FRAMATOME ANP

February 5, 2001
GR01-021.doc

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, D. C. 20555

Reference: 1. Stewart Bailey, NRC, to T. A. Coleman, Framatome Cogema Fuels, Request for Additional Information – Framatome Topical Report BAW-10231P (TAC NO. MA6792), August 11, 2000.

2. T. A. Coleman, Framatome Cogema Fuels, to U. S. Nuclear Regulatory Commission, GR00-142.doc, September 29, 2000.

Gentlemen:

Reference 1 provided a request for additional information (RAI) on Framatome Cogema Fuels (FCF) topical report BAW-10231P, "COPERNIC Fuel Rod Design Code." In reference 2, FCF agreed to provide responses to the RAI by January 31, 2001. The responses are enclosed. The responses are being submitted with the prefix 14 on each page. When the final NRC-approved version of BAW-10231P is issued, the responses will comprise chapter 14.

In accordance with the provisions of 10 CFR 2.790, Framatome ANP requests that these responses be considered proprietary and withheld from public disclosure. Attachment 1 is an affidavit supporting this request. Attachment 2 is the proprietary version of the responses and Attachment 3 is the non-proprietary version.

The approval of the COPERNIC code at this time is requested for the advanced alloy M5™ cladding only. Framatome ANP will continue to use the NRC approved code TACO for applications with Zircaloy cladding. Responses for the Zircaloy portions of the RAI (Questions 14, 15, 16, 19, 20, 21, and 23) will be provided at such time that approval for COPERNIC application to Zircaloy cladding is requested by our customers.

Very truly yours,

TAColeman

T. A. Coleman, Vice President
Government Relations

T007

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ATTACHMENT 1

AFFIDAVIT OF THOMAS A. COLEMAN

A. My name is Thomas A. Coleman. I am Vice President of Government Relations for Framatome ANP. Therefore, I am authorized to execute this Affidavit.

B. I am familiar with the criteria applied by Framatome ANP to determine whether certain information of Framatome ANP is proprietary and I am familiar with the procedures established within Framatome ANP to ensure the proper application of these criteria.

C. In determining whether an Framatome ANP document is to be classified as proprietary information, an initial determination is made by the cognizant manager, who is responsible for originating the document, as to whether it falls within the criteria set forth in Paragraph D hereof. If the information falls within any one of these criteria, it is classified as proprietary by the originating cognizant manager. This initial determination is reviewed by the cognizant Section Manager. If the document is designated as proprietary, it is reviewed again by personnel and other management within Framatome ANP as designated by the Vice President of Government Relations to assure that the regulatory requirements of 10 CFR Section 2.790 are met.

D. The following information is provided to demonstrate that the provisions of 10 CFR Section 2.790 of the Commission's regulations have been considered:

(i) The information has been held in confidence by Framatome ANP. Copies of the document are clearly identified as proprietary. In addition, whenever Framatome-ANP transmits the information to a customer, customer's agent, potential customer or regulatory agency, the transmittal requests the recipient to hold the information as proprietary. Also, in order to strictly limit any potential or actual customer's use of proprietary information, the substance of the following provision is included in all agreements entered into by Framatome ANP, and an equivalent version of the proprietary provision is included in all of Framatome ANP's proposals:

"Any proprietary information concerning Company's or its Supplier's products or manufacturing processes which is so designated by Company or its Suppliers and disclosed to Purchaser incident to the performance of such contract shall remain the property of Company or its Suppliers and is disclosed in confidence, and Purchaser shall not publish or otherwise disclose it to others without the written approval of Company, and no rights, implied or otherwise, are granted to produce or have produced any products or to practice or cause to be practiced any manufacturing processes covered thereby.

Notwithstanding the above, Purchaser may provide the NRC or any other regulatory agency with any such proprietary information as the NRC or such other agency may require; provided, however, that Purchaser shall first give Company written notice of such proposed disclosure and Company shall have the right to amend such proprietary information so as to make it non-proprietary. In the event that Company cannot amend such proprietary information, Purchaser shall, prior to disclosing such information, use its best efforts to obtain a commitment from NRC or such other agency to have such information withheld from public inspection.

Company shall be given the right to participate in pursuit of such confidential treatment."

(ii) The following criteria are customarily applied by Framatome ANP in a rational decision process to determine whether the information should be classified as proprietary. Information may be classified as proprietary if one or more of the following criteria are met:

a. Information reveals cost or price information, commercial strategies, production capabilities, or budget levels of Framatome ANP, its customers or suppliers.

b. The information reveals data or material concerning Framatome ANP research or development plans or programs of present or potential competitive advantage to Framatome ANP.

c. The use of the information by a competitor would decrease his expenditures, in time or resources, in designing, producing or marketing a similar product.

d. The information consists of test data or other similar data concerning a process, method or component, the application of which results in a competitive advantage to Framatome ANP.

e. The information reveals special aspects of a process, method, component or the like, the exclusive use of which results in a competitive advantage to Framatome ANP.

f. The information contains ideas for which patent protection may be sought.

The document(s) listed on Exhibit "A", which is attached hereto and made a part hereof, has been evaluated in accordance with normal Framatome ANP procedures with respect to classification and has been found to contain information which falls within one or more of the criteria enumerated above. Exhibit "B", which is attached hereto and made a part hereof, specifically identifies the criteria applicable to the document(s) listed in Exhibit "A".

(iii) The document(s) listed in Exhibit "A", which has been made available to the United States Nuclear Regulatory Commission was made available in confidence with a request that the document(s) and the information contained therein be withheld from public disclosure.

(iv) The information is not available in the open literature and to the best of our knowledge is not known by Combustion Engineering, Siemens, General Electric, Westinghouse or other current or potential domestic or foreign competitors of Framatome ANP.

(v) Specific information with regard to whether public disclosure of the information is likely to cause harm to the competitive position of Framatome ANP, taking into account the value of the information to Framatome ANP; the amount of effort or money expended by Framatome ANP developing the information; and the ease or difficulty with which the information could be properly duplicated by others is given in Exhibit "B".

E. I have personally reviewed the document(s) listed on Exhibit "A" and have found that it is considered proprietary by Framatome ANP because it contains information which falls within one or more of the criteria enumerated in Paragraph D, and it is information which is customarily held in confidence and protected as proprietary information by Framatome ANP. This report comprises information utilized by Framatome ANP in its business which afford

AFFIDAVIT OF THOMAS A. COLEMAN (Cont'd.)

Framatome ANP an opportunity to obtain a competitive advantage over those who may wish to know or use the information contained in the document(s).

THOMAS A. COLEMAN

State of Virginia)
) SS. Lynchburg
City of Lynchburg)

Thomas A. Coleman, being duly sworn, on his oath deposes and says that he is the person who subscribed his name to the foregoing statement, and that the matters and facts set forth in the statement are true.

THOMAS A. COLEMAN

Subscribed and sworn before me
this 5th day of February 2001.

Wanda L. Wade
Notary Public in and for the City
of Lynchburg, State of Virginia.

My Commission Expires 8/31/01

<u>EXHIBITS A & B</u>

<u>EXHIBIT A</u>

Documented Responses to NRC Request for Additional Information On BAW-10231P Dated August 11, 2000

<u>EXHIBIT B</u>

The above listed document contains information which is considered Proprietary in accordance with Criteria b, c, d, and e of the attached affidavit.

ATTACHMENT 3

Table of Contents

List of Figures

List of Tables

Note: Tables 14-13 through 14-59 are listed in Table 14-12.

Question 1

Section 2.4 mentions iterations/convergence on gap conductance or contact pressure and also on axial interaction forces but does not mention an iteration on fissions gas released (FGR and # of moles), however, Figure 2-4 indicates that the code may iterate on number of moles released. Please discuss which is correct. If the code does not iterate on number of moles please discuss why this is satisfactory for code applications including transients.

Response

Figure 2-4 [d]. There is no concern, however, that [d]. Micro-time-steps are generated at subdivisions between the user-selected macro-time-steps. A micro-time-step is [d]. [b, c]. This is illustrated in Figures 14-1 and 14-2 where the macro- and micro-time-steps are defined with the larger diamond and smaller cylindrical shaped symbols, respectively. These illustrations were developed from the [e] example of [e]. A total of [d] and [d] micro-time-steps were generated for the [d, e] macro-time-step transient and [d] macro-time-step entire internal gas pressure case, respectively. These figures illustrate the [d] additional time steps that are generated due to the micro-time-step feature. The [d] micro-time-steps [d].

Figure 14-1: LHGR vs. Macro- and Micro-Time Steps
[e]

[d]

Figure 14-2: Bounding Fission Gas Release Predictions vs. Macro- and Micro-Time-Steps [d]

[d]

Question 2

Please compare the COPERNIC fuel thermal conductivity predictions to out-of-reactor UO_2 thermal diffusivity data from References 1 and 2 and any other high burnup diffusivity data that are applicable. The UO_2 diffusivity data can be converted to thermal conductivity for these comparisons using the COPERNIC equations for specific heat. In order to fully understand the rim model thermal conductivity as applied to Halden temperature predictions, please provide a one axial node calculation of temperature profile for IFA 562 at burnups of 60, 80, and 90 GWd/MTU with and without the rim model. Please provide the radial burnup profiles used for this calculation.

Response

COPERNIC fuel thermal conductivity predictions are compared in Figures 14-3 through 14-5 with fuel thermal conductivities that were obtained from three sets [(2-4)] of fuel thermal diffusivity measurements. These figures show that the COPERNIC thermal conductivities [b, d] with the Nuclear Fuels Research Program (NFIR) data [(3,4)] and somewhat [b,d] the Japan Atomic Energy Research Institute (JAERI) data [(2)]. There are no end-of-life density or porosity measurements presented with the Kinoshita [(1)], et al, data that are needed to calculate the rim thermal conductivities. This fact is illustrated in the following statements[(1)]:

> "It must be noted that the data in Figure 6[(1)] are just measured TD values and the effect of porosity of individual specimens were not considered. As the effect of coarsened pores, typical for the rim structure, on thermal resistance is not clear, the comparison[(1)] was made without corrections. Therefore, this presentation must be considered still preliminary and the evaluation of thermal conductivity should be discussed only after detailed analyses."

[c].

The COPERNIC predicted radial fuel temperature predictions with and without the COPERNIC rim model are shown in Figures 14-6 through 14-8, at burnups of 60, 80, and 90 GWd/tU, respectively. [b, d]. Although these differences are relatively small, Kinoshita[(1)], et al, implies that these differences are very small or should not exist at all. Note, however, that the Kinoshita[(1)], et al, data is preliminary and was obtained without stress inducing fuel restraints. Une[(5)], et al, suggests that fuel restraint may play an important role in suppressing bubble growth within the rim and, therefore, in reducing thermal conductivity. If future work indicates that the Kinoshita[(1)], et al, preliminary conclusions are correct, [b, d]. [b, d].

The radial power distributions at burnups of 60, 80, and 90 GWd/tU, that were used in the COPERNIC temperature predictions of the IFA 562 rods, are shown in Figure 14-9. These radial power distributions [b, d].

Figure 14-3: COPERNIC and NFIR-III Thermal Conductivity Comparison
100% Theoretically Dense Fuel
60 GWd/tU Burnup

[b, c, d]

Figure 14-4: COPERNIC and JAERI Thermal Conductivity Comparison
Sample No.2
100% Theoretically Dense Fuel
63 GWd/tU Burnup, 83-89% Initial Density Range

[b, c, d]

Figure 14-5: COPERNIC and JAERI Thermal Conductivity Comparison
Sample No.3
100% Theoretically Dense Fuel
63 GWd/tU Burnup, 92-96% Initial Density Range

[b, c, d]

Figure 14-6: Rim Effect at 60 GWd/tU
IFA 562

[b, c, d]

Figure 14-7: Rim Effect at 80 GWd/tU
IFA 562

[b, c, d]

Figure 14-8: Rim Effect at 90 GWd/tU
IFA 562

[b, c, d]

Figure 14-9: Radial Burnup Profiles
IFA 562

[b, c, d]

Question 3

The temperature uncertainties for LOCA and fuel melt analyses should ideally be based on data at linear heat generator rates (LHGRs) ≥ 30 kW/m because these analyses are performed at high LHGRs. The problem with determining temperature uncertainties for burnups greater than 30 GWd/MTU is that there is very little measured centerline temperature data with LHGRs ≥ 30 kW/m. Please provide the COPERNIC comparisons to data by plotting predicted minus measured temperatures versus burnup for LHGRs ≥ 30 kW/m to determine whether there is a change in thermal uncertainty with increasing burnup, and provide the uncertainties from this data comparison. Also, provide the COPERNIC predicted minus measured centerline temperature data versus burnup for LHGRs ≥ 15 kW/m, and the uncertainties from this data comparison. These comparisons will help to verify that the uncertainties for the data that includes the lower LHGRs are applicable to the higher LHGRs where LOCA and fuel melting analyses are performed.

Response

FRA-ANP (Framatome Advanced Nuclear Power) has been performing rod average burnup based LOCA analyses for well over a decade. [b, d, e]

.The predicted minus measured centerline temperature differences at LHGRs ≥ [e] and [e] kW/m are shown plotted versus burnup in Figures 14-10 and 14-11, respectively. The predicted minus measured centerline temperature differences that bound 95% of the data with a 95% confidence level are [d, e] and [d, e] for LHGRs ≥ [e] and [e] kW/m, respectively. These uncertainties demonstrate that [b]. [b]

Figure 14-10: Predicted Minus Measured Centerline Temperature Differences vs. Burnup
[e]

[b, c, d]

Figure 14-11: Predicted Minus Measured Centerline Temperature Differences vs. Burnup
[e]

[b, c, d]

Question 4

Please provide LHGRs and design information for the EXTRAFORT test rod.

Response

The EXTRAFORT test rodlet was refabricated from a mother rod that was irradiated in a commercial 900 MW PWR reactor for five cycles to a rod average burnup of 57.2 GWd/tU. [b, c, d].

Table 14-1: Design Information for the EXTRAFORT Mother Rod

[b, c, d]

Table 14-2: Thermal-Hydraulic Conditions for the EXTRAFORT Mother Rod

[b, c, d]

Table 14-3: EXTRAFORT Mother Rod Conditions History

[b, c, d]

Table 14-3: EXTRAFORT Mother Rod Conditions History (Continued)

[b, c, d]

Table 14-4: EXTRAFORT Mother Rod Power Shapes

[b, c, d]

Table 14-4: EXTRAFORT Mother Rod Power Shapes (Continued)

[b, c, d]

Table 14-5: Design Information for the EXTRAFORT Re-fabricated Test Rodlets

[b, c, d]

Table 14-6: Thermal-Hydraulic Conditions for the EXTRAFORT Re-fabricated Test Rodlets

[b, c, d]

Table 14-7: Conditions History for the EXTRAFORT Re-fabricated Rod

[b, c, d]

Question 5

The comparison to IFA 432-1 inlet thermocouple only extends to a burnup of 9 GWd/MTU but the NUREG/CR-4717 report provides data up to a burnup of 27 GWd/MTU at the inlet thermocouple. Please provide the COPERNIC comparison up to the limit of the data or a justification why this comparison is not valid.

Response

The IFA 432-1 inlet thermocouple data presented in NUREG/CR-4717 extends up to a local burnup of 24.072 GWd/tU. A comparison of the COPERNIC centerline temperature predictions with this data is presented in Figure 14-12.

Figure 14-12: Measured and Predicted Fuel Temperatures vs. Burnup

[d]

Question 6

Is Framatome a member of Halden? If so, Halden has refabricated two high (~ 59 GWd/MTU) burnup rods (one with a functional thermocouple) and placed them first in IFA-597.2 (HWR-442) and subsequently in IFA-597.3 (HWR-543) with measured centerline temperatures. Please compare COPERNIC code predictions to this data and include this data in the response to Question 3.1 above.

Response

The COPERNIC centerline fuel temperature predictions are compared with the IFA-597.2 (HWR-442) and IFA-597.3 (HWR-543) fuel temperature measurements in Figures 14-13 and 14-14, respectively. This rodlet attained a burnup of 61.5 GWd/tUO_2 or 69.8 GWd/tU.

Figure 14-13: Fuel Centerline Temperature Measurements and Predictions vs. Burnup, IFA-597.2

[d]

Figure 14-14: Fuel Centerline Temperature Measurements and Predictions vs. Burnup, IFA-597.3

[d]

Question 7

The athermal fission gas release model (Section 5.2.2) is dependent on open porosity but no values are provided for what is used for Framatome fuel. What values are used for open porosity? If more than one value is used, please provide the value for each fabrication process.

Response

The open porosity input to the COPERNIC code is the percentage of open porosity to the total pellet geometric volume. The open porosity percentage of the fuel supplied by FRA-ANP's present vendor is typically [b, d]. The [b, d] will be used until open porosity data obtained from the fuel vendor suggests a need to increase this value to [b, d] pellet fabrication open porosity measurements.

Question 8

The Section 5.2.3.5 explanation is not very clear about how the fission gas release model applies to varying conditions of power and temperature. It would help to have several examples for conditions of both increasing temperature and decreasing temperature. Also, examples of fast and slow rate of change in fuel temperature are warranted. It appears that the resolution thickness is not used in the final equations in COPERNIC for computing fission gas release. Is this interpretation correct?

Response

[b, c, d]

Figure 14-15: FGR Transition Algorithm: Small Power Change

[b, c, d]

Figure 14-16: FGR Transition Algorithm: Significant Power Increase

[b, c, d]

Figure 14-17: FGR Transition Algorithm: Significant Power Decrease

[b, c, d]

Figure 14-18: Rapid Change in Fuel Temperature [d]

[b, c, d]

Figure 14-19: Slower Change in Fuel Temperature [d]

[b, c, d]

Figure 14-20: Local Gas Concentration with Decreasing Temperatures ([d])

[b, c, d]

Question 9

A comparison of the COPERNIC upperbound fission gas release predictions to measured data (with > 7% measured release) from UO_2 - Gd_2O_3 fuel rods with steady-state power operation (from Table 5-3) demonstrates that the code underpredicts 2 out of 6 rods (it is noted that one of the rods is only slightly underpredicted). A comparison of COPERNIC upperbound predictions to the transient measured data with > 5% release from UO_2-Gd_2O_3 rods (from Table 5-4) demonstrates the code underpredicts 5 out of 25 rods. This indicates that the code's upperbound fission gas release model for UO_2 - Gd_2O_3 bounds much less than 95% of the data that are within the range of application for the rod pressure analysis. Also, the code does not appear to have been compared to the B&W segmented rodlets steady-state irradiated in ANO-1 and power ramped in the Studesvik R2 reactor. If not, why was this comparison not made and presented because these rods are representative of U. S. designs?

Response

[b]

. It can be seen from Figures 5-15 and 5-16, however, that one steady-state and two transient UO_2-Gd_2O_3 fission gas release data points are under-predicted by the UO_2-Gd_2O_3 bounding fission gas release model (another steady-state data point is only very slightly under-predicted). [b, d].

[b, d]

The Mark-BEB rodlets have been run with the COPERNIC code and the best-estimate fission gas release predictions are tabulated below:

	R1 Rodlet	R3 Rodlet
FGR Measurements	9.4	11.3
COPERNIC Predictions	[b, d]	[b, d]

[b, d].

Figure 14-21: Upper-bound Predicted vs. Measured Steady-state Fission Gas Release for UO_2-Gd_2O_3 Fuel

[b, d]

Figure 14-22: Upper-bound Predicted vs. Measured Transient Fission Gas Release for UO_2, MOX and UO_2-Gd_2O_3 Fuels

[b, d]

Question 10

The standard deviation of the gaseous swelling model is on the order of the inferred gas porosity from the measured porosity distributions. In fact there are only 3 data points out of 14 that have inferred gaseous swelling greater than 0.6, i.e., significantly greater than the standard deviation. Of these 3 data points only one of these is predicted well by the gaseous swelling model while the other two data points are underpredicted by factors of 1.6 and 2.9. Therefore, the validity and the accuracy of the swelling model appears questionable. What is the impact of the gaseous swelling model on rod pressure, melting and strain predictions? Does the gaseous swelling model use local burnup or pellet average burnup? The COPERNIC steady-state gaseous swelling model (Equations 6-13 to 6-15) has been programmed into FRAPCON-3 with calculational results of 0.007 inches of displacement at a pellet average burnup of 62 GWd/MTU with a centerline temperature of 1200°C. Is this predicted displacement with this model reasonable for these conditions? If not, further discussions are necessary to understand the gaseous swelling model.

Response

Internal gas pressure, fuel melt, and cladding diametral strain predictions with the COPERNIC gaseous swelling model turned on and off are presented in Figures 14-23 through 14-25, respectively. These representative examples were generated with the typical Mark-BW17 Urania-Gadolinia cycle UO_2 rod cases described in Chapter 12. Note that the COPERNIC gaseous swelling model [b, d]. [b, d]
. Predicted diametral cladding strains that contain COPERNIC [b, d].

[b, d]

Although [b, d]

Figure 14-23: Bounding Internal Gas Pressure With and Without COPERNIC Gaseous Swelling Model Effects
Typical Mark-BW17 Urania-Gadolinia Cycle, UO_2 Rods

[b, d]

Figure 14-24: Fuel Melt With and Without COPERNIC Gaseous Swelling Model Effects
Typical Mark-BW17 Urania-Gadolinia Cycle, UO2 Rods

[b, d]

Figure 14-25: 1% Cladding Strain With and Without COPERNIC Gaseous Swelling Model Effects
Typical Mark-BW17 Urania-Gadolinia Cycle, UO_2 Rods

[b, d]

Figure 14-26: Measured and Predicted Cladding Diameter Variations

[b, d]

Figure 14-27: Measured and Predicted Cladding Diameter Variations

[b, d]

Question 11

Figure 6-8 (from September 1999 version) predicted versus measured densification data is significantly different from Figure 6-5 of the July 1998 version of COPERNIC; however, the densification and swelling models appear to be the same. Please explain why the data in the two figures are not the same.

Response

The densification and solid swelling models in the September 1999 and July 1998 versions are [b]. The gaseous swelling models in the two versions [b]. This [b] contributed to the predicted density [b] shown in Figures 6-8 (September 1999) and 6-5 (July 1998). Note that the measured and predicted axes in Figures 6-8 (September 1999) and 6-5 (July 1998) are interchanged.

Question 12

The fuel column growth data in Figure 6-9 (September 1999 version) appears to contain significantly less growth data than the same figure (Figure 6-6) in the July 1998 version of COPERNIC. Please discuss why there is less data in the current version of COPERNIC. Does the column growth data in Figure 6-11 include both ADU and AUC processed fuel or is it just AUC fuel?

Response

The fuel column growth data shown in Figure 6-6 (July 1998) was obtained from [b] irradiated in commercial PWRs, [d]. The fuel column growth data obtained for commercial PWRs only, which consists of the data from the initial [b] fuel rods plus an additional [b] fuel rods, [d]. The measured and predicted fuel column growth data from the commercial PWRs as well as [d] are all listed in Table 9-1 (September 1999). The measured and predicted fuel column growth data obtained from [d] are shown plotted in Figure 14-28. The fuel column growth data shown in Figure 6-11 includes both ADU and AUC processed fuel.

Figure 14-28: Measured and Predicted Fuel Column Growth (UO_2) [d]

[b, d]

Question 13

Equation 7-1 for creep is a function of the shear stress component (σ_θ - σ_r). Please provide a derivation of how this shear stress is determined to be the only active determinant of creep from Hills or Von Mises equations because these are not the only shear stress or stress components in these equations.

Response

[c].

The shear stress along the slip plane (τ_{ns}) can be related to the principal stresses by the transformation of stresses which, expressed in tensor[9] notation, is

$$\tau_{ns} = a_{ni}a_{sj}\tau_{ij}$$

where a_{ni} and a_{sj} are the direction cosines.[c]

[c]

Von Mises[10] was, perhaps, the first to recognize that triaxial yielding of an isotropic material could be described by introducing a generalized stress defined as:

$$\sigma_g = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{zz} - \sigma_{\theta\theta})^2 + (\sigma_{\theta\theta} - \sigma_{rr})^2 + (\sigma_{rr} - \sigma_{zz})^2}$$

Hill[11] extended the Von Mises formulation to anisotropic materials such as Zircaloy with the following generalized stress equation:

$$\sigma_g = \sqrt{\frac{R(\sigma_{rr} - \sigma_{\theta\theta})^2 + RP(\sigma_{\theta\theta} - \sigma_{zz})^2 + P(\sigma_{zz} - \sigma_{rr})^2}{P(R+1)}}$$

where R and P are the anisotropy constants which have been determined by testing[12] to be as follows for the current FRA-ANP Zircaloy-4 cladding:

[c] [c]

Consider the following triaxial principal stress distribution[13] that may be considered typical for nuclear fuel rod cladding:

$$\sigma_{rr} = Q_1 - Q_2$$

$$\sigma_{\theta\theta} = Q_1 + Q_2$$

$$\sigma_{zz} = Q_1$$

where

$$Q_1 = \frac{r_a^2 P_a - r_b^2 P_b}{r_b^2 - r_a^2}$$

$$Q_2 = \frac{r_a^2 r_b^2 (P_a - P_b)}{r_m^2 (r_b^2 - r_a^2)}$$

and

r_a = cladding inside radius
r_b = cladding outside radius
$r_m = \frac{r_a + r_b}{2}$ = cladding mean radius
P_a = internal pressure
P_b = external pressure

[c]

Question 14

Will the FRAGEMA AFA 2G cladding that is fabricated in Europe be used in U. S. plants? Sections 7.1.2.2.1 and 7.1.2.3.1 refer to a number of cladding tube (AFA 2G) irradiation tests in the SILOE test reactor. Please provide further information on the manufacturing differences between the cladding from these tests and those manufactured commercially for U. S. plants, e.g., FCF Base Zr-4 and AFA 2G. Also, were the hoop stresses quoted in Table 7-1 positive or negative? (The creep model needs to be validated against the current U.S. fabricated FCF Zr-4 cladding, see next question).

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for this Zr-4-based question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

Question 15

Section 7.1.2.3.2 and Figures 7-20, 21 and 22 all refer to creep data from fuel rods irradiated in the CAP test reactor. Pacific Northwest National Laboratory (PNNL) nor NRC is familiar with this test reactor. Please provide the test reactor or loop conditions that are pertinent to in-reactor creep such as coolant inlet-outlet temperatures, fast flux, system pressure, etc. Also, provide predicted versus measured creep for the FCF Zr-4 cladding used in the U.S. and the background information on this data.

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for this Zr-4-based question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

Question 16

Section 7.1.2.3.3 notes that creep data from one rod was excluded from the uncertainty determination because it was next to gadolinia rods. Does this mean that the creep model uncertainty does not apply to fuel rods near gadolinia rods? Also, Figure 7-20 shows a considerable amount of measured-to-predicted data that are outside of the uncertainty bounds proposed. Please discuss why it is ok to discard this data from the uncertainty determination for creep and those data in Figure 7-20 that are not within the proposed bounding creep uncertainty. Please identify those analyses where over prediction of creep is conservative and those analyses where under prediction is conservative.

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for this Zr-4-based question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

Question 17

Section 7.1.3.2.1 discusses the development of the M5 creep model from tube irradiations but no comparison to this data is provided, and the stress and temperature parameters of this data are also not provided. Please provide this data and comparisons to the M5 creep model. It is also stated that the secondary thermal creep rate is independent of alloy type, but no data is presented to corroborate this statement. Please provide this data.

Response

The advanced alloy M5 creep rate is modeled as [b, d].

Table 14-8: Calibration Database for Creep Hardening Effects [b]

Fuel rod	Test tube	Material	Cycle	Fast Fluence (x 10^{25} n/m²)	Diametral Strain (%)	Secondary Thermal Creep Rate (%/s)
[b, d]						

Figure 14-29: Advanced Alloy M5 Creep Tests of Unirradiated Tubes at [b]

[b, d]

Figure 14-30: Advanced Alloy M5 Creep Tests of Unirradiated Tubes at [b]

[b, d]

Figure 14-31: Advanced Alloy M5 Secondary Thermal Creep Rate vs. Fluence
[b]

[b, d]

Figure 14-32: [b] Creep Strain vs. Fluence
[b]

[b, d]

Question 18

Does COPERNIC consider the effects of cladding growth (Section 7.3.2) in the diametral direction or is this implicit in the creep data? Also, the upperbound model underpredicts a significant amount of growth data in Figure 7-50. Please explain why this is acceptable. The alloy 5 growth model, Equation 7-27, is not linearly dependent but has a decreasing slope with fluence while the majority of Zircaloy growth data show a linear dependence with fluence. In addition, an initial examination of Figure 7-54 appears to show that a linear dependent model would provide as good or better prediction of the alloy 5 growth data compared to the model proposed. Please provide further information on why Equation 7-27 is more appropriate for predicting alloy 5 growth even through a linear model would be more conservative and provide as good a fit to the growth data.

Response

The effects of cladding growth (Section 7.3.2) in the diametral direction [b, d]. FRA-ANP [b, d]. [b, d]. Recent additional measured data[14] with rod average fluences up to 1×10^{22} n/cm^2, E >1.0 MeV, demonstrates [b, d].

Question 19

Section 8.1 discusses the COPERNIC corrosion model and comparisons to data. The coolant inlet temperatures are provided for some of the reactors from which corrosion data was taken but coolant outlet temperatures and LHGR are also important parameters. What were the outlet temperatures and average LHGR/cycle for both the Zr-4 and alloy 5 data (including the adjustment rod data) and identify high duty, medium duty and low duty plants (see 20 below)? Section 8.1.3.2 states that the alloy 5 data is based on the maximum average azimuthal oxide thickness over the span height. Please discuss how this is determined from actual measurements, e.g., is it an average over a given length and how many azimuthal orientations are measured?

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for the Zr-4-based portion of this question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

The inlet and outlet temperatures and the average linear heat generation rate (LHGR) for each cycle are presented in Table 14-9 for the M5 data. FRA-ANP [b,e]. However, [b, e]. Average azimuthal oxide thicknesses are evaluated [b, d, e]. The maximum oxide thickness [b, e].

Table 14-9: Plant and Fuel Rod Data

Plant	CORE INLET TEMP. (°C)	CORE OUTLET TEMP. (°C)	Average LHGR / cycle (kW/m) [b, e]	Plant Classification
		[b, d, e]		

Plant Classification:
[b, e]

Question 20

Also, oxide predictions and comparisons to data from Zr-4 are provided for all axial rod locations; however, NRC is most concerned with rod locations that experience maximum oxide thicknesses and corrosion from high duty plants. The axial locations with maximum oxide thicknesses are typically in the next to last span or the next to last two spans from the top of the assembly depending on the number of spacer grids per assembly. Please provide predicted minus measured versus both burnup and measured oxide thickness only for those axial spans with maximum measured oxide thickness for each rod and identify high duty, medium duty and low duty plants as well as defining the differences between the operating parameters of these different plants.

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for this Zr-4-based question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

Question 21

From examination of Figure 8-11, the COPERNIC code appears to significantly underpredict a large amount of the measured oxide data from U. S. plants with Zr-4 cladding. Please provide predicted minus maximum measured oxide thickness only from rods from U. S. plants using both the COPERNIC and COROS02 corrosion models. Please provide predictions of this same U. S. data using the COPERNIC upper bound corrosion model. PNNL's comparison of the COROS02 and COPERNIC corrosion models at various temperatures for both Zr-4 and alloy 5 has demonstrated that COROS02 predicts the greater oxide thicknesses. Please discuss why this is acceptable.

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for the Zr-4-based portion of the question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

The COROS02 and COPERNIC advanced alloy M5 models differ. The pre-transition phase of the COPERNIC M5 model uses a [e] function rather than [e] used in COROS02. This change provided [b] between oxide thickness measurements and predictions. Also, the initial COROS02 model was developed with [d] (see the response to Question 22), while the COPERNIC corrosion model was developed with the oxide thermal conductivity relationships described in Section 8.1.2.1.

Question 22

What is the basis for the oxide layer thermal conductivity functions provided at the bottom of page 8-3? It appears that the oxide thermal conductivity is determined based on the oxide surface temperature. Is this interpretation correct?

Response

Experimental data from a CEA (Commissariat à l'Energie Atomique - Atomic Energy Commission) program provided the basis for the COPERNIC oxide thermal conductivity relationships presented on page 8-3. The COPERNIC oxide thermal conductivities and the NFIR-III (Nuclear Fuel Industry Research Program) thermal conductivity[16] are plotted together for comparison in Figure 14-33. [b, d].

Figure 14-33: Oxide Thermal Conductivity vs. Temperature and Oxide Layer Thickness

[b, d]

Question 23

Please provide the average LHGR/cycle for the hydrogen pickup data provided in Figure 8-22. The applicability of using only 5 cycle data to estimate the hydrogen pickup fraction is questionable because there maybe other factors (such as heat flux) in the 3 and 4 cycle data that results in the 5 cycle data giving the lowest hydrogen pickup fractions.

Response

Approval of the COPERNIC code at this time is requested first for the advanced alloy M5 cladding only. A response for this Zr-4-based question will be provided at such time that approval for the COPERNIC code applications to Zr-4 cladding is requested.

Question 24

Please provide the background data for the fuel melting temperature relationship used by COPERNIC (Equations 10-11 and 12-2).

Response

[c] . Open and closed systems for heating the test samples have been used in fuel melt experiments. Closed systems[24,28] are generally preferred because the test sample is enclosed in a hermetically sealed crucible with a controlled atmosphere that restrains stoichiometry changes. Open systems[18-23,25] without controlled atmospheres, on the other hand, are notorious for causing stoichiometry changes that introduce errors in the measured melt temperatures. Melt temperature measurements have traditionally been performed either by post-cooling observations of microstructural changes or by the thermal arrest method where a marked change in the slope of the measured fuel temperature is observed. The most recent measurements have typically been performed with a closed system and the thermal arrest method because this approach is generally considered to produce more accurate measurements. The melt temperatures of unirradiated UO_2 determined by various investigators are listed below.

Table 14-10: Unirradiated UO_2 Melt Temperature

Reference	Year	Melting Point (°C)
Lambertson [18]	1953	2878
Wisniyi [19]	1957	2760
Ehlert [20]	1958	2860
Christensen [21]	1962	2790
Christensen [22]	1963	2800
Pashos [23]	1965	2800
Hausner [24]	1965	2805
Bannister [25]	1967	2860
Benz [26]	1970	2810
Rubin [27]	1970	2840
Tachibana [28]	1985	2845
Chotard [29]	1987	2852

[b, d].

Christensen's work[21,30] has traditionally been used for fuel melt because it is generally considered to be conservative. However, Christensen's measurements were performed in an open system and the stoichiometry of the test samples was not recorded. Furthermore, his initial data[21] did not report a decrease in melt temperature with burnup.

[b, c, d]

[b, c, d]

[b, d] . Yamamouchi[31], et al data.

A review of the available UO_2-Gd_2O_3 fuel melt data[29,32-33] indicates that there is no significant difference between the UO_2 and UO_2-Gd_2O_3 fuel melt temperatures for gadolinia concentrations less than approximately 12 wt.%.

Table 14-11: Unirradiated $(U,Gd)O_2$ Melt Temperature

Gd_2O_3 Content (wt.%)	Melting Point (°C)	Reference
0	2857	Chotard[29]
4	2881	
8	2861	
12	2867	
16	2865	
0	2844	Busch[32] Stoichiometric oxides
4	2851	
8	2858	
12	2836	
40	2791	
65	2585	
100	2444	
4	2855	Busch[32] substoichiometric oxides
8	2856	
12	2845	
40	2786	
65	2597	
0	2842	Watarumi[33] (homogeneous oxides)
0	2861	
6	2828	
6.6	2868	
8	2842	
10	2828	
13	2775	
19	2745	
25	2753	
31	2707	
37	2687	
6	2836	Watarumi[33] (heterogeneous oxides)
8	2836	
10	2829	

[d].

Question 25

Section 12.0 notes that COPERNIC is used for initialization of core thermal-hydraulic codes. Please list those calculated COPERNIC parameters used for initialization and the specific applications of the thermal-hydraulic codes.

Response

The COPERNIC parameters used for initialization of thermal-hydraulic codes (COBRA-IV, COBRA3C, LYNXT, etc.) are [d]. The specific thermal-hydraulic applications where fuel performance code initialization predictions are used include those related to the evaluation of locked rotor, ejected rod, etc. events.

Question 26

Section 12.1.1 (page 12-2) under discussion on Code Uncertainties it is noted that the code has an option that conservatively bounds the fissions gas release data and that this option is used to bound the fission gas release for the rod pressure predictions. However, there is a concern that this option will not bound the UO2 - Gd2O3 data within the fission gas release range that is important to the rod pressure analysis for UO2 - Gd2O3 rods (see Question 9 above) at the stated level of conservatism. Please discuss this issue further, particularly in relation to Question 9 above.

Response

[d]; see the response to Question 9.

Question 27

Section 12.1.1 (page 12-3) under the discussion on Transients it is noted that plant specific operating data may be used to establish simulated transients. Please explain further by what is meant by sufficient plant operating data and provide an example.

Response

The COPERNIC end-of-life (EOL) internal gas pressure analyses employ [d]. In addition, [d]. The Condition-I design transients discussed in section 12.1.1 account for [b, d]. All plants have the equipment and procedures necessary to gather the operational data required for core follow activities. The plant data gathered includes the time-dependent behavior of the reactor thermal power level, regulating rod and (where applicable) axial power shaping rod positions, RCS boron concentration, average moderator temperature, and axial power imbalance. In general, these data are collected approximately on an hourly basis. Most plants have the equipment necessary to electronically archive this data.

[e]. It would never be possible to eliminate the [e] [b, d] gas pressure analysis because [e]. Generally, it may only be possible, due [b, d], [e]. The [e] Condition I transient in the internal gas pressure analysis examples presented in Chapter 12 produced pressure [b, d] less than approximately [d].

The Condition-I design transients used in the COPERNIC internal gas pressure analyses are [b]. They are produced with [b, d][34&35] (xenon distribution and control rod insertion) that would be [b, d]. [b, d] the typical Urania-Gadolinia cycle documented in Chapter 12 are shown in Figure 14-34. This example includes [b, d] with [b, d] and [e]. The [b] gas pressure difference [d]. This example demonstrates [d, e].

Figure 14-34: Typical Mark-B Urania-Gadolinia Cycle Predictions [b]

[b]

Question 28

There is a concern that the uncertainty factor provided in Equation 12-1 may be too small at the predicted operating temperatures (stored energy) calculated for LOCA initialization. Please discuss this issue further, particularly in relation to Question 3 above.

Response

Based upon the analysis performed for Question 3 above, it is recommended to [b, d]. This [b, d] was determined to be [e] in the Question 3 analysis. The recommended replacement equations that were derived based upon [b, d], therefore, are:

Equation 12-1 replacement

[d, e]

Equation 12-3 replacement

[d, e]

where

T	=	COPERNIC best-estimate temperature (°C),
$T_{95/95}$	=	temperature (°C) that bounds 95% of the data with a 95% confidence,
T_L	=	limiting melt temperature (°C), and
Bu	=	pellet burnup (GWd/tU).

Question 29

Are any of the example calculations provided in Section 12 for fuel cores with two 24-month cycles? It appears that there are no 24-month cycle results presented for the Mark BW-17 design. If so, please explain because it is anticipated that a large number of plants will be switching to 24-month cycles in the next few years.

Response

[b, d].

Question 30

The axial power distributions for the transients were found for the example licensing analyses, but the power distribution for the steady-state power operation were not found for the topical report. Please provide these axial power distributions. If there are more than 20 axial power profiles it would be helpful to condense the number down to 20 or less. Also, the steady-state power histories are only provided as plots versus burnup. Please provide these in tabular form to support the NRC audit calculation of these calculational examples?

Response

Forty-seven data sets of the normalized axial power distributions used for the Chapter 12 examples are listed in Table 14-12. The axial power distributions of each data set are provided in Table 14-13 through Table 14-59. The rod average burnups and linear heat generation rates are listed above each distribution presented.

Several different sets of axial power distributions are provided:

- [b, d, e]
- [b, d, e]
- [b, d, e]

[e] are not presented as separate sets because [e].

All of the steady-state axial power distributions used for the Chapter 12 examples are provided. If the reviewers need 20 or less distributions, it is left up to their discretion to select the appropriate distributions from those provided.

Table 14-12: Axial Power Distribution Data Sets

Typical Mark-B UO_2 Cycle, UO_2 Power Histories	
Table 14-13	[d]
Table 14-14	
Table 14-15	
Table 14-16	
Table 14-17	
Table 14-18	
Table 14-19	
Table 14-20	
Typical Mark-B UO_2-Gd_2O_3 Cycle, UO_2 Power Histories	
Table 14-21	[d]
Table 14-22	
Table 14-23	
Table 14-24	
Table 14-25	
Table 14-26	
Table 14-27	
Table 14-28	
Typical Mark-B UO_2-Gd_2O_3 Cycle, UO_2-Gd_2O_3 Power Histories	
Table 14-29	[d]
Table 14-30	
Table 14-31	
Table 14-32	
Table 14-33	
Table 14-34	
Table 14-35	
Typical Mark-BW UO_2 Cycle, UO_2 Power Histories	
Table 14-36	[d]
Table 14-37	
Table 14-38	
Table 14-39	
Table 14-40	
Table 14-41	
Table 14-42	
Table 14-43	
Typical Mark-BW UO_2-Gd_2O_3 Cycle, UO_2 Power Histories	
Table 14-44	[d]
Table 14-45	
Table 14-46	
Table 14-47	
Table 14-48	
Table 14-49	
Table 14-50	
Table 14-51	
Table 14-52	
Typical Mark-BW UO_2-Gd_2O_3 Cycle, UO_2-Gd_2O_3 Power Histories	
Table 14-53	[d]
Table 14-54	
Table 14-55	
Table 14-56	
Table 14-57	
Table 14-58	
Table 14-59	

Applications:

[d]

Table 14-13: Typical Mark-B Uranium-Dioxide Cycle

[d]

[d]

Table 14-13: Typical Mark-B Uranium-Dioxide Cycle

[d]

[d]

Table 14-13: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-13: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-14: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-15: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-15: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-16: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-16: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-16: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-17: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-17: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-17: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-18: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-18: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-18: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-18: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-19: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-19: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-19: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-19: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-19: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-20: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-20: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-20: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-20: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-20: Typical Mark-B Uranium-Dioxide Cycle

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Table 14-21: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-21: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-21: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-21: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-22: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-23: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-23: Typical Mark-B Urania-Gadolinia Cycle
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Table 14-24: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-24: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-25: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-25: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-25: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-26: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-26: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-26: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-26: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-27: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-27: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-27: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-27: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-28: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-28: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-28: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-28: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-29: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-29: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-29: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-29: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-30: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-31: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-31: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-32: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-34: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-35: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-35: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-35: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-35: Typical Mark-B Urania-Gadolinia Cycle

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Table 14-36: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-36: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-36: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-36: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-36: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-37: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-38: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-38: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-39: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-39: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-39: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-40: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-40: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-40: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-41: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-41: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-41: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-41: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-42: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-42: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-42: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-42: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-43: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-43: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-43: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-43: Typical Mark-BW17 Urania-Dioxide Cycle

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Table 14-44: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-44: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-44: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-45: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-46: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-46: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-47: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-47: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-48: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-48: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-49: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-49: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-49: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-49: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-50: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-50: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-50: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-50: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-50: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-51: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-51: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-51: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-51: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-51: Typical Mark-BW17 Urania-Gadolinia Cycle
63 GWd/tU, UO2 Single Limiting Rod Analyses (Continued)

Table 14-52: Typical Mark-BW17 Urania-Gadolinia Cycle

UO2 Max Burnup Rod, Cladding Oxide

Table 14-52: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-52: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-52: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-52: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-53: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-53: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-53: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-53: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-54: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-55: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-55: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-56: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-56: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-56: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-57: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-57: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-57: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-58: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-58: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-58: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-58: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-59: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-59: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-59: Typical Mark-BW17 Urania-Gadolinia Cycle

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Table 14-59: Typical Mark-BW17 Urania-Gadolinia Cycle

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Question 31

Section 12.4.1 states that the cladding strain analysis will be run with ...... and the gaseous swelling option turned off. Performing these analyses without gaseous swelling ...... produces more accurate predictions ...... at the very high local power levels that accompany these analyses. This appears to be contradictory to the comparisons to data in Figures 6-17, 6-18, and 6-19 that demonstrate that COPERNIC with gaseous swelling option turned on provides an adequate prediction of diametral strains. Please provide data that supports the conclusion that the exclusion of gaseous swelling in COPERNIC produces more accurate strain predictions.

Response

[e]

Ramp tests were recently performed to study the effects of pellet cladding mechanical interaction (PCMI) on cladding deformation[36]. Three rodlets, which were part of a segmented rod, were ramped to terminal power levels ranging from 39.5 to 41.5 kw/m. The ramp time to the terminal power levels was approximately 2-min. and the rods were held at the terminal power levels for 0 (zero hold time), 16-min. and 12-hrs. Although the terminal power level of these rods was well below fuel melt, it was sufficient to cause partial dish filling for the rodlets with hold times of 16-min. and 12-hrs. These power ramps were simulated with 2 and 3 dimensional finite element codes that don't contain gaseous swelling models. The overall computational results of the 2D finite element code agreed well with the data from the rodlets with terminal power level hold times of zero and 16-min. but the cladding diameter changes for the 12 hour hold time were underestimated because gaseous swelling was not included. The 3D finite element code, which is currently under development, tended to moderately overestimate the measured cladding diameter changes for these cases. [e].

Question 32

Section 12.5 states that COPERNIC will be used to generate cladding creep collapse initial conditions and example rod pressure results are provided in Figures 12-34 and 12-35. Are there any other initial conditions provided by COPERNIC for the creep collapse analysis, e.g., cladding temperatures? If so, please provide predictions of these initial conditions.

Response

The other initial conditions that are provided by COPERNIC for the creep collapse analysis include [e].

Figure 14-35: Typical Mark-B Fuel Cycles
Creep Collapse Analyses [d]

[d]

Figure 14-36: Typical Mark-BW17 Fuel Cycles
Creep Collapse Analyses [d]

[d]

Figure 14-37: Typical Mark-B Fuel Cycles Creep Collapse Analyses [d]

[d]

Figure 14-38: Typical Mark-BW17 Fuel Cycles Creep Collapse Analyses [d]

[d]

Figure 14-39: Typical Mark-B Fuel Cycles Creep Collapse Analyses [d]

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Figure 14-40: Typical Mark-BW17 Fuel Cycles Creep Collapse Analyses [d]

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Figure 14-41: Typical Mark-B Fuel Cycles Creep Collapse Analyses [d]

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Figure 14-42: Typical Mark-BW17 Fuel Cycles Creep Collapse Analyses [d]

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