framatome

Response to Request for Additional Information – ANP-10323P

ANP-10323, Rev. 1, Q2NP
Revision 0

GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors

January 2019

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	All	Initial Issue

Contents

List of Tables

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Nomenclature

Acronym	**Definition**
AO	Axial Offset
AOO	Anticipated Operational Occurrence
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CUF	Cumulative Usage Factor
FGR	Fission Gas Release
GAD / Gd_2O_3	Gadolinia
ID	Inner Diameter
LCO	Limiting Conditions for Operation
LHGR	Linear Heat Generation Rate
LOCA	Loss of Coolant Accident
MLI	Mean Linear Intercept
NRC	U.S. Nuclear Regulatory Commission
OD	Outer Diameter
PNNL	Pacific Northwest National Laboratory
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
RIA	Reactivity Insertion Accident
RPS	Reactor Protection System
SAFDLs	Specified Acceptable Fuel Design Limits
UO_2	Uranium Dioxide
UO_2-Gd_2O_3	Urania-Gadolinia

1.0 RAI-1

RAI-1 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

2.0 RAI-2

2.1 *Request*

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.

2.2 *Response*

Examples of the radial power profiles generated by GALILEO for UO_2 and UO_2-Gd_2O_3 fuel pellets are given in Tables 2-1 and 2-2 and are also shown graphically in Figures 2-1 and 2-2, respectively. The example radial power profiles (for both UO_2 and UO_2-Gd_2O_3) have been provided at pellet average burnups of 1, 5, 10, 20, 40, 60, and 75 gigawatt-days per metric ton of uranium (GWd/mtU) and are reported as a function of fractional radius (ratio of the distance from the fuel pellet center to the cold pellet outer radius, r/r_o) to generically represent fuel pellets which may have different radius dimensions.

[

]

To demonstrate the validity of the radial power profiles up to high burnup, Figure 2-3 shows a comparison of the GALILEO predicted radial burnup profile to the measured data [

]

Table 2-1: UO_2 Radial Power Profile Examples

[ ]

Figure 2-1: UO_2 Radial Power Profile Examples

[ ]

Table 2-2: UO_2-Gd_2O_3 Radial Power Profile Examples

[ ]

Figure 2-2: UO_2-Gd_2O_3 Radial Power Profile Examples

Figure 2-3: Comparison of Measured Radial Burnup Profile (Top) and GALILEO Prediction (Bottom)

2.3 *References for RAI-2*

1. NUREG/CR-6534, Volume 1 (PNNL-11513), "FRAPCON-3: Modifications to Fuel Rod Material Properties and Performance Models for High-Burnup Application," October 1997.

3.0 RAI-3

3.1 *Request*

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.

3.2 *Response*

Sample calculations of pellet thermal relocation displacement (micrometers, μm) as a function of burnup (gigawatt-days per metric ton of uranium, GWd/mtU) generated by GALILEO for power levels of 15, 30, and 45 kilowatt per meter (kW/m) are shown graphically in Figures 3-1, 3-2, and 3-3, respectively. The total pellet relocation as a function of burnup is also shown in these figures.

The sample calculations provided for pellet relocation displacement as a function of burnup are based on [

] Each power level (15, 30, and 45 kW/m) is analyzed over a fuel rod burnup irradiation history [

]

[

]

[

]

Figure 3-4 shows an example [

]

Figure 3-1: Sample UO_2 Fuel Pellet Relocation at 15 kW/m

Figure 3-2: Sample UO_2 Fuel Pellet Relocation at 30 kW/m

Figure 3-3: Sample UO_2 Fuel Pellet Relocation at 45 kW/m

[ ]

Figure 3-4: Sample UO_2 Fuel Pellet Deformation from Cracking at 30 kW/m

[ ]

3.3 *References for RAI-3*

1. FS1-0004682-4.0, GALILEO Fuel Rod Performance Code Theory Manual.

4.0 RAI-4

RAI-4 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

5.0 RAI-5

RAI-5 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

6.0 RAI-6

RAI-6 will be addressed at a later date.

7.0 RAI-7

7.1 *Request*

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.

7.2 *Response*

Compliance with cladding strain limit and fuel melting limit is addressed in Reference 1. Table 2-1 of the GALILEO Topical Report provides a list of addressed criteria (Reference 2, p. 2-17). The GALILEO Topical Report addresses [

]

[

]

Fuel rod power history without power uncertainty is provided in Table 7-1.

The normalized axial power distributions without power uncertainty are provided in Table 7-2.

The fuel rod geometry is provided in Table 7-3.

The reactor coolant conditions are provided in Table 7-4. The nominal reactor pressure, coolant inlet temperature and mass flow rate are used in GALILEO analysis (Section 5.2.1 of Reference 2).

The manufacturing uncertainties are provided in Table 7-5.

The frequency plot of rod internal pressure is Figure 7-1.

The frequency plot of cladding oxide thickness is Figure 7-2.

The randomly sampled manufacturing values for 59 cases are provided in Table 7-6.

Fuel centerline temperature and clad strain vs rod average burnup based on the nominal case (no uncertainties) are provided in Table 7-7. All values correspond to [ ] Clad strain is defined and calculated with the following equation:

[ ]

Table 7-1: Power History

[ ]

Table 7-2: Steady State Axial Power Shapes

[ ]

Table 7-2 (Continued): Steady State Axial Power Shapes

[ ]

Table 7-3: Fuel Rod Geometry

[ ]

Table 7-4: Coolant Conditions

[ ]

Table 7-5: Statistical Values for Manufacturing Parameters

Figure 7-1: Rod Internal Pressure, Frequency of Results

[ ]

Figure 7-2: Oxide Thickness, Frequency of Results

Table 7-6: Sampled Value for Manufacturing Parameters

[ ]

Table 7-6 (Continued): Sampled Value for Manufacturing Parameters

[ ]

Table 7-7: Fuel Centerline Temperature and Clad Strain vs Burnup

7.3 *References for RAI-7*

1. ANP-10339(P), Revision 0, ARITA – ARTEMIS/RELAP Integrated Transient Analysis Methodology.
2. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.

8.0 RAI-8

RAI-8 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

9.0 RAI-9

RAI-9 will be addressed at a later date.

10.0 RAI-10

RAI-10 will be addressed at a later date.

11.0 RAI-11

RAI-11 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

12.0 RAI-12

12.1 *Request*

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.

12.2 *Response*

In Revision 1 of the GALILEO Topical Report, the limits on cladding corrosion and hydrogen content are referenced to the NRC approved Topical Reports for each cladding material (Reference 1, p. 3-3).

a. The corrosion limits have been previously reviewed and approved by the NRC and continue to be valid. There have been no issues of poor fuel performance due to corrosion for Zr-4 or M5 cladding within the corrosion limits that are currently approved. Justification and NRC approval of the corrosion limits are provided in Reference 2, Section 3.5 of the Revised Safety Evaluation dated February 4, 2000 for M5 cladding and Reference 3, Section 5.1 for Zr-4 cladding.

   The original corrosion limits were based on preventing fuel failure due to excessive oxidation. [ ] The corrosion limits were not based on hydrogen content but over time, as the importance of hydrogen to fuel performance during accidents was understood, the corrosion limits came to be viewed as an indirect limit on the hydrogen content of the cladding. Revision 1 of the GALILEO topical report

recognizes the altered importance of corrosion versus hydrogen in the following manner.
First, the limit on corrosion is maintained for the purpose of eliminating the potential to fail during normal operation due to excessive corrosion by placing a limit on the maximum corrosion value allowed to be predicted [

]

The numerical limits on the approved maximum allowed oxidation have been retained but their interpretation has changed. [

] Thus, the previously approved M5 corrosion limit is conservatively implemented in Revision 1 of the GALILEO topical report. The Zr-4 corrosion limit has also been reinterpreted and this is addressed in part b of this response.

Hydride limits for cladding are implicitly set by the safety criteria highly affected by hydrogen concentrations, namely Reactivity Insertion Accident (RIA), Loss Of Coolant Accident (LOCA), and AOO transient clad strain. These safety criteria are addressed in other topical reports. Since these define the impact of hydrogen on the safety analysis, they are more appropriate means to set hydrogen limits. Therefore, no additional hydride limits need to be established (Reference 1, p. 3-3).

b. In Revision 1 of the GALILEO Topical Report, the oxide corrosion limit for Zr-4 is taken from Reference 3, Section 5.1. [

]

Figures 4-70 and 4-71 in the original version of the Topical Report are now captioned with Figures 4-51 and 4-52 in Reference 1. The measured oxide thickness data in Figures 4-51 and 4-52 of Reference 1 are [ ]

[ ] The data in Figure 4-52 demonstrates acceptable fuel rod performance with [ ] Therefore, the [ ] limit remains conservative relative to the observed performance and to the metal/oxide interface temperature.

12.3 *References for RAI-12*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. BAW-10227P-A, Revision 1, Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel.
3. ANF-88-133(P)(A) and Supplement 1, Qualification of Advanced Nuclear Fuels PWR Design Methodology for Rod Burnups of 62 GWd/MTU.

13.0 RAI-13

RAI-13 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

14.0 RAI-14

14.1 *Request*

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.

14.2 *Response*

a. Strain fatigue data for M5 cladding was provided during the NRC review and approval of Reference 2 (see page 13 of the Safety Evaluation Report). [

]

b. The statistical methodology for cladding fatigue analysis has been removed from Revision 1 of the GALILEO Topical Report (Reference 1). Cladding fatigue analyses will continue to use the NRC approved methodology described in Section 3.6 of Reference 2.

c. [

]

14.3 *References for RAI-14*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. BAW-10227P-A, Revision 1, Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel.

15.0 RAI-15

15.1 *Request*

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.

15.2 *Response*

Analysis of fuel centerline temperature and cladding strain during transient events has been removed from Revision 1 of the GALILEO Topical Report (Reference 1). This is now described in Reference 2.

The GALILEO methodology for [

]

[

]

15.3 *References for RAI-15*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. ANP-10339(P), Revision 0, ARITA – ARTEMIS/RELAP Integrated Transient Analysis Methodology.
3. ANP-10297(P)(A), Revision 0, The ARCADIA® Reactor Analysis System for PWRs Methodology Description and Benchmarking Results.

16.0 RAI-16

16.1 *Request*

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.
[

]

[ ] (B.2)

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

a. [

]

b. Please provide information demonstrating the assumption [
]

c. Is rod bow effect on power uncertainties included in the calculational/measurement uncertainty value obtained from the neutronics calculation?

16.2 *Response*

a. As described in 5.2.2.2 of Reference 1, [

]

Figure 16-1: Axial Power Profile Variation due to Maximum Positive Axial Power Uncertainty

[ ]

Figure 16-2: Axial Power Profile Variation due to Maximum Negative Axial Power Uncertainty

[ ]

b. As mentioned above in the response to Part a, [

]

c. [

]

16.3 *References for RAI-16*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. BAW-10247(P)(A), Revision 0, Realistic Thermal-Mechanical Fuel Rod Methodology for Boiling Water Reactors.
3. ANP-10297(P)(A), Revision 0, The ARCADIA® Reactor Analysis System for PWRs Methodology Description and Benchmarking Results.

17.0 RAI-17

17.1 *Request*

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 [ ]

17.2 *Response*

a. The GALILEO methodology provides a [ ]

At the GALILEO audit meeting held in Lynchburg November 29, 2018, Framatome and NRC employees further discussed the statistical sampling methodology employed by GALILEO. Specifically, it was requested that Framatome provide further justification that [ ]

[

] and demonstrate the appropriateness of the GALILEO methodology.

[

]

b. The approach taken assumes that [

]

[

]

Densification is primarily an early-in-life phenomena that is caused by the resintering of the fuel pellet at operating temperatures. Solid swelling is effectively linear with burnup (number of fissions) over the entire burnup range, and it is caused by the generation of fission products within the fuel pellet. [

]

Figure 17-1: Dependence of Mean Log(C/M) of FGR on log(ADIFF123)

[ ]

Figure 17-2: Dependence of Mean Log(C/M) of FGR on delta-FQE

[ ]

Figure 17-3: Dependence of standard deviation of Log(C/M) of FGR on log(ADIFF123)

[ ]

Figure 17-4: Dependence of standard deviation of Log(C/M) of FGR on delta-FQE

[ ]

17.3 *References for RAI-17*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. SCR-607, Factors for One-Sided Tolerance Limits and for Variables Sampling Plans, D. B. Owen, March 1963, NRC ADAMS document ML14031A495.

18.0 RAI-18

RAI-18 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

19.0 RAI-19

RAI-19 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

20.0 RAI-20

RAI-20 will be addressed at a later date.

21.0 RAI-21

RAI-21 will be addressed at a later date.

22.0 RAI-22

RAI-22 will be addressed at a later date.

23.0 RAI-23

23.1 *Request*

Section 4.1 of the methodology document suggests that [

]

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.

23.2 *Response*

a. [

]

b. [

]

[

]

23.3 *References for RAI-23*

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.
2. ANP-10323(P), Revision 0, Fuel Rod Thermal-Mechanical Methodology for Boiling Water Reactors and Pressurized Water Reactors.

24.0 RAI-24

24.1 *Request*

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.

24.2 *Response*

a. Figure 4-16 in Revision 0 of the topical report (Reference 1) has been replaced by Figure 4-14 in Revision 1 of the topical report (Reference 2). Figure 4-14 is replotted below in Figure 24-1 with UO_2 and gadolinia rods distinguished by separate symbols and with an x-axis range of 0 to 15 percent fission gas release (FGR).

   Figure 4-19 in Revision 0 of the topical report (Reference 1) has been replaced by Figure 4-17 in Revision 1 of the topical report (Reference 2). Figure 4-17 is replotted below in Figure 24-2 with UO_2 and gadolinia rods distinguished by separate symbols.

Figure 24-1: Trend vs. Measurement of Steady-State FGR (Validation Database)

[ ]

Figure 24-2: Burnup Trend of FGR Validation Database

[ ]

b. Figure 4-17 in Revision 0 of the topical report (Reference 1) has been replaced by Figure 4-15 in Revision 1 of the topical report (Reference 2). In Figure 4-15, the low rated 17x17 rods correspond to linear power values around [ ] throughout the life of the rod. In contrast, the high rated 15x15 rods correspond to linear power values between [ ] in the first three cycles while dropping below [ ] in later cycles.

24.3 *References for RAI-24*

1. ANP-10323(P), Revision 0, Fuel Rod Thermal-Mechanical Methodology for Boiling Water Reactors and Pressurized Water Reactors.
2. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors.

25.0 RAI-25

RAI-25 will be addressed at a later date.

26.0 RAI-26

RAI-26 will be addressed at a later date.

27.0 RAI-27

RAI-27 was addressed in the following report:

ANP-10323, Rev. 1, Q1P, Revision 0, Response to Request for Additional Information – ANP-10323P, December 2018.

28.0 RAI-28

RAI-28 will be addressed at a later date.

29.0 RAI-29

RAI-29 will be addressed at a later date.

30.0 RAI-30

RAI-30 will be addressed at a later date.

31.0 RAI-31

RAI-31 will be addressed at a later date.

32.0 RAI-32

RAI-32 will be addressed at a later date.

33.0 RAI-33

RAI-33 will be addressed at a later date.

34.0 RAI-34

RAI-34 will be addressed at a later date.

APPENDIX A TOPICAL REPORT MARKUP