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RODEX2A (BWR) Fuel Rod Thermal-Mechanical Evaluation Model: Validation

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RODEX2A (BWR) Fuel Rod Thermal-Mechanical Evaluation Model: Validation

1.0 INTRODUCTION AND SUMMARY

Siemens Power Corporation (SPC) BWR fuel designs are currently licensed up to a maximum assembly exposure of [ ] GWd/MTU. However, this licensed BWR burnup limit is not consistent with the limitations of the RODEX2A code.[1] This supplement provides additional information to support the application of RODEX2A to a rod exposure in agreement with the licensed assembly exposure limit.

RODEX2A is used to evaluate the thermal mechanical design of a BWR fuel rod. RODEX2A's use is restricted to a pellet exposure limit of 60 GWd/MTU. This topical report submits data to support changing the RODEX2A exposure limit [ ].

RODEX2 has been approved by the NRC to a maximum of 62 GWd/MTU rod average exposure.[2,3] The only difference between RODEX2 and RODEX2A is in the fission gas release model. Fission gas release validation calculations were performed with RODEX2A using the same validation data base as used for RODEX2. The RODEX2A code gives compatible fission gas release predictions in comparison with the RODEX2 code between 50 and 60 MWd/kgU rod burnup. RODEX2A gives more conservative (higher) predictions between 60 MWd/kgU peak pellet exposure and the 62 MWd/kgU peak rod exposure than the approved RODEX2 code. In addition, RODEX2A is conservative when compared to the data. Thus, the RODEX2A code is justified to be used [ ].

In addition to the presentation of fission gas release validation calculations, a review of the approved BWR generic design criteria was conducted.[4] The review shows that the current methods are still applicable. Since the fuel assembly exposure limit is unchanged at [ ] GWd/MTU, all criteria and methods related to fuel bundle design are unaffected.

All design criteria apply to the increased rod exposure without modification, except for the cladding transient strain limit of 1%. Criterion for the uniform cladding strain caused by power transients has been conservatively reduced from 1% [ ]. This reduction is taken to be consistent with the SPC PWR requirements.[3] The strain limit reduction is a conservative measure since fuel rod cladding ductility has been observed to decrease on high exposure fuel.

Example fuel rod analyses are provided to show acceptable results to a peak rod exposure of [ ].

2.0 RODEX2A FISSION GAS RELEASE VALIDATION RESULTS

Since the only difference between the RODEX2 and RODEX2A codes is in the fission gas release models, the resultant differences in high burnup gas release predictions are presented here.

Comparing the RODEX2A fission gas release validation data base documented in Table B.1 of Reference 1 to the RODEX2 validation data base documented in Table A.1 of Reference 2 shows that the only difference is in the Zorita case. The Zorita rods were included in the RODEX2 validation report,[2] but not in the RODEX2A report.[1]

Table 1 is an updated version of Table B.1 of Reference 1 to include the Zorita rods. This table lists the rod ID, burnup, the fission gas release predictions for RODEX2A, and the measured releases.

Figures 1 and 2 plot the RODEX2A calculated versus measured release, with and without Zorita rods, respectively. The points in the figures closely spread along the ideal correlation lines where the calculated release equals the measured release. These two figures demonstrate that adding the Zorita rods does not affect the results of the RODEX2A fission gas release validation, i.e., the code gives good fission gas release predictions to the measured data.

Figure 1 demonstrates that the RODEX2A code gives good fission gas release predictions to the data using the same validation data base as the RODEX2 code.

For the Table 1 data, rods with a burnup between 50 and 62 MWd/kgU were selected and are listed in Table 2. This table compares the RODEX2 and RODEX2A fission gas release predictions. [

].

Fission gas release predictions are shown again in Figure 3 in terms of the deviation from the measurement data versus exposure. In the extended exposure range, the predictions are conservative relative to both the data and the lower exposure predictions.

The RODEX2 code has been approved for application up to 62 MWd/kgU rod burnup. Based on Figures 1 and 3 and Table 2, the RODEX2A code is justified [

].

3.0 REVIEW OF DESIGN METHODOLOGY

Each of the areas addressed by Section 4.2 of the Standard Review Plan (SRP) has been reviewed to determine if the existing SPC criteria and methods[4,5] are applicable with RODEX2A at [ ]. Except for a modification to the fuel rod cladding strain criteria, the existing criteria and methods are applicable to an extension to rod burnups [ ].

<u>Fuel System Damage</u>

(a) <u>Stress</u> - The stress limits of Reference 5 are conservative for extended burnup applications because the Zircaloy yield strength has been shown to increase with

increased irradiation exposure. Beginning-of-life cladding tensile properties are used in establishing the stress limits.

Corresponding with the strength increase at higher exposures, the ductility is greatly reduced. However, the limits, as based on the ASME Code, restrict cladding stress levels to be within the elastic regime such that the corresponding strains remain low (<0.2% yield point offset). Such strains are lower than the expected failure strains for irradiated Zircaloy.

To account for corrosion at end-of-life (EOL), the wall thickness loss is considered in the analysis.

(b) Strain - SPC maintains the 1% transient strain limit as specified in the SRP up to a pellet exposure of 60 MWd/kgU. Higher PWR exposure data has indicated lower cladding ductility at high exposures.[3] Consistent with the SPC PWR criteria, the strain limit is reduced to [ ].

(c) Fatigue - The number of expected duty cycles is unchanged since the assembly exposure limit has not changed. The higher rod exposure peaking will therefore not reduce the applicability of the fatigue limit.

(d) Fretting Wear - SPC assemblies have been designed so that, under the most adverse projected spacer relaxation and deformation conditions, there is no significant fretting wear. These conditions have not changed since the bundle exposure limit remains the same.

(e) Oxidation and Crud - The effects of oxidation and crud are specifically modeled in SPC's fuel rod calculations. The EOL stress analysis includes a wall thickness reduction to account for oxidation. The extension in rod exposure will lead to higher oxidation. However, this increase is small. The amount of oxidation observed on SPC BWR fuel has been low, even for higher exposure fuel. Figure 4 shows

measured peak oxide thickness data on SPC BWR fuel. [

].

The current amount of wall thinning used in the stress analysis at EOL conditions continues to apply at the increased rod exposure.

(f) Rod Bow - The approved rod bow model is conservative at high burnups, particularly since rod bow saturates at lower burnup.

(g) Axial Growth - SPC's method of determining maximum and minimum conservative limits on the rod and assembly growth data continues to be conservative for increased burnup. The growth data shows well-behaved trends with increased exposure and fluence.

(h) Rod Internal Gas Pressure - The SPC methodology for calculating EOL internal gas pressure has a large margin of conservatism, due in part to the conservatism in the RODEX2A code and the power history input. The preceding section presents benchmark cases demonstrating the conservativeness and applicability of the RODEX2A code for the higher rod exposures.

(i) Assembly Lift-Off - Assembly lift-off criterion is not exposure-dependent and is therefore unaffected by pellet or rod exposure.

Fuel Rod Failure

(j) Hydriding - Internal hydriding as a cladding failure mechanism is precluded by controlling the level of hydrogen impurities in the fuel pellets during fabrication. Since it is an early-in-life failure mechanism, it is not an issue for the RODEX2A change.

(k) Clad Collapse - SPC's method for verifying that creep collapse does not occur is [ ] independent of extended rod burnup operation, and it is therefore still acceptable.

(l) Overheating of Cladding - Compliance with the criterion for avoiding DNB is confirmed as a part of the reload thermal-hydraulics analysis. Experimentally-based critical heat flux correlations which have been accepted by the NRC are used. These correlations are not burnup dependent.

(m) Overheating of Pellets - The SPC evaluation of the fuel centerline melt limit is performed with the RODEX2A fuel performance code which, aside from differences in the fission gas release model, is identical to the RODEX2 code. RODEX2 has been approved by the NRC for burnup applications to 62 MWd/kgU (rod average). The extension of this methodology to the proposed burnup is [ ].

(n) PCI - PCI is addressed by the 1.0% strain criterion, which is reduced [ ]. RODEX2 is used to evaluate initial conditions for ramping analyses for the determination of the cladding strain. As discussed in the previous section, the validity of RODEX2 to the higher exposures has already been approved for PWRs. RODEX2A is not used in this evaluation.

In addition, fuel melting is not permitted. Fuel temperatures are evaluated using RODEX2A which is justified based on the code validation results presented in the preceding section.

(o) Cladding Rupture - Cladding rupture limits and evaluation are an integral part of the LOCA/ECCS methodology, which is considered in (q) and (s) below. RODEX2A is not used in this evaluation.

(p) Fuel Rod Mechanical Fracturing - Fuel rod mechanical fracturing caused by externally applied forces can result from seismic/LOCA loading. The design limits are based on unirradiated yield and ultimate tensile strengths. Because yield and ultimate tensile strengths will only increase with increased irradiation and burnup, and because the decrease in cladding ductility is not limiting, these criteria are acceptable for the extended rod burnup limits. RODEX2A is not used in this evaluation.

Fuel Coolability

(q) Fragmentation of Embrittled Cladding - The most severe occurrence of cladding oxidation and possible fragmentation during an accident results from a LOCA. Those burnup-dependent input parameters important to the LOCA, such as stored energy and fission gas release from steady-state operation, are provided by the approved RODEX2 steady-state performance code. As noted earlier, this code accounts for those fuel performance phenomena which are important. Therefore, this criteria is unaffected by the RODEX2A change.

(r) Violent Expulsion of Fuel - In a severe reactivity-initiated accident, the deposition of energy is the critical item. This is evaluated on a cycle-specific basis and is not part of the SPC mechanical design analysis. Currently, an industry-wide re-evaluation of this transient is underway due to recent test data showing a lower failure threshold with exposure. The SPC cycle-specific evaluations will be modified as required by these industry/NRC re-evaluations.

(s) Cladding Ballooning - Zircaloy cladding will balloon under certain combinations of temperature, heating rate, and stress during the LOCA. Therefore, the LOCA analysis must consider the cladding swelling and burst strain impacts on the flow. SPC uses the models in NUREG 0630. This swelling and rupture model is an integral part of the LOCA evaluation and is not part of the SPC mechanical design analysis. The occurrence of swelling and rupture results in conservative overpredictions of the cladding temperature in the SPC Appendix K model.

Therefore, not considering the cladding ductility reduction for high exposure fuel is conservative.

(t) Structural Deformations - Since the fuel assembly exposure has not changed, methods and criteria related to assembly structural deformations are unaffected.

4.0 EXAMPLE FUEL ROD DESIGN ANALYSIS

Fuel rod calculations were performed consistent with an assembly exposure of [ ] MWd/kgU. The rod design is the same as presented in Reference 6, except for small modifications to the pellet-to-cladding gap, pellet dish volume and density. Rod parameters used in the analyses are listed in Table 3. The methods are also the same as given in Reference 6 and documented in Reference 5. Applicable LHGR limits and power history inputs are given in Figures 3.1, 3.3 and 3.5 of Reference 6.

All calculation results meet the design limits.

Overheating of Fuel Pellets

Fuel temperatures were evaluated at both normal operating conditions and for AOOs. Figure 5 shows the maximum calculated temperatures for the UO_2 fuel rod versus exposure. Also shown in the figure is the calculated temperature at powers coinciding with the LHGR limit for AOOs. At all exposures, the fuel temperatures remain below melting.

Pellet-Cladding Interaction

Initial conditions for transients are obtained from RODEX2 output. From these initial conditions, RAMPEX is used for the determination of cladding transient strain.[7] The initial conditions include gas release, fuel densification, fuel swelling, and fuel relocation due to pellet cracking, all of which depend on the prior operating history. Additional inputs for ramp rates and powers are prescribed. The ramp rates coincide with essentially

unrestricted power maneuvering, with selected terminal ramp powers based on the LHGR limits given in Reference 6.

The maximum calculated transient strain is less than 1.0% for LHGRs below the transient overpower limit and at pellet exposures [ ]. As described in the previous section, the fuel temperatures remain below the melting point at LHGRs at or below the overpower limits, in agreement with the criterion.

In addition to the ramping analyses described above, cladding strain was analyzed under steady-state conditions. The calculated creep strain is shown in Figure 6. Maximum steady-state creep strain is less than the 1.0% limit.

Rod Internal Pressure

Figure 7 shows the results from the analysis of the UO_2 fuel rod. The pressure is less than the system pressure [ ]. This satisfies the criteria for gas pressure.

Table 1

RODEX2A Fission Gas Release Predictions

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[ ]

Table 1

RODEX2A Fission Gas Release Predictions (Continued)

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[

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Table 1

RODEX2A Fission Gas Release Predictions (Continued)

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Table 2

RODEX2A Fission Gas Release Predictions for Rods Above 50 MWd/kgU Rod Average Burnup

[

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Table 3

Fuel Rod Parameters for Example Calculations

Characteristic	Material	Value
Fuel Rod Cladding	Zircaloy-2 with zirconium liner	
Cladding outside diameter, inch (mm)		0.433 (11.00)
Cladding inside diameter, inch (mm)		0.3807 (9.670)
Fuel Column	UO_2	
Pellet outside diameter, inch (mm)		0.3737 (9.492)
[ ]		[ ]
Active length, inch (mm)		150.00 (3810.0)
Percent theoretical density		96.0
[ ]		[ ]
[ ]	[ ]	[ ]

[

]

Figure 1

RODEX2A Fission Gas Release Prediction vs. Measurement (with Zorita Rods)

[

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Figure 2

RODEX2A Fission Gas Release Prediction vs. Measurement (without Zorita Rods)

[

]

Figure 3

RODEX2A Fission Gas Release Deviation
(Calculated-Measured) vs. Exposure

[

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Figure 4

SPC BWR Peak Oxide Thickness Measurements vs. Exposure

[

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Figure 5

RODEX2A Calculated Fuel Temperature vs. Exposure

[

]

Figure 6

RODEX2A Calculated Cladding Creep Strain vs. Exposure

[

]

Figure 7

RODEX2A Calculated Fuel Rod Internal Pressure vs. Exposure

5.0 REFERENCES

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