REQUEST FOR ADDITIONAL INFORMATION

RELATED TO AREVA NP, INC.

TOPICAL REPORT ANP-10323P

"FUEL ROD THERMAL MECHANICAL METHODOLOGY FOR BOILING WATER REACTORS AND PRESSURIZED WATER REACTORS"

Request for Additional Information (RAI) Questions Related to Understanding the Models

RAI 1 Equation 7-100 in the Theory Manual that describes the M5 fuel rod cladding irradiation free growth appears to be in error. The exponential term appears to saturate at very low fluence values and the first term does not appear to be the correct order of magnitude to give strain in percent. Please review this equation and provide a revised growth equation.

RAI 2 Please provide examples of the radial power profile for the uranium oxide (UO_2) fuel pellets and the UO_2-gadolinia (Gd_2O_3) fuel pellets. Provide profiles for each fuel type at 1, 5, 10, 20, 40, and 60 gigawatt-days per metric ton of uranium (GWd/MTU) pellet average burnup.

RAI 3 Please provide a sample calculation of pellet thermal relocation displacement as a function of burnup for power levels of 15, 30, and 45 kilowatt per meter (kW/m). It is unclear from the Theory Manual how the term u_{th_rel} is calculated since u_{th_rel}, g_{norel}, and $\varepsilon_\theta^{pel\_rel}$ are all functions of each other (Equations 7-44, 7-48, and 7-50). Please describe how these terms are calculated.

RAI 4 Fission gas release (FGR) models are complex and their review requires a series of sample calculations to provide insights into the behavior of the steady state and transient models under different conditions. To assist in the evaluation of the GALILEO FGR models, a set of assessment cases are requested for GALILEO as outlined below. In addition, FRAPCON-3 calculations will be performed for comparison. For each case below please provide all appropriate input information including rod geometry, reactor conditions, and power history. Also, please provide a plot or table of FGR, fuel centerline temperature, and pellet-cladding gap thickness as a function of time (or burnup).

a. A pressurized water reactor (PWR) 17x17 M5/UO_2 and M5/UO_2-Gd_2O_3 fuel assembly with flat axial power profile and constant power history of 6 kilowatt per foot (kW/ft) to 70 GWd/MTU

b. A PWR 17x17 M5/UO_2 and M5/UO_2-Gd_2O_3 fuel assembly with flat axial power profile and constant power history of 10 kW/ft to 40 GWd/MTU

c. A PWR 17x17 M5/UO_2 and M5/UO_2-Gd_2O_3 fuel assembly with flat axial power profile and constant power history of 6 kW/ft to 30 GWd/MTU then power ramped to

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the linear heat generation rate (LHGR) limit and held for a limiting Condition I event. Perform same analysis but power ramped to a limiting power for a Condition II event.

d. A PWR 17x17 M5/UO_2 and M5/UO_2-Gd_2O_3 fuel assembly with flat axial power profiled and constant power history of 6 kW/ft to 50 GWd/MTU then power ramped to the LHGR limit and held for a limiting Condition I event. Perform same analysis but power ramped to a limiting power for a Condition II event.

RAI 5 Equation 9-27 in the Theory Manual describes the zirconia conductivity model. Please provide data to justify the rather steep temperature dependence and the dependence on oxide thickness.

RAI 6 The hydrogen pickup fraction of **[ ]** percent for Zircaloy-4 (Zr-4) seems low based on the data in Figures 12-7 and 12-8 of the Validation Report. The average hydrogen pickup fraction of the data in Figure 12-8 is **[ ]** percent. Please justify the use of a lower than average pickup fraction or propose a pickup fraction consistent with the data.

RAI Questions Related to the Methodology

RAI 7 Please provide the fuel rod power history, fuel rod geometry, and reactor coolant conditions for a rod (or rods) that challenges the following specified acceptable fuel design limits (SAFDLs):

a. Cladding strain limit
b. Rod internal pressure limit
c. Fuel melting limit
d. Cladding oxidation limit

In the data transmittal, please include the uncertainties for the fuel rod geometry (manufacturing uncertainties) and reactor coolant conditions used by AREVA in the GALILEO analysis. Using GALILEO, perform an uncertainty analysis with 59 cases that considers the manufacturing, models, and reactor coolant (if used) uncertainties. No power uncertainties should be applied. Please provide the frequency plot of the parameter of interest for each case requested. Please provide the input manufacturing values obtained from the random sampling process for each of the 59 cases.

RAI 8 The phenomena identification and ranking table (Table 5-3) of the methodology document ranks **[ ]** as having a low impact on the thermal analysis and is not considered in the uncertainties for steady-state modeling. **[ ]** and, therefore, can impact the mechanical analyses. Please justify this ranking as low.

RAI 9 As described in Section 5.4 of topical report ANP-10323-P (GALILEO), **[**

], the following is requested:

a. Please re-run the temperature validation cases listed in Table 7-3 and 7-4 of the GALILEO Validation Manual using upper bound and lower bound values of ADIFF123 (**[** **]**). Please plot these results on Figures 7-77 of the validation and verification (V&V) document and/or Figure 4-2 in ANP-10323P. Please plot the results as a function of burnup as shown in Figure 7-78 of the V&V manual.

b. Please re-run cladding strain (diameter change) cases list in terms of Table 4-12 of ANP-10323-P using upper bound and lower bound values of ADIFF123 (**[** **]**). Please plot these results for strain (diameter change) due to power ramping on Figures 4-33 thru 4-39 of ANP-10323-P.

RAI 10 The following are related to how the uncertainties and distributions for manufacturing and model parameters are determined.

a. Normal or log-normal distributions are used for the uncertainties associated with most of the manufacturing parameters (Table 5-5), model parameters (Table 5-8 and Table 5-9), and rod linear power parameters (Appendix B). Please provide the results of normality tests for the parameters listed in these tables using the Shapiro-Wilk or similar methods.

b. A first order relationship is assumed between the log of the model parameter to the mean/average (log of the calculated value (C) divided by the measured value (M)(log(C/M))) to calculate the standard deviation for the model parameter. This approach is used for both single parameter and multiple parameter uncertainty determinations. Please provide the results of the regression analysis for each parameter (e.g., coefficient of determination (R^2)) and plots of log (model parameter) versus average log(C/M) for each parameter. For the model parameter(s) with the lowest R^2 using a linear relationship, please estimate the impact of using a non-linear (polynomial) relationship. Critical to this approach is the assumption of normality for the distribution of the resulting log(C/M) for a given model parameter. Please provide an example of the frequency distribution versus average log(C/M) for the plus or minus 2 sigma (2σ) model parameter. Use both fission gas diffusion coefficient model parameter and the PWR Zr-4 stress relief annealed (SRA) cladding low stress irradiation creep model parameter as an examples (see RAI-15d).

c. For the percent standard deviation values listed in Table 5-8 for the model parameters, please provide the method used to determine the percent standard deviation for the PWR Zr-4 SRA cladding low stress irradiation creep model parameter ACREEPL (listed as **[** **]**). Please indicate if the same method is used for all the lognormal distributions listed in Table 5-8.

d. The uncertainties for the UO_2 thermal expansion, thermal conductivity, and specific heat were obtained from **[**

]. In determining the model

parameter uncertainty values in Table 5-9, a **[ ]** factor is used to calculate the one-sided 95^{th} percentile values. This assumes that the standard deviation and mean are from a normal distribution with an infinite number of data points. Please explain why the **[ ]** to calculate the 95^{th} percentile upper/lower bound parameters for these models. Please indicate if the method used to apply these model uncertainties also used for gadolinia fuel?

RAI 11 Please provide a plot of rod node power versus burnup for rods used in the PWR 17x17 assembly sample problem analysis cases #3 (Section 6.2.3) and #5 (Section 6.2.5) described in Section 6 of ANP-10323P.

RAI 12 The cladding limits on corrosion thickness and hydrogen content are proposed in Section 3.1.1 for each of the cladding materials included in GALILEO application methodology.

a. For each cladding type discussed in Section 3.1.1, please provide measured cladding permanent strains and the coolant temperature from in-reactor power ramp tests from fuel rods with corrosion layer and hydrogen levels at or exceeding the limits requested. Also provide uniform strains and test temperature from ex-reactor cladding mechanical tests on irradiated cladding from fuel rods with corrosion and hydrogen levels developed in reactor at or exceeding the limits requested. Specify the type of mechanical property test performed.

b. Please provide the technical basis for using an oxide corrosion limit for Zr-4 based **[ ]** as described on page 3-4 of the methodology document when using a corrosion model that calculates **[ ]**. Please indicate whether the measured oxide thickness data used in Figures 4-70 and 4-71 of the methodology document is the circumferential average value or is the maximum local (point) value around the circumference.

RAI 13 Little information is given on the uncertainties and how they are applied in the analyses of ovality (GALILEO) and collapse (CROVINC) models.

a. The ovality enhancement factors for M5 and Zry-2 (Section 4.3.11.1 of the methodology document) appear to not be based on any data. In addition, the ovality data for Zry-2 recrystallized annealed (RXA) cladding appears to be based on only small observations of ovality that may not be applicable to large ovalities **[ ]** (cladding has contacted the pellet). Please justify the use of these enhancement factors for each cladding type as being conservative in relation to creep collapse analysis.

b. The application of creep, measurement uncertainties, and additional conservatism is unclear. Section 5.4.7 of the methodology document states “**[ ]**” Please provide plots of the ovality data with the bounding relationships. Please provide information on how these uncertainties are determined

from the data, particularly, when there is no or little ovality data for each cladding type. Please justify that these assumed conservatisms will result in adequately conservative predictions of cladding contact with the pellet at two points (resulting in pellet hangup) that leads to the formation of an axial gap in the pellet column. Do these analyses account (implicitly or explicitly) for the effect of pellet ridging?

c. The CROVINC model **[** **]** appears to be validated only against M5 cladding collapse data from unirradiated cladding. It is noted that the M5 prediction of collapse contains significant scatter in Figure 4-56 of the methodology document. Please demonstrate that the assumed conservatisms will result in adequately conservative predictions of creep collapse for each cladding type.

d. Please provide a calculation of ovality change versus burnup/time for the most limiting current AREVA design with Zry-4 cladding using the methodology in report BAW-10084P-A and using the uncertainties in this current submittal.

e. Please provide results from the CROVINC model for the collapse pressure (P_{coll}) and clad ovalization rate as a function of clad through-wall average temperature (T_{avg}) and fast neutron flux. Present the results of P_{coll} versus a range of T_{avg} for the clad spanning the expected range for Zr-4 and M5. Please perform these calculations at three fast neutron levels: nominal, 0.8 nominal, and 1.2 nominal.

RAI 14 The following is related to the cladding fatigue model and its application.

a. Has any fatigue data been taken from cladding alloys requested in this submittal, or is the O'Donnell data the only data used to justify the fatigue threshold. If so, please provide cladding cyclic fatigue data for any cladding type with the burnup level and hydrogen content of the cladding, of concern are the lack of data at the hydrogen levels requested.

b. Please provide a specific example with the uncertainties and distributions considered in the fatigue analysis and how cumulative usage factor (CUF) is determined. Is a CUF calculated for at least 2,995 fuel rod samples?

c. From Tables 6-3 and 6-4 of the methodology document it appears that cladding transients are not included in the analysis of cladding fatigue. Please justify excluding transient events in the analysis of cladding fatigue.

RAI 15 The following are related to how analyses are performed for slow and fast transients.

a. Section 3.4.4.1 of the methodology document states that **[** **]** at 10, 25, and 35 GWd/MTU for typical power levels used in these PWR anticipated operational occurrence (AOO) analyses.

b. The model uncertainties for fuel creep, gaseous swelling, dish filling, relocation, and gap conductance do not appear to be considered for slow and fast transients.

Please provide quantitative justification why the uncertainties in each of these models are not considered for each transient application other than the qualitative discussion given in Section 5.4.9 of the methodology document.

c. How are the limiting fast AOO transient events determined? Also, discuss how the ramp hold times are assumed for fast and slow transients.

d. Please provide an example analysis for PWR fast and slow transients and how exposure points are selected for these transients. The example should include the input (including uncertainties and distributions) used to determine the limiting overpower and burnup for fuel melt and cladding strain at a 95/95 level (for the **[ ]** cases). Please provide the calculated output fuel melt and cladding strain distributions.

e. Is fuel relocation included in the cladding mechanical analyses performed for fast and slow transients? If not, please justify with data at low to moderate burnup levels.

RAI 16 Appendix B in ANP-10323P provides an overview of the application of fuel rod average power and axial power shape uncertainties in the AREVA GALILEO methodology. **[**

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[ ] (B.2)

The following are questions about the application of the uncertainties within Equation B.2.

a. **[**

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b. Please provide information demonstrating the assumption **[**
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c. Is rod bow effect on power uncertainties included in the calculational/measurement uncertainty value obtained from the neutronics calculation?

RAI 17 The following are related to the applying and combining of statistical probabilities.

a. **[** **]**. This appears to be non-conservative, please justify.

b. The uncertainties for **[** **]**.

RAI 18 The following are related to the sensitivity analyses (Section 6.3 of the methodology document).

a. Why is the fuel centerline temperature excluded from the PWR sensitivity results (Table 6-31 of the methodology document)?

b. How is that only propagating the PWR model parameter uncertainties (Table 6-31 of the methodology document) results in a **[** **]**?

c. The sensitivity analyses show **[** **]** (Table 6-31 of the methodology document). A significant variation in oxidation is often seen between rods with differing power histories, typically, higher power operation later in life result in much higher oxidation than a rod with low rod powers late in life. **[** **]**.

RAI 19 Please provide an example calculation of the rod pressure limit based on no cladding liftoff and hydride reorientation for each cladding type. What is the assumed system pressure for this analysis?

RAI 20 The low stress cladding creep model uncertainty analysis described in Section 5.4.5.1 and 5.4.5.2 appears to use data from **[** **]**.

a. In Figure 5-9 and 5-12, please indicate which data points correspond to the **[** **]**.

b. Please confirm that the data contained in Figure 5-9 are from the **[** **]** or rods given in Tables 10-1 in the GALILEO Validation Report (FS1-0004683). For the Zr-4 model, please indicate if the test rods used in the validation of the model **[** **]** were used in the uncertainty analysis.

c. The relationship between the calculations/data reported in Figure 5-12 and the M5 creep model calibration and validation described in FS1-0004683 is ambiguous. Please describe the relationship between Figure 5-12 in the GALILEO topical report and Figure 10-47 shown in the validation manual (FS1-0004683).

RAI Questions Related to Code Applicability

RAI 21 The following are related to determining the operational (power and burnup) range the code has been calibrated and validated against.

a. Please provide rod average LHGR versus burnup for the thermal data used to calibrate and validate the code. Provide separate plots for UO_2 and gadolinia rods. Provide the fuel design LHGR limit versus burnup on each of these plots for each fuel design.

b. Please provide rod average LHGR versus burnup for the FGR data used to calibrate and validate the code. Provide separate plots for UO_2 and gadolinia rods.

c. Please provide rod average LHGR versus burnup for the corrosion data used to calibrate and validate the code. Provide separate plots for UO_2 and gadolinia rods.

d. Please provide ramp terminal peak and ramp terminal rod-average LHGR versus burnup for the transient FGR data from power ramp tests used to calibrate and validate the code. Provide separate plots for UO_2 and gadolinia rods.

e. Please provide ramp terminal LHGR versus burnup for the cladding diameter change data from power ramp tests used to calibrate and validate the code. Provide separate plots for UO_2 and gadolinia rods.

RAI 22 The following are in reference to the limits of applicability of the code stated in Section 4.6 of the methodology document.

a. A lower limit is placed on fuel density; however, no upper limit is defined. The concern with very high density pellets is micro-cracking and axial/radial variation in density. Please define an upper-limit on fuel density with pellet fabrication data on a commercial scale to substantiate this upper density limit.

b. An upper limit is placed on fuel grain size, however, a lower limit is not defined. Please define a lower limit as grain size is known to impact fuel creep, FGR and fuel densification, particularly, at low values along with justification for the lower limit. Please provide a plot of predicted-minus-measured FGR versus grain size for measured values greater than 5 percent mean linear intercept. Identify UO_2 and gadolinia rod data and power ramped rods in these plots. Please provide a similar

plot of predicted-minus-measured strain versus grain size from power ramping (transient) tests.

c. A limit of 10 percent by weight for the gadolinia level in UO_2-Gd_2O_3 rods is specified in Table 4-1 of the V&V document, but not in ANP-10323P. Please provide a justification for this limit including past experience up to this limit.

RAI 23 Section 4.1 of the methodology document suggests that **[**

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a. Please propose a limit on changes to the model parameter uncertainties in terms of a biased deviation in the new data from the current model/database. Is it acceptable to input a bias or only an increased uncertainty band?

b. Please clarify if it will be acceptable to make modifications to the cladding oxidation and crud models for a particular plant that deviates from the previous oxide and crud database on a temporary basis. Please propose a specific criteria and approach to notify NRC and prepare a plan of action if this becomes a trend for more than a given number of cycles of operation.

RAI 24 The following are related to FGR data comparisons.

a. Please replot Figure 4-16 of the methodology document with an x-axis range of 0 to 15 percent FGR. Please plot the UO_2 and gadolinia rods with separate symbols (the same as that used in Figure 4-13 would be sufficient). Please separate the data in Figure 4-19 in the same way.

b. Please provide linear power values (cycle average and cycle maximum) for all the data used in Figure 4-17 of the methodology document. Identify which rods are 15x15 assemblies and which are 17x17 assemblies.

RAI 25 The following questions are associated with the fuel rod elongation and stack length calculations and comparison to measurements for the PWR fuel types.

a. Please provide predicted minus measured (P-M) versus fluence for the rod axial elongation data shown in Figures 4-60 and 4-62 of the methodology document, identifying the length-to-diameter (L/D) datasets. Please provide P-M vs burnup for the stack length change data shown in Figures 4-61 and 4-63.

b. Please provide an explanation for the over predictions in the cladding elongation calculations shown in Figure 4-60 for the M5/UO_2 16x16 fuel assembly.

RAI Questions Related to Code Validation

RAI 26 The following are related to verifying the code's prediction of PWR cladding corrosion thickness (and/or liftoff). It is noted that the Zr-4 cladding corrosion model **[**

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a. Please identify the reactors (see Tables 4-8 of the methodology document and 6-3 of the V&V document) from which the Zr-4 corrosion measurement data were taken. Please provide the core average LHGR, inlet and exit temperatures, and cycle lengths for each reactor, and the number of measurements and rods from each reactor.

b. Please provide predicted-minus-measured oxide thickness for both calibration and validation data versus burnup and effective full power days that illustrates the best estimate and upper bound predictions for Zr-4 (greater than 50 µm) and M5. Please separate the data for each cladding type by “thick” rods and “thin” rods.

c. Please demonstrate that the Zr-4 oxidation data are bound with a 95/95 tolerance level, particularly at high measured oxide thicknesses where oxidation is limiting. This can be accomplished by plotting the predicted 95/95 for each measurement shown in Figure 4-71 versus the measured value. Other approaches can be used as well.

d. The PWR rod corrosion data are noted to be a **[**

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e. How is the calculated Zr-4 oxide thickness value compared with the oxide thickness limit? The **[**

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f. Please provide the P-M vs measured (M) and P-M versus burnup for the oxide thickness data plotted in Figures 4-71 and 4-74 of the methodology document. Please bin the data into the following fuel assemblies and cycle lengths:

18x18
17x17 12-month and18-month cycles
16x16 12-month, 18-month, and 24-month cycles
15x15 12-month, 18-month, and 24-month cycles
14x14 12-month and 24-month cycles

g. Please provide the core coolant temperatures (inlet/outlet), core average LHGR, and maximum cycle average LGHR for the PWR fuel rods comprising the both the so-called “commercial” and “commercial FGR” databases (Tables 4-2 and 4-8, respectively, of the methodology document, and Table 6-3 of the V&V document) and the oxidation database.

RAI 27 The following are related to the modeling and verifying the fuel thermal conductivity model.

a. Please perform a one axial node (15x15 fuel assembly) temperature prediction versus burnup up to 72 GWd/MTU for constant linear heat generation rates of 5 kW/ft, 6 kW/ft, and 8 kW/ft assuming a constant value of gap conductance. From these calculations please provide a table of calculated radial temperatures for at least 15 equal volume nodes at burnups of 20, 40, 50 and 70 GWd/MTU. Perform one axial node (15x15 fuel assembly) temperature predictions for 10, 12, and 13 kW/ft up to 35 GWd/MTU assuming a constant value of gap conductance. From these calculations please provide a table of calculated radial temperatures for at least 15 equal volume nodes at burnups of 10, 20 and 35 GWd/MTU.

b. Please compare the GALILEO fuel thermal conductivity model to data from Carrol et al. (Halden Project Report (HPR) 345, Paper 13) and Ronchi et al. (JNM 327, pages 58 – 76) at burnups less than 60 GWd/MTU, only data without annealing. Provide P versus M and P-M versus burnup. On a separate plot provide P versus M for data at burnups greater than 60 GWd/MTU and P-M versus burnup.

RAI 28 The following are related to the calibration and validation of the code to measured fuel centerline temperatures.

a. Are any of the SAFDLs for any AREVA fuel designs limiting at beginning-of-life or below a rod average burnup of 5 GWd/MTU?

b. The GALILEO thermal database for UO_2 relies heavily on data from older tests. Please provide one of the following for the Halden tests IFA-681 Rods 1 and 5 (Figures 5 and 10 from Halden Work Report (HWR) 832); IFA-677.1 Rod 2 (Figures 6 and 8 from HWR-872); and IFA-558 Rod 6 (NUREG/CR-7022 Volume 2, Figure 3.15):

   i. Comparison of the measured centerline temperatures in the GALILEO V&V database with the measured centerline temperatures from the these test rods or

   ii. The calculated GALILEO results of predicted and measured temperatures versus burnup for each of these tests; do not include any data below 15 kW/m. Include these additional data comparisons plotted as P/M versus burnup, P versus M, and P/M versus LHGR along with the original database (calibration and validation) that allows the additional test data to be identified by test.

c. The amount of thermal data for the gadolinia rods is very small. Provide additional comparisons to IFA-681 Rods 2, 4 and 6. Provide individual plots of P and M temperatures versus burnup for each of these tests; do not include any data below 15 kW/m. Also provide P/M versus gadolinia level for the new rod data as well as the calibration and validation rod data.

RAI 29 The following are related to the modeling, calibration, and validation of the code to measured FGR.

a. Please provide one of the following for the Halden tests IFA-597.3 rod 8 (HWR-543), IFA-677.1 rod 6 (Figures 5 and 10 from HWR-832), IFA515.10 rods A1 and A2 (HWR-671), and the FUMEX-III test rods FUMEX-6F and 6S (in IFPE database):

i. Comparison of the measured centerline temperatures in the GALILEO V&V database with the measured temperatures in these experiments or

ii. GALILEO predictions of fuel temperatures versus burnup and end-of-life FGR.

b. Please provide absolute differences (P-M) as well as relative differences (P-M/M) versus burnup for release values greater than 5 percent identifying UO_2, and gadolinia rods for calibration and verification data including the data comparisons from Part a above. Provide these same plots versus grain size. All plots should be on a linear scale.

c. Please provide absolute differences (P-M) as well as relative differences (P-M/M) versus M release for UO_2 identifying the rods by burnup range, e.g., 5 to 20 GWd/MTU, greater than 20 to less than 35 GWd/MTU, greater than 35 to less than 55 GWd/MTU, and greater than 55 GWd/MTU for calibration and verification data including the data comparisons from Part a above. Provide the same plots for gadolinia rods.

d. Please provide absolute differences (P-M) as well as relative differences (P-M/M) versus terminal LHGR for the transient (power ramped) FGR data for releases greater than 3 percent identifying UO_2, and gadolinia rods including the data comparisons from Part a above if power ramped. Please provide these same plots versus hold time, gadolinia content, and burnup.

e. Please provide C/M and C-M versus measured FGR for the upper and lower bound FGR models using calibration and verification steady-state data including the data comparisons from Part a above. It appears the lower bound model is not as bounding in terms of number of data as the upper bound model suggesting that the assumed distribution is not correct. Please provide justification why this is acceptable. Provide the same plot for the power ramped calibration and verification data.

f. The FGR model has **[ ]** uncertainties. Please justify the power uncertainties assumed for both the commercial and experimental reactor fuel rods.

g. Is the variability in FGR due to the vintage of the fuel or the duty of the fuel, or a combination of vintage or duty? Please explain the higher FGR observed for the 15x15 fuel assembly from the D24 reactor.

h. How does the duty of 17x17 fuel assembly population compare with 17x17 fuel assembly operating in high duty 17x17 fuel assembly reactors, e.g., on 2 x 18-month cycles, with burnups up to 36 GWd/tU during the first cycle and peak burnup of up to 60 GWd/tU in two cycles?

i. In a number of cases, rod internal pressure is under-predicted and rod internal void volume is over-predicted. Please provide a plot of the measured rod internal pressure versus the measured rod internal volume (P_m versus V_m) and calculated rod internal pressure versus the calculated rod internal volume (P_{cal} versus V_{cal}) for the

commercial UO_2, and gadolinia rods used to validate the GALILEO rod internal pressure calculation described in Section 4.3.15 of the methodology document. Create separate plots for PWR and BWR rods. In Figures 4-66 through 4-69, please indicate the measurements that are from the rods listed in commercial reactor database summarized in Table 4-13. Provide the as-fabricated void volumes for the current commercial fuel designs.

RAI 30 The following are related to the modeling and calibration/verification of the code to low stress cladding creep data for normal operation.

a. Please identify the burnup levels at which the gap typically closes for different PWR rod designs with Zr-4 SRA and M5 RXA cladding types. How is it determined that the gap is open such that the rod may be used to assess the creep model? Provide the data used to determine the open gap assumption for each cladding type and design. Identify those commercial fuel rods used for creep comparisons where the gap is assumed to be open identifying the design, burnup and cladding type. Also identify those data that are creep specimens (no active fuel present).

b. Please provide more information on the number of measurements per rod for the data that were used in the clad diameter change model validation summarized in Figures 4-43, 4-44, 4-49, 4-52, and 4-53 of the methodology document.

c. Please provide P-M versus axial position and P-M versus burnup for the cladding diameter change comparisons in Figures 4-43, 4-44, 4-49, 4-52, and 4-53 of the methodology document

d. It appears that the **[** **]**. Please provide a comparison of the fast flux (greater than 1 MeV) of this calibration Zr-4 creep data to the average fast flux in a commercial PWR. Please justify the applicability of this data for application to commercial PWRs.

e. Is the Zr-4 model applicable to both low tin and standard tin Zr-4 cladding? If so, please justify applicability because tin is known to have a significant impact on zirconium alloy cladding creep. If not what cladding type (low tin or standard) creep data were used to verify the Zr-4 creep model?

f. Figure 10-47 of the V&V document and Figure 5-11 of the methodology document appear to demonstrate that the GALILEO M5 creep model **[** **]**. Are these data included in the uncertainty for M5 creep? If not, why not?

g. The uncertainty for M5 cladding creep is **[**

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h. Please provide plots of P-M and ratio of P/M in-reactor creepdown versus stress (only in-reactor creep specimens unless stress was relatively constant for a commercial rod), versus fast flux, versus fast fluence, and versus temperature for each cladding type. For these plots distinguish between commercial fuel rods and in-reactor creep specimens. Provide the same but separate plots for those data with a positive stress for each alloy. Please provide the one sided upper and lower 95/95 bounds on these same plots for both compressive and tensile (positive) stress creep data.

i. Please provide plots of P-M and ratio of P/M steady-state (secondary) creep rate versus stress, versus fast flux, and versus temperature for in-reactor (commercial rods and creep specimens) data for each alloy. Identify those creep specimen data with a positive stress.

j. Please provide one of the following for the Zr-4 SRA creep data from IFA-585.1, IFA-585.4 (HWR-413 Figures 6 and 7, HWR-532 Figure 8) and IFA-699, and the M5 creep data from IFA-699 (HWR-882 Figure 13(a) and 13(b)).

    i. Comparison of the measured cladding creep strains in the GALILEO V&V database with the measured cladding creep strains in the experiments or

    ii. GALILEO predictions of creep strains for these experiments plotted as a function of full power hours.

k. Creep specimens are usually much better characterized (in terms of both operation and fabrication) than commercial fuel rods, therefore, having a much lower uncertainty than creep data from the latter. The use of the creep specimens for determining the best estimate coefficients appears to be justified but the uncertainties from these data appear to not be prototypical of commercial fuel application. Please justify the use of the creep specimens in determining the uncertainties in creep for commercial fuel applications.

l. Please provide the distributions for each cladding type in terms of P-M and ratio of P/M excluding any closed gap data (similar to Figures 5-8, 5-11, 5-14, and 5-17 of the methodology document) and include any new data comparisons requested (identifying this data by different colors). Identify those rods with a positive stress (strain). Please provide the one sided upper and lower 95/95 bounds on these distribution plots.

RAI 31 The following are related to the calibration, validation and application of the code to cladding diameter change (strain) due to power ramp tests.

a. Provide P-M diameter change versus ramp terminal power for ramped rods with long hold times (greater than 60 minutes) identifying the rods by burnup range, e.g., 5 to 15 GWd/MTU, greater than 15 to less than 25 GWd/MTU, greater than 25 to less than 35 GWd/MTU, greater than 35 to less than 45 GWd/MTU, greater than 45 to

less than 55 GWd/MTU and greater than 55 GWd/MTU. Identify different fuel designs.

b. Provide P-M diameter change versus ramp terminal power for ramped rods with short hold times (less than 30 minutes) identifying the rods by burnup range, e.g., 5 to 15 GWd/MTU, 15 to 25 GWd/MTU, 25 to 35 GWd/MTU, 35 to 45 GWd/MTU, 45 to 55 GWd/MTU and greater than 55 GWd/MTU.

c. Provide P-M diameter change versus ramp hold time for ramped rods identifying the rods by burnup range, e.g., 5 to 15 GWd/MTU, 15 to 25 GWd/MTU, 25 to 35 GWd/MTU, 35 to 45 GWd/MTU, 45 to 55 GWd/MTU and greater than 55 GWd/MTU. Identify different fuel designs.

d. Provide P-M diameter change versus pellet L/D ratio power for ramped rods with short hold times (less than 30 minutes) and long hold times identifying these rods separately. Provide the current L/D ratio used for each of the different AREVA fuel designs. Also, identify different fuel designs, and ramped rods with gadolinia fuel.

e. Provide P-M diameter change versus elevation for ramped rods for rods with greater than 2 foot lengths identifying the rods by burnup range, e.g., 5 to 15 GWd/MTU, 15 to 25 GWd/MTU, 25 to 35 GWd/MTU, 35 to 45 GWd/MTU, 45 to 55 GWd/MTU and greater than 55 GWd/MTU. Different length rods can be plotted separately. Identify different fuel designs, and rods with gadolinia fuel.

f. Please provide plots similar to those requested above but with the 95/95 uncertainties included in the calculation (upper and lower bound). Please justify the exclusion of any data from Tables 4-11 and 4-12 of the methodology document and identify the number of data bounded by the upper bound prediction.

RAI 32 The following are related to the high stress creep (plasticity) model for each cladding type.

a. Please provide P-M data diametral strain from the irradiated Zr-4 data in Figure 4-46 versus temperature, stress and fluence; identify (pressurized tube data and uniaxial tensile data). Provide similar plots for irradiated M5 identifying different fuel designs and burst versus uniaxial data.

b. From the **[ ]** burst tests on irradiated Zr-4 please provide P-M yield strength and ultimate tensile strength versus fluence and temperature. Provide similar plots for irradiated and M5 identifying burst versus uniaxial data. Also, provide similar plots of Figure 4-47 from **[ ]** irradiated burst tests with more than one temperature and fluence level up to 1.0 percent total strain or burst whichever occurs first for each of the cladding types.

c. Please provide P versus M, P-M versus fast fluence, and P-M versus temperature for the Zr-4 and M5 0.2 percent yield stress ($R_{p0.2}$).

d. Are unirradiated properties used for any AOO or accident events? If so, please define the event.

RAI 33 The following are related to the verification of the solid and gaseous swelling models for UO_2 and gadolinia fuel.

a. Please justify the swelling rate values of **[ ]** or **[ ]** for UO_2 gadolinia, fuel used in GALILEO. The swelling rate used in GALILEO is **[ ]**.

b. Please justify the use of fuel density data to predict fuel diameter and length changes due to solid swelling.

c. Please indicate which predicted density variation values (in Figure 4-26 in the Methodology document) were calculated using Equation 7-32 (**[ ]**) and which were calculated using Equation 7-33 (**[ ]**). These equations are described in the Theory Manual.

d. How is the fuel porosity data used in the validation of the gaseous swelling model obtained and what is the uncertainty in the data?

e. Are there any other data used to validate the gaseous swelling model, **[ ]**? Please provide an example of how the gaseous swelling model is validated against this data. What is the range of ramp rates for the cladding strain data and how do these compare to the ramp rates for the different AOO events modeled?

f. Rod diameter data seems to be a more relevant parameter to demonstrate the fuel gaseous swelling model. Please provide the measured cladding diameter change during the ramp as a function of burnup. Also, include the predicted values (or could be a separate plot).

RAI 34 The Zr-4 hydrogen pickup model is based on a **[ ]** if the data are applicable to current PWR operation. Of concern is the applicability of this **[ ]**.

a. Please provide the cladding tin level, fuel design, plant core average power, primary inlet and outlet temperatures, cycle lengths, and power histories (nodal LHGR) for the **[ ]** Zr-4 data points used to calibrate the hydrogen pickup model. Provide the same information on any Zr-4 rods used in the validation but not used to calibrate the Zr-4 pickup model.

b. Please provide a P-M hydrogen versus burnup and effective full-power day for the Zr-4 data identifying the fuel rod design geometry.

c. Please provide P-M versus axial location for the Zr-4 data identifying the fuel rod design geometry.

d. Please provide a demonstration that the hydrogen pickup model can provide bounding hydrogen predictions when uncertainties in the corrosion model and hydrogen pickup model are combined according to your statistical methodology.