FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10247PA, REVISION 0, SUPPLEMENT 1P, REVISION 0,

"REALISTIC THERMAL-MECHANICAL FUEL ROD METHODOLOGY FOR BOILING WATER REACTORS SUPPLEMENT 1: QUALIFICATION OF RODEX4 FOR RECRYSTALLIZED ZIRCALOY-2 CLADDING"

AREVA INC.

(CAC NO. MF5421)

1.0 INTRODUCTION AND BACKGROUND

By letter dated December 22, 2009, AREVA NP, Inc., (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review Topical Report (TR), BAW-10247PA, Revision 0, Supplement 1P, Revision 0, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors Supplement 1: Qualification of RODEX4 for Recrystallized Zircaloy-2 Cladding" in Reference 1. Supplemental information was received by the NRC staff in Reference 2. The NRC provided request for additional information (RAI) questions regarding this TR in Reference 3. The responses to RAI questions 2 through 12 were received by the NRC staff in Reference 4. The response to RAI question 1 was submitted to the NRC in Reference 5. The response to RAI question 13 and a correction to the response to RAI question 1 were received by the NRC in Reference 6.

By letter dated February 8, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML16351A486), an NRC draft safety evaluation (SE) regarding our approval of TR BAW-10247PA, Revision 0, Supplement 1P, Revision 0, was provided for your review and comment. By letter dated March 13, 2017 (ADAMS Accession No. ML17075A325), AREVA provided comments on the draft SE. The NRC staff's disposition of the AREVA comments on the draft SE is discussed in the attachment.

The submitted TR (Reference 1) is an extension to the NRC-approved TR BAW-10247PA, Revision 0 (Reference 7).

The TR only describes the qualification of the RODEX4 computer code for licensing analyses using fuel rods with recrystallized (RX) Zircaloy-2 cladding and a new hydrogen pickup model to be applied to both cold-worked, stress-relieved (CWSR), and RX Zircaloy-2 cladding. The TR also covers:

- Thermal creep and recalibration for RX Zircaloy-2
- Irradiation creep and recalibration for RX Zircaloy-2
- Irradiation growth and recalibration for RX Zircaloy-2

Enclosure

- Model parameter uncertainty evaluation for RX Zircaloy-2 thermal and irradiation creep models
- Calibration of the RX Zircaloy-2 cladding corrosion model and evaluation of its associated model parameter uncertainty
- Validation of the recalibration of the RX Zircaloy-2 mechanical models by benchmarking the free (void) volume database

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC staff in this review. As a result of the NRC staff's and PNNL's consultant review of the TR, the supporting theory manual (Reference 8), and validation report (Reference 9), an RAI was sent by the NRC to AREVA (Reference 3). AREVA provided a response to the RAI questions (References 4, 5, and 6). A second round of RAI questions was sent to AREVA (Reference 24) and AREVA provided a response (Reference 6). PNNL provided a technical evaluation report (Reference 25).

This safety evaluation (SE) addresses the following major areas of the application of the RODEX4 code to RX Zircaloy-2 cladding;

- Material property updates for RX Zircaloy-2 (Section 3.1)
- Application of approved CWSR Zircaloy-2 properties to RX Zircaloy-2 (Section 3.2)
- Rod void volume assessment (Section 3.3)
- The impact of using RX cladding on approved licensing applications (Section 3.4).

Models from the NRC audit code, FRAPCON (Reference 10), have been used as an aid in this review to assess the models and calculation results from RODEX4. This code has recently been assessed against a large volume of low and high burnup fuel performance data (Reference 11).

2.0 <u>REGULATORY EVALUATION</u>

The NRC staff used the guidance of Standard Review Plan (SRP), NUREG-0800, Section 4.2 (Reference 16), "Fuel System Design" for the review of BAW-10247PA, Revision 0, Supplement 1P, Revision 0 (References 1). 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.

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 (SAFDLs) 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.

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 NRC staff reviewed the TR to: (1) ensure that the material properties and in-core behavioral characteristics of fuel and cladding as analyzed using the supplement and supported by confirmatory calculations using the FRAPCON audit code are capable of accurately (or conservatively) ensuring the fuel system safety criteria, (2) identify any limitations on the behavioral characteristics of the fuel, and (3) ensure compliance of fuel design criteria with licensing requirements of fuel designs and is capable of ensuring compliance with SRP Section 4.2 guidance criteria

3.0 TECHNICAL EVALUATION

3.1 MATERIAL PROPERTY UPDATES FOR RX CLADDING

The purpose of the TR is to extend applicability of the approved RODEX4 boiling water reactor (BWR) realistic methodology (Reference 7) to allow analyses with RX Zircaloy-2 cladding. The BAW-10247PA, Revision 0, final SE restricts application to only CWSR Zircaloy-2 cladding (Condition c.). This restriction was imposed since the NRC staff determined that the experimental dataset for irradiation growth and creep of RX Zircaloy-2 cladding was insufficient and more data would be needed in order to assure an adequate verification and validation of the mechanical properties of RX Zircaloy-2 material. In order to overcome this restriction, AREVA has expanded the RX Zircaloy-2 database based on operating experience with the RX Zircaloy-2 cladding type in Europe for many years.

The expanded RX Zircaloy-2 database was used to recalibrate several of the cladding models. These models are:

- Thermal and irradiation creep
- Free-stress irradiation growth
- Corrosion

The following sections will assess these models and their associated uncertainties relative to those models for RX Zircaloy-2 in FRAPCON and relative to the data provided by AREVA.

3.1.1 Thermal and Irradiation Creep

The NRC staff asked AREVA in RAI-3 to provide more details regarding the type of measurements that were made that were used to validate the thermal and irradiation creep models. AREVA provided new coefficients for their cladding creep model for use with RX Zircaloy-2 cladding. Responding to NRC staff's RAI-3, AREVA stated that the thermal creep component "is partly based on mechanical tests," which were performed in a hot cell on samples taken from fuel rods pre-irradiated in a commercial reactor. Other model parameters of thermal creep derived from non-fueled tubes taken from as-manufactured cladding. Irradiation creep measurements are obtained by profilometry measurements of fuel rods at poolside.

AREVA provided updated fitting parameters for the thermal and irradiation creep models, which are the same models as those approved for CWSR, although several parameters are different. Certain parameters were not provided and some parameters were provided twice with different value on each instance. The NRC staff asked AREVA to provide the parameters H_2, H_3, and H_4. The NRC staff also asked that AREVA clarify which values of H_6 and H_7 are used in RODEX4 (RAI-2).

AREVA responded that the creep coefficients H_2, H_3, and H_4 do not change (and thus were not provided in the TR), and are independent of metallurgical state, i.e., CWSR or RX (RAI-2b). On the other hand, H_5 has been changed to **[ ]**, and H_6 (**[ ]**) and H_7 (**[ ]**) were provided on Page 13 as opposed to intermediate values on Page 11 of the TR. AREVA states that the new model fits more modern data for RXA Zircaloy-2 whereas the old model had been used to fit some older Babcock & Wilcox Company (B&W) RXA data (RAI-2c).

The Hill's parameters R and P are different for RXA cladding than for CWSR, and AREVA provided updated R and P parameters from those provided in EMF-2994 (Reference 8) and EMF-3014 (Reference 9). The older values for R and P were determined based on RXA Zircaloy-4 cladding that was produced by B&W. That cladding is not representative of AREVA RXA Zircaloy-2 cladding. Furthermore, AREVA has determined that P is a function of fast fluence (Reference 12) and the function is described as decaying exponential, which saturates by a fluence of 6 E21 n/cm^2 (E greater than (>) 1 MeV). AREVA indicates that RX cladding becomes less anisotropic or more isotropic with irradiation, an observation which is supported in the literature (Reference 13).

With respect to irradiation creep, AREVA clarified that parameters L_2 and L_4 do not change and are provided in the RODEX4 Theory Manual (EMF-2994(P)). The value L_1 has changed from **[ ]** (old) to **[ ]** (new), which provides better agreement with measured irradiation creep (RAI-2d).

The thermal creep model parameters for CWSR and RX Zircaloy-2 are compared in Table 1, and the irradiation creep model parameters are compared in Table 2. The parameter P is given by a decaying exponential.

Table 1. Comparison of AREVA Cladding Thermal Creep Model Parameters

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Table 2. Comparison of AREVA Cladding Irradiation Creep Model Parameters

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In Figure 1, AREVA shows good agreement between the RX Zircaloy-2 thermal creep model and measurements for long-term creep tests up to the 10,000 hours with as-manufactured cladding at low stresses of 80, 100, and 120 megapascals (MPa). Comparisons were also made between the FRAPCON creep model for RX cladding and the RODEX4 creep model for RX cladding, and the two model predictions were found to be in reasonable agreement.

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Figure 1: Comparison of predicted to measured creep hoop strains during long-term creep tests of as-manufactured RX Zicaloy-2 cladding. (Taken from Reference 1)

AREVA provided plots of creep strain for RX Zircaloy-2 similar to those provided for CWSR Zircaloy-2 in Section 7 of in RODEX4 Theory Manual (EMF-2994(P)) (RAI-2e). The plots show that the creep rate of RX cladding is much greater than that of CWSR Zircaloy-2 cladding at high stresses. This is consistent with observations reported by Limbäck and Anderson (Reference 14).

The NRC staff requested that AREVA compare its updated RX Zircaloy-2 creep model to other known creep experiments in RAI-4. AREVA provided these comparisons that demonstrated that its model is in reasonable agreement with the measurements from these experiments.

AREVA used the same methodology as previously approved for RODEX4 to determine upper and lower bound uncertainties on the thermal and irradiation creep model parameters, L_1 and H_1. L_1 is **[ ]** for the lower bound and **[ ]** for the upper bound. H_1 is **[ ]** for the lower bound and **[ ]** for the upper bound. The NRC staff asked AREVA to provide more justification for these upper and lower bounds in RAI-5b. AREVA provided more discussion on how this was done and provided plot to demonstrate that the upper and lower bound models provide a 95/95 upper and lower bound relative to those data.

The NRC staff finds the creep models and the upper bound and lower bound uncertainties to be acceptable for modeling RXA Zircaloy-2 cladding with RODEX4.

3.1.2 Free Stress Irradiation Growth

The RODEX4 has one axial growth model that is a function of cladding temperature and fast fluence with different sets of coefficients. There are two sets of coefficients approved for CWSR Zircaloy-2 in BWR 9x9 and 10x10 fuel designs. This supplement presented a third set for RX Zircaloy-2 cladding.

The rod growth models for RX Zircaloy-2 cladding were compared against the model in FRAPCON for RX Zircaloy-2. The FRAPCON model for RX Zircaloy-2 cladding is based on the EPRI model (Reference 15) and is validated up to a local burnup of 65 gigawatt days per metric ton of uranium (GWd/MTU). The original comparison showed significant disagreement between the FRAPCON and RODEX4 models. The NRC staff asked AREVA to verify that the model parameters provided are correct (RAI-9a).

AREVA responded with a new growth model for RX Zircaloy-2 (RAI-9). AREVA states that they modified the stress-free irradiation growth model and added a model to reflect the liner effect on the axial pellet/cladding mechanical interaction (PCMI). The new model for RX Zircaloy-2 is based on RXA channel material (BAW-10247Q3(P)). PNNL compared the results of the new model and the original model to FRAPCON and these are shown in Figure 2.

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Figure 2: Fuel rod axial growth in RODEX4 and FRAPCON for BWR RX Zircaloy-2.

The NRC staff noted that is it difficult to assess the calculations of the RX Zircaloy-2 model relative to the data provided in Figure 9 of the TR, with respect to the separate effects of stress-free growth and PCMI. AREVA provided a revised figure showing calculated and measured growth of RX clad fuel rods (RAI-9), which shows greater values of growth for fluences above **[ ]**. The NRC staff requested that AREVA provide a plot of predicted minus measured axial strain as a function of fast fluence. AREVA responded with a plot of P-M for growth (RAI-9b) shown in Figure 3. The plot shows that the model tends to underestimate growth for fluence below **[ ]**, and overestimate for fluences **[ ]**. The plot of P-M for growth is consistent with the plot of the axial growth data in Figure 4.

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Figure 3: Predicted-Measured Axial Strain for AREVA BWR fuel as a function of fast fluence.

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Figure 4: AREVA plot of fuel rod axial growth calculated with RODEX4 and compared to measured growth data.

The NRC staff asked AREVA about the impact of spacer spring loads and friction on the growth of fuel rods. AREVA responded that the impact of grid interaction is minimal, and concluded that, "the main effect on cladding axial elongation is due to the plenum spring and not to spacers. (RAI-9c).

The NRC staff concludes that the RODEX4 model for RX Zircaloy-2 cladding growth is acceptable.

3.1.3 Corrosion

The uniform oxidation rate in RODEX4 for a BWR is a two-stage model that is a function of both time (exposure), a corrosion enhancement factor (depends on reactor and chemistry) and temperature at the metal-oxide interface, and therefore, linear heat generation rate (LHGR). It is recognized that both nodular corrosion and diffusion-controlled uniform corrosion occur on BWR cladding. Nodular corrosion is treated as athermal, and the diffusion-controlled corrosion is temperature-driven. RODEX4 does not have a nodular corrosion model. The uniform two-stage corrosion model includes a pre-transition model and a post transition model with the transition temperature a function of the metal-oxide interface temperature. AREVA stated that the RX database on cladding corrosion is more conservative than the CWSR database because only maximum values are recorded for RX cladding and some of the data come from plants that exhibit nodular corrosion.

In order to model the RX cladding, AREVA uses a **[**

] (Reference 1). The BWR oxidation model in FRAPCON-3, that is based on the EPRI-ESCORE model, and in turn is based on correlations of BWR data, was compared to the oxidation models in RODEX4 for CWSR and RX Zircaloy-2. The results of this comparison are shown in Figure 5 for typical BWR 10x10 conditions at a constant power of 7 kilowatt (kW) per foot. It can be seen in this figure that the RODEX4 RX Zircaloy-2 model predicts about the same as FRAPCON. Also shown in this figure are the 95/95 upper bound predictions from RODEX4 (RX) and FRAPCON. It can be seen that the RODEX4 upper bound is greater than the FRAPCON upper bound for high oxide predictions. This will lead to a similar temperature change across the cladding, and similar temperature predictions relative to FRAPCON.

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Figure 5: Oxide layer thickness predictions in RODEX4 CWSR and RX Zircaloy-2 and FRAPCON-3 for standard BWR 10x10 conditions with no crud buildup.

The NRC staff requested that AREVA provide corrosion data with the corresponding temperature and other relevant conditions in RAI-1A. AREVA provided oxide thickness measurement data and corresponding calculated oxide thicknesses for **[ ]** fuel rods. Figure 6 plots the calculated values versus the measured values, and Figure 7 plots calculated minus measured (C-M) versus the measured value. There seems to be a slight bias towards underestimating the oxide thickness based on the uniform corrosion model, and this is more apparent in Figure 7 in which the C-M decreases as the measured oxide thickness increases. AREVA has indicated that the measured values will include some crud and nodular corrosion, so it is important to consider this on a plant-specific basis.

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Figure 6: Calculated versus Measured Oxide Thickness

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Figure 7: Calculated minus Measured Oxide Thickness versus Measured Oxide Thickness

AREVA also presented upper and lower bound values of the oxidation enhancement model parameter that can be used to provide a 95/95 upper or lower bound predictions of RX Zircaloy-2 corrosion. The NRC staff determined that the upper bound parameter only bounded about [ ] of the data in the RX corrosion dataset. AREVA stated, “Plant conditions create some variability in measured liftoff due to differences in water chemistry. Also, crud deposition can lead to apparent differences in the AREVA liftoff measurements because normal levels of crud are not easily separable from the total liftoff. Therefore, the corrosion enhancement parameter and associated uncertainties may need to be updated as more liftoff data are acquired for different plants or changed water chemistry conditions. AREVA will resubmit updated corrosion parameters in the event the values exhibit a significant general change (i.e., the upper and lower bounds change by more than one standard deviation). Otherwise, updated corrosion parameters will be used as needed for plant-specific application in order to provide the same or greater level of conservatism in the methodology” (Reference 1).

The NRC staff accepts that some of the variation in liftoff is likely due to crud and nodular corrosion.

The NRC staff finds the RODEX4 uniform corrosion model and the upper bound uncertainty to be satisfactory for RX Zircaloy-2. AREVA should account for crud and nodular corrosion on a plant specific basis.

3.2 APPLICATION OF APPROVED CWSR MATERIAL PROPERTIES FOR RX CLADDING

3.2.1 Density

RODEX4 uses the same density correlation for CWSR and RX Zircaloy-2 cladding. This is the same approach that is used in FRAPCON. The NRC staff does not expect the density of the Zircaloy-2 to change based on the final heat treatment.

The NRC staff finds that the use of the approved CWSR Zircaloy-2 density correlation for RX Zircaloy-2 is acceptable.

3.2.2 Thermal Expansion

RODEX4 uses the same thermal expansion for CWSR and RX Zircaloy-2 cladding. This is the same approach that is used in FRAPCON. The NRC staff does not expect the thermal expansion of the Zircaloy-2 to change based on the final heat treatment.

The NRC staff finds that the use of the approved CWSR Zircaloy-2 thermal expansion correlation for RX Zircaloy-2 is acceptable.

3.2.3 Heat Capacity

RODEX4 uses the same heat capacity correlation for CWSR and RX Zircaloy-2 cladding. This is the same approach that is used in FRAPCON. The NRC staff does not expect the heat capacity of the Zircaloy-2 to change based on the final heat treatment.

The NRC staff finds that the use of the approved CWSR Zircaloy-2 heat capacity correlation for RX Zircaloy-2 is acceptable.

3.2.4 Elastic Moduli

AREVA uses the MATPRO equation for Young's Modulus (E) and Shear Modulus (G), but does not include any terms for fast fluence or oxygen concentration. The effect of fast fluence causes the moduli to increase somewhat. The NRC staff previously determined that this correlation was acceptable for CWSR Zircaloy-2, and also finds that it is acceptable for RX Zircaloy-2.

3.2.5 Thermal Conductivity

RODEX4 uses the same thermal conductivity correlation for CWSR and RX Zircaloy-2 cladding. This is the same approach that is used in FRAPCON. The NRC staff does not expect the thermal conductivity of the Zircaloy-2 to change based on the final heat treatment.

The NRC staff finds that the use of the approved CWSR Zircaloy-2 thermal conductivity correlation for RX Zircaloy-2 is acceptable.

3.2.6 Oxide Conductivity

RODEX4 uses the same oxide thermal conductivity correlation for CWSR and RX Zircaloy-2 cladding. This is the same approach that is used in FRAPCON. The NRC staff does not expect the oxide thermal conductivity of the Zircaloy-2 to change based on the final heat treatment of the cladding.

The NRC staff finds that the use of the approved CWSR Zircaloy-2 oxide thermal conductivity correlation for RX Zircaloy-2 is acceptable.

3.2.7 Hydrogen Pickup

RODEX4 has previously used a constant hydrogen pickup fraction of **[** **]** for CWSR and RX Zircaloy-2 under BWR conditions. Recent data suggests that pickup fraction in BWRs increases significantly with burnup and can exceed a 30 percent pickup fraction at high burnups (greater than 50 GWd/MTU) (References 16, 17, 18, and 19). The NRC staff notes that it is known that hydrogen content impacts the cladding ductility and therefore, the threshold for failure during AOOs and certain postulated accidents, e.g., Reactivity-Initiated Accidents (RIAs). It was also noted that due to these effects, in the future the NRC may impose a limit on hydrogen uptake to avoid brittle cladding failure for normal operation and AOOs to maintain the 1 percent total (elastic + plastic) failure strain limit. In addition, new limits on RIAs and loss-Of-coolant accidents (LOCAs) will require that hydrogen effects be accounted for on embrittlement criteria.

During the review of RODEX4 TR (Reference 7), the NRC did not approve the use of the hydrogen pickup model. AREVA submitted Supplement 1 without addressing hydrogen pickup, therefore, the NRC staff asked AREVA if a hydrogen pickup model would be used in RAI-1b.

AREVA responded with a new model that uses a power dependent hydrogen pick-up rate (RAI-1b). In the new model, the hydrogen pickup fraction is determined to be a function of **[** **]**. AREVA presents four fuel rod evaluations comparing the calculated hydrogen content with measured values. This model is shown in Figure 8.

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Figure 8: AREVA hydrogen pickup model

AREVA has published examples of the new model (References 12 and 20). Two case studies are provided, one with low hydrogen content (149 parts per million (ppm)) and one with high hydrogen content (436 ppm). Both cases are taken from European BWR fuel operating for 6 annual cycles for 2018 and 2001 days of operation, respectively, so they encompass an equivalent operation of three 24-month cycles in the US. AREVA provides the local linear power for the axial location from where the hydrogen measurements were made. The low hydrogen location operated above 20 kW per meter (kW/m) for four cycles, and moderate linear powers in the range of 13 to 15.5 kW/m during the fifth and sixth cycles. In contrast, the high hydrogen case operated for three cycles with a local LHGR > 15 kW/m, but with very lower power, approximately 5 to 6 kW/m during last three cycles.

In the TR, AREVA provided additional evidence to support the power dependence of hydrogen pickup in Zircaloy-2. In addition to the two previously published cases, AREVA provided two additional cases, one of low hydrogen pickup, and one with high hydrogen pickup.

Some additional circumstantial evidence suggesting a power dependence on hydrogen pickup is also found in other published work (References 21, 22, and 23). A dramatic increase in hydrogen content is observed in 7 and 9 cycles for Asea Brown Boveri BWR with LK3 cladding. The local LHGRs were in the range of 5 to 9 kW/m for Cycle 7 and increased during Cycles 8 (8-12 kW/m) and 9 (8-15 kW/m), depending on axial location (Reference 21). Additional data are needed to confirm a power dependency. Japanese 9x9 BWR fuel has been observed to have an increase in hydrogen content with burnup, particularly during the last cycle (References 22 and 23). During the first four cycles, the local LHGR was typically greater than 17 kW/m, while during the fifth and last cycle, the local LHGR was generally less than 15 kW/m (Reference 23). Nevertheless, the experience of other fuel suppliers tends to support AREVA's model.

The NRC staff concludes that the hydrogen pickup model in RODEX4 is acceptable for CWSR or RX Zircaloy-2 cladding and may be used for analyses where hydrogen content is required.

3.3 ROD VOID VOLUME ASSESSMENT

The rod growth model has a significant impact on the calculation of the rod void volume. As noted in Section 3.1.2 of this SE, a new rod growth model was presented for RX Zircaloy-2. This section will assess the predictions of RODEX4 void volume for RX cladding.

The void volume in RODEX4 is dependent on several phenomena including the following fuel models for densification, swelling, creep (dish filling), thermal expansion, and cracking; and the cladding models for creep down, thermal expansion, axial creep, and irradiation growth. The RODEX4 code has been compared to measured void volumes from **[ ]** irradiated commercial rods with RX Zircaloy-2 cladding. The RODEX4 code appears to provide a best estimate prediction of these commercial rods with little scatter (plus or minus **[ ]** cubic centimeters (cm^3)) between predicted and measured values.

AREVA was asked in RAI-10 to provide an updated plot and confirm if more than **[ ]** points exist. AREVA provided details from **[ ]** fuel rods (RAI-10a) and explained that **[ ]**. No additional fuel rod void volume data are available at the time that the TR was submitted (RAI-10b).

The **[ ]** fuel rods include **[ ]** full-length fuel rods and **[ ]** part-length fuel rods. The initial fill gas pressure was essentially identical for all the rods, and AREVA provided the details of the initial void volume, the calculated and measured post-irradiation void volumes, and the exposures. The void volumes calculated by RODEX4 tend to be greater than measured for burnups greater than 60 GWd/MTU.

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Figure 9: AREVA Calculated and Measured Void Volume as a Function of Rod Average Burnup

Figure 9 shows a comparison of Calculated (C) and Measured (M) void volumes for the set of sixteen fuel rods provided by AREVA. For burnups up to approximately 57 GWd/MTU rod average, the data indicate a tendency to underestimate void volume, while there is a tendency to slightly overestimate void volume at rod average burnups of 65 GWd/MTU and greater. However, the maximum of overestimation is less than **[ ]**.

Figure 10 provides a plot of the calculated versus measured void volume. The scatter above and below the C equal M line is consistent with trends observed for CWSR Zircaloy-2 and Zircaloy-4 cladding.

The NRC staff concludes that results and trends obtained for void volume predictions for RX Zircaloy-2 cladding are comparable to those obtained for CWSR Zircaloy-2 cladding. Therefore the void volume assessment provides adequate assessment of the RX Zircaloy-2 models in RODEX4.

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Figure 10: AREVA Calculated versus Measured Void Volumes

3.4 IMPACT ON LICENSING APPLICATIONS

This section describes the impact of the use of RX Zircaloy-2 cladding on various licensing calculations.

AREVA provided example calculations of application of the RODEX4 code to design analyses to satisfy SAFDLs identified in Section 4.2 of the SRP and criteria in the 10 CFR 50.46 when the code was originally reviewed. The code applications to these analyses include:

- Fuel melting
- Fuel rod internal pressure
- Clad strain
- Pellet column creep collapse

The NRC staff used the latest version of FRAPCON (FRAPCON-4.0) to assess the impact of using RX Zircaloy-2 relative to CWSR Zircaloy-2. The following Sections (3.4.1 to 3.4.4.) will discuss the impact of this change on these calculations and make an assessment regarding the acceptability of RODEX4 to perform these calculations with RX Zircaloy-2 cladding. The NRC staff also requested that AREVA provide (RAI-12) sample calculations of calculations with uncertainties of maximum rod internal pressure, fuel melting calculation, and maximum cladding hoop strain increment. AREVA provided these calculations.

The application of power histories, uncertainties and statistics to these calculations are very important but have not changed relative to what was done for CWSR Zircaloy-2 other than the uncertainty values in the creep and oxidation models. These areas are briefly discussed in Sections 3.4.5 to 3.4.7.

The steady state LHGR limit of RODEX4 is reviewed with respect to the limit of the data used in the calibration and verification of RODEX4 Section 3.4.8 and burnup limits are discussed in Section 3.4.9.

The NRC staff asked AREVA to discuss the impact of the introduction of RX Zircaloy-2 on the ridging parameter in RAI-8. AREVA responded that the original calibration of this parameter for RODEX4 was performed using data from CWSR and RX Zircaloy-2, so recalibration was not necessary. Additionally, AREVA stated that the ridging strain is not used in any licensing analysis.

The code will not be applied to calculating fuel stored energy or other input for initiating LOCA analyses.

3.4.1 Fuel Melting

The use of RX Zircaloy-2 cladding does not significantly impact the fuel temperature, and has no impact on the fuel melting temperature. The use of RX Zircaloy-2 would affect the fuel-cladding gap early in life at low to moderate burnup, due to the lower creep rate of the cladding. At power levels, which close the gap such as those that cause fuel melting, there would be no significant difference in the fuel temperature.

AREVA provided sample calculations in the response to RAI-12 for fuel rod melting that demonstrate that there is little change in the maximum temperature with CWSR Zircaloy-2 (**[** **]**) and RX Zircaloy (**[** **]**).

The NRC staff concludes that RODEX4 is acceptable for calculating fuel melting with RX Zircaloy-2.

3.4.2 Fuel Rod Internal Pressure

AREVA previously has provided example calculations for ATRIUM 10 (10x10) rod design applications to different BWR plant designs/cores (e.g., BWR4 and BWR6 equilibrium core and transition cores) with maximum rod internal pressure with CWSR Zircaloy-2. The NRC staff has modeled the BWR4 equilibrium core rod in FRAPCON for RX and CWSR Zircaloy-2. The results for the rod internal pressures and fission gas release (FGR) are shown in Figure 11 and Figure 12, respectively. It can be seen that FRAPCON predicts virtually no difference in rod internal pressure or fission gas release when the cladding is change from CWSR Zircaloy-2 to RX Zircaloy-2. Given the models that are changed in RODEX4 for RX Zircaloy-2, there would be virtually no change in these results for RODEX4 either. Additionally, it has been confirmed in Section 3.3 that RODEX4 provides acceptable predictions of void volume for RX Zircaloy-2.

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Figure 11: Comparison of rod pressure history resulting in maximum rod pressure from RODEX4 analysis for a BWR CWSR fuel rod (no uncertainties included) to that calculated with FRAPCON for CWSR and RX Zircaloy-2

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Figure 12: Comparison of fission gas release history resulting in maximum rod pressure from RODEX4 analysis for a BWR CWSR fuel rod (no uncertainties included) to that calculated with FRAPCON for CWSR and RX Zircaloy-2

The NRC staff asked AREVA in RAI-6 if the new RX Zircaloy-2 creep model would impact the fission gas release predictions. AREVA responded that the RX Zircaloy-2 creep model would have minimal impact on the fission gas release predictions, which is in good agreement with the FRAPCON calculations shown in Figure 12. AREVA also provided comparisons to new FGR data from high exposure rods with RX Zircaloy-2 that show that RODEX4 overpredicts the fission gas release, which is conservative.

The NRC staff asked AREVA in RAI-11 to provide and justify the rod internal pressure limit that would be used for RX Zircaloy-2. AREVA stated that the limit previously approved for CWSR Zircaloy-2 of **[ ]** pounds per square inch (psi) over system pressure will be used for RX Zircaloy-2. AREVA performed a gap opening analysis with the RX Zircaloy-2 creep model that showed more margin to the **[ ]** psi limit. This is expected since the RX Zircaloy-2 creep rate is less than the CWSR creep rate and a lower creep rate will lead to gap reopening at a higher pressure.

AREVA provided sample calculations in the response to RAI-12 for rod internal pressure (with uncertainties that demonstrate that there is little change in the maximum pressure with CWSR Zircaloy-2 (**[ ]**) and RX Zircaloy (**[ ]**). Both calculations show margin to the **[ ]** psi limit over system pressure.

The NRC staff concludes that RODEX4 is acceptable for calculating rod internal pressure with RX Zircaloy-2.

3.4.3 <u>Clad Strain</u>

AREVA has previously provided example calculations for a rod with maximum permanent hoop strain and incremental strain (during a control rod withdrawal error with CWSR cladding. The NRC staff has modeled this rod in FRAPCON for RX and CWSR Zircaloy-2. The results for the permanent hoop strain are shown in Figure 13. It can be seen that FRAPCON predicts less creep down for the RX case and no increase in permanent hoop strain as the gap closes later in life. PNNL has assessed the cladding creep model in RODEX4 and it is expected that RODEX4 would predict similar differences between CWSR and RX Zircaloy-2 fuel rods. AREVA provided sample calculations in the response to RAI-12 for clad transient strain that demonstrate less strain for the RX case (**[ ]**) than for the CWSR case (**[ ]**).

The NRC staff concludes that RODEX4 is acceptable for calculating cladding hoop strain increments with RX Zircaloy-2.

[

]

Figure 13: RODEX4 predictions of permanent hoop strain for audit calculation containing an AOO for a BWR CWSR fuel rod (no uncertainties included) to that calculated with FRAPCON for CWSR and RX Zircaloy-2.

3.4.4 Pellet Column Creep Collapse Axial Gap

AREVA's methodology remains unchanged. PNNL requested in RAI-5c that AREVA discuss the impact of the new RX Zircaloy-2 creep properties on creep collapse. AREVA stated that there is about a **[ ]** percent difference in irradiation creep strain rate, but did not show specifics of the impact on creep collapse. The NRC staff asked in RAI-13 for AREVA to provide a sample calculation to demonstrate the impact of this change. AREVA provided results for the five ovality benchmark cases that demonstrated that the new creep model increases the calculated ovality by about **[ ]** percent.

The NRC staff concludes that the RODEX4 methodology for prediction of axial gap formation is conservative and acceptable for RX Zircaloy-2.

3.4.5 Power Histories

This section describes the treatment of power histories and the application of uncertainties to the steady state power histories and AOO slow power transients.

Since AREVA has not changed the treatment of power uncertainties, The NRC staff expects that the power uncertainties remain the same, and the use of RX or CWSR would not affect the treatment of uncertainties.

The NRC staff concludes that the RODEX4 application of power histories for licensing analyses is acceptable for CWSR and RX Zircaloy-2.

3.4.6 Application of Uncertainties

With respect to irradiation creep uncertainty, AREVA mentioned that, "the determination of creep (irradiation and thermal components) uncertainty followed the same procedure as initially reported in BAW-10247PA" (RAI-5b). While the methodology is the same as previously reported, the uncertainty values are different. For example, the best estimate model parameter, L_1, did change, and therefore the uncertainty bounds are different from those of CWSR or previously reported values for RXA. PNNL has reviewed the uncertainties proposed for the revised models (creep and oxidation) and has found them to be acceptable.

The NRC staff concludes that the application of uncertainties in the RODEX4 methodology for licensing analyses is acceptable for CWSR and RX Zircaloy-2.

3.4.7 Statistical Approach

AREVA uses the same statistical approach as previously described in BAW-10247PA and accepted and approved by the NRC. This approach has been previously reviewed and found to be acceptable. PNNL has found no reason that this approach would not be applicable to RX Zirclaoy-2.

The NRC staff concludes that the statistical approach approved for RODEX4 is acceptable for performing licensing analyses for CWSR and RX Zircaloy-2.

3.4.8 LHGR Limits

The same LHGR limits applied to CWSR cladding also apply to RX Zircaloy-2 BWR cladding. The properties and behavior (e.g., creep) of the cladding are determined by temperature, and the temperature is a function of the heat flux, which is governed by the LHGR and cladding diameter, and the heat transfer coefficient, which is governed by the cooling channel geometry and coolant properties. The LHGRs are governed by lattice and core designs (nuclear methods), which are independent of cladding mechanical properties. The CWSR and RX claddings tend to have the same radial geometry, and therefore the choice of cladding is not a factor with respect to LHGR.

The NRC staff has previously reviewed this limit along with the data presented by AREVA NP to support this limit. The NRC staff has also reviewed in Section 5.5 the application of this limit to their RODEX4 input power histories used for demonstrating that they meet their SAFDLs. The NRC staff concludes that the calibration and verification data used in the development of RODEX4 support operation at or below this LHGR limit. It should be noted that this limit applies only to steady state LHGR and does not apply to transient LHGR such as for an AOO. The peak LHGR during an AOO may exceed this LHGR limit for the short duration of the transient but must meet the LHGR versus time duration used for analyzing AOO events.

3.4.9 Exposure (Burnup) Limits

AREVA was asked for justification for the exposure limits on the cladding creep and corrosion models (RAI-7). AREVA responded that "the fast fluence on the x-axis of Figure 8 of Supplement 1 is the rod average fast fluence and the maximum value of **[** **]** (E > 1

MeV) corresponds to **[ ]** MWd/KgU. The burnup span of the corrosion data in Figure 12 of Supplement 1 is **[ ]** MWd/KgU rod average burnup."

The range of fluences and burnups are greater than the requested rod average burnup of 62 GWd/MTU, and thus the NRC staff concludes that the limit of 62 GWd/MTU is justified.

4.0 LIMITATIONS AND CONDITIONS

The limitations and conditions stipulated in Section 4 of the SE for the NRC-approved TR BAW- 10247PA (Reference 7) continue to apply, with the exception of the third limitation that was removed per Section 3.2.7 of this SE. In addition, a second paragraph is added to Condition 5 for RX Zircaloy-2 applications. The amended limitations and conditions are as follows:

1. Due to limitations within the FGR model, the analytical fuel pellet grain size shall not exceed 20 microns 3-D when the as-manufactured fuel pellet grain size could exceed 20 microns 3-D. (Section 3.2 of the Reference 7 SE)

2. RODEX4 shall not be used to model fuel above incipient fuel melting temperatures. (Section 3.7.1 of the Reference 7 SE)

3. Removed per Section 3.2.7.

4. Due to the empirical nature of the RODEX4 calibration and validation process, the specific values of the equation constants and tuning parameters derived in BAW-10247(P), Revision 0 (as updated by RAI responses) become inherently part of the approved models. Thus, these values may not be updated without necessitating further NRC review. (Section 1.0 of the Reference 7 SE)

5. RODEX4 has no crud deposition model. Due to the potential impact of crud formation on heat transfer, fuel temperature, and related calculations, RODEX4 calculations must account for a design basis crud thickness. The level of deposited crud on the fuel rod surface should be based upon an upper bound of expected crud and may be based on plant-specific history. Specific analyses would be required if an abnormal crud or corrosion layer (beyond the design basis) is observed at any given plant. For the purpose of this evaluation, an abnormal crud/corrosion layer is defined by a formation that increases the calculated fuel average temperature by more than 25 ºC beyond the design basis calculation. (Section 3.3. of the Reference 7 SE)

   As more liftoff data is acquired for different plants or when water chemistry conditions change at plants, the corrosion enhancement parameters and associated uncertainties for RX Zircaloy-2 may need to be updated. AREVA shall resubmit the updated parameters in the event the values reported in this supplement to RODEX4 exhibit significant general changes in the upper and lower bounds by more than one standard deviation (Section 3.1.3).

5.0 CONCLUSION

The result of the review of the supplement to BAW-10247PA, Revision 0 (Reference 1) is that the RODEX4 code and methods are acceptable for the inclusion of RX Zircaloy-2 and therefore, Condition c. in Section 5 of the Reference 7 SE is removed. All other limitations as discussed above in Section 4 continue to apply. Additionally, the hydrogen pickup model in the RODEX4 code and methods has been found to be acceptable for RX and CWSR Zircaloy-2 cladding for BWR applications.

The NRC staff concludes that the RODEX4 code is acceptable to model BWR fuel rods with and without solid pellet (non-annular) UO_2 fuel and with CWSR and RX Zircaloy-2 cladding up to a peak rod average burnup of 62 GWd/MTU as requested by AREVA NP. The code is also acceptable for modeling mixed urania, gadolinia fuel rods with up to 10 weight percent gadolinia up to a peak rod average burnup of 62 GWd/MTU as requested by AREVA NP.

The statistical methodology and uncertainties are approved with increased uncertainties in fuel thermal conductivity, cladding creep, and fuel solid swelling from the original submittal.

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Attachment: Resolution of Comments

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