ENCLOSURE 3

CALLAWAY ROD EJECTION ACCIDENT ANALYSIS REPORT
(NON-PROPRIETARY VERSION)

The following pages provide the non-proprietary version of the Callaway Rod Ejection Accident Analysis report provided by Framatome, Inc. supporting the license amendment request submitted in Ameren Missouri letter ULNRC-06768 dated October 12, 2022 (ADAMS Accession No. ML22285A115).

ANP-4012NP, "Callaway Rod Ejection Accident Analysis," Revision 1,
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[NON-PROPRIETARY]

48 pages follow this cover sheet

Callaway Rod Ejection Accident Analysis

ANP-4012NP
Revision 1

Technical Report

November 2022

Nature of Changes

Revision No.	Section(s) or Page(s)	Description and Justification
0	All	Initial Issue
1	All	Updated Proprietary notations throughout document.

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Nomenclature

Acronym	**Definition**
BOC	Beginning of Cycle
DNBR	Departure from Nucleate Boiling Ratio
DTC	Doppler Temperature Coefficient
EFPD	Effective Full Power Days
EOC	End of Cycle
HZP	Hot Zero Power
LOCA	Loss of Coolant Accident
MDNBR	Minimum Departure from Nucleate Boiling Ratio
MOC	Middle of Cycle
MTC	Moderator Temperature Coefficient
NRC	Nuclear Regulatory Commission
PCMI	Pellet Clad Mechanical Interaction
RCCA	Rod Control Cluster Assembly
REA	Rod Ejection Analysis
RIL	Rod Insertion Limit
RTP	Rated Thermal Power
SAFDL	Specified Acceptable Fuel Design Limit
TIL	Time in Life
VQP	Vendor Qualification Program

1.0 INTRODUCTION

The Callaway Rod Ejection Analysis (REA) with ARCADIA is described in this document. The analysis was performed based on the Vendor Qualification Program (VQP) representative cycle design and is applicable to transition cycles (containing co-resident fuel with the GAIA fuel) and cycle designs containing a full core of GAIA provided the conditions of the cycle design are bounded by the requirement of the Callaway REA analysis described in this document.

The analysis is performed using Framatome's ARCADIA Rod Ejection Accident (AREA) methodology (Reference 1). This methodology is compliant with the criteria defined in Reference 2. Application of the criteria within the AREA methodology is provided below:

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- The enthalpy rise is based on excess hydrogen as defined in Reference 2.
- The enthalpy limit used for high temperature cladding failure threshold in Reference 2 is a function of internal pin pressure with a maximum of 170 cal/g for internal pressures less than system pressure and a minimum limit of 100 cal/g for internal pressures higher than system pressure.
- Reference 2 has the following restrictions for coolability:
  - Peak radial average fuel enthalpy must remain below 230 cal/g.
  - A limited amount of fuel melting is acceptable provided it is restricted to the fuel centerline region and is less than 10 percent of pellet volume. The peak fuel temperature in the outer 90 percent of the pellet's volume must remain below incipient fuel melting conditions.

Both restrictions are met even with the near prompt critical events that occur at the EOC low power conditions. The peak radial average maximum fuel enthalpy remains below 100 cal/g and fuel temperature throughout the pellet remains below the melt temperature. Based on the results of the analysis, core coolability during a rod ejection event at Callaway is not a consideration and is not discussed in this document.

Clarifications to the methodology that are different from those implied by Reference 1 are as follows:

1. GALILEO (Reference 3) is used as the fuel performance code in this analysis, which is the GALILEO version approved by the Nuclear Regulatory Commission (NRC). The GALILEO version discussed in Reference 1 is the Reference 4 version of GALILEO. The benchmark analysis in Section 5.2.2 of Reference 1 using the Reference 3 version of GALILEO was repeated, and results are comparable, with some improvements seen in some of the results. These improvements are not factored into this analysis.

2. Section 6.8.3 of the Reference 1 methodology states that a **[**

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3. In the Callaway REA analysis, prompt critical is defined when transients have a **[**

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Criteria (c) and (d) defined in associated affidavit for this document apply to bracketed material on this page.

4. The enthalpy rise limits are based on prompt critical testing. For non-prompt critical ejected rod worths, there is no fast power pulse. [

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5. For prompt critical cases, [

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6. System pressure calculations were not performed as part of the Callaway REA event analysis.

The Callaway AREA analysis is based on the representative VQP cycle design. The analysis is intended to be bounding for GAIA fuel in other cycles including transition cycles. Justification is provided for use of the analysis for transition cycles as long as key parameters from these cycles are bounded by the analysis parameters.

2.0 OVERVIEW OF CYCLE INPUTS

A full core of Framatome's GAIA fuel with M5 cladding was analyzed in the Callaway REA analysis. The impact of transition cycles is considered through the development of cycle-to-cycle biases.

The analysis is performed for [ ] times in life (TIL) and at [ ] power levels for each TIL. The TILs considered are [ ] This correspondence of rod position to power level used in this analysis is provided in Table 2-1. The selected power levels are [ ]

The required penalizations applied in the AREA analysis are stated in Table 2-2 with the depressurization curve supporting the Minimum Departure from Nucleate Boiling Ratio (MDNBR) analysis provided in Figure 2-1. Cycle flexibility biases were also included to extend applicability of the cycle analyzed to transition cycles and future cycles. These include biases on rod worth, Moderator Temperature Coefficient (MTC), Doppler Temperature Coefficient (DTC), β_{eff}, and power peaking factors.

Table 2-1
Callaway Rod Insertion Limits with Respect to Power

[ ]

Table 2-2
Core Penalization Parameters and Values

[ ]

Criteria (c) and (d) defined in associated affidavit for this document apply to bracketed material on this page.

Figure 2-1
Depressurization Curve

[ ]

3.0 REA LIMITS GENERATED BY GALILEO

The Callaway REA analysis contains a full core of GAIA fuel with M5 cladding. The Pellet Clad Mechanical Interaction (PCMI) limits for excess hydrogen are calculated using GALILEO (Reference 3). [

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The hydrogen update model in GALILEO calculates the total hydrogen content in the clad as a function of fuel rod burnup. The enthalpy deposition limits from Reference 2 provide an acceptable correlation for solubility of hydrogen in zirconium alloys as a fraction of clad temperature. [

] The enthalpy rise limit for M5 cladding based on the excess hydrogen criteria from Reference 2 is shown in Figure 3-1.

Figure 3-1
Enthalpy Rise Limits for M5 Fuel Based on Excess Hydrogen

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4.0 FUEL INTEGRITY SUMMARIES

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] The general timing of the event is provided in Table 4-1.

The most limiting results for the transient cases at each power level are provided for each TIL. The margins reported are based on the calculated value minus the limit so that a negative number is favorable. Minimum margin is defined as the least negative value. A positive value indicates a violation of the limit. Additional detail is provided for the cases with the least margin to the limit for fuel melt, fuel rim melt, MDNBR, enthalpy, and enthalpy rise. [

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Limiting cases for enthalpy, enthalpy rise, and fuel rim temperature are provided for those cases with a [ ] Prompt critical transients occur at EOC conditions based on the criteria stated above.

Table 4-1
General Timing of Event

Event	Timing
Time to eject rod	0.1 second * fraction of insertion
Trip signal reached	Case dependent
Time to core peak neutron power	Included with power plot
Time to maximum enthalpy rise	One pulse width past the time of peak core neutron power for prompt critical conditions
Start of Scram	Total delay time (0.5 s)
Rods to full insertion	Total scram time (3.78 s)
Simulation ended for event	[ ]

4.1 *Evaluation of VQP Cycle REA with all GAIA Fuel*

For each TIL analyzed, limiting results for the transient cases at each power level are provided in Table 4-2 through Table 4-6. More detail is provided for the cases with the minimum margin. There are no cases that produce fuel failure in the Callaway REA analysis. Therefore, there are no dose consequences. For the parameters of concern, the minimum margins along with the corresponding TIL are listed below:

- The fuel temperature case with minimum margin occurs at **[**

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- The MDNBR case with minimum margin occurs at **[**

  ]
- The Enthalpy case with minimum margin occurs at **[**

  ]
- The Enthalpy rise case with minimum margin occurs at **[**

  ]
- And the fuel rim temperature case with minimum margin occurs at **[**

  ]

[

]

4.1.1 Minimum Margin to Fuel Melt Limits

From the [ ] results presented in Table 4-2, the minimum margin to the fuel melt limit is [ ], which occurs in the [ ] initial power REA transient case. No fuel melt occurs which meets the fuel melt criteria. For the maximum fuel temperature transient, core power, $F_{\Delta H}$, and F_Q are shown in Figure 4-1. The fuel temperature and clad temperature with time are shown in Figure 4-2. [ ] the difference between fuel temperature and the melt limit is shown in the [ ] plot in Figure 4-3.

4.1.2 Minimum Margin to DNBR SAFDL

Exceeding the DNBR Specified Acceptable Fuel Design Limit (SAFDL) is a failure criterion [ ] In the Callaway REA analysis (Table 4-3), no DNB failures (SAFDL/MDNBR-1 > 0) occur. The minimum margin of [ ] occurs at the [ ] power initial condition and [ ]

For the limiting MDNBR transient, the results for core power, $F_{\Delta H}$, and F_Q are shown in Figure 4-4. The MDNBR as a function of time is provided in Figure 4-5. The SAFDL is divided by the MDNBR of [ ] The limit is reached when the ratio becomes 1.0. All fuel pins above 1.0 are assumed failed and those below 1.0 are not. SAFDL/MDNBR values [ ] are shown in the [ ] in Figure 4-6.

4.1.3 Minimum Margin to Enthalpy Limits

For cases that are prompt critical, enthalpy is used as a measure of fuel failure in lieu of MDNBR. As discussed previously, for this analysis, prompt critical is defined as any case that has a [ ] Based on this definition and the results from Table 4-6, the minimum margin for enthalpy is [ ] The peak power, $F_{\Delta H}$ and F_Q are presented in Figure 4-7. The enthalpy as a function of time is presented in Figure 4-8 and the (enthalpy – limit) values by fuel type are presented as a function of [ ] in Figure 4-9. Enthalpy does not exceed limits, and no fuel failures occur.

4.1.4 Minimum Margin to Enthalpy Rise Limit

For the prompt critical [ ] cases, the transient with the minimum margin to the enthalpy rise limit occurs at [ ] condition. From the results in Table 4-6, the minimum enthalpy rise margin is [ ] The peak power, $F_{\Delta H}$, and F_Q are presented in Figure 4-7. Figure 4-10, then provides the enthalpy rise versus [ ] along with the [ ] limit. No fuel failures occur based on the enthalpy rise limit being exceeded for the Callaway REA analysis.

4.1.5 Minimum Margin of Fuel Rim Temperature to Melt Limit

During a prompt transient, the fuel rim temperature can be the limiting temperature during the pulse. For this reason, the fuel rim temperature is considered to determine fuel melt in prompt critical cases. For the Callaway REA analysis, the minimum margin to the melt limit (value – limit) for the fuel rim occurs at **[ ]** From the results in Table 4-5, the minimum margin is **[ ]** The peak power, $F_{\Delta H}$, and F_Q are presented in Figure 4-11 and the fuel, fuel rim, and clad temperatures are presented in Figure 4-12. The fuel temperature, fuel rim temperature, and clad temperature as a function of time are shown in Figure 4-12. **[ ]** the differences between its fuel rim temperature and melt limit are presented as a function of **[ ]** in the **[ ]** plot in Figure 4-13.

4.2 *Trip/No Trip Evaluation*

For transients that are terminated by reactor trip, a no trip evaluation is performed. **[**

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4.3 *Conservatism of Biasing Method*

Based on the results in Table 4-2 through Table 4-6, an assessment of the limiting case for fuel temperature, fuel rim temperature, MDNBR, enthalpy, and enthalpy rise is presented and summarized in Table 4-7. For each of the applicable limiting criteria, the power level, cycle burnup, [ ] are provided. There is ample conservatism for each of the parameters listed in this table. [ ]

Table 4-2
Limiting Results Summary for [ ] – GAIA Fuel

[ ]

Table 4-3
Limiting Results Summary for [ ] – GAIA Fuel

[

]

Table 4-4
Limiting Results Summary for [ ] – GAIA Fuel

[

]

Table 4-5
Limiting Results Summary for [ ] – GAIA Fuel

[ ]

Table 4-6
Limiting Results Summary for [ ] – GAIA Fuel

[ ]

Table 4-7
Measure of Conservatism for Limiting Results

[ ]

Figure 4-1
Transient Core Power, F_Q, and $F_{\Delta H}$ – Fuel Temperature – GAIA Fuel

[

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Figure 4-2
Transient Fuel and Clad Temperature – Fuel Temperature – GAIA Fuel

Figure 4-3
Fuel Temperature by Fuel Type – Margin to Limits – Fuel Temperature – GAIA Fuel

[ ]

Figure 4-4
Transient Core Power, F_Q, and $F_{\Delta H}$ – MDNBR – GAIA Fuel

[ ]

Figure 4-5
Transient MDNBR – GAIA Fuel

[ ]

Figure 4-6
SAFDL to MDNBR Ratio by Fuel Type – GAIA Fuel

[ ]

Figure 4-7
Transient Core Power, F_Q, and $F_{\Delta H}$ – Enthalpy – GAIA Fuel

[ ]

Figure 4-8
Transient Enthalpy – GAIA Fuel

[ ]

Figure 4-9
Transient Enthalpy – Limit – GAIA Fuel

Figure 4-10
Transient Enthalpy Rise Compared to Limit – GAIA Fuel

Figure 4-11
Transient Core Power, F_Q, and $F_{\Delta H}$ – Fuel Rim Temperature – GAIA Fuel

[

]

Figure 4-12
Transient Fuel, Fuel Rim, and Clad Temperature – Fuel Rim Temperature – GAIA Fuel

[ ]

Figure 4-13
Fuel Rim Temperature by Fuel Type – Margin to Limits – Fuel Rim Temperature – GAIA Fuel

[ ]

5.0 SUMMARY OF AREA RESULTS

The AREA methodology described in Reference 1 was applied to Callaway for a full core of Framatome's GAIA fuel. Mixed core application of this analysis is addressed in the development of parameter biasing to account for the impact of cycle-to-cycle changes including cycle designs with co-resident fuel assemblies. [

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In the AREA analysis for the Callaway, REA provides ample margin to limits for fuel temperature, fuel rim temperature, MDNBR, enthalpy, and enthalpy rise, which means there are no fuel failures associated with this event and, therefore, no dose consequences.

6.0 CYCLE TO CYCLE VERIFICATION

No limiting conditions are approached with high fuel burnup in the Callaway AREA analysis. For this reason, checking the peak analysis static conditions as outlined in the AREA topical report (Reference 1, Section 8.2) is a valid method to perform a cycle-to-cycle verification. Table 6-1 summarizes the values for the key parameters used in this check for the AREA analysis. This table forms a basis to perform a cycle specific verification to determine if the cycle key parameters remain within the range of values used in the analysis. The steady state key parameters are listed below:

- Ejected rod worth
- β_{eff}
- Moderator Temperature Coefficient
- Doppler Temperature Coefficient
- Initial F_Q (at power cases only)
- Initial $F_{\Delta H}$ (at power cases only)
- Static post ejected F_Q
- Static post ejected $F_{\Delta H}$

In the event that any of these key parameters are not bounded in future cycles, there are two approaches available besides redesigning the cycle to meet the conditions in the tables:

1. Complete reanalysis of the matrix of cases. This approach is selected when a new baseline matrix of cases is needed. This option is typically employed for major fuel design changes, increase in core power level, or the extension of the cycle length well beyond the analysis cycle length (e.g., going from an 18-month to a 24-month cycle).
2. Reanalysis of a portion of the matrix of cases for the condition where a specific parameter is found to be outside the initial application analysis range. [ ] This option is typically employed for minor fuel design changes that are challenging isolated conditions of the original analysis.

These key parameters include the effects of a mixed core of Westinghouse Performance+ fuel and GAIA fuel. Analyses were performed that show, for the DNB analysis, the results are more conservative for a full core of GAIA fuel as compared to a mixed core of GAIA and Westinghouse Performance+ fuel. Use of the Callaway AREA analysis is valid as long as the above parameters remain within the bounds specified in Table 6-1.

Table 6-1
Key Parameter Values for Cycle-to-Cycle Checks

7.0 REFERENCES

1. ANP-10338P-A, Revision 0, AREA – ARCADIA Rod Ejection Accident, December 2017.

2. Regulatory Guide RG 1.236, Pressurized-Water Reactor Control Rod Ejection and Boiling Water Reactor Control Rod Drop Accidents, Paul Clifford, July 2020.

3. ANP-10323P-A, Revision 1, GALILEO Fuel Rod Thermal Mechanical Methodology for Pressurized Water Reactors, November 2020.

4. ANP-10323P, Revision 0, Fuel Rod Thermal-Mechanical Methodology for Boiling Water Reactors and Pressurized Water Reactors, July 2013.

5. XN-75-32(P)(A) and Supplements 1, 2, 3, & 4, Computational Procedure for Evaluating Fuel Rod Bowing, February 1983.