October 3, 2016

MEMORANDUM TO: Kevin Hsueh, Chief
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

FROM: Joseph A. Golla, Project Manager ***/RA/***
Licensing Processes Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

SUBJECT: GLOBAL NUCLEAR FUEL – THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD THERMAL – MECHANICAL PERFORMANCE, NEDC-33840P/NEDO-33840 AUDIT REPORT (CAC NO. MF7687)

By letter dated April 22, 2016 (Agencywide Documents Access and Management System Accession No. ML16113A264), Global Nuclear Fuel (GNF) submitted Topical Report NEDC-33840P/NEDO-33840, Rev. 0, “The PRIME Model for Transient Analysis of Fuel Rod Thermal – Mechanical Performance,” for U.S. Nuclear Regulatory Commission (NRC) staff review.

The NRC staff conducted an audit, following Office of Nuclear Reactor Regulation Office Instruction LIC-111, “Regulatory Audits.” The audit was conducted at the GNF facilities in Wilmington, North Carolina on May 23 - 25, 2016. A public version of the NRC staff Regulatory Audit Report is enclosed.

Project No. 712

Enclosure:
Audit Report

CONTACT: Paul Clifford, NRR/DSS
(301) 415-4043

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DATE	9/28/2016	9/27/2016	9/15/2016	9/30/2016	10/3/2016

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AUDIT REPORT:
THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD
THERMAL – MECHANICAL PERFORMANCE
NEDC-33840P/NEDO-33840, REVISION 0, APRIL 2016
GLOBAL NUCLEAR FUEL WILMINGTON, NORTH CAROLINA, MAY 23-25, 2016

1.0 BACKGROUND

By letter dated April 22, 2016, Global Nuclear Fuel (GNF) submitted a Topical Report (TR), "The PRIME Model for Transient Analysis of Fuel Rod Thermal – Mechanical Performance," NEDC-33840P/NEDO-33840 (Documents Access and Management System (ADAMS) Accession No. ML16113A264). The TR covers application of PRIME to the analysis of fast transient anticipated operational occurrences (AOOs) to determine compliance to SAFDLs for fuel temperature and cladding strain.

GNF TRs NEDC-33256P-A, NEDC-33257P-A, and NEDC-33258P-A document the technical basis, qualification and application methodology for steady-state application, including steady-state (long duration relative to the fuel rod thermal time constant) transients, of the PRIME fuel rod thermal-mechanical performance model. Subsequent to approval of the PRIME steady-state TRs, the fast (short duration relative to the fuel rod thermal time constant) transient functionality of PRIME has been developed and qualified and a new application methodology specifically utilizing the transient functionality has been developed. The objectives of this TR are to document the:

1) technical basis of the PRIME analysis capability utilizing the transient functionality;

2) experimental qualification of PRIME predictions of fuel cladding strains for transients utilizing the transient functionality, which includes reactivity-initiated accident (RIA) tests performed at the CABRI and Nuclear Safety Research Reactor (NSRR) test reactors, and operational transient (OPTRAN) tests conducted in the Power Burst Facility (PBF) test reactor; and

3) application methodology of the PRIME transient analysis capability to commercial fuel rod behavior and licensing analyses.

2.0 REGULATORY AUDIT OBJECTIVES

To assist in its review of NEDC-33840P, the staff conducted an audit at the GNF facilities in Wilmington, North Carolina on May 23-25, 2016. The specific objectives of this audit are listed below:

- gain a better understanding of the scope and content of the PRIME Transients TR;
- review the underlying software verification documents;
- gather necessary inputs to perform FRAPCON/FRAPTRAN benchmark calculations;
- develop scope of benchmark calculations;
- identify and resolve code-to-code differences; and
- perform benchmark calculations.

The GNF and NRC staff which participated in the audit are listed in Table 1 below.

Table 1: List of Attendees

Name	Organization
Paul Clifford	NRC/NRR
Ian Porter	NRC/RES
James Harrison	GNF
Robert Rand	GNF
Randall Dunavant	GNF

3.0 REGULATORY AUDIT BASES

Regulatory guidance for the review of fuel system designs and adherence to General Design Criteria (GDC)-10, GDC-27, and GDC-35 is provided in NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants” (SRP), Section 4.2, “Fuel System Design.” In accordance with SRP Section 4.2, the objectives of the fuel system safety review are to provide assurance that:

a. The fuel system is not damaged as a result of normal operation and AOOs,

b. Fuel system damage is never so severe as to prevent control rod insertion when it is required,

c. The number of fuel rod failures is not underestimated for postulated accidents, and

d. Coolability is always maintained.

In addition to licensed reload methodologies, an approved fuel rod thermal-mechanical model and application methodology is utilized to demonstrate compliance to SRP 4.2 fuel design and performance criteria. NEDC-33840P describes the technical basis, qualification, and application methodology for the PRIME Transients thermal-mechanical fuel rod performance model. The staff’s review of this TR is to ensure that the PRIME Transient models are capable of accurately (or conservatively) predicting the in-reactor performance of fuel rods under fast transient AOO conditions, to identify any limitations on the code’s ability to perform this task, and ensure that the application methodology conservatively accounts for model uncertainties and is capable of ensuring compliance to SRP 4.2 criteria.

4.0 DISCUSSION

During the audit, the staff performed multiple activities to meet the audit objectives defined in Section 2 above. These activities are summarized below.

PRIME03 Software Validation Reports

PRIME03 software and topical report NEDC-33840P was validated in accordance with GNF’s 10 CFR Part 50 Appendix B qualified software verification and validation procedure. During the audit, the staff reviewed the following associated GNF documentation:

Software Test Report 0000-0027-3332 R1, PRIME03P (2007)

- Documents the original thermal transient validation. [

]

PRIME03P eECPER 0000-0027-3319 Rev 11 and Rev 12 (along with associated STP 0000-0027-3333 Rev 6)
- Minor error corrections

PRIME Transient TR Verification Report ECO-0020947 (2016)
- Documents independent review and management authorization to release TR

Application Methodology

Section 5 of NEDC-33840P documents the application methodology for PRIME transient. During the audit, GNF staff described the three application methods and provided sample calculations for the Method #3 screening criteria for GNF2 fuel using TRACG. The different methods are summarized below.

Method #1: Full PRIME Transient Calculations
Use PRIME transient temperature solution with fast transient power profile from fast transient nuclear code (e.g., TRACG, ODYN). PRIME prediction for fuel centerline temperature and cladding hoop strain compared with respective GESTAR acceptance criteria. Fuel centerline temperature and cladding strain predictions based on upper tolerance and worst dimensions respectively. Calculations may be design-specific, AOO-specific and cycle-specific.

Method #2: **[** **]**
Extract the best-estimate temperature and strain corresponding to the Method #1 type calculations. **[**

] Calculations may be design-specific and AOO-specific.

Method #3: **[**

]

Benchmark Calculations

The purpose of these benchmark calculations was to investigate PRIME's prediction of time-dependent parameters such as energy deposition, fuel centerline temperature, and cladding incremental strain. The NRC maintains validated fuel rod thermal-mechanical codes, FRAPCON-4.0 (steady-state) and FRAPTRAN-2.0 (transient), for the purpose of performing independent, confirmatory calculations. During the audit, GNF and NRC staff worked to develop simplified AOO overpower simulations which limited code-to-code differences, while achieving the objective of confirming the transient temperature solution and fuel thermal time constant.

The first set of benchmark calculations were designed to investigate the inherent, exposure-dependent fuel thermal time constant within the code's fuel rod properties and fuel thermal temperature solution. The fuel thermal time constant is defined as the time required to achieve 63 percent of the steady-state fuel temperature following a power change. For a given transient temperature over-power scenario, the fuel thermal time constant is an important parameter in defining the rate at which fuel temperature increases. A smaller thermal time constant means a more rapid temperature response. A larger thermal time constant means a more lethargic temperature response.

Section 4.1 of NEDC-33840P describes the qualification of PRIME's transient temperature solution via comparison with steady-state fuel temperature predictions. Figure 4-3 illustrates this comparison. During the audit, it was decided to expand this qualification exercise and calculate the fuel thermal time constant at several exposure points. The benchmark cases included a GNF2 fuel rod exposed to a base depletion along the bounding thermal-mechanical operating limit (TMOL) with an instantaneous 50 percent power spike held for 50 seconds at 0.01, 14.6, 45, and 55 GWd/MTU. The GNF staff used the PRIME steady-state and transient fuel centerline temperature predictions to calculate the inherent fuel thermal time constant at each exposure point. The same approach was taken by NRC staff using the FRAPCON-4.0 and FRAPTRAN-2.0 codes. The results of these benchmark cases are summarized in Table 2 below.

Table 2: PRIME03P versus FRAPTRAN-2.0 Fuel Thermal Time Constant

Exposure Point (GWd/MTU)	PRIME03P (seconds)	FRAPTRAN-2.0 (seconds)
0.01	6.0	6.7
14.6	6.4	7.4
45	6.3	8.1*
55	6.3	6.5*

* Due to significant differences in initial conditions between FRAPCON and FRAPTRAN, the fuel thermal time constant was calculated based on FRAPTRAN's stabilized temperature (towards end of 50 second hold).

Examination of Table 2 reveals that PRIME03P's inherent fuel thermal time constant is smaller than FRAPTRAN-2.0's inherent fuel thermal time constant at each exposure level. A smaller inherent fuel thermal time constant promotes a more rapid fuel temperature excursion which is conservative with respect to calculating approach to fuel centerline melting and incremental cladding hoop strain.

The second set of benchmark calculations were designed to compare changes in time-dependent parameters for identical power ramps at several exposure points. The benchmark cases included a GNF2 fuel rod exposed to a base depletion along the bounding thermal-mechanical operating limit (TMOL) with both a 1-second and 5-second duration power ramp up to 3 times the initial rod power at 0.01, 14.6, 45, and 55 GWd/MTU. These benchmark calculations investigate the burnup dependence on the fuel response to a fast AOO with limited energy deposition versus a slower AOO with a much larger energy deposition.

During the audit, GNF staff ran the PRIME03P cases and provided the results to the NRC staff. The NRC staff completed the corresponding FRAPTRAN-2.0 calculations and compiled the results. Tables 3 through 10 provide PRIME03P and FRAPTRAN-2.0 code predictions, calculated changes in important parameters, and calculated code-to-code differences.

It is important to recognize that these benchmark comparisons are based on best-estimate calculations. While validated against similar empirical databases, each code has its own quantified uncertainties on fuel temperature and fuel swelling predictions. Coupled with normal code-to-code variability in fuel characterization and analytical solutions, differences in both initial conditions (at start of transient) and peak transient parameters are expected. In an attempt to minimize code-to-code differences, the cladding inner diameter was artificially reduced to minimize initial pellet-to-cladding gap differences and the PRIME03P cladding heat transfer film coefficients were imported into FRAPTRAN-2.0.

In the discussion below, a negative (-) difference means that PRIME03P predictions were smaller and a positive (+) difference means that PRIME03P predictions were larger than those of FRAPTRAN-2.0.

Examination of the benchmark cases for a fresh fuel rod (Tables 3 and 4, 0.01 GWd/MTU) reveal reasonable differences in initial fuel centerline temperature (T_{CL}), -3.9%, stored energy (H_{fuel}), -2.0%, and pellet-to-clad gap size, 0 inches. For the 1-second duration ramp, code-to-code comparisons are in reasonable agreement with differences in predictions of changes in fuel centerline temperature (ΔT_{CL}) of -2.2%, changes in stored energy (ΔH_{fuel}) of -1.2%, and changes in cladding hoop strain ($\Delta\varepsilon_{hoop}$) of +0.08%. For the 5-second duration ramp, code-to-code comparisons are also in reasonable agreement with differences in ΔT_{CL} of -0.3%, ΔH_{fuel} of -1.3%, and $\Delta\varepsilon_{hoop}$ of +0.48%. Given a lower ΔH_{fuel}, these results suggest that the PRIME03P fuel thermal swelling model and resulting cladding strain are conservative relative to FRAPTRAN-2.0.

Examination of the benchmark cases at the knee of the TMOL (Tables 5 and 6, 14.6 GWd/MTU) reveal reasonable differences in initial T_{CL}, -2.1%, H_{fuel}, +0.7%, and pellet-to-clad gap size, 0 inches. For the 1-second duration ramp, code-to-code comparisons are in good agreement with differences in predictions of ΔT_{CL} of +0.3%, ΔH_{fuel} of -0.9%, and $\Delta\varepsilon_{hoop}$ of -0.05%. For the 5-second duration ramp, code-to-code comparisons are also in reasonable agreement with differences in ΔT_{CL} of +2.1%, ΔH_{fuel} of -4.8%, and $\Delta\varepsilon_{hoop}$ of +0.31%.

Examination of the benchmark cases at 45 GWd/MTU (Tables 7 and 8) reveal reasonable differences in initial T_{CL}, -1.4% and H_{fuel}, +0.5%. However, the reduced power has opened the pellet-to-clad gap in the FRAPTRAN case. For the 1-second duration ramp, code-to-code comparisons are in reasonable agreement with differences in predictions of ΔT_{CL} of +4.4%, ΔH_{fuel} of -1.0%, and $\Delta\varepsilon_{hoop}$ of 0.0%. For the 5-second duration ramp, code-to-code comparisons are also in reasonable agreement with differences in ΔT_{CL} of +3.2%, ΔH_{fuel} of -0.6%, and $\Delta\varepsilon_{hoop}$ of +0.22%.

Examination of the benchmark cases at 55 GWd/MTU (Tables 9 and 10) reveal large differences in initial T_{CL}, -11.2% and H_{fuel}, +16.3%. This is likely due to the presence of a pellet-to-clad gap in the FRAPTRAN case. For the 1-second duration ramp, code-to-code comparisons are in poor agreement with differences in predictions of ΔT_{CL} of +8.6%, ΔH_{fuel} of +12.2%, and $\Delta\varepsilon_{hoop}$ of 0.0%. For the 5-second duration ramp, code-to-code comparisons are also in poor agreement with differences in ΔT_{CL} of +10.1%, ΔH_{fuel} of +18.5%, and $\Delta\varepsilon_{hoop}$ of +0.27%. The presence of the pellet-to-clad gap has introduced significant differences. However, in both ramp cases, PRIME03P predicted a larger increase in centerline temperature and fuel enthalpy which is conservative.

5.0 REGULATORY AUDIT CONCLUSIONS AND FINDINGS

All of the regulatory audit objectives listed in Section 2 were completed. No errors or negative findings were identified during the audit.

Table 3: Transient Power Ramp Benchmark, 0.01 GWd/MTU

	1-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2620	2721	-101	-3.9
Tsurface (F)	686	687	-1	-0.1
Stored Energy (cal/g)	57.53	58.7	-1.17	-2.0
Radial Gap Size (mils)	0	0		
Clad Strain (in/in)	0.0033	0.00204	0.00126	38.2
Tclad ID (F)	668	670.1	-2.1	-0.3
Tclad OD (F)	567	566.4	0.6	0.1
Peak Transient				
Tcenterline (F)	3021	3131	-110	-3.6
[ ]	**[ ]**	**[ ]**	-9	-2.2
Tsurface (F)	703	700	3	0.4
[ ]	**[ ]**	**[ ]**	4	23.5
Time of Peak TCL (sec)	2	2.4	-0.4	-20.0
Stored Energy (cal/g)	69.98	71.3	-1.32	-1.9
[ ]	**[ ]**	**[ ]**	-0.15	-1.2
Time of Peak Stored (sec)	0.9	0.9	0	0.0
Clad Strain (in/in)	0.005	0.00291	0.00209	41.8
[ ]	**[ ]**	**[ ]**	0.00083	0.08
Time of Peak Strain (sec)	1	1	0	0.0
Post-Ramp				
Tcenterline (F)	2637	2773	-136	-5.2
Tsurface (F)	694	711.9	-17.9	-2.6
Stored Energy (cal/g)	58.08	60.3	-2.22	-3.8
Radial Gap Size (mils)	0	0.121	-0.121	
Clad Strain (in/in)	0.0049	0.002941	0.001959	40.0
Tclad ID (F)	668	669.7	-1.7	-0.3
Tclad OD (F)	567	566.4	0.6	0.1

Table 4: Transient Power Ramp Benchmark, 0.01 GWd/MTU

	5-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2620	2721	-101	-3.9
Tsurface (F)	686	687	-1	-0.1
Stored Energy (cal/g)	57.53	58.7	-1.17	-2.0
Radial Gap Size (mils)	0	0		
Clad Strain (in/in)	0.0033	0.00204	0.00126	38.2
Tclad ID (F)	668	670.1	-2.1	-0.3
Tclad OD (F)	567	566.4	0.6	0.1
Peak Transient				
Tcenterline (F)	4235	4341	-106	-2.5
[ ]	**[ ]**	**[ ]**	-5	-0.3
Tsurface (F)	748	748.2	-0.2	0.0
[ ]	**[ ]**	**[ ]**	0.8	1.3
Time of Peak TCL (sec)	5	4.88	0.12	2.4
Stored Energy (cal/g)	100.01	101.75	-1.74	-1.7
[ ]	**[ ]**	**[ ]**	-0.57	-1.3
Time of Peak Stored (sec)	4	4.05	-0.05	-1.3
Clad Strain (in/in)	0.0122	0.0061	0.0061	50.0
[ ]	**[ ]**	**[ ]**	0.00484	0.48
Time of Peak Strain (sec)	4.5	4.5	0	0.0
Post-Ramp				
Tcenterline (F)	2841	3259.8	-418.8	-14.7
Tsurface (F)	792	942.06	-150.06	-18.9
Stored Energy (cal/g)	62.56	75.78	-13.22	-21.1
Radial Gap Size (mils)	0.258	0.96	-0.702	-272.1
Clad Strain (in/in)	0.0122	0.006	0.0062	50.8
Tclad ID (F)	668	667	1	0.1
Tclad OD (F)	567	566	1	0.2

Table 5: Transient Power Ramp Benchmark, 14.6 GWd/MTU

	1-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	3000	3062	-62	-2.1
Tsurface (F)	719	699.4	19.6	2.7
Stored Energy (cal/g)	67.99	67.5	0.49	0.7
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.0047	-0.000287	0.004987	106.1
Tclad ID (F)	667	671.3	-4.3	-0.6
Tclad OD (F)	567	566.5	0.5	0.1
Peak Transient				
Tcenterline (F)	3359	3420	-61	-1.8
[ ]	**[ ]**	**[ ]**	1	0.3
Tsurface (F)	716	711	5	0.7
[ ]	**[ ]**	**[ ]**	-14.6	486.7
Time of Peak TCL (sec)	2	2.6	-0.6	-30.0
Stored Energy (cal/g)	80.38	80	0.38	0.5
[ ]	**[ ]**	**[ ]**	-0.11	-0.9
Time of Peak Stored (sec)	0.9	0.9	0	0.0
Clad Strain (in/in)	0.0049	0.000426	0.004474	91.3
[ ]	**[ ]**	**[ ]**	-0.000513	-0.05
Time of Peak Strain (sec)	2	1.02	0.98	49.0
Post-Ramp				
Tcenterline (F)	3001	3069	-68	-2.3
Tsurface (F)	719	703.7	15.3	2.1
Stored Energy (cal/g)	68.01	67.7	0.31	0.5
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.0049	0.000483	0.004417	90.1
Tclad ID (F)	668	671.2	-3.2	-0.5
Tclad OD (F)	567	566.5	0.5	0.1

Table 6: Transient Power Ramp Benchmark, 14.6 GWd/MTU

	5-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	3000	3062	-62	-2.1
Tsurface (F)	719	699.4	19.6	2.7
Stored Energy (cal/g)	67.99	67.5	0.49	0.7
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.0047	-0.000287	0.004987	106.1
Tclad ID (F)	667	671.3	-4.3	-0.6
Tclad OD (F)	567	566.5	0.5	0.1
Peak Transient				
Tcenterline (F)	4454	4486	-32	-0.7
[ ]	**[ ]**	**[ ]**	30	2.1
Tsurface (F)	761	759	2	0.3
[ ]	**[ ]**	**[ ]**	-17.6	-41.9
Time of Peak TCL (sec)	5	4.95	0.05	1.0
Stored Energy (cal/g)	109.7	111.2	-1.5	-1.4
[ ]	**[ ]**	**[ ]**	-1.99	-4.8
Time of Peak Stored (sec)	3.5	4.09	-0.59	-16.9
Clad Strain (in/in)	0.0118	0.003694	0.008106	68.7
[ ]	**[ ]**	**[ ]**	0.003119	0.31
Time of Peak Strain (sec)	5	4.95	0.05	1.0
Post-Ramp				
Tcenterline (F)	3186	3634	-448	-14.1
Tsurface (F)	822	1036	-214	-26.0
Stored Energy (cal/g)	74.55	88.2	-13.65	-18.3
Radial Gap Size (mils)	0.1905	0.638	-0.4475	-234.9
Clad Strain (in/in)	0.0118	0.003699	0.008101	68.7
Tclad ID (F)	668	669	-1	-0.1
Tclad OD (F)	567	566	1	0.2

Table 7: Transient Power Ramp Benchmark, 45 GWd/MTU

	1-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2486	2520.8	-34.8	-1.4
Tsurface (F)	728	695.9	32.1	4.4
Stored Energy (cal/g)	59.79	59.5	0.29	0.5
Radial Gap Size (mils)	0	0.0332	-0.0332	
Clad Strain (in/in)	0.0063	0	0.0063	100.0
Tclad ID (F)	636	637.95	-1.95	-0.3
Tclad OD (F)	565	565.14	-0.14	0.0
Peak Transient				
Tcenterline (F)	2744	2767.5	-23.5	-0.9
[ ]	**[ ]**	**[ ]**	11.3	4.4
Tsurface (F)	712	702.5	9.5	1.3
[ ]	**[ ]**	**[ ]**	-22.6	141.3
Time of Peak TCL (sec)	2	2.5	-0.5	-25.0
Stored Energy (cal/g)	68.4	68.2	0.2	0.3
[ ]	**[ ]**	**[ ]**	-0.09	-1.0
Time of Peak Stored (sec)	0.9	0.9	0	0.0
Clad Strain (in/in)	0.0063	0	0.0063	100.0
[ ]	**[ ]**	**[ ]**	0	0
Time of Peak Strain (sec)			0	
Post-Ramp				
Tcenterline (F)	2486	2520.85	-34.85	-1.4
Tsurface (F)	728	695.9	32.1	4.4
Stored Energy (cal/g)	59.79	59.5	0.29	0.5
Radial Gap Size (mils)	0	0.0332	-0.0332	
Clad Strain (in/in)	0.0063	0	0.0063	100.0
Tclad ID (F)	636	637.95	-1.95	-0.3
Tclad OD (F)	565	565.14	-0.14	0.0

Table 8: Transient Power Ramp Benchmark, 45 GWd/MTU

	5-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2486	2520.8	-34.8	-1.4
Tsurface (F)	728	695.9	32.1	4.4
Stored Energy (cal/g)	59.79	59.5	0.29	0.5
Radial Gap Size (mils)	0	0.0332	-0.0332	
Clad Strain (in/in)	0.0063	0	0.0063	100.0
Tclad ID (F)	636	637.95	-1.95	-0.3
Tclad OD (F)	565	565.14	-0.14	0.0
Peak Transient				
Tcenterline (F)	3620	3618.7	1.3	0.0
[ ]	**[ ]**	**[ ]**	36.1	3.2
Tsurface (F)	738	783.5	-45.5	-6.2
[ ]	**[ ]**	**[ ]**	-77.6	-776.0
Time of Peak TCL (sec)	5	4.9	0.1	2.0
Stored Energy (cal/g)	90.02	89.9	0.12	0.1
[ ]	**[ ]**	**[ ]**	-0.17	-0.6
Time of Peak Stored (sec)	4	4.1	-0.1	-2.5
Clad Strain (in/in)	0.0101	0.0015919	0.0085081	84.2
[ ]	**[ ]**	**[ ]**	0.0022081	0.22
Time of Peak Strain (sec)	4.5	4.8	-0.3	-6.7
Post-Ramp				
Tcenterline (F)	2634	2887	-253	-9.6
Tsurface (F)	825	967.6	-142.6	-17.3
Stored Energy (cal/g)	65.11	73.1	-7.99	-12.3
Radial Gap Size (mils)	0.0815	0.30744	-0.22594	-277.2
Clad Strain (in/in)	0.0101	0.0016323	0.0084677	83.8
Tclad ID (F)	636	637.2	-1.2	-0.2
Tclad OD (F)	565	565.1	-0.1	0.0

Table 9: Transient Power Ramp Benchmark, 55 GWd/MTU

	1-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2265	2518	-253	-11.2
Tsurface (F)	713	892	-179	-25.1
Stored Energy (cal/g)	55.38	64.4	-9.02	-16.3
Radial Gap Size (mils)	0	0.253	-0.253	
Clad Strain (in/in)	0.0073	0	0.0073	100.0
Tclad ID (F)	625	628.5	-3.5	-0.6
Tclad OD (F)	565	564.6	0.4	0.1
Peak Transient				
Tcenterline (F)	2485	2719	-234	-9.4
[ ]	**[ ]**	**[ ]**	19	8.6
Tsurface (F)	703	785	-82	-11.7
[ ]	**[ ]**	**[ ]**	97	-970.0
Time of Peak TCL (sec)	2	2.2	-0.2	-10.0
Stored Energy (cal/g)	62.67	70.8	-8.13	-13.0
[ ]	**[ ]**	**[ ]**	0.89	12.2
Time of Peak Stored (sec)	0.9	0.83	0.07	7.8
Clad Strain (in/in)	0.0073	0	0.0073	100.0
[ ]	**[ ]**	**[ ]**	0	0
Time of Peak Strain (sec)			0	
Post-Ramp				
Tcenterline (F)	2259	2519	-260	-11.5
Tsurface (F)	714	892	-178	-24.9
Stored Energy (cal/g)	55.19	64.4	-9.21	-16.7
Radial Gap Size (mils)	0	0.253	-0.253	
Clad Strain (in/in)	0.0073	0	0.0073	100.0
Tclad ID (F)	626	628.5	-2.5	-0.4
Tclad OD (F)	565	564.6	0.4	0.1

Table 10: Transient Power Ramp Benchmark, 55 GWd/MTU

	5-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	2265	2518	-253	-11.2
Tsurface (F)	713	892	-179	-25.1
Stored Energy (cal/g)	55.38	64.4	-9.02	-16.3
Radial Gap Size (mils)	0	0.253	-0.253	
Clad Strain (in/in)	0.0073	0	0.0073	100.0
Tclad ID (F)	625	628.5	-3.5	-0.6
Tclad OD (F)	565	564.6	0.4	0.1
Peak Transient				
Tcenterline (F)	3270	3421	-151	-4.6
[ ]	**[ ]**	**[ ]**	102	10.1
Tsurface (F)	721	743.8	-22.8	-3.2
[ ]	**[ ]**	**[ ]**	156.2	1952.5
Time of Peak TCL (sec)	5	4.77	0.23	4.6
Stored Energy (cal/g)	81.26	85.5	-4.24	-5.2
[ ]	**[ ]**	**[ ]**	4.78	18.5
Time of Peak Stored (sec)	4	3.9	0.1	2.5
Clad Strain (in/in)	0.0103	0.00032	0.00998	96.9
[ ]	**[ ]**	**[ ]**	0.00268	0.27
Time of Peak Strain (sec)	5	4.8	0.2	4.0
Post-Ramp				
Tcenterline (F)	2359	2591	-232	-9.8
Tsurface (F)	782	946.4	-164.4	-21.0
Stored Energy (cal/g)	58.78	67	-8.22	-14.0
Radial Gap Size (mils)	0.0475	0.3094	-0.2619	-551.4
Clad Strain (in/in)	0.0103	0.00032	0.00998	96.9
Tclad ID (F)	626	628.3	-2.3	-0.4
Tclad OD (F)	565	564	1	0.2