FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT ANP-10340P-A, REVISION 0, SUPPLEMENT 1, REVISION 0

“INCORPORATION OF CHROMIA-DOPED FUEL PROPERTIES IN FRAMATOME PWR METHODS”

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1.0 INTRODUCTION AND BACKGROUND

By letter dated June 28, 2021 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21187A198), as supplemented by letter dated April 11, 2022 (ADAMS Accession No. ML22105A047), Framatome Inc. (Framatome) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval Topical Report (TR) ANP-10340P-A, Revision 0, Supplement 1, Revision 0, “Incorporation of Chromia-Doped Fuel Properties in Framatome PWR [Pressurized Water Reactor] Methods” (Ref. 1). The TR is a supplement to the base approved TR (Ref. 2) for the incorporation of chromia-doped fuel in Framatome approved methods, which dealt only with boiling water reactor (BWR) methodologies. This supplement documents the effects of the use of chromia-doped fuel and its implementation in Framatome PWR methodologies.

During this review, a regulatory audit was conducted (Refs. 3 and 19). After conclusion of the audit, a request for additional information was issued (Ref. 4) and responses were received (Ref. 5).

2.0 REGULATORY EVALUATION

The NRC staff used the guidance in NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” (SRP), Section 4.2, “Fuel System Design,” for the review of ANP-10340P-A, Revision 0, Supplement 1, Revision 0. SRP Section 4.2 acceptance criteria are based on meeting the requirements of General Design Criteria (GDC) 10 of Appendix A of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Reactor Design.” Specifically, GDC 10 establishes specified acceptable fuel design limits that should not be exceeded during any condition of normal operation, including the effects of AOOs.

In accordance with SRP Section 4.2, 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.

The regulation at 10 CFR Part 50, Appendix A, GDC 28, "Reactivity Limits," requires reactivity control systems to be designed with appropriate limits on potential amount and rate of reactivity increase to assure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor coolant pressure boundary greater than local yielding nor (2) sufficiently disturb the core, its support structures, or other reactor pressure vessel internals to impair significantly the capability to cool the core.

In addition, the following paragraphs of 10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," (b) require in part that:

(1) "Peak cladding temperature." The calculated maximum fuel element cladding temperature shall not exceed 2200°F [degrees Fahrenheit].

(2) "Maximum cladding oxidation." The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.

(3) "Maximum hydrogen generation." The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(4) "Coolable geometry." Calculated changes in core geometry shall be such that the core remains amenable to cooling.

3.0 TECHNICAL EVALUATION

The NRC staff reviewed ANP-10340P-A, Revision 0, Supplement 1, Revision 0 to: (1) ensure that the material properties and in-core behavioral characteristics of chromia-doped fuel, as analyzed using the GALILEO and other Framatome PWR methodologies (ARCADIA, ARITA, AREA, and Westinghouse and Combustion Engineering (W&CE) loss-of-coolant accident (LOCA), which are discussed in Section 3.5 of this safety evaluation (SE)), are capable of accurately (or conservatively) ensuring the fuel system safety criteria, (2) identify any limitations on the behavioral characteristics of the additive fuel, and (3) ensure compliance of fuel design criteria with licensing requirements of fuel designs.

3.1 Applicability of Base Topical Report

The subject TR (Ref. 1) is a supplement to the approved base TR, ANP-10340-PA, Revision 0, "Incorporation of Chromia-Doped Fuel Properties in AREVA Approved Methods," May 2018 (Ref. 2), which covers the material properties of chromia-doped fuel along with the implementation of chromia-doped fuel in Framatome approved methods for BWRs. As stated in the base TR, the material properties, behavioral assessment, qualification database, and operating experience are generic for both BWR and PWR applications. The base TR describes the database that is used to qualify the models in GALILEO for chromia-doped fuel. Since Reference 2 was approved, **[[**

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In the subject TR (Ref. 1), Framatome did not repeat the parts of the approved base TR that are applicable to both BWRs and PWRs, and only presented specific changes needed for implementation into the PWR methods. Therefore, this review is focused specifically on the code specific implementation of chromia-doped fuel in the Framatome PWR methodologies. Any items previously approved in the base TR that have not changed when implementing in the PWR methodologies were not reviewed again.

3.2 Impacts of Chromia-Doped Fuel During Accidents

3.2.1 Loss-of-Coolant Accident

The performance of the emergency core cooling system is judged relative to the performance of the reactor fuel under postulated LOCA conditions. The regulations at 10 CFR 50.46 and Appendix K provide analytical requirements and prescriptive limits (2,200 degrees Fahrenheit (°F) peak cladding temperature (PCT) and 17 percent equivalent cladding reacted maximum cladding oxidation) applicable to uranium dioxide (UO_2) fuel pellets within cylindrical zircaloy or ZILRO cladding. These analytical limits preserve a coolable rod bundle array by ensuring adequate post-quench cladding ductility. The introduction of chromia-doped fuel pellets does not directly alter the applicability of the 10 CFR 50.46 analytical requirements and prescriptive limits associated with maintaining adequate cladding ductility; however, changes in fuel properties and performance may alter the accident progression and influence PCT and oxidation calculations.

The fuel properties including thermal conductivity, gaseous swelling, and FGR impacts the fuel rod internal pressures and fuel temperatures and has the potential to influence the LOCA cladding response. **[[**

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A change in fuel thermal conductivity will impact the amount of stored energy in the fuel pellet. Section 4.1, “Material Properties - Thermal Conductivity,” of the TR (Ref. 1) describes the impact of chromia addition on fuel thermal conductivity and Section 5.1, “GALILEO Thermal Conductivity Model for Chromia-doped Fuel,” describes changes in the GALILEO thermal conductivity model. See Section 3.3.1, “Thermal Conductivity,” of this SE for further assessment of fuel thermal conductivity. In general, the addition of chromia **[[**

]] This potential impact is being explicitly addressed in the GALILEO calculated stored energy and initial fuel conditions (input) to the downstream LOCA calculations.

Ceramography data show that larger intragranular bubbles exist in the case of chromia-doped fuel, which corroborates with the observed larger cladding deformation. Standard fuel exhibits very low intragranular gaseous swelling and has not been modelled previously in GALILEO. Section 5.3, “GALILEO Intragranular Gaseous Swelling Model for Chromia-doped Fuel,” of the TR describes the GALILEO Intragranular Gaseous Swelling Model. See Section 3.3.4, “Intragranular Gaseous Swelling,” of this SE for further assessment of gaseous swelling. In general, the larger intragranular bubbles are a consequence of enhanced intragranular gaseous swelling, which in turn contributes to larger pellet deformation and therefore larger cladding deformation. This potential impact is being explicitly addressed in the GALILEO initial fuel conditions (input) to the downstream LOCA calculations.

A change in FGR will impact rod internal pressure which, in turn, will impact the probability of fuel rod ballooning and rupture. Section 5.2, “GALILEO Fission Gas Release Model for Chromia-doped Fuel,” of the TR (Ref. 1) describes the GALILEO FGR model for chromia-doped fuel. Section 3.3.3, “Fission Gas Release,” of this SE describes further assessment of the FGR model. In general, **[[**

]] These potential impacts are being explicitly addressed in the GALILEO fuel conditions which are used in the LOCA methodologies.

Therefore, the NRC staff finds that chromia-doped fuel will behave **[[** **]]** to that of standard fuel during LOCAs and that any impact is explicitly assessed with GALILEO.

3.2.2 Reactivity Initiated Accidents

The regulation at 10 CFR Part 50, Appendix A, GDC 28, “Reactivity Limits,” requires reactivity control systems to be designed with appropriate limits on potential amount and rate of reactivity increase to assure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor coolant pressure boundary greater than local yielding nor (2) sufficiently disturb the core, its support structures, or other reactor pressure vessel internals to impair significantly the capability to cool the core. For PWRs, Regulatory Guide (RG) 1.236, “Pressurized-Water Reactor Control Rod Ejection and Boiling-Water Reactor Control Rod Drop Accidents,” identifies the postulated control rod ejection accident (CREA) as the limiting reactivity initiated accident. In addition, RG 1.236 provides fuel cladding thresholds for fuel rod cladding failure and allowable limits on radiological dose, reactor coolant system (RCS) pressure, and core coolability. With the exception of radiological dose, these thresholds and allowable limits are addressed by the AREA methodology (Ref. 6).

Framatome stated that the chromia doping of the fuel **[[**
]] As discussed in the TR as well as the base TR (Ref. 2), test results and code calculations have indicated that specific heat, enthalpy, thermal conductivity, and fuel pellet cracking **[[** **]]**

Framatome states that any interaction between chromia-doped fuel and fission products may alter the amount or chemical species released during a design basis accident or a severe accident. However, the presence of chromia in the fuel **[[**
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Framatome states that the chromia-doped fuel is not expected to have a significant impact on the maximum RCS pressure. This is due to the fact that the reactor coolant pressure calculation is based on heat transfer from the fuel. While there are minor differences expected in the pin powers and local flow conditions for a core with chromia-doped fuel, the overall heat transfer would be expected to remain essentially the same as that with standard undoped fuel.
[[
]] The inclusion of chromia-doped fuel in the reactor design has no impact on the RG 1.236 reactor coolant pressure allowable limit. In addition, the reactor coolant pressure allowable limit is specifically addressed as part of the AREA methodology (Ref. 6).

As discussed in Section 4.2, “Behavioral Assessment – Fuel Melting,” of the TR (Ref. 1), the melting point of chromia-doped fuel was found to be **[[** **]]** than standard UO_2 fuel.

Framatome states that the limited amount of chromia in the fuel does not result in a significantly different radial average fuel enthalpy threshold for incipient melting verses standard UO_2 fuel.

Based on test results and code calculations, Framatome found that **[[** **]]** In addition, the AREA methodology (Ref. 6) includes the chromia-doped properties, and therefore, any change to the average fuel enthalpy threshold for incipient melting is explicitly addressed, which confirms that the coolability criterion is not violated.

Test data and code calculations have shown that **[[** **]]**

The NRC staff reviewed the test data for fuel specific heat, thermal conductivity, and fuel melting as well as code calculations provided in both the TR (Ref. 1) and base TR (Ref. 2) and finds that the inclusion of chromia-doped fuel in the fuel assemblies does not violate or alter the limits established by RG 1.236 used as a basis to evaluate a postulated CREA with chromia-doped fuel and is therefore acceptable.

3.3 Qualification of GALILEO for Chromia-Doped Fuel

GALILEO is Framatome’s best-estimate fuel rod performance code approved for PWR fuel design and licensing analyses with standard UO_2 and gadolinia-bearing UO_2. The GALILEO code models the thermal-mechanical behavior of the fuel rods during normal operation and transient scenarios. The following sections detail changes made to GALILEO to accommodate the properties and behavior of chromia-doped fuel.

3.3.1 Thermal Conductivity

Fuel thermal conductivity is essential to the modeling of both steady state and transient phenomena, as it directly impacts fuel temperature and stored energy. Higher thermal conductivity results in lower fuel temperatures and less stored energy in the fuel.

As described in Section 4.5, “Thermal Conductivity,” of the base TR (Ref. 2), Framatome conducted two in-house thermal diffusivity measurement campaigns, one each in 2006 and 2015. In both cases Framatome also sent a sub-set of samples to the Joint Research Center-Institute for Transuranium Elements (JRC-ITU) for confirmation and complementary measurements. **[[** **]]**

After thermal diffusivity values are obtained, the thermal conductivity is calculated as a function of diffusivity, density, and specific heat.

As stated by Framatome in the TR (Ref. 1), GALILEO’s thermal conductivity model consists of **[[**

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Based on the conclusion from the base TR (Ref. 2), **[[**

]] The final adjusted model parameters of the chromia-doped thermal conductivity are presented in Equations 5-1 to 5-6 of the TR (Ref. 1). During the regulatory audit, the NRC staff asked how the coefficients in the new term (Equation 5-6) were determined. Framatome responded that the new term was fine-tuned to envelope all chromia-doped data **[[**
]] Figures 5-1, “Chromia-doped GALILEO Model against 2006 Campaign Data,” and 5-2, “Chromia-doped GALILEO Model against 2015 Campaign Data,” of the TR (Ref. 1) show good agreement with the test data from both the 2006 and 2015 campaigns.

One of the conclusions from the base TR (Ref. 2) is **[[**

]]however,**[[**
]] This will result in GALILEO computing a different thermal conductivity for chromia-doped gadolinia fuel than gadolinia fuel without the chromium. During the regulatory audit, the NRC staff asked Framatome why **[[**
]] Framatome responded that **[[**

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Framatome subsequently provided confirmation (Ref. 5) that the concentration of gadolinia will always be **[[**
]] Framatome stated that their low leakage fuel management requires the power of the fresh fuel assemblies be depressed, which is achieved by their usage of gadolinia fuel. In addition, gadolinia as a burnable absorber is used to reduce core excess reactivity (boron concentration) and the power mismatch between the assemblies of successive reloads, which becomes more important when the goal is to increase fuel burnup and cycle length. Given that very low levels of gadolinia concentration are essentially not effective for power distribution control, the GALILEO methodology (Ref. 7) has only an upper limit and is approved for gadolinia concentrations of **[[** **]]**. Framatome also states that the Framatome Richland manufacturing facility is qualified to fabricate gadolinia pellets with gadolinia concentration ranging from **[[** **]]**. In about 30 years of history of PWR neutronics cycle design using gadolinia in the United States, the minimum gadolinia concentration used has been **[[** **]]**.

Standard UO_2 fuel experiences degradation of thermal conductivity with increased burnup. To validate that this effect is also present in chromia-doped fuel, Framatome benchmarked GALILEO to the REMORA2 test, where a pellet centerline temperature was measured online using thermocouples after achieving **[[** **]]** In Ref. 5, Framatome stated that the main purpose of the REMORA2 test was to provide experimental results for the global validation of thermal behavior models for chromia-doped fuel with a high burnup through online measurement of the fuel pellet central temperature, and to study the FGR during the power transient for chromia-doped fuel at high burnup. In addition, the post-irradiation examinations also recorded gas components, fuel density, and microstructure from ceramography examinations. Framatome provided some details on the test rod dimensions and described **[[** **]]** Framatome agreed with NRC staff that the test does not validate thermal conductivity directly and that the REMORA2 test is an integral test that demonstrates the validity of the thermal models, including fuel thermal conductivity. During the regulatory audit, the NRC staff examined the calculation notebook for the REMORA2 benchmark. As seen in Figure 5-3, "Calculated and Measured Temperatures in the REMORA2 Test," of the subject TR (Ref. 1), GALILEO demonstrates good agreement over the whole range of test powers and **[[** **]]** as shown in Figure 4-2, "Predicted vs. Measured Fuel Centerline Temperature (Validation Database)," of Reference 7.

Framatome validated the applicability of the standard fuel thermal conductivity uncertainty on the chromia-doped fuel using the approach as described in Section 5.4.5, "Transient Model Uncertainties," of Reference 7. The uncertainty was confirmed for the chromia-doped UO_2 model over the whole range of measured fuel centerline temperatures from the REMORA2 experiment. As shown in Figure 5-4, "Calculated and Measured Temperatures Using Lower Bound FTC Uncertainty," of the TR (Ref. 1), **[[** **]]**

Given the experimental measurements and satisfactory benchmarking of GALILEO, the NRC staff finds Framatome's thermal conductivity models for chromia-doped fuel and chromia-doped $(U\text{-}Gd)O_2$ in GALILEO to be acceptable.

3.3.2 Fuel Melting

Framatome has previously measured the melting point of standard UO_2, chromia-doped UO_2, and chromia-doped $(U\text{-}Gd)O_2$ fuel using laser heating and fast multi-channel pyrometry at the JRC-ITU as described in detail in Section 5.2, "Fuel Melting," of the base TR (Ref. 2). Framatome found that the fuel melting temperature of chromia-doped UO_2 is **[[** **]]** in comparison to standard UO_2 fuel and that **[[** **]]**

The standard UO_2 fuel melting temperature in GALILEO **[[** **]]** In Reference 5, Framatome stated that **[[**

]] In the base TR (Ref. 2), the same **[[** **]]** was applied, however, the RODEX4 methodology uses a constant melting temperature that is not burnup dependent where the constant value reflects the minimum over the anticipated burnup range. Therefore, using a **[[** **]]** over all burnup values is consistent with the base TR (Ref. 2).

Section 8.2.1, “ARITA Methodology,” of the TR (Ref. 1) states “In addition, **[[**

]] Section 4.2.4.7.1, “Criteria for FCM and TCS,” of Reference 9 shows the **[[** **]]** uncertainty in the equation for UO_2 melt temperature, however, Equation 4-2 in the TR (Ref. 1) does not include this value as it is the best estimate fuel melt temperature and the lower bound is applied as part of ARITA.

When implementing in GALILEO, Framatome used Equation 4-2 in the TR where the chromia-doped UO_2 melting point is **[[** **]]** from the non-doped UO_2 melting point. By **[[** **]]**, GALILEO is appropriately capturing the results from the JRC-ITU experiments, therefore, the NRC staff finds this acceptable. **[[** **]]** which is consistent with the experimental data, therefore, the NRC staff finds this acceptable.

3.3.3 Fission Gas Release

Framatome states that chromia-doped fuel is similar to standard fuel with an enlarged grain microstructure and the same phenomenological FGR model is applicable to both fuel types. **[[**

]] as described in Section 3.3.3.3, “FGR Processes,” of Reference 7. In this model, **[[**

]]

However, Framatome notes that **[[**

]] In order to adjust to the experimental results, Framatome implemented the **[[** **]]** Framatome used **[[** **]]** During the regulatory audit, Framatome confirmed that the value is best-estimate and used in the predictions shown in Figure 5-5, “Fission Gas Release Predicted and Measured for Chromia-Doped Database,” of the TR (Ref. 1). In addition, Framatome used **[[** **]]**

To validate the FGR model in GALILEO, Framatome compared code results to the experimental database. **[[**

]] The best estimate results, shown in Figures 5-5, “Fission Gas Release Predicted and Measured for Chromia-Doped Database,” and 5-6, “Burnup Trend of FGR for Chromia-doped UO_2,” of the TR (Ref. 1), show good agreement. Framatome validated the applicability of the standard fuel diffusion coefficient uncertainty for FGR on the chromia-doped fuel. As shown in Figure 5-7, “Predicted vs. Measured FGR – Upper Bound,” of the TR (Ref. 1), **[[**

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As discussed in Framatome document FS1-0049110, “GALILEO Fission Gas Release of Cr-doped Fuel Calibration and Validation,” Revision 1.0, July 27, 2020, there is **[[**

]] This document states **[[**

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Framatome explained (Ref. 5) that in principle, the phenomena controlling the release of fission gas in chromia-doped UO_2 and chromia-doped UO_2-Gd_2O_3 fuel are the same as the standard UO_2 fuel. In the base TR (Ref. 2), **[[**

]] In addition, Framatome **[[**

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Framatome described the changes to the base UO_2 FGR model as follows:

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In Table 8-1, “Maximum Rod Internal Pressure Results,” of the subject TR (Ref. 1), an example of the maximum rod internal pressure analysis is shown for UO_2 and chromia-doped UO_2. The example shows that the maximum pressure for a chromia-doped rod design is **[[** **]]** and the pressure licensing criterion is **[[** **]]**; thus, the available margin is **[[ ]]**. In Reference 5, Framatome performed the same calculations for a chromia-doped UO_2-Gd_2O_3 rod and obtained a maximum pressure of **[[ ]]**. In addition, when going from chromia-doped UO_2 to chromia-doped UO_2-Gd_2O_3, the FGR **[[ ]]** These changes in pressure and FGR are noticeably lower in the chromia-doped UO_2-Gd_2O_3 rods than for chromia-doped UO_2 rods. For rods containing gadolinia, the poison suppresses power early in life while the enrichment reduction limits power late in life. The lower power results in **[[ ]]** Given the lower power of the rods containing gadolinia, Framatome states that it is **[[ ]]**.

To further demonstrate the chromia-doped UO_2-Gd_2O_3 FGR model, Framatome performed a comparative analysis against standard (non-doped) UO_2-Gd_2O_3 fuel as discussed in Reference 5. The analysis is based on a **[[ ]]** This is a reasonable scenario where a **[[ ]]** Since the purpose of the analysis is to compare FGR and rod internal pressure between chromia-doped UO_2-Gd_2O_3 fuel and standard (non-doped) UO_2-Gd_2O_3 fuel, the only difference between the standard (non-doped) and chromia-doped fuel is the **[[ ]]** The results of this comparison showed the **[[ ]]** Based on the larger grain size in the chromia-doped fuel, and all other properties identical, the FGR reduction is expected. The pressure **[[ ]]** in the chromia-doped fuel due to the addition of the intragranular gaseous swelling model for chromia-doped fuel. Framatome states that **[[ ]]** for the standard UO_2-Gd_2O_3 fuel (as seen in Figures 4-10, "UO_2 and Gadolinia Transient FGR Calibration," and 4-11, "UO_2 and Gadolinia Steady-State FGR (Validation Database)," of Ref. 7) and that given the mechanism of FGR is the same for these types of fuel, it is expected that the FGR model for chromia-doped UO_2-Gd_2O_3 fuel would also have similar conservatism. The comparison demonstrates that GALILEO predicts **[[ ]]**

FGR measurements are used to calibrate and validate fuel models and quantify the uncertainty on these model predictions. Given the **[[ ]]** the NRC staff is including the following limitation and condition:

- Fuel licensing application of chromia-doped UO_2-Gd_2O_3 fuel is acceptable **[[ ]]** This limitation can be removed after sufficient FGR measurement data for chromia-doped UO_2-Gd_2O_3 fuel are available and the validity of the FGR model for chromia-doped UO_2-Gd_2O_3 is confirmed by NRC.

With **[[ ]]** Given the results from the Framatome calculations for UO_2-Gd_2O_3 and chromia-doped UO_2-Gd_2O_3, as described in Reference 5, there is significant margin to the rod internal pressure limitation for rods containing gadolinia. The **[[** **]]** compensates for any concern in FGR and rod internal pressure calculations and ensures that this issue remains low safety significance given rods containing gadolinia are not expected to be limiting.

Given the use of experimental measurements and satisfactory benchmarking of GALILEO, the NRC staff finds Framatome's FGR model for chromia-doped UO_2 with **[[** **]]** to be acceptable. In addition, the NRC staff finds the changes to the FGR model for chromia-doped UO_2-Gd_2O_3 suitable for use **[[**

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3.3.4 Intragranular Gaseous Swelling

In standard UO_2, fission gases collect and may form bubbles along the grain boundary, known as intergranular bubbles. As chromia-doped fuel has larger grains and enhanced creep and plasticity it has a propensity for forming intragranular bubbles instead, as the gases collect inside the grain instead of along the grain boundary. These bubbles lead to increased fuel pellet and cladding deformation, especially following a power ramp. Standard fuel exhibits very low intragranular gaseous swelling, so this phenomenon has not been modelled previously in GALILEO.

To accurately capture this phenomenon for chromia-doped fuel, Framatome added an intragranular swelling model to GALILEO. This model, which is described in detail in Section 7.3, "RODEX4 Intragranular Gaseous Swelling Model for Chromia-doped Fuel," of the base TR (Ref. 2), was modified with a new calibration over that from the base TR. During the regulatory audit, the NRC staff asked Framatome for details on the new calibration and why it was necessary. Framatome responded that because the FGR model is different in RODEX4, the model parameters f_{ig} and C_{gig} in the intragranular swelling model were varied to arrive at an appropriate prediction of transient cladding strain as shown in the best-estimate benchmark result in Figure 5-8, "Clad Diameter Change Predicted vs. Measured for Chromia-doped Database," of the TR (Ref. 1). The TR states "Figure 5-8 confirms that the addition of the intragranular gaseous swelling model conservatively predicts the diameter change during power ramps and outward creep for chromia-doped fuel. Therefore, the transient cladding strain prediction will be conservative."

Framatome stated (Ref. 5) that Figure 5-8 in the subject TR (Ref. 1) is a "best-estimate" comparison, and that it shows **[[** **]]** Framatome stated that **[[**

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Comparison between Figure 5-8 in the subject TR (Ref. 1) and Figures 4-25, "Rod Diameter Change for Pellets with L/D Ratio less than 1.4," through 4-30, "UO_2-Gd_2O_3 Ramps - Calculated vs. Measured Rod Diameter Increase," in Reference 7 show that the scattering band for the chromia-doped fuel is like that for standard fuel. In addition, Framatome provided Figures 4-2, "Clad Diameter Change Predicted vs. Measured - Upper Bound with Rod Q09_03," and 4-3, "Clad Diameter Change Predicted vs. Measured - Upper Bound," in Reference 5 which show the predicted versus measured clad diameter change using the upper bound model with and without inclusion of data from a ramp rod test labeled Q09_3. Framatome states that **[[**

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The upper bound model includes use of the following uncertainties: **[[**

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3.3.5 Rod Free Volume and Internal Pressure

The prediction of rod internal pressure is directly linked to the rod free volume along with the predictions for FGR and fuel temperatures and is dependent on the collective effects from other thermal and mechanical models. Framatome performed calculations to compare rod free volume and internal pressure to the available data. The validation database of free volume and rod internal pressure is a subset of the FGR database. The results for rod free volume, shown in Figures 5-11, “Predicted vs. Measured Free Volumes for Chromia-doped UO_2,” and 5-12, “Burnup Trend of Free Volume for Chromia-doped UO_2,” of the TR (Ref. 1), show good agreement and **[[** **]]**. The results for internal pressure, shown in Figures 5-13, “Predicted vs. Measured Internal Pressure for Chromia-doped UO_2,” and 5-14, “Burnup Trend of Internal Pressure for Chromia-doped UO_2,” of the TR (Ref. 1), also show good agreement and no bias versus burnup. The code predictions versus measured data for both rod free volume and internal pressure for chromia-doped fuel show similar agreement to that of standard fuel as seen in Figures 4-47, “Measured and Predicted Free Volumes for UO_2 and Gadolinia Fuel,” and 4-49, “Measured and Predicted Internal Pressure for UO_2 and Gadolinia Fuel,” of Reference 7. Therefore, based on the comparisons to experimental data, the NRC staff finds that rod free volume and internal pressure for chromia-doped UO_2 are adequately predicted in GALILEO.

3.4 Qualification of Rod Growth to Chromia-Doped Fuel

As a general fuel design requirement, the fundamental mechanical and hydraulic functions of a fuel assembly shall not be impaired due to irradiation growth of the fuel rods. In particular, the fuel assembly shall give sufficient space for differential rod growth to occur without it becoming restrictive. The clearance between the fuel rod top ends and the top nozzle is known as the shoulder gap.

As described in Section 11.2, "Fuel Rod Axial Growth," of Reference 10, an upper bound fuel rod axial growth model was defined from over **[[**

]] To address applicability of this data set to chromia-doped fuel, Framatome stated (Ref. 5) that the database of $M5_{Framatome}$ fuel rod axial growth contains **[[** **]]** from fuel rods with chromia-doped fuel. The measurements include three different fuel designs: **[[**

]] There are no measurements with chromia-doped gadolinia fuel rods, however, Framatome states that gadolinia rods are non-limiting with respect to fuel rod axial growth due to their reduced power during operation and lower discharge burnup. Figure 5-1, "Axial Growth of Chromia-Doped Fuel Rods," of Reference 5 shows the chromia-doped fuel rod axial growth measurements relative to the upper bound and best estimate fuel rod axial growth models. The best estimate model provides accurate predictions of the nominal axial growth, and the upper bound model over predicts a significant percentage of the chromia-doped measurements. For those fuel types used in the US, the upper bound model **[[**

]] When the AFA-3G fuel, which is not used in the US, is included, the upper bound model overpredicts **[[** **]]** of the measurements from chromia-doped fuel. Framatome stated that the upper bound fuel rod axial growth model is specific to $M5_{Framatome}$ cladding, and therefore, chromia-doped fuel for PWR applications will only use $M5_{Framatome}$ cladding.

Given that the upper bound fuel rod axial growth model overpredicts **[[** **]]** of the measurements from US fuel designs (GAIA and HTP) with chromia-doped fuel, the NRC staff finds this model acceptable for use with chromia-doped fuel.

3.5 Qualification of Framatome Methodologies to Chromia-Doped Fuel

Framatome states that chromia-doped fuel will be analyzed with the ARCADIA, ARITA, AREA, and W&CE LOCA methodologies as described in the associated TRs. Framatome does not plan to make any revisions to the existing NRC-approved TRs to specifically list chromia-doped fuel as an approved fuel material. This approach is being used as any operating PWR plant that would implement chromia-doped fuel would need to incorporate the subject TR (Ref. 1) into their licensing basis using an appropriate licensing change process. The NRC staff finds this approach acceptable.

3.5.1 ARCADIA Methodology

As described in Reference 8, ARCADIA is a code package that was developed for worldwide application and provides a converged code system for neutronic and thermal-hydraulic core design and safety evaluation. The main components of the ARCADIA system are the spectral/lattice code APOLLO2-A and the core simulator ARTEMIS. APOLLO2-A is a state-of-the-art lattice physics code that features several high-level physics enhancements and requires fewer approximations compared to the previous generation of lattice physics codes. The core simulator ARTEMIS is a 3D nodal multigroup reactor burnup code with pin power reconstruction for PWRs.

As stated by Framatome, the ability to model chromia-doped fuel is primarily dependent upon the accuracy of the cross-section data. The chromium data are part of the standard cross section libraries validated with APOLLO2-A and approved in the ARCADIA TR. During the regulatory audit, the NRC staff requested the licensee provide the reference to where the standard cross section libraries, including chromium, were approved. Framatome responded that the cross-section information for chromium is included in the nuclear data library JEFF3.1.1 used by APOLLO2-A and the data is processed by HERMES and used by the ARTEMIS neutronic solver. Framatome stated that this library was approved implicitly as part of the ARCADIA TR (Ref. 8). Framatome found that no changes are required to the approved neutronics codes or methodologies (Refs. 8 and 11).

Given that the effect of chromium on core reactivity has already been quantified through inclusion of chromium in the cross-section libraries, NRC staff finds that no changes are required to the approved neutronics codes or methodologies (Refs. 8 and 11) for chromia-doped fuel.

3.5.2 AREA Methodology

As described in Reference 6, the AREA methodology is used for the evaluation of a CREA in a PWR. The methodology is used to demonstrate compliance with the acceptance criteria specified in NUREG-0800, Section 4.2. The methodology makes use of several codes and methods. The ARCADIA code system is used to analyze the three-dimensional neutronics and thermal-hydraulics behavior during the transient. The GALILEO code provides the thermal-mechanical properties of the fuel pins. The S-RELAP5 code is used to model the RCS response for W&CE plants and the RELAP5/MOD2-B&W code is used for Babcock & Wilcox plants. The methodology provides compliance with the regulatory criteria for energy deposition, fuel rim melt, fuel centerline melt, minimum departure from nucleate boiling ratio (MDNBR), and RCS pressure response.

During the regulatory audit, the NRC staff questioned Framatome about any changes made to S-RELAP5 and RELAP5/MOD2-B&W. Framatome responded that the only updates to the S-RELAP5 code are the incorporation of the chromia-doped GALILEO adaptations into the GALILEO module within S-RELAP5. As part of the regulatory audit, the NRC staff reviewed the S-RELAP5 code changes to the GALILEO module and found it consistent with the changes to GALILEO described in the TR. In Reference 5, Framatome stated **[[**

]]

Framatome performed an analysis with an AREA Evaluation Model which included chromia-doped fuel that indicates **[[** **]]** The results of the AREA analysis are described in more detail in Section 3.6.2.2, “Control Rod Ejection Accident,” of this SE. The Framatome results confirmed that all margins are preserved in a core design based on chromia-doped fuel and demonstrate the AREA methodology is not challenged by the inclusion of chromia-doped fuel in a core design.

As part of the AREA methodology, GALILEO is used to define the fuel thermal properties and fuel rod internal pressure. The NRC staff reviewed the use of GALILEO in the AREA methodology and finds that the inclusion of chromia-doped fuel properties and other model changes (i.e., FGR and intragranular gaseous swelling models) in GALILEO do not alter the overall workflow of the methodology. The revised GALILEO code w/chromia-doped modifications continues to interact with the ARCADIA and S-RELAP5 codes in the same manner, therefore, the NRC staff finds that the AREA methodology is acceptable for use with chromia-doped fuel.

3.5.3 ARTEMIS/RELAP Integrated Transient Analysis (ARITA) Methodology

As described in Reference 9, the ARITA methodology is intended to analyze the non-LOCA events defined in Chapter 15 of the SRP (with the exception of the control rod ejection event) using a statistical approach. In this methodology, S-RELAP5 is used for the system thermal-hydraulic analysis, ARTEMIS is used for core analysis, and GALILEO is used for thermal-mechanical analysis. The methodology allows running S-RELAP5 and ARTEMIS, either independently or in a coupled fashion, depending on the non-LOCA event being considered.

Framatome states that the ARITA methodology is not affected by the inclusion of chromia-doped fuel as the thermal conditions are dependent on pin powers and local flow conditions. It is expected that **[[** **]]** During the regulatory audit, the NRC staff asked Framatome if the slight differences in **[[** **]]** are explicitly considered, or if they are assumed small and ignored. Framatome responded that the transient analysis considers the explicit representation of chromia-doped fuel with no approximations.

Framatome performed an analysis with the ARITA methodology for an uncontrolled bank withdrawal (UCBW). The results of the ARITA analysis are described in more detail in Section 3.6.2.1, “Uncontrolled Bank Withdrawal,” of this SE. Framatome found that **[[** **]]** and that use of the ARITA methodology will be exercised or dispositioned as part of the reload analysis process when deploying core designs that include chromia-doped fuel. During the regulatory audit, the NRC staff asked Framatome what criteria would be used to determine if the ARITA methodology will be exercised or dispositioned during the reload analysis process. Framatome responded that the methodology will be exercised in its fullness during the first reload designed with chromia-doped fuel, however, subsequent reloads will assess the effect of chromia with respect to the previous cycle. Framatome stated that there is no change to the reload process analysis or the methodologies that will be used to analyze chromia-doped fuel and that Section 11, “Disposition of Event Process,” of the ARITA TR (Ref. 9 (not approved yet)) defines the disposition process.

As part of the ARITA methodology, GALILEO is used for fuel thermal-mechanical analysis to compute fuel centerline melt and transient clad strain. The NRC staff reviewed the use of GALILEO in the ARITA methodology and finds that the inclusion of chromia-doped fuel properties and other model changes (i.e., FGR and intragranular gaseous swelling models) and in GALILEO do not alter the overall workflow of the methodology. The revised GALILEO code w/chromia-doped modifications continues to interact with the ARTEMIS and S-RELAP5 codes in the same manner, therefore, the NRC staff finds that the ARITA methodology is acceptable for use with chromia-doped fuel, provided the ARITA methodology (Ref. 9) is approved for use with the base GALILEO code (Ref. 7).

3.5.4 W&CE LOCA Methodology

Framatome's LOCA methodology is described in References 12 through 15. The small-break LOCA (SBLOCA) evaluation model uses a deterministic approach based on the requirements of 10 CFR Part 50, Appendix K, to determine the expected PCT, maximum local oxidation (MLO), and core-wide oxidation (CWO) response. The realistic large-break LOCA (RLBLOCA) EM uses a best-estimate approach based on statistical sampling of uncertainty contributors and propagation of uncertainty to determine the expected PCT, MLO, and total CWO response. The RLBLOCA EM is patterned after the Code Scaling, Applicability, and Uncertainty (CSAU) methodology and follows the recommendations of RG 1.203, "Transient and Accident Analysis Methods," Evaluation Model Development and Assessment Process (EMDAP).

The LOCA methodologies in References 12 through 15 discuss using either RODEX2 or COPERNIC as the fuel performance code, while Reference 16 implements the GALILEO fuel performance code into S-RELAP5 for use as part of the Framatome LOCA methodologies.

Framatome states that the chromia-doped fuel specific physical models and material properties are supplied by GALILEO and the implementation of these model adaptations will not change the current fuel rod analysis workflow or basic model capabilities of the current W&CE LOCA EMs. The S-RELAP5 code remains the thermal-hydraulic system code and no changes are made to the general capabilities of the code in terms of systems, components, phases, geometries, fields, and processes modeled. As discussed above in Section 3.5.2 of this SE, the only updates to the S-RELAP5 code are to incorporate the chromia-doped GALILEO adaptations into the GALILEO module within S-RELAP5.

Framatome performed a review of the SBLOCA and RLBLOCA EMs, as supplemented by GALILEO, with respect to chromia-doped fuel pellet properties and identified **[[**

]] This review also identified the important fuel-related LOCA phenomena that could potentially be affected by chromia-doped properties, including **[[**

]]

The NRC staff has examined the results of the LOCA calculations and find they are consistent with the expected changes using chromia-doped fuel. For the SBLOCA, the use of chromia-doped fuel resulted in **[[**

]] Therefore, the NRC staff finds that the Framatome LOCA methodology from Reference 16, using the revised GALILEO code with chromia-doped updates along with the S-RELAP5 code, is acceptable for use with chromia-doped fuel.

3.6 Licensing Criteria Assessment

Framatome performed sample design analyses for chromia-doped fuel. The results of those analyses were compared to standard fuel analyses to evaluate the impacts of the chromia dopant. These examples were examined in greater detail at the regulatory audit conducted by the NRC staff. No discrepancies were discovered.

3.6.1 Fuel Rod Thermal-Mechanical Evaluation

Framatome performed an analysis with GALILEO using the chromia-doped model options on a CE 14x14 fuel design with $\text{M5}_{\text{Framatome}}$ cladding. The sample calculations examined rod internal pressure, cladding collapse, and cladding fatigue. For rod internal pressure, the example analyses show that **[[** **]]** This is primarily because **[[** **]]** While the **[[** **]]** the results show there is significant margin to the limiting value as defined by the GALILEO methodology (Ref. 7).

Cladding collapse was historically observed due to high levels of densification of fuel pellets, which left gaps in the fuel column into which the cladding could ovalize and collapse. Current fuel designs have greatly reduced the likelihood of cladding collapse through the use of pressurized fuel rods and fuel pellets with high initial density and low in-reactor densification, thereby preventing the occurrence of gaps large enough to permit clad collapse. **[[** **]]** For cladding collapse, the CROV creep collapse analysis code was used in addition to GALILEO. The CROV methodology was limited to B&W Fuel Company cladding as described in Section 1.2, “Limits,” of Reference 17. During the regulatory audit, the NRC staff asked Framatome why this methodology is applicable to $\text{M5}_{\text{Framatome}}$ cladding. Framatome responded that the CROV methodology was approved in Reference 18 to be applicable to $\text{M5}_{\text{Framatome}}$. Section 3.7, “Fuel Rod Cladding Creep Collapse,” of Reference 18 states “Since the creep rate of M5 is considerably slower than the standard **[[** **]]** the creep collapse life of an M5 fuel rods is much greater than the standard rods and is not limiting at burnups up to 62 GWd/mtU.” Reference 10, Section 10.3 states **[[**

]]

The CROV methodology defines three criteria for cladding collapse as follows:

- **[[**
-
-
]]

The results from the Framatome analyses show the **[[** **]]** with the chromia-doped fuel as expected.

For the cladding fatigue analysis, Framatome performed transient calculations with GALILEO using the methodology defined in Appendix C, “Fuel Rod Fatigue Initialization,” of Reference 7. The GALILEO results are then used to calculate the cumulative usage factor (CUF) using the methodology described in Section 10.5, “Fuel Rod Fatigue,” of Reference 10. The CUF design limit for $\text{M5}_{\text{Framatome}}$ cladding is **[[** **]]**. The results of the analysis show that standard (non-doped) fuel has a **[[** **]]** CUF than chromia-doped fuel. Framatome states that this is because fatigue usage is driven by the magnitude of stress fluctuations (i.e., stress amplitude), and not the magnitude of stress at any given moment. For the sample analyses, Framatome explains that the majority of fatigue usage comes from **[[** **]]**

Given that the cladding fatigue is primarily driven by events with **[[** **]]** the sample analyses confirmed that the chromia-doped fuel is **[[** **]]** than standard fuel.

The NRC staff has examined the results of the fuel rod thermal-mechanical evaluation presented in the TR, as well as the detailed calculations made available at the regulatory audit. The NRC staff finds the results acceptable, as they demonstrate expected behavior of Cr-doped fuel including **[[** **]]**

3.6.2 Safety Analyses

Framatome performed calculations of AOOs and postulated accidents to demonstrate the methodologies work with the chromia-doped fuel. These sample analyses detail the results of comparisons between standard fuel and chromia-doped fuel using the ARITA methodology from Reference 9, a CREA using the AREA methodology in Reference 6, and a LOCA using the methodology in Reference 16.

3.6.2.1 Uncontrolled Bank Withdrawal

For a sample analysis using the ARITA methodology, Framatome selected an UCBW from part-power initial conditions (AOO transient). The analysis is based on a 4-loop Westinghouse plant with a 17x17 fuel assembly design. Specified acceptable fuel design limits considered for the UCBW include fuel centerline temperature, transient cladding strain, and departure from nucleate boiling (DNB).

The results for fuel centerline temperature, as shown in Table 8-4, “Fuel Centerline Temperature Comparison,” of the TR (Ref. 1), show that the chromia-doped fuel has **[[** **]]** The analysis for the chromia-doped fuel assumes the fuel melting temperature is **[[** **]]** In addition, both standard fuel and chromia-doped fuel take into account the **[[** **]]** when computing margin to the melting temperature.

The results for transient cladding strain, as shown in Table 8-5, “Transient Cladding Strain in AOO Comparison,” of the TR (Ref. 1), show that the chromia-doped fuel has a **[[** **]]** as expected.

The DNB calculations are performed with the COBRA-FLX thermal-hydraulic code module used by ARTEMIS. Given that the critical heat flux correlations implemented inside COBRA-FLX are not dependent on fuel pellet type or properties, Framatome states that the ability to use COBRA-FLX to calculate DNB will not be challenged by the inclusion of chromia in the fuel design. The DNB calculations are mainly dependent on water properties, local geometry, and local heat flux within the assembly. The local heat flux is dependent on the pin powers and local flow conditions. **[[**

]] However, Framatome states that the DNB evaluation will be performed for chromia-doped fuel as part of the reload analysis process.

The NRC staff has examined the results of the UCBW evaluation presented in the TR (Ref. 1), as well as the detailed calculations made available at the regulatory audit. The NRC staff finds the results acceptable, as they demonstrate expected behavior for chromia-doped fuel, including **[[** **]]**

3.6.2.2 Control Rod Ejection Accident

As described above in Section 3.5.2, "AREA Methodology," of this SE, the AREA methodology is used for the evaluation of a CREA in a PWR. The methodology is used to demonstrate compliance with the acceptance criteria specified in NUREG-0800, Section 4.2. For the CREA sample analyses, Framatome used the Westinghouse 4-loop plant described in Appendix A of Reference 6 and made modifications to include chromia-doped fuel. The results were then compared with the results from the sample problem in Appendix A of Reference 6.

Framatome provided an assessment of the limiting case for each of the limiting criteria presented in Table A-7 of Reference 6. The results for a core containing chromia-doped fuel is summarized in Table 8-6, "W 4-Loop, Measure of Conservatism for Limiting Result Cases," of the TR (Ref. 1). For each of the CREA limiting criteria, the power level, cycle burnup, **[[**

]] are provided.

Framatome provided a comparison between the conservatisms of the standard fuel (Table A-7 of Ref. 6) and chromia-doped fuel as presented in Table 8-7 of the TR (Ref. 1). The results of this comparison show that **[[**
]] and that there is ample conservatism for each criterion.

The comparisons provided by Framatome for the CREA analyses show that the margin to the criteria for a core design with chromia-doped pellets is **[[** **]]** with respect to a core design with standard fuel. The maximum observed change in margin is **[[**
]] as presented in Table 8-7 of the TR (Ref. 1).

The NRC staff has examined the results of the CREA evaluation presented in the TR, as well as the detailed calculations made available at the regulatory audit. The NRC staff finds the results acceptable, as they demonstrate expected behavior for chromia-doped fuel including **[[**

]]

3.6.2.3 Loss-of-Coolant Accident

For the LOCA, Framatome performed sample analyses representative of a Westinghouse 4-loop PWR plant. The sample problem calculations are similar to those presented in the LOCA methods with GALILEO (Ref. 16) and compare results from standard fuel with chromia-doped fuel.

For the small break LOCA analyses, Framatome performed **[[** **]]** as required by the SBLOCA methodology. Framatome found that the limiting case for both fuel types resulted in **[[** **]]** Therefore, Framatome concludes that the results demonstrate that the SBLOCA EM changes with chromia-doped fuel have **[[** **]]** on the results of the analyses.

For the large break LOCA, Framatome performed **[[** **]]** as required by the RLBLOCA methodology. As described above in Section 3.5.4 of this SE, the RLBLOCA EM uses a best-estimate approach based on statistical sampling of uncertainty contributors and propagation of uncertainty to determine the expected PCT, MLO, and total CWO response. Given the statistical sampling of parameters and phenomena, **[[** **]]** Framatome found that the results for the **[[** **]]** The results for PCT, MLO, and CWO are shown in Table 8-9 of the TR (Ref. 1) and demonstrate that the RLBLOCA EM changes with chromia-doped fuel have **[[** **]]** on the results of the analyses.

The NRC staff has examined the results of the LOCA evaluations presented in the TR. The NRC staff finds the results acceptable, as they are in line with expectations for the changes introduced by the chromia-doped fuel.

3.6.3 Impact on Nuclear Design Requirements

Framatome states that the observations made in Section 9.3 of the approved base TR (Ref. 2) remain valid and applicable to analyses of PWRs, except that the APOLLO2-A code with corresponding cross section libraries is used in place of the CASMO-4 lattice code that is used for BWR analyses. Framatome further states that no other changes to existing neutronics codes or methodologies will be required.

Given that the chromium cross sections are already included in the nuclear data library as part of the APOLLO2-A code, the addition of chromia to the fuel will require no changes to existing neutronics codes or methodologies. Therefore, the NRC staff finds that any impact of chromia addition on core physics predictions is explicitly accounted for in the APOLLO2-A code.

3.6.4 Fuel Design Criteria

Section 4.2 of the SRP discusses the acceptance criteria needed for fuel system damage, fuel rod failure, and fuel coolability in order to meet the requirements of GDC 10. Framatome stated that there is no change to cladding materials, structural materials, or fuel assembly design with the use of chromia-doped fuel. When modeling chromia-doped fuel versus standard fuel, the significant changes needed are in the physical properties of the fuel pellets. Table 3-1 of the TR provides a list of the individual criteria from Section 4.2 of the SRP along with the Framatome assessment of how each criterion is affected by use of chromia-doped fuel. Framatome found that, with the few exceptions noted below, the methodologies used to evaluate each criterion are not affected by the use of chromia-doped fuel. Based on the unique properties of the chromia-doped fuel pellets, the margin to a given acceptance criterion may be affected, however, Framatome provided sample analysis to demonstrate that the acceptance criteria are met with the use of chromia-doped fuel. NRC staff reviewed Table 3-1 of the TR and finds that Framatome appropriately categorized each item related to any required methodology changes. As an example, one of the fuel system damage criteria is rod internal pressure. The methodology used to compute the rod internal pressure does not change depending on the fuel type. What is changed are the physical properties of the selected fuel type. In this example, described in Section 8.1.1 of the TR and Section 3.6.1 of this SE, using the same methodology, the **[[**

]] This is the expected result as **[[**

]]

Changes to the methodologies include **[[**

]] These changes are reviewed above in Sections 3.3.3, 3.3.4 and 3.4 of this SE and were all found to be acceptable to the staff.

Overall, NRC staff finds that the Framatome methodologies used to determine if the acceptance criteria of SRP Section 4.2 are met are acceptable for use with chromia-doped fuel and meet the requirements of GDC 10 related to specified acceptable fuel design limits.

4.0 LIMITATIONS AND CONDITIONS

Consistent with the final SE of the approved base TR (Section 4.0 of Ref. 2), the usage of chromia-doped fuel in PWR methods is subject to the same limitations and conditions (1 through 3 below). In addition, one new limitation has been added.

1. The limitation imposed on grain size of standard fuel in Reference 7 is unchanged. GALILEO is approved for **[[** **]]**

2. Chromia-doped fuel is limited to a rod average burnup limit of **[[** **]]**

3. Chromia concentration is limited to the range of **[[** **]]** The limit also applies to chromia-doped gadolinia fuel.

4. Fuel licensing application of chromia-doped UO_2-Gd_2O_3 fuel is acceptable up to a rod average burnup of **[[** **]]**

5.0 CONCLUSIONS

Framatome has presented data and analyses to support their request for approval of chromia-doped UO_2 fuel for use in PWRs, where the dopant is within the range **[[** **]]** Material property changes have been implemented in both the GALILEO thermal-mechanical fuel performance code and other Framatome PWR analysis methodologies as necessary. The impact of the chromia dopant on in-reactor fuel performance (such as reactivity initiated accident behavior, LOCA behavior, and FGR) has been adequately analyzed.

The NRC staff concludes that thermal-mechanical performance of the proposed chromia-doped fuel in PWRs is adequately addressed in the Framatome submittal with the application of the GALILEO fuel performance code. **[[**

]]

The NRC staff's SE of chromia-doped fuel is subject to the limitations and conditions listed in Section 4.0.

6.0 REFERENCES

1. ANP-10340P-A, Revision 0, Supplement 1, Revision 0, "Incorporation of Chromia-Doped Fuel Properties in Framatome PWR Methods," Framatome, Inc., June 2021 (ADAMS Package Accession No. ML21187A202)

2. ANP-10340P-A Revision 0, "Incorporation of Chromia-Doped Fuel Properties in AREVA Approved Methods," June 2018 (ADAMS Package Accession No. ML18171A107)

3. Letter from D. Morey (NRC) to G. Peters (Framatome), "November 18 and December 7, 2021, Regulatory Audit Plan for Framatome Inc. Topical Report, ANP-10340P, Revision 0, Supplement 1, Revision 0, "Incorporation of Chromia-Doped Fuel Properties in Framatome PWR Methods" (EPID L-2021-TOP-0015), November 5, 2021 (ADAMS Package Accession No. ML21302A116)

4. Letter from N. Otto (NRC) to G. Peters (Framatome Inc.), "Request for Additional Information Regarding Framatome Topical Report, ANP-10340P, Revision 0, Supplement 1, Revision 0, "Incorporation of Chromia-Doped Fuel Properties in Framatome PWR Methods" (EPID L-2021-TOP-0015)," December 16, 2021 (ADAMS Package Accession No. ML21349A908)

5. Framatome Inc. submittal of "Response to Request for Additional Information Regarding ANP-10340, Revision 0, Supplement 1P, Revision 0 "Incorporation of Chromia-doped Fuel Properties in Framatome PWR Methods," April 11, 2022 (ADAMS Package Accession No. ML22105A049)

6. ANP-10338P-A, Revision 0, "AREA™ - ARCADIA® Rod Ejection Accident," February 2018 (ADAMS Package Accession No. ML18059A753)

7. ANP-10323P-A, Revision 1, "GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors," December 2020 (ADAMS Package Accession No. ML21005A028)

8. ANP-10297P-A, Revision 0, "The ARCADIA® Reactor Analysis System for PWRs Methodology Description and Benchmarking Results," February 2013 (ADAMS Package Accession No. ML14195A145)

9. ANP-10339P, Revision 0, "ARITA - ARTEMIS/RELAP Integrated Transient Analysis Methodology," August 2018 (ADAMS Package Accession No. ML18242A480)

10. BAW-10227P-A, Revision 2, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," January 2023 (ADAMS Package Accession No. ML23037A928)

11. ANP-10297P-A, Revision 0, Supplement 1PA, Revision 1, "The ARCADIA Reactor Analysis System for PWRs Methodology Description and Benchmarking Results," December 2020 (ADAMS Package Accession No. ML21071A062)

12. EMF-2328P-A, Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," March 2001 (ADAMS Package Accession No. ML011410426)

13. EMF-2328P-A, Revision 0, Supplement 1(P)(A), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," December 2016 (ADAMS Package Accession No. ML16356A396)

14. BAW-10240P-A, Revision 0, "Incorporation of M5 Properties in Framatome ANP Approved Methods," August 2004 (ADAMS Accession No. ML042800308)

15. EMF-2103P-A, Revision 3, "Realistic Large Break LOCA Methodology for Pressurized Water Reactors," September 2016 (ADAMS Package Accession No. ML16286A579)

16. ANP-10349P-A, Revision 0, "GALILEO Implementation in LOCA Methods," December 2021 (ADAMS Package Accession No. ML21354A136)

17. BAW-10084P-A, Revision 3, "Program to Determine In-Reactor Performance of BWFC Fuel Cladding Creep Collapse," April 1995 (ADAMS Package Accession No. ML20086N796)

18. BAW-10227P-A, Revision 1, "Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel," June 2003 (ADAMS Package Accession No. ML15162B043)

19. Audit Report for Framatome Topical Report ANP, 10340P, Revision 0, Supplement 1, Revision 0, "Incorporation of Chromia-Doped Fuel Properties in Framatome PWR Methods" (ADAMS Package Accession No. ML22129A158)

Principal Contributors: Robert Beaton, Adam Rau

Date: October 16, 2023

Summary Table for Comments on Framatome TR ANP-10340P, Revision 0, Supplement 1, Revision 0 "Incorporation of Chromia-Doped Fuel Properties in Framatome PWR Methods," Draft Safety Evaluation

#	Page/Line	SE Text	Comment	Proposed Change	NRC Staff Response
1	p.3, lines 38-39	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
2	p.4, lines 8-11	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
3	p.4, line 14	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
4	p.6, line 19	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
5	p.6, lines 27-28	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
6	p.6, lines 30-32	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
7	p.6, lines 32-34	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.

#	Page/Line	SE Text	Comment	Proposed Change	NRC Staff Response
8	p.9, line 7	chromia-doped Fuel Calibration…	Corrected for actual title	Cr-doped Fuel Calibration…	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
9	p.9, lines 7-8	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
10	p.10, line 21	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
11	p.10, line 23	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
12	p.10, lines 35-36	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
13	p.10, lines 39-40	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
14	p.10, lines 44-45	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
15	p.10, line 48	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.

#	Page/Line	SE Text	Comment	Proposed Change	NRC Staff Response
16	p.11, lines 4-5	As marked with highlight and bracketed in the draft SE markup	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
17	p. 16, lines 24-26	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
18	p.17, line 11	**[[ ]]**	In Reference 18, the response to RAI 15 changed the creep rate multiplier to **[[ ]]**. See the first paragraph on page I-57 (p. 292 of 572 in PDF).	**[[ ]]**	The NRC staff accepts the proposed change and have incorporated in the final SE.
19	p.17, line 12		Reference 18 is revised with Reference 10, which is intended to be used with this methodology. Please add reference 10 wording. Alternatively, the reference 10 wording could replace the Reference 18 wording in its entirety, and Reference 18 could be deleted, since it is not referenced in the topical report or in this safety evaluation in any other location.	Added text: Reference 10, Section 10.3 states "**[[ ]]**".	The NRC staff accepts the proposed change and have incorporated in the final SE.
20	p.17, line 31	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
21	p. 17, lines 48-49	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.

#	Page/Line	SE Text	Comment	Proposed Change	NRC Staff Response
22	p.18, lines 17-18	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
23	p.18, line 42	…behavior for Cr-doped fuel,	changed for consistency in text	…behavior for chromia-doped fuel,	The NRC staff accepts the proposed change and have incorporated in the final SE.
24	p.18, line 43	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
25	p.19, lines 29-31	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
26	p.20, line 34	Table 3 1 of the TR…	typo - "-" missing	Table 3-1 of the TR…	The NRC staff accepts the proposed change and have incorporated in the final SE.
27	p.20, line 41	NRC staff reviewed Table 3 1	typo - "-" missing	NRC staff reviewed Table 3-1.	The NRC staff accepts the proposed change and have incorporated in the final SE.
28	p.20, line 50	...conductivity of chromia-doped fuel,	extraneous comma	...conductivity of chromia-doped fuel and	NRC staff accepts the proposed change and have incorporated in the final SE.
29	p.21, lines 2-3	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
30	p.21, lines 27-28	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	NRC staff partially accepts the proposed proprietary markings and have incorporated in the final SE.

#	Page/Line	SE Text	Comment	Proposed Change	NRC Staff Response
31	p.21, lines 42-46	As marked with highlight and bracketed in the draft SE markup.	Proprietary material	As marked with highlight and bracketed in the draft SE markup	The NRC staff accepts the proposed proprietary markings and have incorporated in the final SE.
32	Reference [2]	ANP-10340-PA		ANP-10340P-A,	The NRC staff accepts the proposed change and have incorporated in the final SE.
33	Reference [2]	June 2018		May 2018	The NRC staff will leave as is.
34	Reference [6], [7]			Insert blank line.	The NRC staff accepts the proposed change and have incorporated in the final SE.
35	Reference [10]	BAW-10227P		BAW-10227P-A	The NRC staff accepts the proposed change and have incorporated in the final SE.
36	Reference [10]	December 2019		January 2023	The NRC staff accepts the proposed change and have incorporated in the final SE.
37	Reference [10]	ML20003E125	Replace with -A prop ML#	New prop ML #	The NRC staff accepts the proposed change and have incorporated in the final SE.