**FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION**

**TOPICAL REPORT EMF-92-116(P)(A), REVISION 0, SUPPLEMENT 1, REVISION 0**

**"GENERIC MECHANICAL DESIGN CRITERIA FOR PWR FUEL DESIGNS"**

**AREVA NP, INC.**

**TAC NO. ME7962**

ENCLOSURE 1

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## 1.0 INTRODUCTION

By letter dated December 19, 2011, AREVA NP Inc. (AREVA) submitted Topical Report (TR) EMF-92-116(P)(A), Revision 0, Supplement 1, Revision 0, "Generic Mechanical Design Criteria For PWR [Pressurized Water Reactor] Fuel Designs" (Reference 1) to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. The purpose of this report was to address NRC staff concerns that the RODEX2 code (Reference 2) lacks a fuel thermal conductivity model that accurately captures the thermal conductivity degradation (TCD) of uranium dioxide ($UO_2$) fuel with burnup. The supplement describes the RODEX2 results that are potentially impacted by the effects of TCD. These criteria are then evaluated and dispositioned by establishing that TCD does not significantly affect the criteria, crediting known conservatisms to account for TCD, or by developing correction factors to account for the effects of TCD.

Experiments carried out at the Halden Reactor Project in the 1990's have led to a much better understanding of the effects of TCD on high burnup fuel. The NRC issued Information Notice 2009-23, "Nuclear Fuel Thermal Conductivity Degradation," dated October 8, 2009 (Reference 3) to make the industry aware of the potential effects of TCD.

AREVA's RODEX2 thermal-mechanical code was approved in 1984, at this time the effect of TCD was known but sufficient data was not available to accurately account for its effects. However, RODEX2 models were adjusted to predict the high burnup data available at the time. During recent reviews of AREVA supported fuel transitions and extended power uprates (EPUs), the NRC staff has determined that RODEX2 predicts certain specified acceptable fuel design limits (SAFDLs) non-conservatively. AREVA worked with their customers to develop correction factors to satisfy the NRC staff's concerns regarding the lack of a TCD model in RODEX2. At the conclusion of the ongoing affected licensing actions, the NRC staff requested that AREVA submit a TR to gain generic approval for the correction factor methodology. This supplement contains very similar methods as used in these previous licensing actions. However, there are some differences, including the development of generic bounding correction factors to be applied to all RODEX2 analyzed fuel.

The NRC staff sent an initial Request for Additional Information (RAI), dated October 18, 2013 (Reference 4) to AREVA. AREVA responded to the RAI by submittal of "Response to a Request for Additional Information Regarding EMF-92-116(P)(A), Revision 0, Supplement 1, Revision 0," dated November 11, 2013, and August 7, 2014 (Reference 5).

## 2.0 REGULATORY EVALUATION

Regulatory guidance for the review of fuel system designs and adherence to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Appendix A, General Design Criteria (GDC) for Nuclear Power Plants, GDC-10, "Reactor Design," GDC-27, "Combined Reactivity Control Systems Capability," and GDC-35, "Emergency Core Cooling," is provided in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants"

(SRP), Section 4.2, "Fuel System Design" (Reference 6). 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.

In addition to licensed reload methodologies, an approved fuel rod thermal-mechanical (T-M) model and application methodology are utilized to demonstrate compliance with SRP, Section 4.2, fuel design and performance criteria. EMF-92-116(P)(A), Supplement 1, describes the adjustments made to the RODEX2 code results to account for the impact of fuel thermal conductivity degradation. The NRC staff reviewed this TR to: (1) ensure that with the adjustments RODEX2's models are capable of accurately (or conservatively) predicting the in-reactor performance of fuel rods, (2) identify any limitations on the code's ability to perform this task, and (3) ensure that the application methodology conservatively accounts for model uncertainties and is capable of ensuring compliance with SRP Section 4.2 criteria.

## 3.0 **TECHNICAL EVALUATION**

The NRC staff's review of the supplement is summarized below:

- Verify each model of RODEX2 affected by TCD is correctly identified.
- Verify correction factor calculation methodologies are sufficient to bound the effects of TCD.
- Verify generic correction factors remain bounding for all AREVA fuel types.
- Verify application methodology properly accounts for second and third burned fuel.

The NRC staff compared RODEX2 corrected predictions to data as well as results of confirmatory calculations performed using the NRC audit code FRAPCON-3. The fuel performance models in FRAPCON-3 have been validated against an extensive database and are continually assessed against newer data as it becomes available (see Reference 7).

In addition to reviewing the material presented in the supplement and in response to RAI questions, the NRC staff met with AREVA to discuss the supplement review on July 9-11, 2013 (AREVA – Lynchburg, VA).

### 3.1 Impact of TCD on Mechanical Design Criteria

The main impact of TCD is on the temperature of the fuel, a code that does not properly account for TCD will under predict the temperature of the fuel. Therefore a correction must be made to the fuel temperatures that RODEX2 predicts. AREVA benchmarked RODEX2 against the extended Halden database that includes rods up to a local burnup of 100 gigawatt-days per metric ton of uranium (GWd/MTU). The results of the benchmarking show that RODEX2 conservatively predicts fuel temperatures up to about **[ ]**. Therefore, AREVA proposes to apply a correction factor to RODEX2 fuel temperature predictions at burnups greater than **[ ]**.

An expression was derived by selecting **[ ]**. The temperature expression was defined such that, **[ ]**. This correction factor will be applied to $UO_2$ fuel rods and $UO_2$-Gadolinium fuel rods starting at **[ ]**.

#### 3.1.1 Cladding Collapse

AREVA's cladding collapse model is not affected by fuel thermal conductivity degradation. The methodology demonstrates that the pellet-to-clad gap remains open during fuel densification, which occurs up to about **[ ]** before significant effects from TCD are observed. RODEX2 benchmarking to the extended Halden database shows that it conservatively predicts fuel temperatures in this burnup range.

#### 3.1.2 AOO Cladding Strain

RODEX2 does not account for fuel TCD and therefore under predicts fuel temperatures as burnup increases. This under prediction of fuel temperature **[ ]**. AOO cladding strain is the delta strain that occurs from the power spike introduced by a transient. In AREVA analyses this is the difference between the pre-transient power level and the peak transient power level. The increase in power causes an increase in fuel temperature which leads to thermal expansion of the pellet. The expansion of the pellet then increases the amount of strain on the cladding.

**[**

**]**.

AREVA developed a generic, bounding AOO strain penalty to avoid the need for excessive calculation on a reload basis. This was done by applying the above described methodology to hundreds of different design cases. The results were then plotted as corrected incremental strain versus original incremental strain. A 95/95 upper tolerance limit line was calculated for the data and **[** **]**. The equation for this new bounding line is the correction factor that will be applied to all uncorrected AOO cladding strain results from RODEX2. The correction will be verified for use prior to analyses on fuel designs that fall outside of the design attributes in Table 2 of the TR or operating temperature beyond the maximum considered in the survey.

On a case specific basis, AREVA may use the methodology presented to calculate the corrected AOO strain if the generic bounding correction factor is determined to be overly conservative and challenges design margins. This is acceptable because the methodology is conservative and the generic correction factor was developed to reduce extensive calculation time.

3.1.3 Steady-State Strain

For the same reasons as given above for AOO cladding strain, TCD will impact RODEX2 predictions of steady-state strain. Therefore a correction is needed to ensure that the RODEX2 results will remain conservative for licensing analyses. AREVA performed a survey of several prior reload analyses, including EPUs, that encompassed a representative sample of their current fuel products and operating parameters. **[**

**]**.

To create a bounding steady-state strain correction applicable to any rod in the survey, **[** **]**. This value represented a bound to the increase in **[** **]**. To ensure that this **[** **]** was bounding to every case in the survey, a comparison was made between two uncorrected **[** **]**. The first was a distribution that was back-calculated as a function of burnup using the **[** **]**. The second was the set of all **[** **]** from the survey plotted against their respective burnups. This comparison showed that **[** **]** value proposed was in-fact bounding for every case in the survey.

The steady-state strain correction factor was calculated as the **[** **]**. To ensure conservatism, it was assumed that the entirety of the **[** **]**. To further ensure that the most limiting case is represented, **[** **]**.

The combination of **[** **]** ensure a bounding maximum increase in steady-state strain based on the effects of TCD. This correction factor will be added to the uncorrected RODEX2 steady-state strain results for all RODEX2 licensing applications. The correction will be verified for use prior to analyses on fuel designs that fall outside of the design attributes in Table 2 of the TR or operating temperature beyond the maximum considered in the survey.

3.1.4 Cladding Fatigue

The increased fuel temperatures from the effects of TCD would result in a small increase in the cladding fatigue usage factor. This is because the higher temperatures would result in larger pellet outer diameters due to additional thermal expansion, which could cause greater stresses on the cladding during power maneuvering. AREVA's licensed cladding fatigue methodology contains very large conservatisms built into the power levels used for the duty cycles. The power level amplitudes are conservatively increased for the high power and conservatively decreased for the low power to ensure a bounding duty cycle. The NRC staff also reviewed previous results of cladding fatigue analyses for a number of plants including EPU analyses that show a significant margin to the Zircaloy-4 alloy and M5® alloy limits.

The combination of the large conservatisms in the analysis and the significant margins available to the criterion more than compensate for the effects of TCD.

3.1.5 Fuel Densification and Swelling

RODEX2 contains fuel densification and swelling models that have been benchmarked against measured data over the approved burnup range. The models are calibrated to provide best estimate results for rod void volume. The nature of the calibration inherently accounts for the effects of TCD on densification and swelling. Therefore, correction to these models is not necessary.

3.1.6 Cladding Oxidation, Hydriding, and Crud Buildup

TCD does not impact the RODEX2 predictions of the temperatures on the very edge of the fuel pellet or of the cladding. Therefore, the cladding oxidation, hydriding, and crud buildup analyses are unaffected by TCD.

3.1.7 Fuel Rod Internal Pressure

AREVA's RODEX2 code is a best estimate code that has been calibrated to measured experimental data. This calibration of the code to data inherently accounts for the permanent burnup effects of TCD. The code was validated at cold zero power conditions against a database that included the available high burnup data at the time of development.

While RODEX2 accurately predicts the moles of fission gas release and the cold zero power rod internal void volume **[** **]**. This causes the code to under-predict rod internal pressure at operating conditions. AREVA modified the originally submitted TR to account for these issues via RAI by performing a study to determine a bounding correction factor to apply to the RODEX2 rod internal pressure predictions. This study used the **[** **]** of this safety evaluation to determine a conservative value for **[** **]**. This process was applied to a population of more than 2,000 cases to develop a 95/95 upper tolerance limit correction factor.

The application of a bounding correction factor developed using conservative assumptions for the fuel centerline temperature adequately accounts for the effects of TCD on the RODEX2 rod internal pressure calculation. The correction will be verified for use prior to analyses on fuel designs that fall outside of the design attributes on Table 2 of the TR.

3.1.8 Fuel Centerline Melt

Fuel TCD directly impacts the centerline fuel temperature and the impact becomes greater with burnup. This will cause fuel melt to occur at lower powers than what RODEX2 predicts and this effect becomes greater as burnup increases. AREVA chose to perform a code-to-code comparison with the NRC approved code COPERNIC, which accurately models TCD, to determine appropriate correction factors to apply to RODEX2's fuel centerline melt (FCM) results. The approved methodology for each code was used to model the same fuel designs.

The RODEX2 fuel melt temperature was then lowered until the RODEX2 results became conservative as compared to the COPERNIC results. This lowering of the fuel melt temperature was increased with burnup to ensure that RODEX2 always remained conservative compared to COPERNIC in a stair-step fashion. This type of analysis was performed for a representative sample of AREVA fuel designs. The analysis was also done for $UO_2$ and urania-gadolinia concentrations of 2 percent, 4 percent, 6 percent, and 8 percent.

The results for the varying fuel types were then combined into a single set of bounding RODEX2 fuel melt temperature reductions. These reductions were confirmed by the NRC staff to be bounding based on the figures provided in the TR and through independent confirmatory calculations using the NRC code FRAPCON-3. The correction factors are provided in Table 6 of the TR.

AREVA's reload methodology shows that **[** **]**. To accomplish this, AREVA compares the **[**

**]**.

To demonstrate that the process outlined in the TR will remain conservative when extending to burnups **[** **]**, Figure 6 in the TR was revised and submitted as part of RAI response 1.b. In the revised figure, the model in COPERNIC was revised and extended to a burnup of 62 GWd/MTU. This revised COPERNIC model used **[**

**]**; this change resulted in a more realistic FCM limit at higher burnups. Additionally, the revised COPERNIC model used a **[** **]**. The revised figure provided a comparison between the revised COPERNIC model and the penalized RODEX2 model from Figure 6 conservatively extrapolated to 62 GWd/MTU. This showed that the process outlined in the TR remained conservative even when extended to the current licensed maximum burnup of 62 GWd/MTU.

3.2 RODEX2 Rod Internal Pressure Methodology Validation

To further validate RODEX2's fission gas release and cold void volume calculations AREVA re-benchmarked the codes results for these two parameters to an expanded database. RODEX2's fission gas release continues to be shown as best-estimate and the cold void volume proves conservative with no bias as burnup is increased.

The RODEX2 methodology, as presented in the original TR and amended in this supplement, includes several modelling adjustments that ensure the code predicts a conservative rod internal pressure. These adjustments include analyzing several limiting power histories for each cycle and ensuring that **[ ]** is achieved by at least the most limiting history, applying a transient axial power shape at a frequency that is conservative based on operating experience, biasing the **[ ]** to either it's maximum or minimum value to obtain the most conservative result, applying a TCD penalty to the final result predicted by the code as described above in Section 3.1.7 of this safety evaluation, and by comparing the final RODEX2 calculated and adjusted rod internal pressure to a conservative overpressure limit.

The combination of the above adjustments to the RODEX2 rod internal pressure calculation methodology ensures that the code conservatively predicts rod internal pressure while accounting for the effects of TCD.

## 4.0 <u>**CONCLUSION**</u>

Based on the review above, the NRC staff has reasonable assurance that the use of RODEX2, as supplemented by Reference 1, is acceptable for performing fuel T-M calculations for U.S. PWRs using $UO_2$ and urania-gadolinia fuel rods with Zircaloy-4 or M5® cladding materials. The basis for this conclusion is that AREVA has proposed sufficient correction factors, or penalties, to account for the lack of fuel TCD modeling in the RODEX2 code. The NRC staff found that AREVA conservatively applied these corrections to the steady-state strain, AOO strain, fuel centerline melt, and rod internal pressure results calculated by RODEX2. All other criteria specified in Section 4.2 of the SRP were confirmed to not be affected by the lack of TCD modeling in RODEX2.

## 5.0 <u>**REFERENCES**</u>


1. EMF-92-116(P)(A), Revision 0, Supplement 1, Revision 0, "Generic Mechanical Design Criteria for PWR Fuel Designs," December 2011 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML11363A131/ML11363A130 (Non-Publicly Available/Publicly Available)).

2. XN-NF-81-58(P)(A), Revision 2, and Supplements 1 and 2, "RODEX2 Fuel Rod Thermal Mechanical Response Evaluation Model," March 1984 (ADAMS Accession No. ML081340725 (Non-Publically Available)).

3. NRC Information Notice 2009-23, "Nuclear Fuel Thermal Conductivity Degradation," October 8, 2009 (ADAMS Accession No. ML091550527 (Publicly Available)).

4. Letter, Joseph Golla (NRC) to Pedro Salas (AREVA NP Inc.), "Request for Additional Information Re: AREVA Topical Report EMF-92-116(P)(A), Revision 0 Supplement 1, Revision 0, 'Generic Mechanical Design for PWR Fuel Design,' October 18, 2013 (ADAMS Accession No. ML13275A256).

5. Letter, Pedro Salas (AREVA NP Inc.) to NRC, “Response to a Request for Additional Information Regarding EMF 92-116(P)(A), Revision 0, Supplement 1, Revision 0,” November 11, 2013 and August 7, 2014 (ADAMS Accession No. ML13317B942 and ML14220A469).

6. NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” Section 4.2, Revision 3, “Fuel System Design,” March 2007 (ADAMS Accession No. ML070740002 (Publicly Available)).

7. NUREG/CR-7022, “FRAPCON-3.4: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup,” March 2011 (ADAMS Accession No. ML11101A005 (Publicly Available)).

Attachment: Resolution of Comments Table

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