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Additional Information – ANP-10323P

ANP-10323
Revision 1, Q5NP
Revision 0

GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors

July 2020

Nature of Changes

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

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Nomenclature

Acronym	**Definition**
BE	Best-Estimate
EOL	End of Life
FSAR	Final Safety Analysis Report
HPUF	Hydrogen Pickup Fraction
ID	Inner / Inside Diameter
L&Cs	Limitations and Conditions
MOL	Middle of Life
NRC	U.S. Nuclear Regulatory Commission
OD	Outer / Outside Diameter
PCMI	Pellet-Cladding Mechanical Interaction
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
UO_2	Uranium Dioxide
UO_2-Gd_2O_3	Urania-Gadolinia
Zr-4	Zircaloy-4

1.0 INTRODUCTION

The purpose of this report is to provide additional information for the topical report ANP-10323P, Revision 1, "GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors". Additional information is provided in Section 2.0 for the cladding fatigue analyses and in Section 3.0 for the Zr-4 and M5 hydrogen models. The additional information for the cladding fatigue analyses is with respect to the input to the fatigue analyses provided by GALILEO. The additional information for the hydrogen models are: 1) model pickup fraction versus oxidation rate, 2) hydrogen model uncertainties, and 3) hydrogen model uncertainty for use in other safety analyses. Markups of the topical report to reflect this additional information are provided in Section 5.0.

This additional information was discussed in a telephone call with the NRC staff on May 14, 2020 regarding the draft Limitation and Conditions (L&Cs) for the GALILEO topical report (Reference 1). The purpose of the additional information is to support the elimination of the draft L&Cs related to the cladding fatigue analyses and the hydrogen models.

2.0 FUEL ROD FATIGUE INITIALIZATION

As stated in Section 2.1.4 of Reference 1, GALILEO analyses will be performed to establish fuel rod initialization data for downstream fuel rod fatigue analyses which follow the NRC-approved methodology documented in Section 3.6 of Reference 4. A detailed application methodology for fuel rod fatigue initialization and accompanying sample analyses are presented below to demonstrate how GALILEO is used to generate input (cladding diameters, rod internal pressure, and cladding temperatures) for the fuel rod fatigue analyses. Previous information regarding GALILEO fuel rod fatigue initialization was provided in Reference 2 (RAI-12.a and RAI-14) and Reference 3 (RAI-28.a).

2.1 *Methodology*

The GALILEO methodology for fuel rod fatigue initialization includes the following modeling characteristics and conservatisms:

- Design transients for component fatigue evaluations are defined in the plant specific design basis documentation (e.g. Final Safety Analysis Report (FSAR)). This defines the transient progression and the expected number of occurrences over the lifetime of the plant. [

]

- GALILEO predictions will be performed using best-estimate (nominal) fuel rod characteristics and thermal-hydraulic conditions [

  ]

- All GALILEO cases (UO_2 and gadolinia fuel) will be analyzed using a [

  ] produce conservative (higher) cladding temperatures and rod internal pressures which increase cladding stresses calculated in the downstream fatigue analysis. [

  ]

- The cladding inner/outer diameters (ID/OD) from GALILEO which will be used in downstream stress calculations will conservatively [

  ]

Considering the modeling characteristics and conservatisms defined above, the GALILEO code will be used to generate fuel rod fatigue initialization data for input into downstream fuel rod fatigue analyses. [ ] GALILEO predictions of rod internal pressure, cladding inner/outer diameters, and cladding temperatures will be used in downstream stress calculations to ultimately calculate the fatigue cumulative usage factor. Cladding fatigue evaluations will be performed during the fuel rod design process.

2.2 *Application Example*

Analyses for fuel rod fatigue initialization are performed on a sample design representative of a 17x17 fuel rod design with M5 cladding irradiated for up to three 18-month cycles in a Westinghouse reactor (Section 6.1.3 of Reference 1). The design includes UO_2 and UO_2-Gd_2O_3 rods; however, for purposes of this sample analysis, only UO_2 rods are analyzed since the application methodology is identical for both fuel types. For this application example, the core parameters and nominal (unbiased) fuel rod characteristics are presented in Tables 6-7 and 6-8 of Reference 1. The [ ] cladding outer/inner diameters are shown below in Table 2-1.

[ ] used in the sample creep collapse initialization analysis presented in Figure 6-9 of Reference 1 is used. Consistent with the prescribed methodology, [ ] induces conservatism into the fatigue initialization data.

Design transients are defined in the plant specific design basis documentation. For the fatigue initialization sample cases, two primary system transients during normal operating conditions are considered. These design transients are briefly summarized below.

- Unit Loading and Unloading at 5 Percent of Full Power per Minute – Continuous and uniform ramp power change of 5 percent/min. between 15 percent load and full load.
- Step Load Increase and Decrease of 10 Percent of Full Power – The 10 percent step change in load demand is a transient which is assumed to be a change in turbine control valve opening due to disturbances in the electrical network into which the plant output is tied.

These design transients are chosen for demonstration purposes [

]

GALILEO predictions of cladding inner/outer diameters, rod internal pressure, and cladding temperatures as a function of time from the sample analyses are presented in Figures 2-1 through 2-4 for the unit loading/unloading transient and Figures 2-5 through 2-8 for the step load increase/decrease transient. Only a portion of the irradiation history corresponding to a single, representative axial node is depicted for each case to provide a reasonable plotting scale which allows magnification on the fatigue initialization data near and during the design transient.

Table 2-1: Cladding Diameters

[ ]

Figure 2-1: Unit Loading/Unloading, Cladding OD vs Time

Figure 2-2: Unit Loading/Unloading, Cladding ID vs Time

Figure 2-3: Unit Loading/Unloading, Rod Internal Pressure vs Time

[ ]

Figure 2-4: Unit Loading/Unloading, Cladding Surface Temperature vs Time

[ ]

Figure 2-5: Step Load Increase/Decrease, Cladding OD vs Time

Figure 2-6: Step Load Increase/Decrease, Cladding ID vs Time

Figure 2-7: Step Load Increase/Decrease, Rod Internal Pressure vs Time

Figure 2-8: Step Load Increase/Decrease, Cladding Surface Temperature vs Time

[ ]

3.0 HYDROGEN PICKUP MODELS

3.1 *M5 Hydrogen Pickup Fraction*

The behavior of M5 [

] The current M5 model in GALILEO accurately predicts this behavior throughout the life of the fuel rods. Application of [

] This is not the desired model behavior. Therefore, the current M5 hydrogen pickup model in GALILEO (described in Section 4.3.14.2 of Reference 1) is appropriate with a minor modification as described below.

In typical design analyses, [

]

[

]

[

] Also, design analyses are primarily focused on high oxidation rates that maximize the oxide thickness and cladding hydrogen concentration. Figure 3-1 shows the M5 HPUF.

3.2 *Hydrogen Model Uncertainties for the GALILEO Statistical Methodology*

Hydrogen model uncertainties are developed for application in the GALILEO statistical methodology. This uncertainty will be used in conjunction with the other model uncertainties typically applied in the GALILEO statistical methodology, [

] The following sections detail the uncertainties for Zr-4 and M5.

3.2.1 *Zr-4 Cladding*

Hydrogen predictions based on the [

] were previously compared with measured data in Figure 34-6 of Reference 6. These upper bound predictions are used to determine an additional Zr-4 hydrogen model uncertainty to be used in the GALILEO statistical methodology. Consistent with the approach used in the calculation of [

]

Figure 3-2 shows the distribution of P-M values for the Zr-4 hydrogen predictions.

[

]

Evaluation of the P-M data demonstrates that [ ] provides upper bound predictions that are greater than [ ] of the measured data points. Figure 3-3 shows the Zr-4 upper bound hydrogen predictions, including the [ ] versus the measured data points.

In the GALILEO statistical methodology, a [ ] the limiting Zr-4 hydrogen concentration.

3.2.2 *M5 Cladding*

Hydrogen predictions based on the [ ] were previously compared with measured data in Figure 34-7 of Reference 6. These upper bound predictions are used to determine if an additional M5 hydrogen model uncertainty is needed in the GALILEO statistical methodology. Consistent with the approach used in the calculation [

]

[ ]

Figure 3-4 shows the distribution of P-M values for the M5 hydrogen predictions.

[ ] Figure 3-5 shows the M5 upper bound hydrogen predictions versus the measured data points.

In the GALILEO statistical methodology, [ ] the limiting M5 hydrogen concentration.

3.3 *Hydrogen Model Uncertainties for Safety Analysis Methodologies*

Hydrogen model uncertainties are developed below for application in downstream safety analysis methodologies. This uncertainty will be used independently from the other model uncertainties typically applied in the GALILEO statistical methodology, [ ] Stated differently, this uncertainty converts a best-estimate hydrogen prediction into an appropriate upper bound. The following sections detail the uncertainties for Zr-4 and M5 cladding.

3.3.1 *Zr-4 Cladding*

Hydrogen predictions based on the best-estimate (BE) Zr-4 oxidation model were previously compared with measured data in Figure 34-6 of Reference 6. These BE predictions are used to determine a hydrogen model uncertainty that may be used in applications outside of the GALILEO statistical methodology. [

]

Figure 3-6 shows the distribution of M/P values for the Zr-4 BE hydrogen predictions.

[

]

Evaluation of the M/P data provides the following parameters for the Zr-4 hydrogen model uncertainty.

[

]

Figure 3-7 shows the Zr-4 M/P values versus the measured data points.

3.3.2 *M5 Cladding*

Hydrogen predictions based on the best-estimate (BE) M5 oxidation model were previously compared with measured data in Figure 34-7 of Reference 6. These BE predictions are used to determine a hydrogen model uncertainty that may be used in applications outside of the GALILEO statistical methodology. [

]

Figure 3-8 shows the distribution of M/P values for the M5 BE hydrogen predictions.

[

]

Evaluation of the M/P data provides the following parameters for the M5 hydrogen model uncertainty.

[

]

Figure 3-9 shows the M5 M/P values versus the measured data points.

3.4 *Demonstration*

To demonstrate the similarity of the two hydrogen model uncertainty applications, a set of sample calculations is provided. These sample cases demonstrate how the model uncertainties are applied and show that the predicted upper bound hydrogen concentrations are similar for both applications. The following sections provide the sample cases for Zr-4 and M5 cladding.

3.4.1 *Zr-4 Cladding*

The sample case for the 14x14 fuel rod design in Section 6.1.1 of Reference 1 is used for the demonstration of the Zr-4 hydrogen model uncertainties. **[**

]

Table 3-1 compares the results of the two applications. The two methods provide nearly the same prediction of hydrogen concentration for Zr-4.

3.4.2 *M5 Cladding*

The sample case for the 17x17 fuel rod design in Section 6.1.3 of Reference 1 is used for the demonstration of the M5 hydrogen model uncertainties. [

]

Table 3-2 compares the results of the two applications. The two methods provide similar predictions of hydrogen concentration for M5. [

]

Table 3-1: Zr-4 Sample Case Comparison

[ ]

Table 3-2: M5 Sample Case Comparison

[ ]

Figure 3-1: M5 Hydrogen Pickup Fraction

[ ]

Figure 3-2: Distribution of Upper Bound P-M for Zr-4 Hydrogen

Figure 3-3: Zr-4 Upper Bound Hydrogen Predictions vs Measurements

[ ]

Figure 3-4: Distribution of Upper Bound P-M for M5 Hydrogen

[ ]

Figure 3-5: M5 Upper Bound Hydrogen Predictions vs Measurements

[ ]

Figure 3-6: Distribution of Zr-4 M/P Hydrogen

[ ]

Figure 3-7: Zr-4 M/P Hydrogen vs Measured Hydrogen

[ ]

Figure 3-8: Distribution of M5 M/P Hydrogen

[ ]

Figure 3-9: M5 M/P Hydrogen vs Measured Hydrogen

[

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4.0 REFERENCES

1. ANP-10323(P), Revision 1, GALILEO Fuel Rod Thermal-Mechanical Methodology for Pressurized Water Reactors, June 2018.

2. ANP-10323, Rev. 1, Q2P, Revision 0, Response to Request for Additional Information – ANP-10323P, January 2019.

3. ANP-10323, Rev. 1, Q3P, Revision 0, Response to Request for Additional Information – ANP-10323P, June 2019.

4. BAW-10227P-A, Revision 1, Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel, June 2003.

5. FS1-0004682-6.0, GALILEO Fuel Rod Performance Code Theory Manual.

6. ANP-10323, Rev. 1, Q4P, Revision 0, Response to Request for Additional Information – ANP-10323P, September 2019.

7. SCR-607, Factors for One-Sided Tolerance Limits and for Variables Sampling Plans, D. B. Owen, March 1963, NRC ADAMS document ML14031A495.

5.0 TOPICAL REPORT MARKUPS

Below are markup pages for the GALILEO topical report (Reference 1) which are necessary to incorporate the additional information provided in Sections 2.0 and 3.0 of this report. It should be noted that markup pages are only provided for instances where the supplemental information will be referenced or briefly described. Section 2.0 (fuel rod fatigue initialization) of this report will become Appendix C and Section 3.0 (hydrogen pickup models) of this report will become Appendix D in the final approved version of Reference 1. Markup pages are not provided for these additions.

[ ]

The following markup page supersedes the markup page previously provided in Appendix C of Reference 6 (p. 66).

The following markup page supersedes the markup page previously provided in Appendix C of Reference 6 (p. 72).

The following markup page supersedes the markup page previously provided in Appendix C of Reference 6 (p. 73).

The following markup page supersedes the markup page previously provided in Appendix C of Reference 6 (p. 74).

The following markup page supersedes the markup page previously provided in Appendix C of Reference 6 (p. 77).