the fuel performance code PAD5 (Ref. 16) to predict the cladding oxide thickness and hydrogen content. Table 5.3-1of the TR lists the applicable oxidation and hydrogen predictions and limits for both AXIOM and Optimized

ZIRLO claddings for normal and accident conditions. This table indicates that the AXIOM corrosion oxide thickness from best estimate model is ≤ 100 µm. The corrosion cladding hydrogen for AXIOM cladding is ≤ **[ ]** For analyses using UB hydrogen, the two uncertainties of corrosion and HPU are combined to obtain the UB estimate. Figures 5.3-1 and 5.3-2 illustrates UB hydrogen vs TRD both best estimates.

For the LOCA evaluation, the ductile to brittle transition based on PQD testing is used to set ECR limits as a function of hydrogen. AXIOM cladding PQD based ECR limits as a function of TRD are plotted in Figure 5.3-3 of the TR. The Optimized ZIRLO cladding ECR limits are based on the **[ ]**

For the REA, as per RG 1.236, the total measured hydrogen inventory from both the metal and oxide are used in the HPU fraction calculation for AXIOM cladding. The AXIOM cladding hydrogen is calculated based on the best estimate prediction and the UB hydrogen uncertainty. AXIOM cladding and Optimized ZIRLO cladding PCMI enthalpy increase limits as a function of TRD are plotted in Figure 5.3-4 of the TR.

The NRC staff verified the AXIOM cladding corrosion and hydrogen limits for normal operation and accident conditions and determined that the corrosion and hydrogen limits are acceptable.

3.6.4 Fuel Rod Axial Growth

Section 5.4 of WCAP-18546-P/NP describes Westinghouse's fuel rod axial growth measurements on AXIOM fuel rods with standard UO_2 fuel and with Westinghouse's ADOPT fuel (Ref. 15). The data used for the development of the AXIOM axial growth model with standard UO_2 fuel consisted of **[ ]** The rod growth database for AXIOM with ADOPT fuel consists of **[ ]**

The growth model for AXIOM cladding with standard UO_2 fuel, which quantifies growth **[ ]** was developed through **[ ]**

In the response to RAI 1 regarding **[ ]** Additionally, the plots in Section 5.4 of the TR show the growth data and models as a function of fluence. The NRC staff requested that Westinghouse provide these plots as function of burnup in RAI 12c so that the location of the requested burnup limit in relation to the data and models could be more easily seen. In Westinghouse's response to RAI-12c, the rod growth data for AXIOM with standard UO_2 appears to exhibit a consistent trend in agreement with the proposed models to the requested burnup limit of **[ ]** The rod growth models for AXIOM with standard UO_2 appear to be valid beyond **[ ]** but that was outside the scope of the current NRC staff review, i.e., the NRC staff did not assess the models past **[ ]**

The UB fuel rod axial growth models are used in PAD5 for the calculation of the fuel rod shoulder gap to ensure adequate clearance between the fuel rod and the top and bottom nozzles as stated in Section 6.1.2.8 of the TR and Section 7.4.7 of WCAP-17642-P-A (Ref. 16). When the UB AXIOM with standard UO_2 fuel axial growth model is compared to the UB Optimized ZIRLO models reported in WCAP-17642-P-A, it is seen that the AXIOM UB model is **[ ]** than the Optimized ZIRLO UB model after approximately **[ ]** The magnitude by which the AXIOM UB model is **[ ]** than the Optimized ZIRLO UB model **[ ]** with fluence. At fluences greater than **[ ]** the AXIOM UB growth is **[ ]** than that of Optimized ZIRLO. The NRC staff also notes that when the best estimate growth models are compared, the AXIOM best estimate model predicts **[ ]** than that of the Optimized ZIRLO best estimate model. At fluences greater than **[ ]** the AXIOM best estimate growth ranges from approximately **[ ]** than the Optimized ZIRLO best estimate model. Furthermore, when compared to the best estimate ZIRLO growth model reported in WCAP-17642-P-A, it is seen that AXIOM with standard UO_2 fuel displays **[ ]** growth than ZIRLO above **[ ]** The NRC staff concludes that the fuel rod axial growth models for AXIOM with standard UO_2 fuel are acceptable.

Separate growth models were developed for AXIOM cladding fueled with ADOPT fuel. ADOPT fuel has a reduced in-reactor densification, which causes there to be an earlier closure of the fuel-to-cladding gap. After gap closure, irradiation-induced swelling influences fuel rod growth. The empirical database of ADOPT fuel cladded with AXIOM presented in WCAP-18546-P/NP, as well as ADOPT fuel cladded with Optimized ZIRLO presented in WCAP-18482-P/ WCAP-18482-NP, Revision 0 (Ref. 15), shows an increase in fuel rod growth compared to the standard UO_2 fuel rods. The growth models for AXIOM with ADOPT fuel were developed in a similar way to that done for the NRC-approved growth models for Optimized ZIRLO with ADOPT fuel detailed in Westinghouse's response to RAI 7a of WCAP-18482-P/WCAP-18482-NP, Revision 0 (Ref. 15). Westinghouse developed **[ ]** The AXIOM with ADOPT fuel rod axial growth UB model predicts **[ ]** growth than the Optimized ZIRLO with ADOPT fuel rod axial growth UB model approved in WCAP-18482-P/WCAP-18482NP, Revision 0 (Ref. 15).

The NRC staff finds the augmented axial fuel rod growth models for AXIOM with ADOPT fuel to be acceptable.

Additionally, if fuel rod growth reaches the extent such that the rod makes contact with the top or bottom nozzles, then the fuel rod may bow. If the fuel rod bows, then the thermal-hydraulic performance, i.e., the departure from nucleate boiling ratio (DNBR), may be impacted. In response to RAI 12b, Westinghouse detailed the AXIOM rod bow data and observations. Westinghouse stated that standard visual inspections were conducted for all AXIOM LTRs after each cycle of irradiation. More detailed visual inspections looking at rod bowing using a high magnification camera were also conducted for select assemblies with AXIOM LTRs. Through both the standard and detailed visual inspections, Westinghouse did not observe any rod bow of AXIOM rods. Westinghouse reported measurements of rod-to-rod spacings for channel closure for the lead test assembly at **[ ]** that contained AXIOM rods. The data from this assembly was below the UB limit for the gap closure correlation that defines the current rod bow penalty for Westinghouse 17x17 fuel assembly designs. The current Westinghouse evaluation methodology for **[ ]**

The NRC staff concludes that the AXIOM rod bow performance and treatment is acceptable.

3.6.5 Cladding Irradiation Creep

Compared to ZIRLO and Optimized ZIRLO, AXIOM cladding has reduced tin content and as a result AXIOM should have exhibited higher creep. However, the pRXA condition of AXIOM cladding has compensated for the decrease in tin content to an extent where the AXIOM creep is comparable to that of ZIRLO and Optimized ZIRLO cladding. This fact is confirmed by the Plant R data discussed in Section 3.5 of this SE and in Section 4.0 of the TR (Ref. 1). The deviatoric hoop stress is considered the driving force for irradiation creep. Deviatoric stress is a stress component in a system which consists of unequal principal stresses. There are three deviatoric stress components obtained by subtracting the mean (hydrostatic stress) from each principal stress component. Deviatoric stresses control the degree of body distortion (creep).

Plant data from plants R, AH, and D is calibrated to obtain the AXIOM cladding creep model. The plant data is listed in Table 3. The data base was not separated into calibration and validation databases due to the limited amount of data from commercial rods. The calibration of data consisted of elimination of significant bias in the data and minimization of standard deviation of M/P (measured/predicted) to the highest degree. Calibration also is slightly biased toward overprediction to achieve less bias in the trend in M/P vs. elevation and fluence.

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Figure 5.5-2 in the TR shows the best estimate PAD5 AXIOM creep down predictions vs. measurements for **[** **]** Figure 5.5-3 and Figure 5.5-4 of the TR show that the AXIOM cladding creep model does not have biased trends associated with the amount of creep strain, fluence or axial temperature variation. These figures indicate that the creep model predicts without any biases based on fluence and temperature.

The uncertainty in the creep model is quantified as **[** **]** obtained from statistical analysis of M/P data as described in Section 5 and RAI 9i of the PAD5 TR for ZIRLO and Optimized ZIRLO (Ref. 16). The AXIOM bounding PAD5 creep model is listed in Table 5.5-3 of the TR. The AXIOM uncertainty is statistically close to the ZIRLO/Optimized ZIRLO uncertainty creep model.

The NRC staff reviewed the irradiation creep property of the AXIOM cladding using the methodology and model described in the PAD5 TR. The NRC staff determined that the analysis and conclusions from the irradiation creep that the AXIOM alloy has lower creep than the ZIRLO cladding are acceptable. The NRC staff verified the model, methodology, plant data, statistical analyses and uncertainty calculations and determined that Westinghouse’s treatment for cladding irradiation creep is acceptable.

3.6.6 Irradiated Mechanical Properties-Axial and Ring Tensile Tests

Irradiated specimens of Optimized ZIRLO and AXIOM claddings from Plant B were hot cell examined for axial tensile tests (ATT) and ring tensile tests (RTT). Each set of samples includes two test temperatures: room temperature (RT) and high temperature at 385°C (HT). For ATT, about 3.5-inch-long pieces were cut from the fuel rod, defueled, and then split axially into two equal halves. For ring tensile tests 5 mm samples were machined to “dog-bone” type samples. Figures 5.6-1 and 5.6-2 in Ref. 1 show stress strain curves from ATT and RTT of AXIOM cladding sample and compared to Optimized ZIRLO cladding samples. Figure 5.6-1 and Figure 5.6-2 in the TR show that the mechanical properties of irradiated AXIOM and Optimized ZIRLO claddings are comparable. Both AXIOM and Optimized ZIRLO cladding show higher necking strain compared to the ZIRLO cladding specimen strain at RT. At 385°C, the Optimized ZIRLO and AXIOM cladding show higher necking strain which means higher resistance to crack propagation. From the results of ATT and RT at higher temperature, the necking strain ranges from 0 percent to 5 percent for ZIRLO cladding specimens, and from 4 percent to 8.7 percent for Optimized ZIRLO and AXIOM cladding specimens.

The NRC staff determined that the axial and ring tensile tests results are acceptable.

3.7 ASSESSMENT OF LICENSING CRITERIA

3.7.1 Steady State and AOO Analyses

Performance Analysis and Design Model (PAD5) (Ref. 16) is the fuel rod design tool which incorporates relevant fuel performance phenomena such as fuel thermal conductivity degradation (TCD) with fuel burnup, and FGR and swelling at high burnup. PAD5 calculates fuel performance parameters such as, cladding stress, strain, oxidation and hydriding, fuel temperatures and volume changes, and rod internal pressure (RIP).

Fuel Performance Models and Methods

The primary objective of the fuel design and safety analyses are as per SRP Section 4.2, “Fuel System Design,” which is repeated in Section 2.1 of this SE. Because of the minor changes in AXIOM cladding behavior in comparison to other Westinghouse’s zirconium-based alloys, the PAD5 fuel performance methodology requires modifications to implement the new AXIOM material properties models such as:

- Density
- Thermal Conductivity
- Yield Strength (Unirradiated and Irradiated)
- Ultimate Tensile Strength (Unirradiated and Irradiated)

- Clad Corrosion
- HPU
- Fuel Rod Axial Growth
- Cladding Creep

3.7.2 Fuel Rod Design Criteria

The fuel rod design criteria ensure the fuel rods perform their intended function throughout the lifetime of the fuel. Sections 7.2, 7.3, 7.4, and 7.5 of WCAP-17642-P-A, Revision 1, TR provides key criteria that impacts Westinghouse fuel performance. Section 7.3.2 of PAD5 methodology describes the treatment of uncertainties in analysis and a method for determining applicable uncertainties of certain parameters.

Section 7.4 of WCAP-17642-P-A, Revision 1, TR provides key criteria that impact the Westinghouse fuel performance:

- Clad Stress
- Clad Strain
- RIP
- Fuel Clad Wear
- Clad Fatigue
- Clad Oxidation
- Clad HPU
- Fuel Rod Axial Growth
- Clad Flattening
- Clad Free Standing
- Fuel Pellet Overheating (Power-to-Melt)
- Pellet-Clad Interaction

3.7.2.1 Clad Stress

The design basis for stress is that the fuel system will not be damaged due to excessive fuel clad stress. The acceptance limit for cladding stress is that the maximum cladding stress intensities, excluding PCI induced stress, are not to exceed various criteria that are based on the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) and also updates previously approved by NRC. These criteria are listed in Table 6.1-2 of the submittal.

Table 6.1-1 of Ref. 1 compares BOL finite element analysis (FEA) clad stress to the criteria. The FEA BOL strain limits are incorporated with the end of life (EOL) PAD5 stress limits to confirm the overall clad stress criterion for AXIOM cladding.

At the BOL condition, the AXIOM cladding unirradiated strength properties are **[**
] relative to the ZIRLO and Optimized ZIRLO cladding materials. Therefore, an alternate clad stress methodology using FEA replaces the previously licensed PAD5 clad stress method. However, the EOL clad stress method remains consistent with the PAD5 cladding stress method.

In the WCAP-18546-P/NP TR Westinghouse stated that: **[**

]

EOL clad stress analyses remain consistent with criteria defined with NRC-approved PAD5 clad stress analysis which is based on the ASME BPVC defined in Section 7.4.1 of Ref. 16. The AXIOM BOL (FEA clad strain based) and EOL clad stress analysis limits will be confirmed to be met on a cycle-specific basis.

The NRC staff verified the AXIOM clad stress analysis for BOL and EOL using a modified approach for BOL and PAD5 methodology for EOL, respectively. The NRC staff found that both BOL and EOL stress methodologies for AXIOM cladding are acceptable for all conditions of operation.

3.7.2.2 Clad Strain

The design basis for clad strain is that the fuel rod will not fail due to excessive fuel clad strain. The acceptance limit for the fuel rod clad strain is that the total tensile strain, elastic plus plastic, due to uniform cylindrical fuel pellet deformation during any single Condition I or II transient shall be less than one percent from the pre-transient value.

Clad strain design analysis is performed using NRC-approved Westinghouse PAD5 code to confirm that the one percent transient strain is satisfied for the limiting rod in the core. The updated cladding strain for AXIOM cladding is based on the fuel performance models described in Section 3.6 of this SE.

3.7.2.3 Rod Internal Pressure

The design basis for RIP is that the fuel system will not be damaged due to excessive fuel rod internal pressure. The acceptance limit for RIP as given in Section 7.4.3 of Ref. 16:

- the RIP be limited to a value below that which case diametral gap to increase (cladding liftoff) due to outward cladding creep during normal operation,
- be limited to a value below that which results in cladding hydride reorientation in the radial direction, and
- be limited to preclude extensive departure from nucleate boiling (DNB) propagation.

PAD5 code is used to calculate the RIP with the inclusion and associate uncertainties.

The RIP with no clad liftoff criterion assures that the pellet-clad gap does not open due to cladding creep rate exceeding the fuel swelling rate. The gap reopening causes positive feedback and the subsequent increase in temperature will result in increase in fission gas release, thereby increase in RIP and further increase in creep rate such that the gap increases in size. Fuel RIP is evaluated using the PAD5 methodology to assess the RIP no clad liftoff criterion to confirm this criterion of a reload specific basis.

DNB propagation analysis requires RIP, the high temperature creep model and the cladding burst model. The RIP is calculated using PAD5 code modified for AXIOM cladding. The high temperature creep model is unaffected by AXIOM cladding. A new burst model is developed for AXIOM cladding for LOCA analysis as described in Section 3.8.2.2.1.

Clad hydride orientation occurs when hydride precipitates formed during reactor operation reorient from circumference to the radial direction. Hydride reorientation is a precipitation driven process that occurs when the fuel cladding is cooled under tensile stress from a temperature where hydrides are dissolved. The formation of radial hydrides can reduce the cladding ductility and increase the potential for brittle failure due to subsequent fuel rod handling. Testing AXIOM cladding for hydride reorientation indicated a slight increase in hydride orientation in the radial direction compared to ZIRLO and Optimized ZIRLO. Further investigation concluded that the **[** **]**

The NRC staff finds that the calculations for RIP impact on no clad liftoff, DNB propagation, and clad hydrogen orientation are acceptable because Westinghouse used approved models and methodologies from the NRC-approved PAD5 TR.

3.7.2.4 Fuel Clad Wear

The design basis for fuel clad wear is that the fuel system will not be damaged due to rod fretting (GTRF). The acceptance limit for clad wear established by Westinghouse is set at a **[** **]** including fretting wear marks. Limiting fuel rod fretting to less than **[** **]** is by considering all pertinent factors such as spring relaxation due to irradiation, clad creep-down, and grid growth. During reactor operation, an oxide film forms on both the spring and rod surfaces. It is these surfaces that are subject to any potential fuel clad wearing. Both spring and rod surfaces are zirconium oxide and there are no differences in the AXIOM cladding oxide characteristics. At lower TRDs the oxide thickness for AXIOM and Optimized ZIRLO **[** **]** and the hotcell and poolside examination have shown **[** **]**

In summary, the wear rate for the AXIOM cladded fuel rods is expected to be comparable to the Optimized ZIRLO. PIEs both in hotcell and poolside have shown no significant cladding wear at spacer grid spring and dimple contact sites through burnups up to 75 GWd/MTU. The NRC staff reviewed the information regarding the clad fretting wear and determined that the AXIOM cladding meets the design and acceptability criteria for clad fretting wear up to their design burnup and it is acceptable.

3.7.2.5 Clad Fatigue

The design basis for clad fatigue is that the fuel system will not be damaged due to fatigue. The acceptance limit for clad fatigue is that life usage factor is limited to less than 1.0 to prevent reaching the material fatigue limit, considering a safety factor of 2 on stress amplitude or a safety factor of 20 on the number of cycles, whichever is more limiting. Fatigue is driven by the accumulated effects of cyclic strains associated with daily load follow.

Clad fatigue was evaluated using NRC-approved fuel performance code PAD5 (Ref. 16). Fuel duty is modeled and simulated a daily load follow cycling scheme **[** **]** The fatigue tests showed that the Langer O'Donnell fatigue model is applicable.

The NRC staff determined that the fatigue model in PAD5 is adequate to evaluate the strains associated with daily load follow. The NRC staff determined that the NRC-approved PAD5 code is adequate to evaluate clad fatigue on a reload specific basis.

3.7.2.6 Clad Oxidation

The design basis for clad oxidation is that the fuel system will not be damaged due to excessive fuel clad oxidation. The acceptance limit for clad oxidation is that the predicted **[** **]** shall be no greater than 100 microns for licensing applications. Clad corrosion is evaluated using AXIOM cladding corrosion model described in Section 3.6.1 of this SE.

3.7.2.7 Clad HPU

The design basis is that the fuel system will be operated to prevent degradation of mechanical properties of the clad at low temperatures, as a result of hydrogen embrittlement caused by the

formation of zirconium hydride platelets. The acceptance limit for HPU is that the **[**
] HPU level in the most limiting case will be less than or equal to **[** **]** at the end of fuel operation.

The best estimate cladding HPU is calculated from the best estimate corrosion calculation as describe in Section 3.6.2 of this SE. The best estimate through-wall average hydrogen content in the cladding is calculated by Equation 5.2-9 using the methods described in Ref. 47.

The NRC staff determined that HPU calculations, which were performed using the accepted methodology in Ref. 47, are acceptable because of the similarity between AXIOM and Optimized ZIRLO. Westinghouse intends to verify and confirm the HPU calculation on a reload basis.

3.7.2.8 Fuel Rod Axial Growth

The design basis for fuel rod axial growth is that fuel system will not be damaged due to excessive axial interference between the fuel rods and the fuel assembly structure. The acceptance limit is that the fuel rods shall be designed with adequate clearance between the fuel rod and the top and bottom nozzles to accommodate the differences in the growth of fuel rods and the growth of the assembly without interference.

As described in Section 3.6.4 of this SE, the PAD5 UB fuel rod axial growth model for AXIOM cladding is used in the calculation of the fuel rod shoulder gap as a function of fast neutron fluence. The fuel rod growth analysis is performed with PAD5. The NRC staff determined that the axial growth analysis performed with PAD5 methodology for AXIOM cladding showed no fuel rod interference with the top and bottom nozzles can occur during planned operation up to the design rod average burnup limit.

3.7.2.9 Clad Flattening

The design basis for clad flattening is that fuel rod failures will not occur due to clad flattening. The acceptance limit for clad flattening is that the fuel rod design shall preclude clad flattening during projected exposure.

Westinghouse reported that its fabricated fuel is sufficiently stable with respect to fuel densification such that the axial column gaps formed are too small to allow clad flattening to occur. The axial column gaps are sufficiently small that a densification power spike factor of 1.0 is appropriate. With the cladding creep properties of AXIOM cladding the pellet to clad gap closure is **[**

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The NRC staff determined that the AXIOM cladding pellet-clad gap closure is **[** **]** Optimized ZIRLO as per Section 3.4.6 of this SE. The densification spike factor of 1.0 with AXIOM cladding preclude pellet-clad closure.

3.7.2.10 Clad Free Standing

The design basis for clad free standing is that the fuel system will not be damaged due to excessive fuel clad stress. The acceptance limit for clad free standing is that the cladding shall be short-term free standing at BOL, at power, and during hot hydrostatic testing. Westinghouse performed autoclave testing consistent with PAD5 methodology with rodlets subjected to high compressive differential pressure consistent with the limiting in-reactor clad temperature and reported in the TR that AXIOM cladding met the clad free-standing criteria.

The NRC staff determined that the clad free standing acceptance criteria for AXIOM cladding has been met and therefore the AXIOM cladding fuel system will not be damaged due to excessive fuel clad stress.

3.7.2.11 Fuel Pellet Overheating (Power-to-Melt)

The design basis for power-to-melt is that the fuel rods will not fail due to fuel centerline melting for Condition I and Condition II events. The acceptance limit is that the fuel rod centerline temperature shall not exceed the fuel melt temperature. The fuel rod centerline (FCL) temperature shall not exceed the fuel melt temperature during Condition I and II operation. The fuel limit temperature is adjusted for degradation of melting temperature due to burnup and the addition of integral burnable absorbers.

The NRC-approved PAD5 code is used to evaluate the fuel rod centerline temperatures. PAD 5 model incorporates the effect of fuel thermal conductivity degradation with burnup and includes updated AXIOM cladding performance models to assess the FCL to preclude the fuel pellet overheating criterion. The NRC staff determined that the methodology for the analysis to prevent fuel power-to-melt is appropriate and, therefore, is acceptable.

3.7.2.12 Pellet-Clad Interaction

The design basis for PCI is that the fuel rod will not fail due to pellet-clad interaction. The acceptance limit is not set in the SRP. However, two related limits, namely, one percent strain limit and the no fuel centerline melt criteria must be met.

It states in the Section 7.4.11 of PAD5 TR (Ref. 16) that the fuel rod will not fail due to pellet-clad interaction. There is no specific design criterion for PCI, so as long as the clad strain and fuel overheating limits are met, PAD5 analysis will continue to confirm that the clad strain and fuel overheating limits are met for AXIOM cladding with no additional PCI calculations required.

The NRC staff has determined that the PCI analysis in PAD5 is acceptable with confirmation on the strain limit and fuel overheating limit.

3.7.2.13 Interface to Safety Analyses

PAD5 is used to generate fuel temperature, RIP, core stored energy, and additional fuel and cladding parameters for LOCA and non-LOCA safety analyses. The required model changes for material properties of AXIOM cladding have a minor effect on fuel temperatures and RIPs for safety analyses. Lower temperatures are expected for AXIOM alloy fuel at higher burnups due to a reduced corrosion thickness, though minor temperature increases are expected prior to gap closure due to a decreased primary creep rate in AXIOM cladding. RIP is expected to be decreased throughout life due to the combination of creep and corrosion behavior. In summary, the minor changes and updates with respect to AXIOM cladding do not change the conservative methods outlined in Section 7.4.1 of Ref. 16. Therefore, the PAD5 methods will continue to be used with AXIOM cladding.

3.8 SAFETY ANALYSES

3.8.1 FULL SPECTRUM™ LOCA Phenomena Identification Ranking Table Review

Although the introduction of AXIOM cladding material to the fuel system meets the overall requirement of 10 CFR 50.46, it does introduce potentially different physical effects that can change the results. The Phenomena Identification Ranking Table from FULL SPECTRUM LOCA (FSLOCA™) evaluation model (EM) (Ref. 19) is used in LOCA analysis. AXIOM cladding test results with respect to both best-estimate and Appendix K LOCA methodologies were evaluated. This section describes affected phenomena for best estimate and Appendix K LOCA methodologies.

Stored Energy

Since the AXIOM cladding normal corrosion is different from other zirconium-based alloys the steady-state pellet temperature will be changed and as a result the initial stored energy will be affected. During small-break LOCA (SBLOCA) the core remains covered during the early periods of the transient during which time the heat transfer causes only a small temperature difference between the fuel centerline temperature and the coolant. This causes the removal of much of the initial stored energy of the fuel, **[**

]

Clad Oxidation

The high temperature oxidation behavior of AXIOM cladding is **[** **]** Therefore, for both SBLOCA and LBLOCA, **[** **]**

Decay Heat

Since decay heat is the main driver for cladding heatup during SBLOCA transient, **[**

]

Clad Deformation (Burst Strain, Relocation)

[

]

The cladding deformation behavior for AXIOM cladding is **[**

] of the WCAP-18546-P/NP TR.

Critical Heat Flux

[

]

Post-Critical Heat Flux Heat Transfer/Steam Cooling

CHF is **[** **]**

Rewet/T_{min}

Rewet/T_{min} in which rewet is possible: for SBLOCA scenarios this phenomenon is **[** **]** For LBLOCA scenarios, this phenomenon **[** **]**

3.8.2 Best Estimate Loss-of-coolant Evaluation Model

This section briefly describes the aspects of FSLOCA EM as detailed in Ref. 19.

3.8.2.1 Thermal and Mechanical Properties

Mechanical and thermal properties of ZIRLO and Optimized ZIRLO are described in Ref. 19. Optimized ZIRLO cladding material is an improvement over ZIRLO cladding material which has reduced tin content.

Specific Heat

Figure 6.2-1 in the TR shows specific heat model for ZIRLO and Optimized ZIRLO cladding to the specific heat test results for ZIRLO, Optimized ZIRLO, and AXIOM cladding. The FSLOCA EM model shows **[** **]**

Thermal Conductivity

Figure 6.2-2 in the TR compares FSLOCA EM thermal conductivity model for ZIRLO and Optimized ZIRLO cladding to the thermal conductivity test results for ZIRLO, Optimized ZIRLO, and AXIOM cladding. Figure 6.2-2 shows reasonable agreement between thermal conductivity of all these types of cladding. The variations in model and test results are small. The LOCA transients are insensitive to these variations of thermal conductivity. Therefore, the thermal conductivity model for ZIRLO and Optimized ZIRLO cladding in the FSLOCA EM can also be applied to AXIOM cladding.

Emissivity

AXIOM cladding is processed identically to the other alloys tested and has an identical surface finishing as ZIRLO and Optimized ZIRLO. Therefore, within the uncertainty the emissivity of oxidized AXIOM cladding is identical to ZIRLO and Optimized ZIRLO cladding. Therefore, the NRC staff determined that the emissivity for ZIRLO and Optimized ZIRLO in the FSLOCA EM can also be applied to AXIOM cladding.

High Temperature Creep

High temperature creep model test for ZIRLO and Optimized ZIRLO for FSLOCA EM was performed at the French Commissariat a l'Energie Atomique using the EDGAR-2 facility. The test consisted of inductive heating the individual samples to the test temperature in steam and pressurizing with argon. **[**

] To evaluate the behavior of AXIOM cladding relative to the ZIRLO and Optimized ZIRLO cladding model, high temperature biaxial creep tests were performed in a vacuum similar to that in Section 3.4.6 of the SE.

High temperature creep rates of AXIOM and Optimized ZIRLO cladding were plotted in Figure 3.7-1 in the WCAP-18546-P/NP TR with the average hoop stress compared to Optimized ZIRLO and ZIRLO cladding test results. This plot indicates similar creep behavior of AXIOM cladding to that of Optimized ZIRLO.

The NRC staff reviewed the high temperature model developed for Westinghouse FSLOCA EM from the strain rate tests and determined that **[**

]

3.8.2.2 Other LOCA Models

Westinghouse best-estimate LOCA methodology parameters such as density, thermal expansion, Young's modulus, and Poisson's ratio have minimal importance in licensing basis. Measurements and tests for these properties over limited temperature ranges have shown to be indistinguishable from Zircaloy-4, ZIRLO, and Optimized ZIRLO which were all previously approved by the NRC.

3.8.2.2.1 Cladding Rupture Models: Burst Temperature

The NRC's NUREG-0630 (Ref. 21) provides the framework for the cladding rupture model used for ZIRLO and Optimized ZIRLO cladding in the FSLOCA EM. The model describes burst temperature as a function of engineering hoop stress and is used to predict the occurrence of rupture depending on local cladding temperature conditions. Figure 6.2-3 of the TR illustrates the results of rupture testing performed on AXIOM cladding in comparison with the existing ZIRLO and Optimized ZIRLO testing performed for FSLOCA EM. **[**

]

[

] The NRC staff verified the results shown in the above references and determined that the AXIOM cladding burst selection temperature is acceptable for FSLOCA EM.

3.8.2.2.2 Cladding Rupture Models: Burst Strain

Section 8.4.1 of Ref. 19 describes the cladding rupture model used for ZIRLO and Optimized ZIRLO cladding in the FSLOCA EM, and the burst strain model is illustrated in Figure 8-20 in Ref. 19. The burst strain associated with ZIRLO and Optimized ZIRLO cladding rupture tests is presented, and uncertainty distributions are provided in Table 29-3b of Ref. 21. The burst temperature ranges are **[**

]

Nominal Burst Strain

Figure 6.2-5 illustrates ZIRLO and Optimized ZIRLO cladding historical burst strain data with AXIOM cladding data from tests. This plot shows the **[** **]** This is consistent with Section 3.3.3 of this SE which indicates that AXIOM cladding has **[**

]

Figure 6.2-6 of the TR provides an **[**

]

In view of the **[**

]

Burst Strain Uncertainty Distributions

The current uncertainty in the burst strain for ZIRLO and Optimized ZIRLO for use in FSLOCA EM **[**

]

[

]

This approach is consistent with the approach described in Section 29.4.2.1 of Ref. 21. The NRC staff reviewed the burst strain uncertainty treatment and determined that the approach is acceptable.

3.8.2.2.3 High Temperature Oxidation

For FSLOCA EM, the Cathcart-Pawel model is used to calculate the oxide buildup throughout the transient and the resulting heat generation in FSLOCA EM. Figure 3.8-2 of the TR (previously referenced in Section 3.4.10 of this SE) compares the parabolic rate constants for the AXIOM cladding tests to the ZIRLO and Optimized ZIRLO cladding test results. The results for AXIOM cladding show **[** **]**

The NRC staff determined that the Cathcart-Pawel model used in FSLOCA EM can also be applied to AXIOM cladding.

3.8.3 NOTRUMP Evaluation Model

This section addresses the impact of the AXIOM cladding on the NOTRUMP EM as described in Refs. 22 and 23. The models and correlations used in the NOTRUMP EM for SBLOCA analyses **[** **]** as discussed below.

3.8.3.1 Thermal and Mechanical Properties

This section summarizes the effect of AXIOM cladding on the relevant thermal and mechanical properties.

Specific Heat

The NOTRUMP model for specific heat of ZIRLO and Optimized ZIRLO cladding is based on ZIRLO cladding. The test results for ZIRLO and Optimized ZIRLO cladding, and the NOTRUMP specific heat model show **[** **]** (Figure 6.2-18 of the TR). Therefore, the NRC staff determined that the **[** **]** to AXIOM cladding.

Thermal Conductivity

Figure 6.2-19 of the TR **[** **]** for AXIOM cladding.

Density

It is stated in Ref. 4 that the density has minimal importance in typical licensing basis SBLOCA transients. Based on the density specified in Section 3.2 of the SE, the RT density of AXIOM cladding is **[** **]** Therefore, the NRC staff determined that the existing NOTRUMP EM model can be used for AXIOM cladding.

Thermal and Elastic Expansion

In Refs. 4 and 14, no adjustments were made to thermal expansion models to accommodate ZIRLO and Optimized ZIRLO cladding. Thermal and elastic expansion have minimal importance in SBLOCA transients due to the **[** **]** Given this, and since the data in Section 3 of this SE indicates **[** **]** variations in chemical compositions of the modern Westinghouse cladding alloys, the existing NOTRUMP EMs can be used for AXIOM cladding.

Emissivity

As indicated in Section 3.4.9 of this SE, all Westinghouse cladding alloys have identical surface finishes, and that the emissivity of oxidized fuel cladding is dominated by the zirconium oxide formed. Emissivity is unaffected by minor differences in alloying elements, and therefore, the existing NOTRUMP EM emissivity values can be used for AXIOM cladding.

High Temperature Creep

Ref. 4 concludes that the **[** **]** Figure 3.7-1 in the TR (Ref. 1) compares the creep rates of AXIOM and Optimized ZIRLO cladding to previous test results and **[**

] Therefore, the NRC staff determined that existing **[**
] for AXIOM cladding.

High Temperature Oxidation

Section I.A.5 of 10 CFR Part 50 Appendix K requires the use of the Baker-Just equation to calculate the rate of energy release, hydrogen generation, and cladding oxidation from the metal-water reaction and to calculate the reaction rate on the inside of the cladding after rupture. Refs. 4 and 14 confirm that the continued use of Baker-Just is conservative for Optimized ZIRLO and ZIRLO cladding, respectively. Table 3.8-2 of the WCAP-18546-P/NP TR lists parabolic oxidation rates of AXIOM cladding as a function of temperature and this is compared to the Baker-Just and Cathcart-Pawel correlations and previously reported ZIRLO and Optimized ZIRLO cladding oxidation rates in Figure 3.8-2 of the TR. The AXIOM cladding results **[**

] Therefore, the NRC staff determined that **[**
] for AXIOM cladding.

Clad Swelling and Rupture

Figure 3.6-1 of the TR shows the comparison of ZIRLO, Optimized ZIRLO, and AXIOM cladding burst strain vs. burst temperature results, and it is concluded that the AXIOM data is **[**
] Figure 3.6-2 of the TR shows the burst temperature vs. burst pressure results for AXIOM cladding along with ZIRLO and Optimized ZIRLO cladding results. Based on this, the NRC staff determined that **[**
] for AXIOM cladding.

3.8.4 Non-LOCA Transient Analysis

This section provides a brief description of the effect of the AXIOM fuel cladding on the non-LOCA safety analyses for both Westinghouse and CE-designed PWR plants.

3.8.4.1 Non-LOCA Analysis Methods and Computer Codes

Mechanical, thermal, and material properties of AXIOM cladding are discussed in Sections 3.1, 3.2, 3.3, and 3.4 of this SE. Generally, there are only insignificant or minor differences such that the current parameters used in the non-LOCA analysis models and codes for the ZIRLO and Optimized ZIRLO alloys will remain valid for AXIOM cladding. Minor adjustments to code inputs will be necessary to model certain AXIOM cladding properties within underlying approved non-LOCA analysis methods. The non-LOCA safety analyses use inputs and models for fuel-related parameters based on the nuclear design, thermal-hydraulic design, and fuel rod design.

3.8.4.2 Non-LOCA Acceptance Criteria

With the change to AXIOM cladding, the following two categories of non-LOCA analyses need to be evaluated: (1) analyses of events that are dependent upon core average effects and (2) analyses of the events for which local effects in the fuel rods are addressed.

For the first category of events, they are analyzed to address gross core or plant criteria, such as no return to criticality, maintaining margin to the hot leg saturation temperature, not exceeding the pressure limits of the reactor coolant system (RCS) and main steam system, and not filling the pressurizer water-solid.

For the second category of analyses, some non-LOCA events are analyzed to address local effects in the fuel rods in two steps: (1) prediction of the average core response to an initiating event and (2) hot channel or hot spot calculations for the following local effects: minimum DNBR, fuel centerline melting, fuel enthalpy (cal/g), and PCT. Based on the confirmations in Section 3.8 of this SE for the AXIOM fuel cladding material, there is no impact on the applicable DNBR limit and linear heat generation rate (kW/ft) acceptance criteria.

Fuel Enthalpy (cal/g)

A limit of 200 cal/g is conservative with respect to the 230 cal/g limit specified for core coolability in the new rod ejection analysis guidance of RG 1.236. However, PCMI cladding failure threshold limits specified in RG 1.236 are expressed in terms of the peak radial fuel enthalpy rise (Δcal/g) versus excess cladding hydrogen content (wppm). Regardless of the specific fuel cladding material used, it is anticipated that RG 1.236 limits for rod ejection core coolability and fuel and cladding failure will ultimately be addressed as part of the implementation of the three-dimensional (3-D) rod ejection analysis methodology for a specific plant.

Peak Cladding Temperature

For the locked rotor accident for Westinghouse plants, the PCT acceptance criterion historically used for this event has been 2700°F. For Optimized ZIRLO cladding a conservatively lower value of 2375°F has been applied as the limit. The locked rotor PCT limits are used in limiting the maximum percentage of zirconium-water reaction limit of 16 percent to show cladding integrity during the accident. As shown in Section 3.4.10 of this SE, AXIOM cladding will have a similar oxidation rate as ZIRLO and Optimized ZIRLO cladding up to a PCT of 1300°C (~2375°F). Therefore, the NRC staff determined that the locked rotor PCT limit currently applied to the Optimized ZIRLO cladding will also be used for the AXIOM cladding, assuming confirmation from the additional high temperature oxidation and ductility testing.

3.8.4.3 Non-LOCA Conclusions

Westinghouse computer codes and methods for non-LOCA licensing basis accident analyses and acceptance criteria remain applicable for fuel rods with AXIOM cladding material, except the REA. The REA limits relative to the new RG 1.236 guidance would be addressed via future implementation of 3-D methodology for a specific plant. The NRC staff reviewed Westinghouse methodology for non-LOCA transients and determined that any change to non-LOCA safety analysis due to the use of AXIOM cladding will be small and applicable limits will continue to be met.

3.8.5 Containment Integrity Analyses

This section discusses the effect of the AXIOM cladding material on the containment integrity analyses. The short-term and long-term mass and energy (M&E) released to the containment due to the pipe rupture accident is examined in the analyses.

3.8.5.1 Short-Term and Long-Term LOCA M&E Release

The short-term LOCA M&E releases are used to determine the maximum differential pressure for structural analyses within sub-compartments inside the containment building resulting from postulated pipe ruptures in the primary system piping. This transient lasts for 1 to 3 seconds in duration and mass flux at the break location. There are four parameters that influence the short-term LOCA M&E releases: break location, corresponding temperature of the fluid, size of the break, and initial RCS pressure. The fuel product and specific aspects of the fuel performance do not influence the short-term LOCA M&E. Therefore, any change in the fuel design including new cladding material would not impact the short-term LOCA M&E releases.

For long-term LOCA M&E release calculations, Westinghouse has three licensed methodologies used for containment integrity, maximum sump temperature, and equipment qualification for Westinghouse and CE designs. The licensed/approved methodologies are:

- WCAP-10325-P-A (Ref. 24)
- WCAP-17721-P-A (Ref. 25)
- CENPD-132D (Refs. 26 and 27)

The NRC staff reviewed the methodologies used for short-term and long-term LOCA M&E releases and determined that no methodological changes are required for a full core AXIOM cladded fuel design.

3.8.5.2 Short-Term and Long-Term Steam Line Break M&E Releases

The short-term steam line break (SLB) M&E releases are used to determine the short-term pressure increase transients for structural analyses within sub-compartments inside or outside the containment building resulting from postulated secondary-side pipe ruptures. The transients are performed (typically 1 to 10 seconds duration) and are governed by the mass flux at the break location. Therefore, the parameters that influence the short-term SLB M&E releases are the break location corresponding to the initial secondary system pressure, temperature, and quality of the fluid in the postulated ruptured pipe, and the size of the break. Since these transients are of short duration, they are influenced only by the mass flux at the break location. Therefore, the parameters that influence the short-term LOCA M&E releases are the break location, the corresponding temperature of the fluid in the postulated ruptured pipe, the size of the break, and the initial RCS pressure. This means that any change in fuel pellet materials have no impact on the short-term SLB M&E releases.

Long-term SLB M&E release analyses use methods and models similar to those for non-LOCA analyses as described in Section 3.8.4.1 of this SE and remain valid for AXIOM cladded pellet design. For the long-term SLB M&E analyses, there are three NRC-approved methodologies:

- LOFTRAN (Refs. 28 and 29)
- RETRAN (Ref. 30)
- SGNIII (Ref. 31)

The NRC staff determined that the computer codes and methods currently used in LOCA and SLB M&E releases used for containment integrity analyses are valid for AXIOM cladded fuel.

3.8.6 Radiological Consequences Analyses

Implementation of AXIOM fuel rod cladding will have no impact on models and method used in performing offsite and control room radiological consequences analyses for accidents. Radiological consequence analysis does not model cladding. Change of cladding material could impact input to accident radiological consequences. Radiological consequences analyses consider the extent of fuel cladding damage resulting from postulated accidents. The analysis would be incorporated in a plant specific analysis using methods consistent with the analysis of record.

3.8.7 Fuel Assembly Seismic and LOCA Evaluation

For seismic and LOCA analyses the full core fuel assembly seismic and LOCA analysis is performed to evaluate the grid impact forces against their allowable grid impact strengths. Subsequently, the fuel assembly stress analysis is performed to confirm that the guide thimble tube and fuel rod cladding stresses do not exceed their respective stress limits as well as confirm that control rod insertability is maintained. Seismic and LOCA models are established based on the fuel assembly mechanical tests. The fuel assembly BOL and EOL analysis models established based on the NRC-approved seismic and LOCA methodologies. The fuel assembly seismic and LOCA evaluation and the demonstration analysis have been performed for the BOL and EOL conditions as described in the TR.

BOL Seismic and LOCA Evaluation

For Westinghouse plants seismic and LOCA evaluations were performed for the AXIOM cladding and compared to the ZIRLO and Optimized ZIRLO cladding for the fuel assembly BOL. The evaluations produced results that show fuel rod cladding stresses for Westinghouse U.S. plants compared with AXIOM cladding LB allowable limits for Condition III and IV. For Condition II Operational Basis Earthquake (OBE) the fuel rod stress results showed additional conservatism than those calculated using the methodology described in Section 7.4.1 of PAD5 TR (Ref. 16). BOL seismic and LOCA analyses for AXIOM cladding will utilize the fuel rod cladding stress acceptance limits for compressive loadings as defined in Table 8 of Ref. 16. The allowable stress limits for Condition II OBE show that the example evaluations continue to meet with AXIOM fuel cladding LB allowable limits for Condition II OBE load. For CE plants the fuel rod stress methods are defined in Section 3.7.2.1 for AXIOM clad fuel rods.

EOL Seismic and LOCA Evaluation

The AXIOM fuel rod cladding seismic and LOCA analysis at the EOL conditions was performed as per NRC Information Notice IN 2012-09 (Ref. 45) and followed by the analysis methodology and process described in Westinghouse and PWR Owner's Group (PWROG) TR (Ref. 46). Westinghouse reported that two example seismic and LOCA analysis cases for fuel assembly designs **[ ]** were evaluated for EOL conditions. The results of the analysis show that the grid impact forces remain below the grid impact allowable limits for both **[ ]** fuel designs for Condition II, III, and IV seismic and LOCA loadings at EOL condition. The stress evaluations of the **[ ]** fuel rods and thimble tubes were also performed. The results show that all the stresses of the fuel rod meet the

AXIOM cladding allowable limits approved by the NRC (Ref. 16) and the thimble tubes meet with ZIRLO cladding allowable limits for both **[ ]** designs. Fuel rod fragmentation will not occur and coolable geometry will be maintained, and RCCA insertion will be maintained.

The NRC staff reviewed the Westinghouse analysis of BOL and EOL seismic/LOCA analysis and determined that PWROG's response (Ref. 46) to the NRC Information Notice IN 2012-09 (Ref. 45) can be applied to the Westinghouse fuel designs in support of AXIOM cladding implementation.

3.9 Impact on Nuclear Design Requirements

The nuclear design methods applied to the calculation of key reload safety parameters (Ref. 12), assumptions made to percentage of heat generated in fuel, and decay heat characteristics of the core are not impacted by the implementation of AXIOM cladding material. Review of a comparison of pin powers, reaction rates, and gamma maps modeled over a bounding burnup has shown negligible neutronic impact when AXIOM cladding is compared to ZIRLO and Optimized ZIRLO cladding materials.

CE methods and codes (Refs. 32, 33, and 48) are not impacted by the implementation of AXIOM cladding. Multi-dimension rod ejection methodology (Ref. 35) is not impacted. AXIOM cladding is nearly indistinguishable from ZIRLO and Optimized ZIRLO cladding neutronically and from the viewpoint of irradiation-induced activity. There will be no limitation imposed on nuclear design aspects of the core design resulting from AXIOM cladding implementation.

3.10 Thermal Hydraulic Design Methods

Westinghouse states that implementation for AXIOM cladding does not require modification or update to any previously NRC-approved methods and TRs for DNB and thermal-hydraulic analyses. The thermal-hydraulic methods applied to PWR DNB analysis consists of a DNB correlation such as WRB-1 (Ref. 34), WRB-2 M (Ref. 37), WSSV (Ref. 38), and WNG-1 (Ref. 39), thermal-hydraulic subchannel code, VIPRE-W (Ref. 40), and a statistical method for determination of a 95/95 DNBR limit, such as the Revised Thermal Design Procedure (Ref. 36) and the Westinghouse Thermal Design Procedure (Ref. 41).

Implementation of AXIOM cladding on existing approved fuel designs does not require modification or update to any previously approved methods and TRs for DNB and thermal-hydraulic analyses, such as Refs. 34 – 43. The AXIOM cladding does not affect any fuel geometry that could adversely affect DNB performance as compared to the Optimized ZIRLO cladding, and the existing DNB correlations remain applicable. The VIPRE-W code can perform steady-state and transient DNBR calculations and non-LOCA post-CHF fuel rod transient analysis. The method using the VIPRE-W code for the DNB propagation evaluation, is applicable to both Westinghouse and CE PWR plants.

3.11 Licensing Criteria Conclusion

The NRC staff concludes that due to the close similarities in performance between AXIOM cladding and previously approved ZIRLO and Optimized ZIRLO claddings, the existing Westinghouse's NRC-approved analytical methods and models for thermal-hydraulics, nuclear design, LOCAs, and non-LOCA transient analyses are appropriate with either minimal or no modifications. The NRC staff determined that the acceptance criteria for safety analysis for standard UO_2 fuel and ADOPT fuel are found appropriate for AXIOM clad fuel safety analyses and are acceptable.

4.0 LIMITATIONS AND CONDITIONS

The NRC staff limits the applicability of the WCAP-18546-P/NP, "Westinghouse AXIOM Cladding for Use in Pressurized Water Reactor Fuel," TR and associated methodology for fuel types, cladding, and reactors to the ranges listed below:

Reactor and Fuel Assembly Designs

- AXIOM cladding must be used with the NRC-approved PWR designs
- AXIOM cladding must be used with the NRC-approved Westinghouse and CE fuel designs with corresponding pellet and assembly dimensions
- AXIOM cladding must be used with the NRC-approved fuel materials and pellet coatings or additives (e.g., ADOPT IFBA, gadolinium)

Fuel Limitations

- Currently fuel burnup shall be limited to 62 GWd/MTU peak rod average for all cladding types, however, fuel rod burnup **[ ]** may be allowed once additional information specific to burnup to **[ ]** is submitted and approved by the NRC
- Best Estimate Oxide Thickness < 100 μm
- Best Estimate HPU ≤ **[ ]**

5.0 CONCLUSIONS

The NRC staff has reviewed the Westinghouse's TR titled WCAP-18546-P/NP, "Westinghouse AXIOM Cladding for Use in Pressurized Water Reactor Fuel." AXIOM cladding is designed to exhibit improved corrosion resistance, lower HPU, and lower creep compared to Westinghouse cladding products, ZIRLO and Optimized ZIRLO. AXIOM cladding is a niobium-bearing alloy with reduced tin content to increase corrosion resistance like Optimized ZIRLO alloy. AXIOM cladding material has alloying elements including vanadium and copper to improve HPU.

The NRC staff's extensive review of the TR consisted of the virtual audit of supporting documents, RAIs, and review of the responses to RAIs. The review consisted of characterization of the AXIOM cladding microstructure, thermal and mechanical properties, and irradiation of AXIOM cladding at various power plants and testing facilities. The review also consisted of characterization of ADOPT fuel behavior, corrosion, HPU, axial rod growth, cladding rupture models and burst strain. The NRC staff reviewed the licensing criteria assessment which included various fuel rod design criteria, safety analyses for both LOCA and non-LOCA transients, and radiological consequence analyses

The NRC staff completed its review of Westinghouse TR titled WCAP-18546-P/NP, "Westinghouse AXIOM Cladding for Use in Pressurized Water Reactor Fuel," and found that

WCAP-18546-P/NP is acceptable for referencing in licensing applications to the extent specified and under the limitations and conditions delineated in the TR and Section 4.0 of the NRC staff's SE.

6.0 REFERENCES

1. Submittal of Westinghouse Topical Report WCAP-18546-P/NP, "Westinghouse AXIOM® Cladding for Use in Pressurized Water Reactor Fuel (Proprietary/Non-Proprietary)," March 2021 (ADAMS Package Accession No. ML21090A110).

2. Letter from Z. Harper, Westinghouse, to NRC, DCD, Submittal of Responses to Requests for Additional Information on Westinghouse Topical Report WCAP-18546-P/NP, "Westinghouse AXIOM® Cladding for Use in Pressurized Water Reactor Fuel (Proprietary/Non-Proprietary)," LTR-NRC-22-9, February 17, 2022 (ADAMS Accession No. ML22049B018).

3. Submittal of "Supplement to WCAP-18546-P/WCAP-18546-NP, 'Westinghouse AXIOM Cladding for Use in Pressurized Reactor Fuel,' to Extend Applicability to Include Westinghouse Advanced Doped Pellet Technology (ADOPT™) Fuel (Proprietary/ Non-Proprietary)," LTR-NRC-21-40, December 17, 2021 (ADAMS Package Accession No. ML21351A253).

4. WCAP-12610-P-A & CENPD-404-P-A, Addendum 1-A, "Optimized ZIRLO™ (Proprietary)," July 2006 (Non-publicly available, Proprietary).

5. NRC NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," June 1987.

6. NRC NUREG-0800, Section 4.2, "Fuel System Design," March 2007 (ADAMS Accession No. ML070740002).

7. NRC NUREG-0800, Section 4.3, "Nuclear Design," March 2007 (ADAMS Accession No. ML070740003).

8. NRC NUREG-0800, Section 4.4, "Thermal and Hydraulic Design," March 2007 (ADAMS Accession No. ML070550060).

9. NRC NUREG-0800, Section 6.2.1, "Containment Functional Design," March 2007 (ADAMS Accession No. ML070220505).

10. NRC NUREG-0800, Chapter 15.0, "Transient and Accident Analyses."

11. WCAP-16500-P-A, Revision 0, "CE 16x16 Next Generation Fuel Core Reference Report," August 31, 2007 (Non-publicly available, Proprietary).

12. WCAP-9272-P-A, "Westinghouse Reload Safety Evaluation Methodology," July 1985 (Non-publicly available, Proprietary).

13. WCAP-12488-A, “Westinghouse Fuel Criteria Evaluation Process,” October 1994 (Non-publicly available, Proprietary), and WCAP-12488-A, Addendum 1-A Revision 1/WCAP1-14204-A, Addendum 1-A, “Westinghouse Fuel Criteria Evaluation Process, Revision to Design Criteria,” January 2002 (ADAMS Package Accession No. ML020520677).

14. WCAP-12610-P-A, “VANTAGE+ Fuel Assembly Reference Core Report,” April 1995 (Non-publicly available, Proprietary).

15. Letter from Z. Harper, Westinghouse, to NRC Document Control Desk (DCD), “Submittal of Topical Report WCAP-18482-P, Revision 0, ‘Westinghouse Advanced Doped Pellet Technology (ADOPT^{TM} Fuel),’” LTR-NRC-20-33, May 8, 2020 (ADAMS Accession No. ML20132A014).

16. Letter from K. Hosack, Westinghouse, to NRC, DCD, “Submittal of WCAP-17642-P-A, Revision 1, ‘Westinghouse Performance Analysis and Design Model (PAD5),’” (ADAMS Accession No. ML17335A826).

17. K. J. Geelhood, et.al., “Fast-1.1: A Computer Code for Thermal Mechanical Nuclear Fuel Analysis under Steady-state and Transients,” Pacific Northwest National Laboratory, April 2022.

18. Submittal of the Approved Version of WCAP-16498-P-A, Revision 0 and WCAP-16498-NP-A, Revision 0, “17x17 Next Generation Fuel (17x17 NGF) Reference Core Report (Proprietary/Non-proprietary),” May 31, 2011 (ADAMS Package Accession No. ML111540488).

19. Letter from J. A. Gresham, Westinghouse, to NRC DCD, “Westinghouse - Submittal of WCAP-16996-P-A/WCAP-16996-NP-A, Volumes I, II, III and Appendices, Revision 1, ‘Realistic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM™ LOCA Methodology),’” LTR-NRC-16-75, November 30, 2016 (ADAMS Accession No. ML16343A232).

20. NRC RG 1.236, Revision 0, “Pressurized-Water Reactor Control Rod Ejection and Boiling-Water Reactor Control Rod Drop Accidents,” June 2020 (ADAMS Accession No. ML20055F490).

21. NRC NUREG-0630, “Cladding Swelling and Rupture Models for LOCA Analysis,” April 1980 (ADAMS Accession No. ML053490337).

22. WCAP-10054-P-A, “Westinghouse Small Break ECCS Evaluation Model Using the NOTRUMP Code,” August 19, 1985 (Non-publicly available, Proprietary).

23. WCAP-10079-P-A, “NOTRUMP A Nodal Transient Small Break and General Network Code,” August 19, 1985 (Non-publicly available, Proprietary).

24. WCAP-10325-P-A, “Westinghouse LOCA Mass and Energy Release Model for Containment Design March 1979 Version,” May 1983 (Non-publicly available, Proprietary).

25. WCAP-17721-P-A, “Westinghouse Containment Analysis Methodology – PWR LOCA Mass and Energy Release Calculation Methodology,” September 2015 (ADAMS Package Accession No. ML15272A050).

26. CENPD-132D, “Calculational Methods for the C-E Large Break LOCA Evaluation Model,” August 8, 1974 (Non-publicly available, Proprietary).

27. CENPD-132D, “Calculational Methods for the C-E Large Break LOCA Evaluation Model,” July 1974 (Non-publicly available, Proprietary).

28. “Acceptance for Referencing of Licensing TR WCAP-8821-P/8859-NP, ‘TRANFLO Steam Generator Code Description’, and WCAP-8822-P/8860-NP, ‘Mass and Energy Release Following a Steam Line Rupture,’” August 22, 1983 (Non-publicly available, Proprietary).

29. WCAP-8822-S1-P-A, “Mass and Energy Releases Following a Steam Line Rupture, Supplement 1 - Calculations of Steam Superheat in Mass/Energy Releases Following a Steam Line Rupture,” September 1986 (Non-publicly available, Proprietary).

30. WCAP-14882-P-A, “RETRAN-02 Modeling and Qualification for Westinghouse Pressurized Water Reactor Non-LOCA Safety Analyses,” April 30, 1999 (Non-publicly available, Proprietary).

31. CE Standard Safety Analysis Report (CESSAR), Appendix 6B, “Description of the SGNIII Digital Computer Code Used in Developing Main Steam Line Break Mass/Energy Release Data for Containment Analysis,” January 1974.

32. CENPD-190-A, “C-E Method for Control Element Assembly Ejection Analysis,” January 31, 1976 (Non-publicly available, Proprietary).

33. CENPD-282-P-A, “Technical Manual for the CENTS Code,” December 1992 (Non-publicly available, Proprietary).

34. WCAP-8762-P-A, “New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids,” July 31, 1984 (Non-publicly available, Proprietary).

35. WCAP-15806-P-A/WCAP-15807-NP-A, “Westinghouse Control Rod Ejection Accident Analysis Methodology Using Multi-Dimensional Kinetics (Proprietary/Non-Proprietary),” November 30, 2003 (ADAMS Package Accession No. ML033350109).

36. WCAP-11397-P-A, “Revised Thermal Design Procedure,” April 1989 (Non-publicly available, Proprietary).

37. WCAP-15025-P-A, “Modified WRB-2 Correlation, WRB-2M, for Predicting Critical Heat Flux in 17x17 Rod Bundles with Modified LPD Mixing Vane Grids,” April 1999 (Non-publicly available, Proprietary).

38. WCAP-16523-P-A, “Westinghouse Correlations WSSV and WSSV-T for Predicting Critical Heat Flux in Rod Bundles with Side-Supported Mixing Vanes,” August 2007 (Non-publicly available, Proprietary).

39. Letter from J. A. Gresham, Westinghouse, to NRC DCD, “Submittal of Approved Version of WCAP-16766-P-A/WCAP-16766-NP-A, ‘Westinghouse Next Generation Correlation (WNG-1) for Predicting Critical Heat Flux in Rod Bundles with Split Vane Mixing Grids (TAC No. 7230) (Proprietary/Non-Proprietary),’” LTR-NRC-10-8, March 2, 2010 (ADAMS Accession No. ML100850530).

40. WCAP-14565-P-A, “VIPRE-01 Modeling and Qualification for Pressurized Water Reactor Non-LOCA Thermal-Hydraulic Safety Analysis,” October 30, 1999 (Non-publicly available, Proprietary).

41. Letter from K. Hosack, Westinghouse, to NRC, “Submittal of WCAP-18240-P-A/ WCAP-18240-NP-A, ‘Westinghouse Thermal Design Procedure (WTDP),’” LTR-NRC-20-29, April 2020 (ADAMS Accession No. ML20104C042).

42. WCAP-10444-P-A, “Westinghouse Reference Core Report Vantage 5 Fuel Assembly,” September 1985 (Non-publicly available, Proprietary).

43. WCAP-16259-P-A, “Westinghouse Methodology for Application of 3-D Transient Neutronics to Non-LOCA Accident Analysis,” August 2006 (Non-publicly available, Proprietary).

44. WCAP-8963-P-A Addendum 1-A, Revision 1-A, “Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis (Departure from Nucleate Boiling Mechanistic Propagation Methodology),” June 2006 (Non-publicly available, Proprietary).

45. NRC Information Notice 2012-09, “Irradiation Effects on Fuel Assembly Spacer Grid Crush Strength,” June 28, 2012 (ADAMS Accession No. ML113470490).

46. PWR Owners Group Transmittal of PWROG-16043-P/NP-A, Revision 2, “PWROG Program to Address NRC Information Notice 2012-09, ‘Irradiation Effects on Fuel Assembly Spacer Grid Crush Strength for Westinghouse and CE PWR Fuel Designs (PA-ASC-1169),’” December 12, 2019 (ADAMS Package Accession No. ML20007E355).

47. WCAP-12610-P-A & CENPD-404-P-A Addendum 2-A, Revision 0, and WCAP-14342-A & CENPD-404-NP-A Addendum 2-A, Revision 0, “Westinghouse Clad Corrosion Model for ZIRLO and Optimized ZIRLO (Proprietary/Non-Proprietary),” October 2013 (ADAMS Package Accession No. ML13308B412).

48. CENPD-188-A, “HERMITE – A Multi-Dimensional Space-Time Kinetics Code for PWR Transients,” Combustion Engineering, July 1976 (ADAMS Accession No. ML22325A282).

Attachment: Resolution of Comments

Principal Contributors: Mathew Panicker, NRR/DSS/SFNB
Joseph Messina, NRR/DSS/SFNB

Date: December 16, 2022

The NRC Staff Resolution of Comments Table Westinghouse Comments on the NRC Draft Safety Evaluation for Westinghouse Topical Report WCAP-18546-P/NP, “Westinghouse AXIOM® Cladding for Use in Pressurized Water Reactor Fuel” (Proprietary/Non-Proprietary)

The table is a record of Westinghouse proprietary markup and comments that Westinghouse provided on the draft SE via letter dated October 21, 2022 (ADAMS Accession No. ML22297A260), and the NRC staff’s response to them. Comment page and line number refer only to the draft SE and will not correspond to the final SE as pages and line numbers have shifted.

Table: Resolution of comments

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
3	31	Suggest adding explanation that “only Fuel Rod Design topical reports” are included.	Acceptable. Clarification added.
6	10	Please mark proprietary as shown below: “… **[** **]** …”	Acceptable. Marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
6	20, 20 - 27	Please remove the closing bracket in line 20 so lines 20-27 are included in the same proprietary marking.	Acceptable. Proprietary marking removed.
7	12 - 19	Please mark proprietary as shown: “This figure shows **[** **]** behavior of the AXIOM samples with the Optimized ZIRLO and ZIRLO samples. As a result, Westinghouse states that the Optimized ZIRLO thermal expansion models in PAD5 **[** **]** for AXIOM. Since there is **[** **]** between the PAD5 Optimized ZIRLO thermal expansion models and the AXIOM data in Figure 3.2-3 of the TR, the NRC staff finds the application of the PAD5 (Ref. 16) Optimized ZIRLO models up to the current licensed temperature of **[** **]** to be acceptable for AXIOM.”	Acceptable. Marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
7	34, 35	Please change "20°C/min (36°F/min)" to "10°C/min (18°F/min)" for consistency with Chapter 3 of the topical report	Acceptable. Change made. The NRC staff noted that "20°C/min (36°F/min)" values are in the RAI response. Westinghouse clarified that correct values are in the Chapter 3 of the TR.
7	46	Please mark proprietary as shown below: "...phase transition temperatures are **[ ]** that of…"	Acceptable. Marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
7	49	Please mark proprietary as shown below: "...the impact of the **[ ]** phase transition temperatures…"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
8	49, 50	Please mark proprietary as shown below: "**[** **]** which are…"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
9	14, 15	Please mark proprietary as shown below: "This change in hardness is **[** **]** This difference..."	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
10	20, 21	Please mark proprietary as shown below: “**[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
10	24, 25	Please mark proprietary as shown below: “Therefore, **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
10	33 - 37	Please mark proprietary as shown below: “... greater than **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
10	41 – 43	Please mark proprietary as shown below: “**[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
11	4 - 5	Please mark proprietary as shown below: “... **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
11	14	Please move the first half prop bracket to include all the highlighted proprietary as shown below: "… conducted **[** **]**"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
11	23-25	Please mark proprietary as shown below: "**[** **]**"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
11	28	For consistency with TR pages 3-17 and 6-19 related to burst testing/modelling descriptions, please mark proprietary as shown below: "… **[** **]** …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
12	5 - 9	Please mark proprietary as shown below: "**[** **]**"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
14	10 - 11	Please mark Figure 3 as proprietary	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
15	17 - 18	Please mark proprietary as shown below. "… a total of **[** **]**"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
15	22	Please remove the prop bracket for "eight"	Acceptable. Proprietary markings removed.
15	30-35	Please change the prop bracket to the following: "… **[** **]** and the subsequent comprehensive hot cell PIE of **[** **]** such rods… electron microscopy images."	Acceptable. Change in proprietary markings made. Proprietary information redacted in the non-proprietary version of the final SE.
17	30-32	Please add prop bracket as shown: "... **[** **]** …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
17	45	Please mark proprietary as shown: "… **[** **]** …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
18	35	Suggest changing "10" to "65" as "… less than 65 percent of the …"	Not acceptable. Proposed change does not add clarity to the technical discussion in Section 3.6.2 of the final SE. Sentence deleted.
18	48	Please remove proprietary brackets around 100 µm	Acceptable. Proprietary markings removed.
19	4-5	Please mark proprietary as shown: "… **[** **]** …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
21	21	Please mark Table 3 proprietary.	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
28	5 - 6	Please mark proprietary as shown: "... pellet-clad gap closure is **[** **]** Optimized ZIRLO as ..."	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
29	34 - 37	Please mark proprietary as shown: "… **[** **]**"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
29	42 - 43	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
29	47 - 50	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
30	9-11	Please mark proprietary as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
30	15-17	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
30	27-28	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
30	40 - 47	Please mark proprietary as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
31	24 - 28	Please mark proprietary as shown: “**[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
31	38-39	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
32	8-13	Please extend proprietary mark to cover all text in lines 11 through 13 as shown: “... **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
32	29-32	Please mark proprietary as shown: “... **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
32	39-42	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
32	44-45	Please extend proprietary marking as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
33	1-3	Please mark proprietary as shown: “... **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
33	8-39	Please extend the staff’s proprietary marking as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	Line No.	Westinghouse Suggested Revision	NRC Resolution
34	1-2	Please add a closing bracket and mark proprietary as shown: "… [ ] …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
34	21	Suggest replacing ", Optimized ZIRLO, and AXIOM claddings" with "and Optimized ZIRLO cladding, and the NOTRUMP" as below: "The test results for ZIRLO and Optimized ZIRLO cladding and the NOTRUMP specific heat model shows…"	Acceptable. Proposed change adds technical clarity. Change made.
34	22	Please mark proprietary as shown: "… [ ] …"	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.

Table: Resolution of comments (Continued)

Pg. No.	**Line No.**	**Westinghouse Suggested Revision**	**NRC Resolution**
35	12-14	Please mark proprietary as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
35	30-31	Please mark proprietary as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
35	36-37	Please mark proprietary as shown: “… **[** **]**”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.
35	39-40	Please mark proprietary as shown: “… **[** **]** …”	Acceptable – marked as proprietary information in the proprietary version and redacted proprietary information in the non-proprietary version of the final SE.