April 3, 2017

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

FROM: Joseph A. Golla, Project Manager ***/RA/***
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SUBJECT: GLOBAL NUCLEAR FUEL – THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD THERMAL – MECHANICAL PERFORMANCE, NEDC-33840P/NEDO-33840 SECOND AUDIT REPORT (CAC NO. MF7687)

By letter dated April 22, 2016 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML16113A264), Global Nuclear Fuel (GNF) submitted Topical Report (TR) NEDC-33840P/NEDO-33840, Rev. 0, "The PRIME Model for Transient Analysis of Fuel Rod Thermal – Mechanical Performance," for U.S. Nuclear Regulatory Commission staff review. The TR covers application of PRIME to the analysis of fast transient anticipated operational occurrences to determine compliance to specified acceptable fuel design limit for fuel temperature and cladding strain.

To assist in its review of NEDC-33840P, the staff conducted a second audit at the GNF facilities in Wilmington, North Carolina on September 27-29, 2016. The objective of this audit was to discuss the remaining open items identified in the audit plan. The enclosed public version report summarizes the staff's activities during the audit with GEH proprietary information redacted.

Project No. 712

Enclosure:
As stated

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SUBJECT: GLOBAL NUCLEAR FUEL – THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD THERMAL – MECHANICAL PERFORMANCE, NEDC-33840P/NEDO-33840 SECOND AUDIT REPORT (CAC NO. MF7687) DATED: APRIL 3, 2017

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DATE	3/20/17	3/16/17	3/1/17	3/31/17	4/3/17

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AUDIT REPORT

THE PRIME MODEL FOR TRANSIENT ANALYSIS OF FUEL ROD

THERMAL – MECHANICAL PERFORMANCE

NEDC-33840P, REVISION 0, APRIL 2016

(GEH WILMINGTON, SEPTEMBER 27-29, 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. The TR covers application of PRIME to the analysis of fast transient anticipated operational occurrences (AOOs) to determine compliance to specified acceptable fuel design limits for fuel temperature and cladding strain.

Global Nuclear Fuel 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 test reactors, and operational transient (OPTRAN) tests conducted in the Power Burst Facility 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 a second audit at the GNF facilities in Wilmington, North Carolina on September 27-29, 2016. The objective of this audit was to discuss the remaining open items identified below:

- Clad to coolant heat transfer correlations and code options
- Transient fission gas release
- Additive fuel pellets
- Defect recovery model and code options
- Plenum gas temperature

- Transient cladding temperature limits
- Transient temperature solution weighting factor
- Fuel Rod Analysis Program Transient (FRAPTRAN) benchmark calculations at high burnup
- Application of uncertainties in nodal power density history
- Application of uncertainties in steady-state versus transient
- Application method #3
- Limitations and conditions

This audit supplemented an earlier audit conducted in May 2016.

The GNF and the U.S. Nuclear Regulatory Commission (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	GEH
Robert Rand	GNF
Randall Dunavant	SNC
Mine Yilmaz	GNF
Curt Robert	GEH
Paul Cantonwine	GNF
Kevin Ledford	GNF
Adam Dickerson	GEH
Jim Banfield	GNF
Peiwan Whysall	GEH

3.0 <u>REGULATORY AUDIT BASES</u>

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” Standard Review Plan (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 Section 4.2 fuel design and performance criteria. NEDC-33840P describes the technical basis, qualification, and application methodology for the PRIME transient thermal-mechanical fuel rod performance model. The NRC staff’s review of this TR is to ensure that the PRIME transient model is 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 Section 4.2 criteria.

4.0 DISCUSSION

During the audit, the NRC staff performed multiple activities to meet the audit objectives defined in Section 2.0 above. These activities are summarized below.

Clad to coolant heat transfer correlations and code options

As described in Section 3.2, the PRIME transient temperature calculation assumes that (1) heat transport is in the radial direction only and (2) the steady-state critical heat flux and clad to coolant heat transfer correlations are valid for transient application. If the second assumption is not applicable, an appropriate clad to coolant heat transfer coefficient determined by transient thermal hydraulics methods can be input. Additionally, PRIME transient functionality allows for direct user input of cladding outer temperature.

- Staff and GNF discussed the underlying assumption that the steady-state critical heat flux and clad to coolant heat transfer correlations remain valid. We agreed that the PRIME transient methodology is limited to fast AOOs which do not experience boiling transition.

- Upon further discussion, it was decided that PRIME transients would only use the Jens-Lottes heat transfer correlation. This is consistent with PRIME steady-state and appropriate given the fast AOOs remain away from boiling transition.

- To support this decision, GNF repeated the 1-second and 5-second ramp benchmark calculations using PRIME transient and varied the Heat Transfer film Coefficients (HTCs). The NRC staff performed similar sensitivity cases using FRAPTRAN-2.0. The results of these benchmark sensitivity cases are shown below in Table 2. Examination of these cases reveals an insignificant change in predicted peak fuel centerline temperature and peak volume average fuel temperature (VAFT) during the transient.

- New Safety Evaluation Limitations and Conditions (L&Cs) needed to (1) preclude boiling transition and (2) require the use of the Jens-Lottes heat transfer correlation for design calculations (i.e., TOP and MOP).

Transient fission gas release

Section 3.1 states, "First, the gas composition within the fuel rod is determined considering the initial fill gas and any fission gases released from the fuel during its irradiation history up to the present increment." In addition, Section 3.7 states, "a user input option to specify the Fission Gas Release (FGR) at each time step."

- Staff and GNF discussed the methodology related to FGR. Specifically, PRIME steady-state FGR predictions, based upon approved methodology including **[[**

  ]] This approach results in a conservatively large concentration of fission gas in the plenum and a reduction in gap gas conductivity.

- For fast AOOs, the PRIME FGR model [[ ]]. This is consistent with the FRAPTRAN-2.0 model [[ ]] and receives initial conditions from FRAPCON steady-state predictions.

- No further action required.

Additive fuel pellets

Section 3.2.3 describes the fuel thermal conductivity model used in the PRIME transient analysis. It states that these models are unchanged relative to PRIME steady state and includes the effects of burnup, gadolinia, and additives (i.e., doped fuel pellets).

- Staff and GNF discussed the prior approval of additive properties in PRIME steady-state. The staff's approval is cited as Reference 5 in NEDC-33840P.

- No further action required.

Defect recovery model and code options

Section 3.2.2 states that the defect recovery model has been modified relative to PRIME steady-state to add [[ ]]

- Staff and GNF discussed the option of using the defect recovery model. [[ ]]

- [[ ]]

Plenum gas temperature

Section 3.8 describes the rod internal pressure calculation. Part of this calculation includes a user defined plenum gas temperature. Section 3.8 mentions that "a different value for the transient portion may be input to simulate specific transient events or conditions."

- Staff and GNF discussed the prior approval of the calculational method for plenum gas temperature in PRIME steady-state. This same method will be used to input a value for PRIME transients.

- No further action required.

Transient cladding temperature limits

The ranges of applicability for key dimensional and performance parameters are provided in Table 3-1 of NEDC-33840P. The limits of application are the same as those in the approved steady-state PRIME TR (Reference 1 of NEDC-33840P) with the exception of cladding temperature for transient events. Approval for the cladding temperature limit for transient events is included as part of the request for approval for application to these events.

- Staff and GNF discussed the bases for the AOO peak cladding temperature limit of **[[ ]]**
- Upon further discussion, it was agreed that with the new L&C precluding boiling transition, the higher limit was no longer necessary. In other words, fuel rods which remain within nucleate boiling will not experience temperatures above **[[ ]]**
- Both NRC and GNF reviewed their respective bounding 5-second ramp benchmark cases and confirmed this to be true.
- New Safety Evaluation L&C needed to limit cladding temperature to **[[ ]]** during fast AOOs (consistent with existing PRIME applicability limit).
- Modify "-A" version of NEDE-33840P to revise Table 3-1 to remove **[[ ]]**

Transient temperature solution weighting factor

As described in last paragraph on Section 4.3.3, how is the weighting factor η determined and controlled?

- Staff and GNF discussed the selection of weighting factor. **[[ ]]** Different values have been used in the past to address convergence issues in RIA-type benchmarks.
- FRAPTRAN-2.0 is hardwired with a weighting factor of 0.5.
- Changing weighting factor helps with convergence problems, similar to reducing time steps.
- GNF showed a previous benchmark case (1-second AOO, 5-second AOO) with a change in weighting factor to demonstrate consistency. **[[ ]]** There were insignificant changes in calculated parameters.
- No further action required.

FRAPTRAN benchmark calculations at high burnup

- Staff and GNF discussed code-to-code differences in the high burnup 1-second and 5-second ramp benchmark cases. For the high exposure cases, FRAPTRAN-2.0 predicts an open fuel-to-cladding gap at the initiation of the ramp, whereas PRIME predicts a closed gap. This difference in initial conditions promotes a poor benchmark on the transient calculation.

- During the first audit (May 2016), the FRAPTRAN-2.0 to PRIME03P benchmark cases showed good agreement. The 1-second and 5-second ramp cases were run at 0.0, 14.6, 45, and 55 GWd/MTU exposure points. During this audit, it was agreed that another benchmark at EOL (70 GWd/MTU) would be a good idea. To address the code-to-code differences in initial conditions, the FRAPCON-4.0 model was modified to force cladding creep down and close the gap at the initiation of the ramp. As a result, the initial conditions for the ramp for FRAPTRAN-2.0 would be consistent with the initial conditions from PRIME03P.

- Tables 3 and 4 provide the benchmark results for the 1-second and 5-second ramp cases. 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 fuel rod at EOL (Tables 3 and 4**,** **[[ ]]** reveal reasonable differences in initial fuel centerline temperature (TCL), +1.8%, stored energy (Hfuel), +3.5%, and pellet-to-clad gap size, 0 inches. For the 1-second duration ramp, code-to-code comparisons of changes during the ramp are in reasonable agreement with differences in predictions of changes in TCL (ΔTCL) of +13.1%, changes in stored energy (ΔHfuel) of +4.2%, and changes in cladding hoop strain ($\Delta\varepsilon$hoop) of +1.0%. For the 5-second duration ramp, code-to-code comparisons are also in reasonable agreement with differences in ΔTCL of 10.6%, ΔHfuel of +3.0%, and $\Delta\varepsilon$hoop of +3.0%. In both cases, PRIME03P predicted a larger increase in centerline temperature, fuel enthalpy, and cladding strain which is conservative.

- During the audit, it was decided to expand the original thermal time constant benchmark. The new benchmark case included a GNF2 fuel rod exposed to a base depletion along the bounding Thermal-Mechanical Operating Limit with an instantaneous 50% power spike held for 50 seconds at **[[ ]]** The GNF staff used the PRIME steady-state and transient fuel centerline temperature predictions to calculate the inherent fuel thermal time constant at EOL. The same approach was taken by NRC staff using the FRAPCON-4.0 and FRAPTRAN-2.0 codes. The results of the new benchmark case, along with the original cases, are summarized in Table 1 below.

- During the audit, it was decided to re-perform the thermal time constant benchmark calculations at 45 and 55 GWd/MTU. The FRAPTRAN-2.0 algorithms were revised to eliminate differences in the initial fuel-to-clad gap relative to PRIME. The results of the revised benchmark cases are shown in Table 1 below.

Table 1: PRIME03P versus FRAPTRAN-2.0 Fuel Thermal Time Constant

Exposure Point (GWd/MTU)	PRIME03P (seconds)	FRAPTRAN-2.0 (seconds)
0.01	6.0	6.9
14.6	6.4	7.5
45	6.3	8.1
55	6.3	8.2
[[ ]]	6.2	7.8

- Examination of Table 1 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. This trend is unchanged at EOL. 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.

- No further action required.

<u>Application of uncertainties in nodal power density history</u>

Section 5.2.1 states, "Nuclear codes and processes used to provide the power histories applied in PRIME transient analyses are separately approved and address other uncertainties, **[[**

]]"

- Staff and GNF discussed the application of uncertainties and overall conservatism of the nodal power histories provided by the nuclear codes. GNF stated that the existing approved Transient Reactor Analysis Code (TRAC)G and ODYN methodologies, including the application of uncertainties, would be used to provide nodal power histories for PRIME transient applications.

- The text in Section 5.2.1 was intended to address duplicate uncertainties. In other words, if an uncertainty is applied in the PRIME statistical TOP or worst case MOP calculation, should it also be applied in the nuclear code prediction of nodal power history?

- It is difficult to define a consistent process to allow the requested flexibility to address duplicate uncertainties. Currently, GNF does not believe such duplicative uncertainties exist.

- The Safety Evaluation should state that approved nuclear methods and PRIME steady-state methods (with respect to uncertainties, tolerances, initial conditions, should be maintained.

- Modify "-A" version to state:

  Nuclear codes and processes used to provide the power histories applied in PRIME transient analyses are separately approved and address other uncertainties, **[[**

  ]]

Application of uncertainties in steady-state versus transient

With respect to application method #2, can it be demonstrated that the effects of the applied uncertainties and tolerances are larger for steady-state than for transient applications? In other words, are the steady-state TOP and MOP screening criteria larger than the transient TOP and MOP screening criteria at all exposure points?

- Staff and GNF discussed the application of uncertainties and tolerances to true transient TOP and MOP calculations, relative to steady-state values. GNF provided calculations demonstrating the inherent margin between method #1 and method #2 approaches.
- No further action required.

Application method #3

Method #3 is convoluted, confusing, and too open ended. Need a more precise description. Also, given the short duration (relative to thermal time constant), **[[ ]]** seems like the wrong parameter.

- Staff and GNF discussed all three application methods, with emphasis on the similarity between the method #2 and method #3 screening criteria.

- TRACG calculations were shown which demonstrate how the screening criteria are determined. Correction factors are applied which ensure under all fast AOO scenarios, that the TRACG/ODYN screening criteria remain conservative relative to PRIME transient detailed analyses.

- New Safety Evaluation L&C requiring periodic confirmation of method #3 screening criteria.

Fuel Specific Heat (Cp) Correlation

Subsequent to the GNF visit and during the audit report preparation, the NRC staff identified that the PRIME transient TR did not define the fuel specific heat correlation. Specific heat is an important material property since it relates temperature raise to energy addition. In response, GNF provided the following information.

The specific heat (C_P) correlation used in PRIME is given by the equation below:

$$C_p({}^{cal}/_{gm-K}) = \left[\frac{5.486x10^6 e^{\frac{535.285}{T}}}{T^2\left(e^{\frac{535.285}{T}}-1\right)^2} + 15.695x10^{-4}T + \frac{1.0744x10^{11}}{T^2}e^{\frac{-19038}{T}}\right]\frac{1}{270}$$

where T = Temperature (K)

This correlation is identical, except for units, to the expression for C_P given by Equation C.1-5 in Section C.1.1 of the TRACG LTR (NEDE-32176P, January 2008).

[[

]]

- New Safety Evaluation L&C needed to capture fuel specific heat correlation discussion in "-A" version of NEDE-33840P.

<u>Proposed Safety Evaluation Limitations and Conditions</u>

1. Limitations and conditions documented within the staff's safety evaluation for the steady-state PRIME fuel rod thermal – mechanical model TRs (NEDC-33256P, NEDC-33257P, and NEDC-33258P) continue to be applicable with the exception of the following:

    a. Reporting requirement in L&C #4 are relaxed from every 5 years to every 7 years.
    b. Periodic model validation requirement in L&C #4c are expanded to include the effects of the augmented database on PRIME transient features.

2. The conservatism of the transient nuclear code-specific screening criteria described in Section 5.2.2 of NEDC-33840P must be periodically confirmed. The overall conservatism of this surrogate screening criteria, relative to a detailed PRIME transient analysis, may be impacted by changes to (1) fuel rod design, (2) PRIME models, (3) uncertainties and tolerances, (4) transient nuclear codes, and (5) plant operations and fuel utilization which may impact the sequence of events and accident progression for the fast AOOs. The results of the periodic confirmation should be added to the L&C #4 report.

3. The PRIME transient methodology is not applicable to fuel rods which are predicted to experience boiling transition.

4. PRIME transient licensing calculations must use the Jens-Lottes heat transfer correlation consistent with PRIME steady-state.

5. PRIME transient licensing calculations must [[
]]

6. The PRIME transient methodology is not applicable to fuel rods which are predicted to experience cladding average temperature [[ ]], consistent with PRIME steady-state. Modify "-A" version of NEDE-33840P to revise Table 3-1 to remove discussion related to [[
]]

7. Modify "-A" version of NEDE-33840P to revise the following text from Section 5.2.1 as follows:

   Nuclear codes and processes used to provide the power histories applied in PRIME transient analyses are separately approved and address other uncertainties, [[
   ]]

8. Modify "-A" version of NEDE-33840P to capture description of PRIME fuel specific heat (Cp)

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 2: HTC Sensitivity Calculations

Case	HTC Film Coeff (Btu/hr-ft^2)	Modified HTC Film Coeff (Btu/hr-ft^2)	HTC Peak Centerline Temp (F)	Modified HTC Peak Centerline Temp (F)	HTC Peak VAFT (F)	Modified HTC Peak VAFT (F)
PRIME Transient						
1-sec benchmark	13000	10000	3608	3608	2247	2252
5-sec benchmark	13000	10000	4695	4698	2804	2815
FRAPTRAN-2.0						
1-sec benchmark	13000	10000	3471	3473	2090	2095
5-sec benchmark	13000	10000	4517	4520	2722	2735

Table 3: Transient Power Ramp Benchmark, **[[ ]]**

	1-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	1677	1647.1	29.9	1.8
Tsurface (F)	674	635	39	5.8
Stored Energy (cal/g)	42.82	41.3	1.52	3.5
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.91	-0.00025	0.91025	100.0
Tclad ID (F)	602	604	-2	-0.3
Tclad OD (F)	563	563	0	0.0
Peak Transient				
Tcenterline (F)	1825	1775.7	49.3	2.7
Change in TCL (F)	148	128.6	19.4	13.1
Tsurface (F)	676	642.5	33.5	5.0
Change in Tsurface (F)	2	7.5	-5.5	-275.0
Time of Peak TCL (sec)	2	2.2	-0.2	-10.0
Stored Energy (cal/g)	47.77	46.04	1.73	3.6
Change in Stored Energy (cal/g)	4.95	4.74	0.21	4.2
Time of Peak Stored (sec)	0.9	0.91	-0.01	-1.1
Clad Strain (in/in)	0.92	-0.00023	0.92023	100.0
Change in Clad Strain (in/in)	0.01	0.00002	0.00998	1.00
Time of Peak Strain (sec)		1.01	-1.01	
Post-Ramp				
Tcenterline (F)	1677	1647.1	29.9	1.8
Tsurface (F)	674	635	39	5.8
Stored Energy (cal/g)	42.82	41.3	1.52	3.5
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.91	-0.00023	0.91023	100.0
Tclad ID (F)	612	604	8	1.3
Tclad OD (F)	563	563	0	0.0

Table 4: Transient Power Ramp Benchmark, **[[ ]]**

	5-Second Duration of Ramp			
Parameter	**PRIME03P**	**FRAPTRAN**	**Difference**	
Pre-Ramp			**Absolute**	**(%)**
Tcenterline (F)	1677	1647.1	29.9	1.8
Tsurface (F)	674	635	39	5.8
Stored Energy (cal/g)	42.82	41.3	1.52	3.5
Radial Gap Size (mils)	0	0	0	
Clad Strain (in/in)	0.91	-0.00025	0.91025	100.0
Tclad ID (F)	602	604	-2	-0.3
Tclad OD (F)	563	563	0	0.0
Peak Transient				
Tcenterline (F)	2359	2257	102	4.3
Change in TCL (F)	682	609.9	72.1	10.6
Tsurface (F)	679	672	7	1.0
Change in Tsurface (F)	5	37	-32	-640.0
Time of Peak TCL (sec)	4.5	4.79	-0.29	-6.4
Stored Energy (cal/g)	59.61	57.58	2.03	3.4
Change in Stored Energy (cal/g)	16.79	16.28	0.51	3.0
Time of Peak Stored (sec)	4	3.57	0.43	10.8
Clad Strain (in/in)	0.94	0.000006	0.939994	100.0
Change in Clad Strain (in/in)	0.03	0.000256	0.029744	2.97
Time of Peak Strain (sec)	5	4.8	0.2	4.0
Post-Ramp				
Tcenterline (F)	1687	1660	27	1.6
Tsurface (F)	682	647	35	5.1
Stored Energy (cal/g)	43.19	41.8	1.39	3.2
Radial Gap Size (mils)	0	0.038	-0.038	
Clad Strain (in/in)	0.94	0.000006	0.939994	100.0
Tclad ID (F)	602	604	-2	-0.3
Tclad OD (F)	563	563	0	0.0