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Generic Mechanical Design Criteria For PWR Fuel Designs

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Table of Contents

List of Tables

List of Figures

1.0 Introduction

AREVA's Thermal Mechanical (T-M) code, RODEX2, was approved in 1984. At the time this code was approved, the effect of thermal conductivity degradation with burnup was known, but adequate benchmarking data was not available to account explicitly for this effect. The models in RODEX2 were adjusted to predict the data available including the high burnup data.

A review of the RODEX2 code predictions has been performed to assure that this effect is adequately addressed. [

] AREVA has conducted an evaluation of the impact of thermal conductivity degradation with burnup on RODEX2 predictions. The results of this investigation indicate the following:

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AREVA has developed correction factors to be applied to the RODEX2 predictions to account for the lack of fuel thermal conductivity degradation with burnup in the cladding strain and fuel centerline melt analyses. [

] The impact of fuel thermal conductivity degradation on the RODEX2 analyses is presented in detail in Section 2.0.

Further validation of the RODEX2 rod internal pressure methodology for a variety of fuel designs is presented in Section 3.0.

2.0 Impact of Fuel Thermal Conductivity Degradation with Burnup on Mechanical Design Criteria

A conservative expression was derived for adjusting the fuel temperature predictions due to the lack of a burnup dependent fuel thermal conductivity model in RODEX2. The benchmark results [

] the extended Halden data base results shown in Figure 1.

The basis [

] The RODEX2

thermal predictions [

] The temperature correction is

defined as

$$Cor._{95/95} = M/P + K\sigma = [\qquad]$$

$Cor._{95/95}$	Temperature correction at the 95%/95% one-sided tolerance limit as a function of nodal burnup
M/P	Mean measured to predicted
K	95/95 one-sided tolerance factor
σ	Standard deviation, measured/predicted
Bu	Nodal burnup (GWd/mtU)]

and is used as a multiplier on RODEX2 temperature predictions

$$T_{Corrected} = Cor._{95/95}\, T_{RODEX2}$$

$T_{Corrected}$	Fuel temperature corrected for the degradation of fuel thermal conductivity
$Cor._{95/95}$	Factor used to increase RODEX2 temperature predictions for fuel thermal conductivity degradation
T_{RODEX2}	Temperature prediction using RODEX2

The application of the temperature correction expression provides a prediction [

]

RODEX2 benchmark results have shown the code to be conservative in the [

]. To avoid over penalizing UO_2 fuel [

] corrections for UO_2 fuel rods will be applied [

] Corrections for urania-gadolinia fuel rods will be applied [ ] using the benchmark results [ ]

A review of the generic mechanical design criteria contained in Reference 1 was performed in order to identify criteria that are potentially impacted by the fuel pellet thermal degradation phenomenon. The criteria contained in Sections 3.0, 4.0 and 5.0 of Reference 1 are presented in Table 1 along with the results of the applicability review. The criteria that pertain to the LOCA and the non-LOCA safety analysis are not evaluated within this document. Therefore, these criteria are shown with a strike-through symbol. Out of the remaining criteria, those that are not analyzed using the RODEX2 code, and therefore are unaffected by the fuel thermal conductivity degradation issue, are designated with "NA" in the applicability column.

The review presented in Table 1 shows that the RODEX2 code is used in evaluating the following mechanical fuel design criteria:

- Cladding collapse
- Cladding strain
- Fuel rod fatigue
- Fuel densification and swelling
- Cladding oxidation, hydriding, and crud buildup
- Fuel rod internal pressure
- Fuel centerline melt

For each criterion listed above, the impact of the fuel thermal conductivity degradation phenomenon has been assessed. For the criteria that are judged to be adversely impacted, bounding correction factors have been developed to restore conservatism in the results predicted by the RODEX2 code.

The following sub-sections present the details of the assessments and the development of correction methodologies for each criterion in Table 1 judged to be affected by the underprediction of fuel temperatures by the RODEX2 code.

2.1 Cladding Collapse

AREVA's cladding collapse methodology (Reference 1) is based on analytically demonstrating that the radial pellet-to-clad gap remains open during fuel densification (up to a rod average burnup of [ ]). Since the RODEX2 code does not underpredict fuel temperatures in this burnup range, the degradation in fuel thermal conductivity at higher burnups does not impact the existing cladding collapse margins.

2.2 AOO Cladding Strain

AREVA's criterion for maximum AOO strain is [

].

[

] This is due to the fact that higher fuel temperatures will result in an increase in the pellet outer diameter (due to thermal expansion) thereby enhancing pellet-to-cladding contact. A larger fuel pellet will result in larger cladding strains and smaller strain margins.

Cladding strain during AOOs is calculated as an incremental strain resulting from a difference in power level between the peak transient power level and the pre-transient power level. Since the diameter of the fuel pellet is a function of fuel temperature, an increase in power level during the transient causes the fuel pellet to expand.

[

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The correction to the AOO strain predicted by the RODEX2 code is calculated as follows –

[( )] Equation 2.2-1

Where,

[

]

In order to calculate the corrected strain predictions, the pre-transient and peak transient fuel centerline temperatures at the time step of interest "t" and for the axial node of interest "n" are first adjusted using the bounding temperature correction expression shown below in Equation 2.2-2.

[.] .Equation 2.2-2

Where,

[ ]

The corrected pre-transient and peak transient nodal strain values that correspond to the adjusted nodal temperatures are then calculated [ ].

The corrected nodal AOO strain value for the axial node of interest "n" and at the time step of interest "t" can now be calculated as [ ]

The methodology described above can be used for calculating a correction to the uncorrected RODEX2 strain prediction for a given axial node "n" and at a given time step "t" for a particular steady-state power history file. The fuel rod models used in RODEX2 typically consist of 12 or 24 axial nodes. For any given cycle-specific analysis (reload), several power history files corresponding to each fuel pin type in core are analyzed. In accordance with the NRC-approved methodology provided in Reference 2, an AOO power transient, [ ] in order to calculate the most limiting cycle-specific AOO strain margin for the reload fuel. Since each power history file consists of a multitude of time steps, a "generic" correction relationship is developed that can be applied independent of the time step or the power history file used.

[ ]. The generic correction relationship is therefore developed in a manner that will [ ] bound the AOO cladding strain for all expected ranges of operation for PWR fuel using RODEX2.

A large number of design analysis cases have been chosen from a survey of prior reload design calculations in order to develop the generic correction relationship. The cases are chosen so as to consider all RODEX2-based fuel designs and plants. Uprated power levels have been considered for applicable plants.

Table 2 provides a summary of the reload designs that have been considered in developing the generic correction relationship. [ ]. Various fuel rod average burnup steps have been selected to provide a relationship that covers a broad range of burnups. [ ]. A total of nearly 800 design cases were selected to formulate the generic correction relationship. For each design case, the methodology for calculating correction to the AOO cladding strain, presented above, was utilized to generate a corresponding strain correction.

The resulting corrected strain values are shown in Figure 2 as a function of the corresponding uncorrected AOO strains as originally predicted by the RODEX2 code as part of the reload design calculations. Large variations in strain correction can be caused due to open pellet-to-clad gap states prior to the application of the power transient. Open gap states are encountered at lower burnup levels typically for the end nodes in the fuel stack, but occasionally for the other nodes as well. For these types of cases, the cladding strain levels are typically low. All data points that correspond to cases with very low uncorrected incremental strain [ ] have been discarded. [ ]

Figure 2 depicts the cladding strain database along with its least squares fit linear trend line. Also shown in Figure 2 is the one-sided 95/95 upper tolerance limit (UTL) line for the database. As shown in Figure 2, [ ]. Thus, the generic correction line is [ ].

The equation for the AOO strain correction line is given by –

[ ]....... Equation 2.2-3

The AOO strain correction will be applied to the uncorrected AOO cladding strain results obtained using the RODEX2 code for licensing applications. The correction is applicable to both Zircaloy-4 and M5® cladding. Applicability of the AOO strain correction will be verified prior to use for fuel designs that fall outside of the fuel design attributes listed in Table 2.

The correction relationship is valid for both hot full power (HFP) and hot zero power (HZP) transients. As shown in Figure 2, the correction line bounds all the data points, including those at the higher strain levels. For any given application, if the generic correction is judged to provide an overly conservative result that challenges design margins, a case-specific correction using the methodology presented earlier for calculation of corrected cladding strain may be used instead.

2.3 Steady-State Strain

AREVA's criterion for maximum steady state strain is [

]

[

] This is due to the fact that higher fuel temperatures will result in an increase in the pellet outer diameter. A larger fuel pellet will in turn result in larger cladding strains and smaller strain margins.

In order to calculate the impact of higher fuel temperatures on the strain margins, a survey of the pertinent fuel design parameters and operating fuel temperatures from prior reload design calculations has been conducted in order to determine limiting designs and plants. The survey considers all RODEX2-based fuel designs and plants. Uprated power levels have been considered for applicable plants. Table 2 provides a summary of the reload designs that have been considered in calculating the impact on strain margins.

[

]

The maximum steady-state strain correction calculated above will be applied to the uncorrected results obtained for licensing applications using the RODEX2 code. The correction is applicable to both Zircaloy-4 and M5® cladding. Applicability of the maximum steady-state strain correction will be verified prior to use for fuel designs that fall outside of the fuel design attributes listed in Table 2 or for fuel operating temperatures that exceed those considered in establishing the maximum correction.

2.4 Cladding Fatigue

AREVA's criterion for maximum cladding fatigue usage factor is [ ] for Zircaloy-4 cladding (Reference 1) and [ ] for M5® cladding (Reference 6). Correction to the fuel temperatures predicted by the RODEX2 code at higher burnups will result in an increase in the pellet outer diameter due to additional thermal expansion. A larger fuel pellet could in turn cause larger cladding stress intensity amplitudes during power cycling due to increased pellet-to-cladding contact. However, AREVA's licensing analyses for cladding fatigue include a large conservatism in the power levels for the duty cycles. The power levels are [ ] to add excess conservatism to the calculated stress amplitudes. The excess conservatism compensates for the underprediction of fuel temperatures by the RODEX2 code. Coupled with the fact that [ ], no correction to the fatigue usage factors predicted by the RODEX2 code is required.

2.5 Fuel Densification and Swelling

Models for fuel densification and swelling are included in the RODEX2 code and are used in calculating margins to the various mechanical design criteria. These models are provided in Appendix K of Reference 3. The fuel densification model is [ ] whereas the swelling models are [ ]. Densification and swelling of the fuel column affect the available free volume inside the fuel rod. The RODEX2 code has been benchmarked against measured free volume data over the entire approved burnup range [ ]. The results of the benchmarking are contained in Supplement 4 of Reference 7.

[ ]. These models do not require any correction to compensate for the underprediction of fuel temperatures by the RODEX2 code.

2.6 Cladding Oxidation, Hydriding, and Crud Buildup

Cladding oxidation is a function mainly of the metal-to-oxide interface temperature and of exposure time. Since the underprediction of fuel temperatures by RODEX2 does not invalidate the metal-to-oxide interface temperature predictions, the existing cladding oxidation margins remain unaffected by the degradation in fuel thermal conductivity with burnup. Similarly, hydriding and crud buildup are also unaffected by the degradation in fuel thermal conductivity with burnup.

2.7 Fuel Rod Internal Pressure

RODEX2 is a best estimate code developed to predict the thermal-mechanical behavior of fuel rods in Light Water Reactors (Reference 3). It is composed of interrelated models which describe all physical phenomena known at the time it was approved. The effects of fuel thermal conductivity degradation with burnup were known at the time RODEX2 was submitted but benchmarking data was not readily available and therefore the code does not include a model to explicitly account for this phenomenon.

The NRC-approved RODEX2 code uses high burnup data (i.e., rod average burnups up to the licensed value of 62 GWd/mtU) to validate the fission gas release, rod internal void volumes, and rod internal pressure models (References 3 and 7). As a result, the effects of fuel thermal conductivity degradation were implicitly captured during the overall code calibration and the rod internal pressure calculations do not require any adjustments to account for the reduced fuel thermal conductivity at high burnups.

The original RODEX2 fission gas release and rod internal void volume validation database is presented in Reference 3 and repeated in Table 3 for completeness. It is composed of [ ] rods including [ ] rods with rod average burnup greater than [ ] GWd/mtU.

The original RODEX2 database was significantly enlarged with the addition of the entire pin pressure calibration database of the RODEX4 code, a modern fuel rod design code approved by the US NRC in Reference 4. The expanded database now includes a total of [ ] rods, almost [ ] times as many rods as in the original database. Additionally, there are now [ ] rods with rod average burnups greater than [ ] GWd/mtU, almost [ ] times as many as in the original RODEX2 database. The maximum rod average burnup in the expanded database is greater than [ ] GWd/mtU. The expanded database is summarized in Table 4.

The results of the RODEX2 fission gas release and rod void volume benchmark against the expanded validation database are shown in Figure 3 and Figure 4 respectively. These figures show no bias with rod average burnup for either the fission gas release or rod void volume predictions [ ].

There is no limit imposed on the amount of fission gas release or rod void volume. Instead, a criterion on rod internal pressure needs to be met for every reload. Figure 5 shows the results of the RODEX2 benchmark against the expanded database in terms of rod internal pressure. The results show no bias with burnup [ ]. The 95/95 uncertainty of the RODEX2 pin pressure calculations is [ ] psi which is consistent with modern fuel rod performance codes such as the US NRC-approved COPERNIC (Reference 5).

[ ]

2.8 Fuel Centerline Melt (FCM)

The RODEX2 code is used to predict the linear heat generation rate (LHGR) at which FCM occurs. The reduction in the LHGR calculated with RODEX2 resulting from the lack of modeling of the degradation in fuel thermal conductivity with burnup was calculated with a code-to-code comparison between the RODEX2 and the COPERNIC fuel performance codes. COPERNIC (Reference 5) is an NRC-approved fuel performance code that models exposure dependent degradation of fuel thermal conductivity. [ ], correction factors were developed as a function of burnup for application to the RODEX2 FCM temperature. The correction factors for the FCM calculation with RODEX2 are reductions in the melt temperature applied over the burnup range which lower the LHGR at which fuel melting occurs.

Correction factors that reduce the melt temperature in RODEX2 were calculated as a function of fuel rod average burnup for both UO_2 and urania-gadolinia fuel types. The correction factors are temperature penalties in degrees Fahrenheit that are applied as reductions to the melt temperature (in RODEX2) in a manner such that the LHGRs predicted with RODEX2 [ ].

The methodology for calculating the correction factors as functions of rod average burnup is provided below for three different reference plants. Based on these results, bounding factors were conservatively selected and are reported as a function of rod average burnup.

RODEX2 and COPERNIC Approved Methodologies:

The methodology for calculating FCM limits with RODEX2 is discussed in detail in References 8 and 9. The methodology for calculating FCM limits with COPERNIC is discussed in Reference 5.

Comparison Methodology:

The methodology for the FCM calculation was developed with a code to code comparison using approved methodologies for each. The following is an overview of the calculation process used in this analysis.

[ ]

Three plants were selected for the analysis (Westinghouse 15x15, Combustion Engineering 14x14 and 15x15). These provide a sample of fuel rod designs and plant types which utilize RODEX2 for the FCM limit calculations.

Range of Application:

The methodology from References 8 and 9 [ ] for FCM limits. The methodology for the correction factors for FCM was calculated to bound the fresh fuel in the example plants. In light of the potential for non-conservatism in the FCM limit that could occur as a result of not explicitly accounting for the degradation of fuel thermal conductivity with burnup, AREVA's reload process [ ] for FCM limits. Since the FCM limit calculated with the RODEX2 methodology is [ ]

This evaluation was performed to a rod average burnup of [ ]. This burnup bounds the [ ]

Results:

The FCM limits as a function of fuel rod average burnup for the reference CE plants analyzed are provided below. Plots of the FCM limit for one of the reference plants are provided for both UO_2 and urania-gadolinia fuel types in Figure 6, through Figure 10. Tables of the bounding correction factors extracted from the figures for the sample plants are provided for UO_2 and urania-gadolinia concentrations of 2%, 4%, 6% and 8% in Table 7.

The correction factors are defined as [ ].

Correction Factor Summary:

Based on the data in Table 6 and Table 7, AREVA will apply the following correction factors to its licensed analyses. Due to the conservatism used in calculating the correction factors, the analysis will not be repeated unless core conditions or fuel designs change from those analyzed. The correction factors were conservatively selected to bound the data in a stair step fashion.

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3.0 RODEX2 Rod Internal Pressure Methodology Validation

The RODEX2 rod internal pressure methodology includes the following conservatisms:

- A set of limiting cycle-specific rod power histories is selected for the analyses so that, when taken as a whole, these power histories bound the entire core. [ ]
- [ ]
- [ ]
- [ ] is used in the calculation to maximize rod internal pressure predictions.

The RODEX2 standard methodology was compared to a statistical methodology based on the US NRC-approved COPERNIC methodology (Reference 5). The alternative RODEX2 methodology consists of running a best estimate case followed by a series of relevant uncertainty cases with RODEX2. In the best estimate case, all manufacturing and model parameters are set to their nominal values and the [ ]. The uncertainty cases are [ ].

Once the best estimate pressure, P_{BE}, and the rod internal pressure P_i of each uncertainty case i are determined, the 95/95 upper bound pressure, P_{UB}, is calculated as follows:

$$[\ P_{UB} = P_{BE} + \mathrm{SQRT}(\mathrm{SUM}_i(P_i - P_{BE})^2)\ ]$$

The upper bound pressure calculated above can then be compared to the results of the original RODEX2 calculations to demonstrate the generic nature of the standard RODEX2 pin pressure methodology and quantify its conservatisms.

The RODEX2 statistical methodology was compared to two recent fuel managements and the detailed results of the analysis are summarized in Table 5. The 95/95 upper bound pressures of [ ] psia and

[ ] psia are comparable to the pin pressure results obtained with the standard RODEX2 methodology (**[ ]** psia and **[ ]** psia respectively). The standard RODEX2 rod internal pressure methodology produces results consistent with or more conservative than a statistical methodology up to the design limit of **[ ]**, and therefore is acceptable for continued use in reload analyses.

4.0 References

1. EMF-92-116(P)(A) Revision 0, "Generic Mechanical Design Criteria for PWR Fuel Designs," February 1999.
2. ANF-88-133(P)(A) and Supplement 1, "Qualification of Advanced Nuclear Fuels' PWR Design Methodology for Rod Burnups of 62 GWd/mtU", December 1991.
3. XN-NF-81-58(P)(A), Revision 2, and Supplements 1 and 2, "RODEX2 Fuel Rod Thermal Mechanical Response Evaluation Model," March 1984.
4. BAW-10247PA, "Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors," April 2008.
5. BAW-10231P-A, Revision 1, "COPERNIC Fuel Rod Design Computer Code," January 2004.
6. BAW-10240(P)-A, Revision 0, "Incorporation of M5™ Properties in Framatome ANP Approved Methods," May 2004.
7. ANF-81-58(P)(A), Revision 2, Supplements 3 and 4, "RODEX2 Fuel Rod Thermal Mechanical Response Evaluation Model," April 1990.
8. EMF-1961(P)(A), Revision 0, "Statistical Setpoint/Transient Methodology for Combustion Engineering Type Reactors."
9. EMF-92-081(P)(A), Revision 1, "Statistical Setpoint-Transient Methodology for Westinghouse Type Reactors, Siemens Power Corporation."
10. XN-NF-82-06(P)(A), Revision 1, Supplements 2, 4, and 5, "Qualification of Exxon Nuclear Fuel for Extended Burnup (PWR)," November 1985.

Table 1: Applicability of RODEX2 Code to the Generic Mechanical Design Criteria

Table 2: Summary of Reload Designs used in Development of Corrections for AOO and Steady-State Strain

[ ]

Table 3: Original RODEX2 Fission Gas Release and Void Volume Database

Table 4: Expanded RODEX2 Pin Pressure Validation Database

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Table 5: Summary of the 95/95 Pin Pressure Analysis with RODEX2

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Table 6: UO2 Penalty Factor Data

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Table 7: Urania-Gadolilnia Correction Penalties

Figure 1: RODEX2 Temperature Prediction Deviation in % versus Nodal Exposure - Expanded Data Base

Figure 2: Generic AOO Strain Correction Relationship

[ ]

Figure 3: RODEX2 Fission Gas Release Benchmark Against Expanded Validation Database

Rod Average Exposure (MWd/kgU)

Figure 4: RODEX2 Rod Void Volume Benchmark Against Expanded Validation Database

Figure 5: RODEX2 Rod Internal Pressure Benchmark Against Expanded Validation Database

Figure 6: W 15x15 UO2 Results

Figure 7: W 15x15 2 wt% Urania-Gadolinia Results

Figure 8: W 15x15 4 wt% Urania-Gadolinia Results

Figure 9: W 15x15 6 wt% Urania-Gadolinia Results

Figure 10: W 15x15 8 wt% Urania-Gadolinia Results