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As-Run Thermal Analysis for the CSM-10584 Experiment

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9. Objective / Purpose

The purpose of this document is to present the as-run specimen temperatures for the CSM-10584 experiment irradiated in position B-5 of the Advanced Test Reactor (ATR) for Cycles 164A and 164B.

10. If revision, please state the reason and list sections and/or page being affected.

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11. Conclusion / Recommendations

The specimen temperatures at nominal power and nominal gas gap are between 263 to 392°C for Cycle 164A and 266 to 387°C for Cycle 164B. The specimen temperatures at nominal power and considering capsule hot gas gaps are between 237 to 383°C for Cycle 164A and 249 to 357°C for Cycle 164B. Detailed nominal power temperatures are in Appendix E.

The maximum temperature at various power level for each cycle at nominal gas gaps and hot gas gaps was calculated and graphed in Appendix E. The data was fit with the following 2nd order polynomial equations used to calculate y, the maximum specimen temperatures (°C), at x, south lobe powers in MW:

Nominal Gas Gaps

Cycle 164A $y = -0.1162x^2 + 17.563x + 56.066$

Cycle 164B $y = -0.1218x^2 + 17.416x + 56.196$

Hot Gas Gaps

Cycle 164A $y = -0.1303x^2 + 17.472x + 56.615$

Cycle 164B $y = -0.1096x^2 + 15.846x + 55.565$

These equations can be used to approximate the temperature of any specimen stack at a desired south lobe power with the following steps:

1) Calculate maximum specimen temperature.
2) Calculate scaling factor between nominal and desired lobe power maximum temperatures.
3) Scale all temperatures by calculated factor.

The temperature will lag behind during power changes, especially during rapid power changes, so these equations are representative of a steady state temperature at a given power. It is most appropriate to use the equations associated with the nominal gas gap at the beginning of the irradiation before the materials expand. The equations associated with the hot gas gap are representative of the highest heating rates and temperatures experienced by the capsule.

CONTENTS

APPENDIXES

1.0 PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name	Organization	Pages Covered (if applicable)
Performer	S. M. Wilson	C130	All
Checker[a]	C. Xing	C130	All
Independent Reviewer[b]	N/A	-----	-----
CUI Reviewer[c]	K. Anderson	-----	-----
Manager[d]	M. A. Lillo	C130	All
Requestor[ef]	K. Anderson	C630	-----
Nuclear Safety[f]	N/A	-----	-----
Document Owner[f]	D. Guillen	B120	All
Reviewer[f]	N/A	-----	-----

Responsibilities:

a. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.

b. Concurrence of method or approach. See definition, LWP-10106.

c. Concurrence with the document’s markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Authorizes the commencement of work of the engineering deliverable. See Appendix A.

f. Concurrence with the document’s assumptions and input information. See definition of Acceptance, LWP-10200.

NOTE: *Delete or mark “N/A” for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

2.0 SCOPE AND BRIEF DESCRIPTION

The purpose of this document is to present the as-run specimen temperature results in support of the CSM-10584 experiment irradiated in position B5 of the ATR for Cycles 164A and 164B. The CSM-10584 experiment is performed in conjunction with the Nuclear Science User Facilities (NSUF).

ABAQUS was used to calculate the temperatures and Mathcad was used to calculate the inputs.

3.0 DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

The requirements for the CSM-10584 experiment were provided in FOR-308 and TFR-966. The actual loading of the holders and capsules were provided in PLN-5306.

As-run heating rates were provided by physics in ECAR-4496.

Heat transfer coefficients and thermal models were provided in ECAR-3626 and ECAR-3672, respectively.

4.0 RESULTS OF LITERATURE SEARCHES AND OTHER BACKGROUND DATA

4.1 Experiment Description

The CSM-10584 experiment was designed to establish the irradiation performance of stainless steel and Inconel specimens produced using commercially available additive manufacturing techniques under three irradiation considerations:

325 +/- 50°C at a low dpa (determined by neutronics, one cycle)

325 +/- 50°C at a medium dpa (determined by neutronics, two cycles)

325 +/- 50°C at a high dpa (determined by neutronics, two cycles)

All capsules contain both Inconel and stainless steel specimens but have different specimen arrangements within aluminum specimen holders and varying Helium-Argon gas mixtures used to control the specimen temperatures for the desired range. The holders are contained inside stainless steel capsules, which are stacked vertically in a Y-basket with stainless steel spacers used to ensure proper elevation. Capsules A and B at the top of the stack contained only tensile specimens. Capsule A was a low DPA capsule which was removed after the first cycle, but Capsule B was a medium DPA capsule that was irradiated for two cycles. Capsules D and E at the bottom of the stack contained only transmission electron microscope (TEM) specimens for both post-irradiation exam (PIE) and thermophysical property (TPP) testing activities. Capsule D was a medium DPA capsule that was irradiated for two cycles, but Capsule E was a low DPA capsule and was removed after the first cycle. Capsule C, the high DPA capsule, was centered around the core centerline and contained both tensile and TEM specimens. All capsules were designed to specimen temperatures of 325 +/- 50°C.

4.2 Model Description

A three-dimensional, steady state heat transfer ABAQUS model was developed for the CSM-10584 programmatic analysis in ECAR-3672. It was considered applicable to this analysis with the following exceptions:

1) The holes in the tensile specimens were removed in Revision 1 of Drawing 605844 for ease of machining. The tensile stacks were regenerated with this design change included.
2) The as-built loading of the tensile specimens in Capsules A and B were different than what was modeled in the programmatic analysis. The materials were switched for the as-run analysis to properly reflect the as-run physics analysis and the loading plan.

Table 1 documents the applicable drawings for the specimens, holder, capsules, basket, and assembly of both the capsules themselves and the entire stackup.

Table 1 – Experiment Component Drawing Numbers and Titles

Drawing Number	Revision	Drawing Title
605840	3	ATR NUCLEAR SCIENCE USER FACILITY (NSUF) CSM-10584 FIRST CYCLE 164A-1 LOW, MEDIUM AND HIGH DPA INSTALLATION
605842	2	ATR NUCLEAR SCIENCE USER FACILITY (NSUF) COLORADO SCHOOL OF MINES (CSM-10584) B5 EXPERIMENT CAPSULES ASSEMBLIES AND DETAILS
605843	3	ATR NUCLEAR SCIENCE USER FACILITY (NSUF) COLORADO SCHOOL OF MINES (CSM-10584) B5 EXPERIMENT SPECIMEN HOLDERS ASSEMBLIES AND DETAILS
605844	1	ATR NUCLEAR SCIENCE USER FACILITY (NSUF) COLORADO SCHOOL OF MINES (CSM-10584) TENSILE AND TEM SPECIMEN DETAILS
605845	1	ATR NUCLEAR SCIENCE USER FACILITY (NSUF) CSM-10584 SECOND CYCLE 164B-1 MEDIUM AND HIGH DPA INSTALLATION

5.0 ASSUMPTIONS

The following assumptions made for the programmatic model are still applicable to the as-built model:

1) Experiment coolant flow rates were determined by hydrodynamic calculations in Mathcad for the thermal safety analysis in ECAR-3626. Since there were no changes to the capsule geometry, they are still considered applicable.

2) The sink temperature for the coolant film condition reflects the inlet temperature with a sensitivity run accounting for the outlet temperatures calculated in the thermal safety analysis in ECAR-3626. If the coolant increased to the maximum allowable inlet temperature, there could be a 9°F (5.0°C) increase in specimen temperatures.

3) Nominal drawing dimensions were used. A sensitivity run in ECAR-3672 determined that specimens manufactured at the lower end of the tolerance could see a 24°F (13.3°C) increase in temperature.

4) The clearance between parts in contact is assumed to be 0.001 inches.

5) The flux and melt wires pictured in the drawing were not discretely included in the analysis. These wires will have a negligible impact on the specimen temperatures. The portion of the holder where these wires are located was modeled as solid aluminum for ease of analysis.

6) Specimens are not assumed to be in contact with the holders. A sensitivity run assuming perfect contact of all parts in ECAR-3672 resulted in a 51°F (28.3°C) decrease in maximum specimen temperature, although a 15°C decrease in specimen temperature was assumed to be more realistic.

7) Radiation heat transfer was not considered as conduction across gas gaps and material contact has the largest impact on specimen temperatures.

Additional assumptions for the as-run model are as follows:

1) The drawings associated with the experiment have been revised various times. The largest change from the programmatic analysis in ECAR-3672 was the removal of the holes in the tensile specimens, but there are other minor changes with negligible impact on the temperatures of the specimens. The spacers, standoff, capsule tube length, and capsule cap length are all slightly different from the drawings, but would have no impact on the specimen temperatures since no heat loads or convection coefficients have an axial distribution. The PIE TEM basket, specimen container tube, and specimen container cap all have variations from the drawings, but not significantly impact the specimen temperatures. None of these minor differences are included in the model.

2) Since there was no change in part dimensions or locations, the heat transfer coefficients calculated in Appendix C of ECAR-3672 were considered applicable to the as-run analysis.

3) Additional gap conductance values for hot gas gaps were calculated. Analyses were performed for both nominal and hot gas gaps for the capsule to ensure the temperatures through the entirety of the irradiation can be determined.
4) The actual temperature history of the specimens was not provided as a transient analysis. Although the temperatures would lag behind the reactor power, steady state temperature values at various power fractions were calculated to generate an equation to estimate the temperature. This approach was deemed acceptable by the program.

6.0 COMPUTER CODE VALIDATION

The finite element heat transfer thermal analysis of the CSM-10584 As-Run experiment was performed using ABAQUS version 6.14-2 on an Intel® Core™ i7-8850H CPU @ 2.60 GHz machine with 16GB of RAM.

ABAQUS is listed in the INL Enterprise Architecture (EA) repository of qualified scientific and engineering analysis software (EA Identifier 336418). ABAQUS has been validated for the thermal analysis of ATR experiments by solving several test problems and verifying the results against analytical solutions provided in heat transfer text books. A complete description of the validation test problems is given in ECAR-131. Scripts were developed to automate the execution, data collection, and relative error calculation for each test problem. The scripts were run on a local computer named INL608356 and a report file containing the validation test results was generated automatically. The results meet the acceptance criterion that the relative error is less than 3%. The report is provided as Appendix C of this document.

Calculations given in the appendices were performed using PTC Mathcad Prime 3.0 and Microsoft Excel. Formal validation of Mathcad and spreadsheet applications is not required, instead random hand calculations are performed during checking to verify that the computer-generated output is correct, as discussed in Appendix E in LWP-10200.

The ABAQUS files containing the models created for this analysis are stored in \\fswcb1\PROJECTS\USUF\IRRADIATION TESTING\C660 Analysts\Stacey Wilson\CSM_AsRun. The files created are listed in Table 2.

Table 2 – ABAQUS/CAE Models, and Input and Output File

File Name	Description
CSM_AsRun.cae CSM_AsRun.jnl	Model for the two cycles the CSM experiment was irradiated
CSM-AsRun-Nominal.inp CSM-AsRun-Nominal.odb	Nominal power (100%) results for the two cycles the CSM experiment was irradiated
CSM-AsRun-Powxx.inp CSM-AsRun-Powxx.odb	Results for the two cycles the CSM experiment was irradiated, where xx stands for the analyzed powers of 10%, 25%, 50%, 60%, 70%, 80%, 90%, 110, 120%
CSM-AsRun-HGG-Nominal.inp CSM-AsRun-HGG-Nominal.odb	Nominal power (100%) results for the two cycles the CSM experiment was irradiated using hot gas gaps
CSM-AsRun-HGG-Powxx.inp CSM-AsRun-HGG-Powxx.odb	Results for the two cycles the CSM experiment was irradiated using hot gas gaps, where xx stands for the analyzed powers of 10%, 25%, 50%, 60%, 70%, 80%, 90%, 110, 120%

7.0 DISCUSSION/ANALYSIS

7.1 Experiment Description

Geometry

As previously stated, a three-dimensional ABAQUS model was developed for the programmatic analysis in ECAR-3672. It used the 8-node linear brick element to model all components.

The only changes to the programmatic model geometry for use with the as-run analysis was the removal of the tensile specimen holes and switching the materials for the Capsule A and B tensile specimens to match the loading plan and physics analysis.

Steps

Two analysis steps were created for the as-run analysis. Step 1 represents Cycle 164A and Step 2 represents Cycle 164B.

Interactions and Constraints

The interactions and constraints for the programmatic model were unchanged for the as-run model. The interaction properties for the nominal gas gaps and the inputs for calculating the gap conductance of the hot gas gap were unchanged for the as-run model, although additional hot gas gap conductance values were calculated in this ECAR to cover all gas mixtures used in the experiment.

Amplitude

The amplitude PowFraction was used to scale all the heat loads to the appropriate power fraction being analyzed.

Heat Loads

The as-run heat loads were provided by physics in ECAR-4496 at nominal core power configurations (22.5 MW and 22.6 MW south source lobe power) for Cycles 164A and 164B, respectively. The heat loads were converted from W/g to BTU/s-in^3 in Appendix B for use in ABAQUS.

To model the removal of Capsules A and E for Cycle 164B, the heat loads for all components in those capsules were set to 0 BTU/s-in^3.

It should be noted that the capsule designations (A, B, C, D, E) are consistent between the physics and thermal analysis despite the differing arrangement of results in the tables.

7.2 Experiment Description

Nominal Gas Gap Results

The specimen temperatures at nominal power with a nominal gas gap are 263 to 392°C and 266 to 387°C for Cycles 164A and 164B, respectively. The temperatures by specimen stack are detailed in Appendix E.

The maximum temperature at various power level for each cycle are provided below in **Table 3**. Note that the removal of Capsules A and E for Cycle 164B cause the maximum temperature in Cycle 164A to be in the Capsule A tensile specimens and the maximum temperature in Cycle 164B to be in the Capsule B tensile specimens.

Table 3 – Maximum Specimen Temperatures at Various Power Levels

Power Fraction	Cycle 164A			Cycle 164B		
	Power (MW)	°F	°C	Power (MW)	°F	°C
0.1	2.25	201	94	2.26	201	94
0.25	5.63	306	152	5.65	305	152
0.5	11.25	464	240	11.30	461	238
0.6	13.50	522	272	13.56	519	271
0.7	15.75	579	304	15.82	574	301
0.8	18.00	633	334	18.08	627	331
0.9	20.25	686	363	20.34	679	359
1	22.50	737	392	22.60	728	387
1.1	24.75	787	419	24.86	777	414
1.2	27.00	836	447	27.12	824	440

These values were graphed in Appendix E. The 2nd order polynomial equations that can be used to calculate the maximum specimen temperatures (°C), y, at south lobe powers (MW), x, are as follows:

Cycle 164A $y = -0.1162x^2 + 17.563x + 56.066$

Cycle 164B $y = -0.1218x^2 + 17.416x + 56.196$

These equations can be used to approximate the temperature of any specimen stack at a desired south lobe power with the following steps:

1) Calculate maximum specimen temperature.
2) Calculate scaling factor between nominal and desired lobe power maximum temperatures.
3) Scale all temperatures by calculated factor.

It should be noted again that the temperature will lag behind the power, especially during rapid power changes, so these equations are representative of a steady state temperature.

Hot Gas Gap Results

The specimen temperatures at nominal power with a hot gas gap for the capsule interactions are 237 to 383°C and 249 to 357°C for Cycles 164A and 164B, respectively. The temperatures by specimen stack are detailed in Appendix E.

The maximum temperature at various power level for each cycle are provided below in Table 4. Note that the removal of Capsules A and E for Cycle 164B cause the maximum temperature in Cycle 164A to be in the Capsule A tensile specimens and the maximum temperature in Cycle 164B to be in the Capsule B tensile specimens.

Table 4 – Maximum Specimen Temperatures at Various Power Levels

Power Fraction	Cycle 164A			Cycle 164B		
	Power (MW)	°F	°C	Power (MW)	°F	°C
0.1	2.25	201	94	2.26	194	90
0.25	5.63	306	152	5.65	288	142
0.5	11.25	460	238	11.30	431	222
0.6	13.50	516	269	13.56	483	251
0.7	15.75	571	299	15.82	534	279
0.8	18.00	623	328	18.08	582	306
0.9	20.25	673	356	20.34	629	332
1	22.50	721	383	22.60	675	357
1.1	24.75	769	409	24.86	719	382
1.2	27.00	814	434	27.12	762	406

These values were graphed in Appendix E. The 2nd order polynomial equations that can be used to calculate the maximum specimen temperatures (°C), y, at south lobe powers (MW), x, are as follows:

Cycle 164A $y = -0.1303x^2 + 17.472x + 56.615$

Cycle 164B $y = -0.1096x^2 + 15.846x + 55.565$

These equations can be used to approximate the temperature of any specimen stack at a desired south lobe power with the following steps:

1) Calculate maximum specimen temperature.
2) Calculate scaling factor between nominal and desired lobe power maximum temperatures.
3) Scale all temperatures by calculated factor.

It should be noted again that the temperature will lag behind the power, especially during rapid power changes, so these equations are representative of a steady state temperature.

Conclusion

The specimen temperatures at nominal power and nominal gas gaps are between 263 to 392°C for Cycle 164A and 266 to 387°C for Cycle 164B. The specimen temperatures at nominal power and capsule hot gas gaps are between 237 to 383°C for Cycle 164A and 249 to 357°C for Cycle 164B. Detailed nominal power temperatures are in Appendix E. Tables E1 through E4 report the temperatures for stacks of specimens, not individual specimens. To ensure that the temperatures are applied to the correct specimens, Table E5 provides the specimen numbers associated with each specimen stack as documented in PLN-5306.

The maximum temperature at various power level for each cycle at nominal gas gaps and hot gas gaps was calculated and graphed in Appendix E. The data was fit with the following 2nd order polynomial equations used to calculate y, the maximum specimen temperatures (°C), at x, south lobe powers in MW:

Nominal Gas Gaps

Cycle 164A $y = -0.1162x^2 + 17.563x + 56.066$

Cycle 164B $y = -0.1218x^2 + 17.416x + 56.196$

Hot Gas Gaps

Cycle 164A $y = -0.1303x^2 + 17.472x + 56.615$

Cycle 164B $y = -0.1096x^2 + 15.846x + 55.565$

These equations can be used to approximate the temperature of any specimen stack at a desired south lobe power with the following steps:

1) Calculate maximum specimen temperature.
2) Calculate scaling factor between nominal and desired lobe power maximum temperatures.
3) Scale all temperatures by calculated factor.

The temperature will lag behind during power changes, especially during rapid power changes, so these equations are representative of a steady state temperature at a given power. It is most appropriate to use the equations associated with the nominal gas gap at the beginning of the irradiation before the materials expand. The equations associated with the hot gas gap are representative of the highest heating rates and temperatures experienced by the capsule.

8.0 REFERENCES

1. FOR-308, Revision 1, “Colorado School of Mines (CSM-10584),” April 2017.

2. TFR-966, “Colorado School of Mines (CSM)-10584 ATR ADDITIVE MATERIALS EXPERIMENT,” May 2017.

3. PLN-5306, Revision 1, “CSM-10584 Loading and Marking Arrangement,” February 2019.

4. ECAR-4496, Revision 1, “AS-RUN NEUTRONICS EVALUATION FOR THE CSM-10584 EXPERIMENT IN THE ATR,” J. Mitchell, October 2020.

5. ECAR-3626, Revision 1, “Thermal and Structural Safety Compliance Analysis for a Non-Fueled Drop-In Experiment in a Small B Position,” C. Hale, June 2017.

6. ECAR-3672, “Programmatic Thermal Analysis for the CSM-10584 Experiment,” S. M. Wilson, July 2017.

7. ECAR-131, “Validation of ABAQUS Standard 6.7-3 Heat Transfer,” P. E. Murray, January 2008.

8. PG-T-91-031, “Thermophysical and Mechanical Properties of ATR Core Materials,” S. T. Polkinghorne, J. M. Lacy, August 1991.

9. ASM Handbook, Volume 1, http://products.asminternational.org/hbk/index.jsp.

10. ASM Handbook, Volume 2, http://products.asminternational.org/hbk/index.jsp.

11. CINDAS Thermophysical Properties of Matter Database (TPMD), https://cindasdata.com/Applications/TPMD/.

Appendix A – Material Properties

Aluminum 6061-T6

From Tables 3.1 and 3.2 in: S. T. Polkinghorne, J. M. Lacy, " Thermophysical and Mechanical Properties of ATR Core Materials," EG&G Internal Technical Report, PG-T-91-031, August 1991

$$T_{Al\_k} := \begin{bmatrix} 273 \\ 300 \\ 350 \\ 400 \\ 450 \\ 500 \\ 550 \\ 600 \\ 650 \\ 700 \\ 750 \\ 800 \end{bmatrix} \cdot K = \begin{bmatrix} 31.73 \\ 80.33 \\ 170.33 \\ 260.33 \\ 350.33 \\ 440.33 \\ 530.33 \\ 620.33 \\ 710.33 \\ 800.33 \\ 890.33 \\ 980.33 \end{bmatrix} \ {}^{\circ}F$$

$$k_{Al} := \begin{bmatrix} 163 \\ 167 \\ 173 \\ 177 \\ 179 \\ 188 \\ 191 \\ 190 \\ 188 \\ 185 \\ 182 \\ 179 \end{bmatrix} \cdot \frac{W}{m \cdot K} = \begin{bmatrix} 0.00218 \\ 0.002234 \\ 0.002314 \\ 0.002367 \\ 0.002394 \\ 0.002514 \\ 0.002555 \\ 0.002541 \\ 0.002514 \\ 0.002474 \\ 0.002434 \\ 0.002394 \end{bmatrix} \frac{BTU}{sec \cdot in \cdot R}$$

$$T_{Al\_cp} := \begin{bmatrix} 290 \\ 400 \\ 500 \\ 600 \\ 700 \\ 800 \end{bmatrix} \cdot K = \begin{bmatrix} 62.33 \\ 260.33 \\ 440.33 \\ 620.33 \\ 800.33 \\ 980.33 \end{bmatrix} \ {}^{\circ}F$$

$$c_{p\_Al} := \begin{bmatrix} 896 \\ 942 \\ 988 \\ 1034 \\ 1080 \\ 1126 \end{bmatrix} \cdot \frac{J}{kg \cdot K} = \begin{bmatrix} 0.214 \\ 0.225 \\ 0.236 \\ 0.247 \\ 0.258 \\ 0.269 \end{bmatrix} \frac{BTU}{lb \cdot R}$$

$$\rho_{Al} := 2702 \cdot \frac{kg}{m^3} = 0.098 \ \frac{lb}{in^3}$$

$$\alpha_{Al} := 25.4 \cdot 10^{-6} \cdot \frac{1}{\Delta {}^{\circ}C}$$

Maximum temperature in range is close to the target temperatures of the capsule (300°C).

304 and 316 Stainless Steel

ASM Handbook Volume 1, Properties and Selection: Irons, Steels, and High-Peformance Alloys, Specialty Steels and Heat-Resistant Alloys, Wrought Stainless Steels, Physical Properties, Table 21.

$$T_{SS\_k} := \begin{bmatrix} 100 \\ 500 \end{bmatrix} °C = \begin{bmatrix} 212 \\ 932 \end{bmatrix} °F$$

$$k_{SS} := \begin{bmatrix} 16.2 \\ 21.5 \end{bmatrix} \cdot \frac{W}{m \cdot K} = \begin{bmatrix} 2.167 \cdot 10^{-4} \\ 2.876 \cdot 10^{-4} \end{bmatrix} \frac{BTU}{sec \cdot in \cdot R}$$

$$c_{p\_SS} := 500 \cdot \frac{J}{kg \cdot K} = 0.119 \ \frac{BTU}{lb \cdot R}$$

$$\rho_{SS} := 8.0 \cdot \frac{gm}{cm^3} = 0.289 \ \frac{lb}{in^3}$$

$$\alpha_{SS} := 17.2 \cdot 10^{-6} \cdot \frac{1}{\Delta °C}$$

For SS304 at 100 °C

Inconel (Nickel Alloy 718)

ASM Handbook Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Specific Metals and Alloys, Nickel and Nickel Alloys, Commercial Nickel and Nickel Alloys, Table 6.

$$k_{Inc} := 11.4 \cdot \frac{W}{m \cdot K} = 0.000152 \ \frac{BTU}{sec \cdot in \cdot R}$$

$$c_{p\_Inc} := 435 \cdot \frac{J}{kg \cdot K} = 0.104 \ \frac{BTU}{lb \cdot R}$$

$$\rho_{Inc} := 8.19 \cdot \frac{gm}{cm^3} = 0.296 \ \frac{lb}{in^3}$$

Appendix B – Heating Rates

Heating Rates provided by physics in Table 8 of ECAR-4496 are oriented from the bottom of the core to the top. Capsule E is the bottom capsule in the experiment stackup and Capsule A is the top. Capsules A2, B2, C3, C4, D2 and E2 contain inconel specimens, the other capsules contain stainless steel specimens. For ease of calculating the ABAQUS input, the heating rates are oragnized as followed:

$$TEMSpecimens := \begin{bmatrix} \text{“PIE Disc Stack 1”} \\ \text{“PIE Disc Stack 2”} \\ \text{“PIE Disc Stack 3”} \\ \text{“PIE Disc Stack 4”} \\ \text{“TPP Disc Stack”} \end{bmatrix}$$

$$TEMBasket\_Holder := \begin{bmatrix} \text{“PIE Basket”} \\ \text{“TPP Basket”} \\ \text{“Specimen Holder”} \end{bmatrix}$$

$$TensileSpecimens := \text{“Tensile Sample Smear”}$$

$$TensileSpacer\_Holder := \begin{bmatrix} \text{“Tensile Spacers”} \\ \text{“Specimen Holder”} \end{bmatrix}$$

The heating rates are provided in two columns to represent the two irradiation cycles, Cycle 164A at 22.5 MW and Cycle 164B at 22.6 MW south source power. Those capsules and samples not irradiated in Cycle 164B have a heating rate of 0 in the second column.

$$HRs := \begin{bmatrix} \text{"Cycle164A"} & \text{"Cycle164B"} \end{bmatrix}$$

Capsule A Heating Rates

$$A1\_TensileSpecimens := \begin{bmatrix} 1.3 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$A1\_TensileHR := A1\_TensileSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.162 & 0 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$A1\_Spacer\&Holder := \begin{bmatrix} 0.9 & 0 \\ 1.1 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$A1\_Spacer\&HolderHR := A1\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.038 & 0.000 \\ 0.046 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$A2\_TensileSpecimens := \begin{bmatrix} 1.8 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$A2\_TensileHR := A2\_TensileSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 0.229 & 0 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$A2\_Spacer\&Holder := \begin{bmatrix} 1.3 & 0 \\ 1.4 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$A2\_Spacer\&HolderHR := A2\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.055 & 0.000 \\ 0.059 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$CapsuleA := \begin{bmatrix} 1.6 & 0 \end{bmatrix} \cdot \frac{W}{gm} \qquad CapsuleAHR := CapsuleA \cdot \rho_{SS} = \begin{bmatrix} 0.199 & 0 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

Capsule B Heating Rates

$$B1\_TensileSpecimens := \begin{bmatrix} 2.2 & 2.2 \end{bmatrix} \cdot \frac{W}{gm}$$

$$B1\_TensileHR := B1\_TensileSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.273 & 0.273 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$B1\_Spacer\&Holder := \begin{bmatrix} 1.7 & 1.7 \\ 1.8 & 1.9 \end{bmatrix} \cdot \frac{W}{gm}$$

$$B1\_Spacer\&HolderHR := B1\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.071 & 0.071 \\ 0.076 & 0.080 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$B2\_TensileSpecimens := \begin{bmatrix} 2.9 & 2.9 \end{bmatrix} \cdot \frac{W}{gm}$$

$$B2\_TensileHR := B2\_TensileSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 0.369 & 0.369 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$B2\_Spacer\&Holder := \begin{bmatrix} 2.0 & 2.0 \\ 2.2 & 2.2 \end{bmatrix} \cdot \frac{W}{gm}$$

$$B2\_Spacer\&HolderHR := B2\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.084 & 0.084 \\ 0.092 & 0.092 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$CapsuleB := \begin{bmatrix} 2.6 & 2.6 \end{bmatrix} \cdot \frac{W}{gm} \qquad CapsuleBHR := CapsuleB \cdot \rho_{SS} = \begin{bmatrix} 0.323 & 0.323 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

Capsule C Heating Rates

$$C1\_TEMSpecimens := \begin{bmatrix} 7.6 & 7.6 \\ 7.7 & 7.7 \\ 7.2 & 7.3 \\ 7.3 & 7.3 \\ 7.4 & 7.4 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C1\_TEMHR := C1\_TEMSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.944 & 0.944 \\ 0.957 & 0.957 \\ 0.895 & 0.907 \\ 0.907 & 0.907 \\ 0.919 & 0.919 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C1\_Holder := \begin{bmatrix} 7.6 & 7.6 \\ 6.8 & 6.8 \\ 5.9 & 5.9 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C1\_HolderHR := C1\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.319 & 0.319 \\ 0.285 & 0.285 \\ 0.248 & 0.248 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C2\_TensileSpecimens := \begin{bmatrix} 7.3 & 7.3 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C2\_TensileHR := C2\_TensileSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.907 & 0.907 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C2\_Spacer\&Holder := \begin{bmatrix} 5.7 & 5.8 \\ 5.9 & 6.0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C2\_Spacer\&HolderHR := C2\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.239 & 0.243 \\ 0.248 & 0.252 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C3\_TensileSpecimens := \begin{bmatrix} 8.0 & 8.0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C3\_TensileHR := C3\_TensileSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 1.018 & 1.018 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C3\_Spacer\&Holder := \begin{bmatrix} 5.8 & 5.8 \\ 6.0 & 6.0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C3\_Spacer\&HolderHR := C3\_Spacer\&Holder \cdot \rho_{Al} = \begin{bmatrix} 0.243 & 0.243 \\ 0.252 & 0.252 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C4\_TEMSpecimens := \begin{bmatrix} 8.4 & 8.5 \\ 8.4 & 8.5 \\ 7.9 & 8.0 \\ 8.3 & 8.3 \\ 8.2 & 8.3 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C4\_TEMHR := C4\_TEMSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 1.069 & 1.081 \\ 1.069 & 1.081 \\ 1.005 & 1.018 \\ 1.056 & 1.056 \\ 1.043 & 1.056 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$C4\_Holder := \begin{bmatrix} 7.6 & 7.6 \\ 6.9 & 6.9 \\ 6.0 & 6.0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$C4\_HolderHR := C4\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.319 & 0.319 \\ 0.290 & 0.290 \\ 0.252 & 0.252 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$CapsuleC := \begin{bmatrix} 8.0 & 8.0 \end{bmatrix} \cdot \frac{W}{gm} \qquad CapsuleCHR := CapsuleC \cdot \rho_{SS} = \begin{bmatrix} 0.994 & 0.994 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

Capsule D Heating Rates

$$D1\_TEMSpecimens := \begin{bmatrix} 3.1 & 3.2 \\ 3.2 & 3.2 \\ 3.1 & 3.1 \\ 3.0 & 3.1 \\ 3.3 & 3.3 \end{bmatrix} \cdot \frac{W}{gm}$$

$$D1\_TEMHR := D1\_TEMSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.385 & 0.398 \\ 0.398 & 0.398 \\ 0.385 & 0.385 \\ 0.373 & 0.385 \\ 0.410 & 0.410 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$D1\_Holder := \begin{bmatrix} 3.2 & 3.2 \\ 3.0 & 3.0 \\ 2.6 & 2.6 \end{bmatrix} \cdot \frac{W}{gm}$$

$$D1\_HolderHR := D1\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.134 & 0.134 \\ 0.126 & 0.126 \\ 0.109 & 0.109 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$D2\_TEMSpecimens := \begin{bmatrix} 3.1 & 3.1 \\ 3.2 & 3.2 \\ 2.9 & 2.9 \\ 2.9 & 2.9 \\ 3.2 & 3.2 \end{bmatrix} \cdot \frac{W}{gm}$$

$$D2\_TEMHR := D2\_TEMSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 0.394 & 0.394 \\ 0.407 & 0.407 \\ 0.369 & 0.369 \\ 0.369 & 0.369 \\ 0.407 & 0.407 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$D2\_Holder := \begin{bmatrix} 2.8 & 2.8 \\ 2.6 & 2.7 \\ 2.3 & 2.3 \end{bmatrix} \cdot \frac{W}{gm}$$

$$D2\_HolderHR := D2\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.118 & 0.118 \\ 0.109 & 0.113 \\ 0.097 & 0.097 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$CapsuleD := \begin{bmatrix} 3.3 & 3.3 \end{bmatrix} \cdot \frac{W}{gm} \qquad CapsuleDHR := CapsuleD \cdot \rho_{SS} = \begin{bmatrix} 0.41 & 0.41 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

Capsule E Heating Rates

$$E1\_TEMSpecimens := \begin{bmatrix} 2.3 & 0 \\ 2.3 & 0 \\ 2.1 & 0 \\ 2.1 & 0 \\ 2.3 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$E1\_TEMHR := E1\_TEMSpecimens \cdot \rho_{SS} = \begin{bmatrix} 0.286 & 0.000 \\ 0.286 & 0.000 \\ 0.261 & 0.000 \\ 0.261 & 0.000 \\ 0.286 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$E1\_Holder := \begin{bmatrix} 2.2 & 0 \\ 2.1 & 0 \\ 1.8 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$E1\_HolderHR := E1\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.092 & 0.000 \\ 0.088 & 0.000 \\ 0.076 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$E2\_TEMSpecimens := \begin{bmatrix} 2.0 & 0 \\ 2.0 & 0 \\ 2.0 & 0 \\ 2.0 & 0 \\ 2.2 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$E2\_TEMHR := E2\_TEMSpecimens \cdot \rho_{Inc} = \begin{bmatrix} 0.254 & 0.000 \\ 0.254 & 0.000 \\ 0.254 & 0.000 \\ 0.254 & 0.000 \\ 0.280 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$E2\_Holder := \begin{bmatrix} 1.8 & 0 \\ 1.7 & 0 \\ 1.5 & 0 \end{bmatrix} \cdot \frac{W}{gm}$$

$$E2\_HolderHR := E2\_Holder \cdot \rho_{Al} = \begin{bmatrix} 0.076 & 0.000 \\ 0.071 & 0.000 \\ 0.063 & 0.000 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

$$CapsuleE := \begin{bmatrix} 2.3 & 0 \end{bmatrix} \cdot \frac{W}{gm} \qquad CapsuleEHR := CapsuleE \cdot \rho_{SS} = \begin{bmatrix} 0.286 & 0 \end{bmatrix} \frac{BTU}{s \cdot in^3}$$

Spacer Heating Rates

$$TopSpacer := [5.4 \;\; 5.4] \cdot \frac{W}{gm}$$

$$TopSpacerHR := TopSpacer \cdot \rho_{SS} = [0.671 \;\; 0.671] \; \frac{BTU}{s \cdot in^3}$$

$$BottomSpacer := [5.7 \;\; 5.7] \cdot \frac{W}{gm}$$

$$BottomSpacerHR := BottomSpacer \cdot \rho_{SS} = [0.708 \;\; 0.708] \; \frac{BTU}{s \cdot in^3}$$

Appendix C – Heat Transfer Coefficients

Conductivity of the Helium-Argon mixtures are from the Thermophysical Properties of Matter Database, Gas Mixture: Monatomic Systems, Argon - Helium Mixtures, Ar - He.

https://cindasdata.com/Applications/TPMD/?action=+Show+Graph+&subaction=&mgcode=TG41&pgcode=&mcode=01600&mname=&pname=&pcode=0101&indvar=0676&prop_and_indvar=0101%3A0676&prop_range_min=&prop_range_max=&smcode%3Alist=01600&sdatacurves%3Alist=4300%3A4

Gas gaps at nominal and hot gap conditions were calculated in ECAR-3672. Gap conductance values for all gas mixtures at nominal gaps and 85HeAr15 for hot gaps were calculated and documented in ECAR-3672 and were not repeated here. The hot gap conductance for He40Ar60, He25Ar75, and Ar100 are calculated below.

$$T_{HeAr} := \begin{bmatrix} 302.2 \\ 793.2 \end{bmatrix} K = \begin{bmatrix} 84 \\ 968 \end{bmatrix} °F$$

$$k_{40He60Ar} := \begin{bmatrix} 0.0451 \\ 0.0957 \end{bmatrix} \cdot \frac{W}{m \cdot K} = \begin{bmatrix} 0.00217 \\ 0.00461 \end{bmatrix} \frac{BTU}{hr \cdot in \cdot R}$$

$$k_{25He75Ar} := \begin{bmatrix} 0.0326 \\ 0.0693 \end{bmatrix} \cdot \frac{W}{m \cdot K} = \begin{bmatrix} 0.00157 \\ 0.00334 \end{bmatrix} \frac{BTU}{hr \cdot in \cdot R}$$

$$k_{100Ar} := \begin{bmatrix} 0.0182 \\ 0.0383 \end{bmatrix} \cdot \frac{W}{m \cdot K} = \begin{bmatrix} 0.00088 \\ 0.00184 \end{bmatrix} \frac{BTU}{hr \cdot in \cdot R}$$

$$d_{hotgasgap} := \begin{bmatrix} 0.00100 \\ 0.00135 \\ 0.00285 \\ 0.00935 \\ 0.03835 \\ 0.10835 \end{bmatrix} \cdot in$$

40% Helium 60% Argon

$$h_{40He60Ar0} := \frac{k_{40He60Ar}}{d_{hotgasgap_0}} = \begin{bmatrix} 0.00060 \\ 0.00128 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{40He60Ar1} := \frac{k_{40He60Ar}}{d_{hotgasgap_1}} = \begin{bmatrix} 0.00045 \\ 0.00095 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{40He60Ar2} := \frac{k_{40He60Ar}}{d_{hotgasgap_2}} = \begin{bmatrix} 0.00021 \\ 0.00045 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{40He60Ar3} := \frac{k_{40He60Ar}}{d_{hotgasgap_3}} = \begin{bmatrix} 0.000065 \\ 0.000137 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{40He60Ar4} := \frac{k_{40He60Ar}}{d_{hotgasgap_4}} = \begin{bmatrix} 0.000016 \\ 0.000033 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{40He60Ar5} := \frac{k_{40He60Ar}}{d_{hotgasgap_5}} = \begin{bmatrix} 0.000006 \\ 0.000012 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

25% Helium 75% Argon

$$h_{25He75Ar0} := \frac{k_{25He75Ar}}{d_{hotgasgap_0}} = \begin{bmatrix} 0.00044 \\ 0.00093 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{25He75Ar1} := \frac{k_{25He75Ar}}{d_{hotgasgap_1}} = \begin{bmatrix} 0.00032 \\ 0.00069 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{25He75Ar2} := \frac{k_{25He75Ar}}{d_{hotgasgap_2}} = \begin{bmatrix} 0.00015 \\ 0.00033 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{25He75Ar3} := \frac{k_{25He75Ar}}{d_{hotgasgap_3}} = \begin{bmatrix} 0.000047 \\ 0.000099 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{25He75Ar4} := \frac{k_{25He75Ar}}{d_{hotgasgap_4}} = \begin{bmatrix} 0.000011 \\ 0.000024 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{25He75Ar5} := \frac{k_{25He75Ar}}{d_{hotgasgap_5}} = \begin{bmatrix} 0.000004 \\ 0.000009 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

100% Argon

$$h_{100Ar0} := \frac{k_{100Ar}}{d_{hotgasgap_0}} = \begin{bmatrix} 0.00024 \\ 0.00051 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{100Ar1} := \frac{k_{100Ar}}{d_{hotgasgap_1}} = \begin{bmatrix} 0.00018 \\ 0.00038 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{100Ar2} := \frac{k_{100Ar}}{d_{hotgasgap_2}} = \begin{bmatrix} 0.000085 \\ 0.000180 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{100Ar3} := \frac{k_{100Ar}}{d_{hotgasgap_3}} = \begin{bmatrix} 0.000026 \\ 0.000055 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{100Ar4} := \frac{k_{100Ar}}{d_{hotgasgap_4}} = \begin{bmatrix} 0.000006 \\ 0.000013 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

$$h_{100Ar5} := \frac{k_{100Ar}}{d_{hotgasgap_5}} = \begin{bmatrix} 0.0000022 \\ 0.0000047 \end{bmatrix} \frac{BTU}{sec \cdot in^2 \cdot R}$$

Appendix D – ABAQUS Validation

```
ABQ EXE: abq6142
COMPUTER: INL608356
OS: Windows
OS TYPE: 10
t1
================================================================================
ODB: Test-1
dictTest[Test-1].Keys:  ['Grp1']
          NT11-n325
Max error: 1.20%  <----------
    Max1:  37.3320     Min1:  10.5200 Range:  26.8120
Abq Max2:  37.7813 Abq Min2:  10.6362 Range:  27.1451
          NT11-n281
Max error: 1.48%  <----------
    Max1:  55.1070     Min1:  13.9970 Range:  41.1100
Abq Max2:  54.7760 Abq Min2:  14.2043 Range:  40.5717
================================================================================

t2
================================================================================
ODB: Test-2
dictTest[Test-2].Keys:  ['Grp2', 'Grp1']
          NT15-n61
Max error: 1.34%  <----------
    Max1:  37.3320     Min1:  10.5200 Range:  26.8120
Abq Max2:  37.7366 Abq Min2:  10.6609 Range:  27.0756
          NT11-n61
Max error: 1.54%  <----------
    Max1:  55.1070     Min1:  13.9970 Range:  41.1100
Abq Max2:  54.7444 Abq Min2:  14.2131 Range:  40.5313
================================================================================

t3
================================================================================
ODB: Test-3
dictTest[Test-3].Keys:  ['Grp1']
          NT11-n130
Max error: 1.65%  <----------
    Max1:  44.5920     Min1:  12.5210 Range:  32.0710
Abq Max2:  44.7825 Abq Min2:  12.7270 Range:  32.0555
          NT11-n59
Max error: 1.85%  <----------
    Max1:  55.3390     Min1:  14.7770 Range:  40.5620
Abq Max2:  55.0396 Abq Min2:  15.0511 Range:  39.9885
================================================================================

t4
================================================================================
ODB: Test-4
dictTest[Test-4].Keys:  ['Grp1']
          NT11-n281
```

```
Error: 0.00%      <----------
Ans:       13.7600      Abq:       13.7600
          NT11-n303
Error: 0.00%      <----------
Ans:       11.3200      Abq:       11.3200
          NT11-n325
Error: 0.00%      <----------
Ans:        4.0000      Abq:        4.0000
          NT11-n314
Error: 0.00%      <----------
Ans:        8.2700      Abq:        8.2700
          NT11-n292
Error: 0.00%      <----------
Ans:       13.1500      Abq:       13.1500
================================================================================

t5
================================================================================
ODB: Test-5
dictTest[Test-5].Keys:  ['Grp3', 'Grp2', 'Grp1', 'Grp5', 'Grp4']
          NT13-n62
Error: 0.00%      <----------
Ans:       11.3200      Abq:       11.3200
          NT12-n62
Error: 0.00%      <----------
Ans:       13.1500      Abq:       13.1500
          NT11-n62
Error: 0.00%      <----------
Ans:       13.7600      Abq:       13.7600
          NT15-n62
Error: 0.00%      <----------
Ans:        4.0000      Abq:        4.0000
          NT14-n62
Error: 0.00%      <----------
Ans:        8.2700      Abq:        8.2700
================================================================================

t6
================================================================================
ODB: Test-6
dictTest[Test-6].Keys:  ['Grp1']
          NT11-n533
Max error: 0.39%  <----------
    Max1:  80.7640     Min1:  61.8970 Range:  18.8670
Abq Max2:  80.4914 Abq Min2:  61.7364 Range:  18.7551
          NT11-n803
Max error: 0.38%  <----------
    Max1:  94.5930     Min1:  71.5310 Range:  23.0620
Abq Max2:  94.3007 Abq Min2:  71.2781 Range:  23.0226
================================================================================

t7
================================================================================
ODB: Test-7
dictTest[Test-7].Keys:  ['Grp1']
```

```
          HFL-e56
Error: 0.19%      <----------
Ans:        -0.1700      Abq:       -0.1697
================================================================================

t8
================================================================================
ODB: Test-8
dictTest[Test-8].Keys:  ['Grp1']
          HFL-e1121
Error: 1.74%      <----------
Ans:         0.1710      Abq:        0.1740
          HFL-e3678
Error: 2.25%      <----------
Ans:        -0.1620      Abq:       -0.1656
================================================================================

t9
================================================================================
ODB: Test-9
dictTest[Test-9].Keys:  ['Grp1']
          NT11-n13
Error: 0.01%      <----------
Ans:        50.0010      Abq:       50.0036
          NT11-n17
Error: 0.00%      <----------
Ans:        55.5500      Abq:       55.5500
          NT11-n328
Error: 0.20%      <----------
Ans:        51.6040      Abq:       51.7074
          NT11-n38
Error: 0.05%      <----------
Ans:        50.0890      Abq:       50.1148
          NT11-n28
Error: 0.11%      <----------
Ans:        50.7010      Abq:       50.7550
          NT11-n218
Error: 0.01%      <----------
Ans:        50.0110      Abq:       50.0176
          NT11-n32
Error: 0.10%      <----------
Ans:        50.3060      Abq:       50.3555
          NT11-n324
Error: 0.20%      <----------
Ans:        52.4260      Abq:       52.5321
          NT11-n4
Error: 0.08%      <----------
Ans:        51.0600      Abq:       51.1006
          NT11-n320
Error: 0.16%      <----------
Ans:        53.6690      Abq:       53.7552
================================================================================

t10
================================================================================
```

```
ODB: Test-10
dictTest[Test-10].Keys:  ['Grp1']
          NT11-n325
Error: 0.15%      <----------
Ans:      215.7130      Abq:      216.0345
================================================================================

t11
================================================================================
ODB: Test-11
dictTest[Test-11].Keys:  ['Grp1']
          HFL-e55
Error: 0.02%      <----------
Ans:       -5.5000      Abq:       -5.4989
================================================================================

t12
================================================================================
ODB: Test-12
dictTest[Test-12].Keys:  ['Grp1']
          NT11-n336
Error: 0.00%      <----------
Ans:      406.6667      Abq:      406.6667
================================================================================
```

Appendix E – Specimen Temperature Results

Table E1 – Cycle 164A Specimen Temperatures at Nominal Power (22.5MW) and Gas Gap

Capsule	Holder	Specimen Stack	Material	Minimum (°F)	Minimum (°C)	Maximum (°F)	Maximum (°C)
A	A-1	Tensile	SS316	586	308	622	328
	A-2	Tensile	Inconel	678	359	737	392
B	B-1	Tensile	SS316	586	308	632	333
	B-2	Tensile	Inconel	655	346	727	386
C	C-1	PIE TPP	SS316	583	306	633	334
		PIE TEM 1	SS316	528	276	537	281
		PIE TEM 2	SS316	528	276	538	281
		PIE TEM 3	SS316	527	275	536	280
		PIE TEM 4	SS316	527	275	536	280
	C-2	Tensile	SS316	547	286	632	333
	C-3	Tensile	Inconel	554	290	681	361
	C-4	PIE TPP	Inconel	609	321	686	363
		PIE TEM 1	Inconel	548	287	565	296
		PIE TEM 2	Inconel	548	287	565	296
		PIE TEM 3	Inconel	547	286	563	295
		PIE TEM 4	Inconel	548	287	564	296
D	D-1	PIE TPP	SS316	594	312	628	331
		PIE TEM 1	SS316	521	272	525	274
		PIE TEM 2	SS316	521	272	526	274
		PIE TEM 3	SS316	521	272	525	274
		PIE TEM 4	SS316	520	271	525	274
	D-2	PIE TPP	Inconel	578	303	624	329
		PIE TEM 1	Inconel	510	266	517	269
		PIE TEM 2	Inconel	511	266	517	269
		PIE TEM 3	Inconel	509	265	516	269
		PIE TEM 4	Inconel	509	265	516	269
E	E-1	PIE TPP	SS316	594	312	621	327
		PIE TEM 1	SS316	523	273	526	274
		PIE TEM 2	SS316	523	273	526	274
		PIE TEM 3	SS316	522	272	525	274
		PIE TEM 4	SS316	522	272	525	274
	E-2	PIE TPP	Inconel	572	300	608	320
		PIE TEM 1	Inconel	505	263	509	265
		PIE TEM 2	Inconel	505	263	509	265
		PIE TEM 3	Inconel	505	263	509	265
		PIE TEM 4	Inconel	505	263	509	265

Table E2 – Cycle 164B Specimen Temperatures at Nominal Power (22.6MW) and Gas Gap

Capsule	Holder	Specimen Stack	Material	Minimum (°F)	Minimum (°C)	Maximum (°F)	Maximum (°C)
A	A-1	Tensile	SS316	---	---	---	---
	A-2	Tensile	Inconel	---	---	---	---
B	B-1	Tensile	SS316	590	310	636	336
	B-2	Tensile	Inconel	657	347	728	387
C	C-1	PIE TPP	SS316	583	306	634	334
		PIE TEM 1	SS316	528	276	538	281
		PIE TEM 2	SS316	528	276	538	281
		PIE TEM 3	SS316	527	275	537	281
		PIE TEM 4	SS316	527	275	537	281
	C-2	Tensile	SS316	549	287	634	334
	C-3	Tensile	Inconel	555	291	682	361
	C-4	PIE TPP	Inconel	612	322	689	365
		PIE TEM 1	Inconel	549	287	567	297
		PIE TEM 2	Inconel	550	288	567	297
		PIE TEM 3	Inconel	548	287	565	296
		PIE TEM 4	Inconel	549	287	566	297
D	D-1	PIE TPP	SS316	594	312	628	331
		PIE TEM 1	SS316	522	272	526	274
		PIE TEM 2	SS316	522	272	526	274
		PIE TEM 3	SS316	521	272	526	274
		PIE TEM 4	SS316	521	272	526	274
	D-2	PIE TPP	Inconel	580	304	626	330
		PIE TEM 1	Inconel	512	267	518	270
		PIE TEM 2	Inconel	512	267	519	271
		PIE TEM 3	Inconel	511	266	517	269
		PIE TEM 4	Inconel	511	266	517	269
E	E-1	PIE TPP	SS316	---	---	---	---
		PIE TEM 1	SS316	---	---	---	---
		PIE TEM 2	SS316	---	---	---	---
		PIE TEM 3	SS316	---	---	---	---
		PIE TEM 4	SS316	---	---	---	---
	E-2	PIE TPP	Inconel	---	---	---	---
		PIE TEM 1	Inconel	---	---	---	---
		PIE TEM 2	Inconel	---	---	---	---
		PIE TEM 3	Inconel	---	---	---	---
		PIE TEM 4	Inconel	---	---	---	---

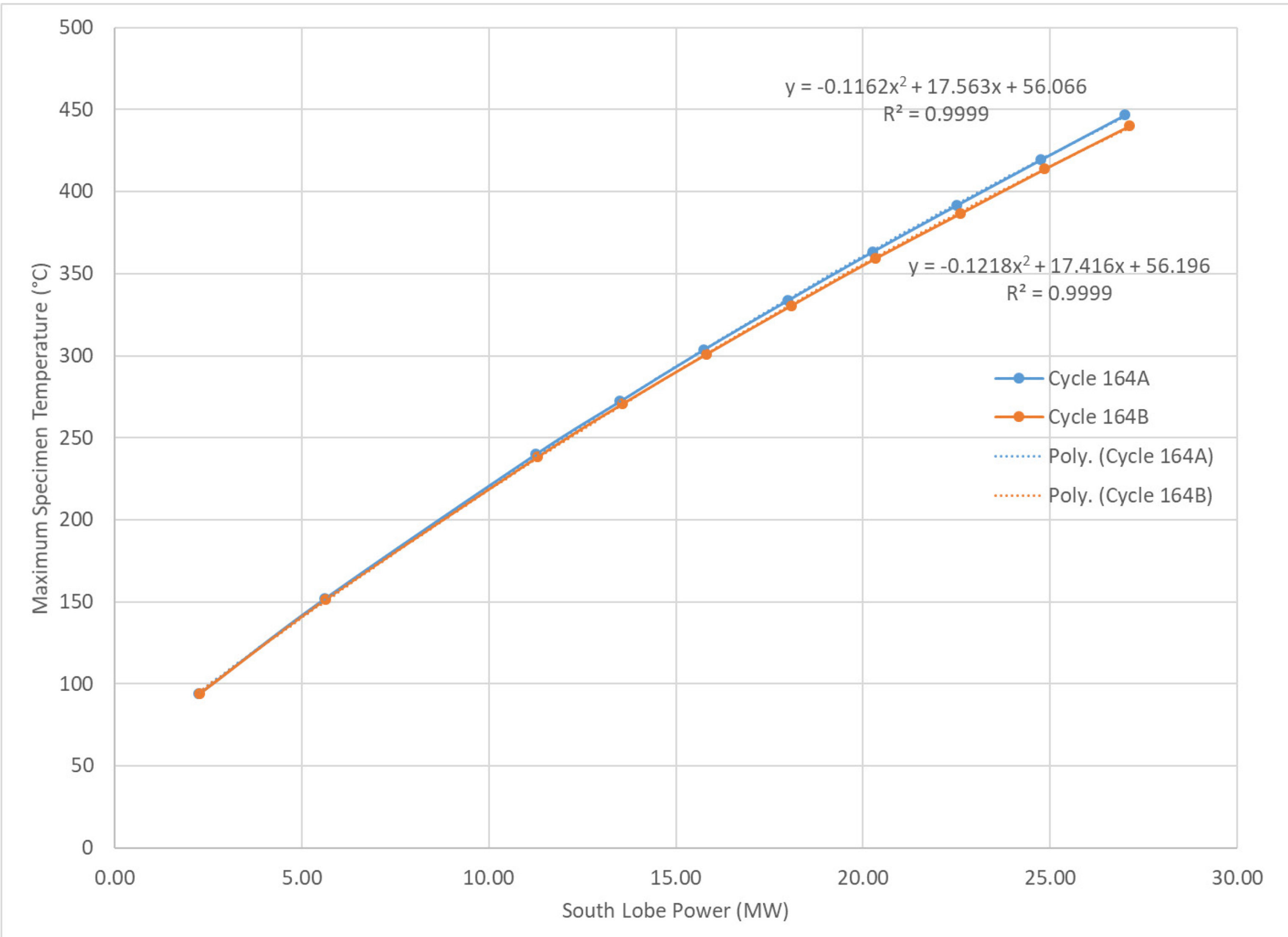

Figure E1 – Maximum Specimen Temperature at Various Power Levels for Each Cycle

Table E3 – Cycle 164A Specimen Temperatures at Nominal Power (22.5MW) and Hot Gas Gap

Capsule	Holder	Specimen Stack	Material	Minimum (°F)	Minimum (°C)	Maximum (°F)	Maximum (°C)
A	A-1	Tensile	SS316	567	297	604	318
	A-2	Tensile	Inconel	660	349	721	383
B	B-1	Tensile	SS316	530	277	578	303
	B-2	Tensile	Inconel	600	316	674	357
C	C-1	PIE TPP	SS316	554	290	605	318
		PIE TEM 1	SS316	496	258	506	263
		PIE TEM 2	SS316	497	258	507	264
		PIE TEM 3	SS316	496	258	505	263
		PIE TEM 4	SS316	496	258	505	263
	C-2	Tensile	SS316	514	268	602	317
	C-3	Tensile	Inconel	521	272	650	343
	C-4	PIE TPP	Inconel	579	304	657	347
		PIE TEM 1	Inconel	515	268	532	278
		PIE TEM 2	Inconel	515	268	532	278
		PIE TEM 3	Inconel	514	268	531	277
		PIE TEM 4	Inconel	515	268	532	278
D	D-1	TPP TEM	SS316	565	296	600	316
		PIE TEM 1	SS316	491	255	495	257
		PIE TEM 2	SS316	491	255	496	258
		PIE TEM 3	SS316	490	254	495	257
		PIE TEM 4	SS316	490	254	495	257
	D-2	PIE TPP	Inconel	550	288	596	313
		PIE TEM 1	Inconel	480	249	487	253
		PIE TEM 2	Inconel	481	249	487	253
		PIE TEM 3	Inconel	479	248	486	252
		PIE TEM 4	Inconel	479	248	486	252
E	E-1	PIE TPP	SS316	550	288	579	304
		PIE TEM 1	SS316	476	247	479	248
		PIE TEM 2	SS316	476	247	479	248
		PIE TEM 3	SS316	475	246	478	248
		PIE TEM 4	SS316	475	246	478	248
	E-2	PIE TPP	Inconel	528	276	565	296
		PIE TEM 1	Inconel	458	237	462	239
		PIE TEM 2	Inconel	458	237	462	239
		PIE TEM 3	Inconel	458	237	462	239
		PIE TEM 4	Inconel	458	237	462	239

Table E4 – Cycle 164B Specimen Temperatures at Nominal Power (22.6MW) and Hot Gas Gap

Capsule	Holder	Specimen Stack	Material	Minimum (°F)	Minimum (°C)	Maximum (°F)	Maximum (°C)
A	A-1	Tensile	SS316	---	---	---	---
	A-2	Tensile	Inconel	---	---	---	---
B	B-1	Tensile	SS316	534	279	582	306
	B-2	Tensile	Inconel	601	316	675	357
C	C-1	PIE TPP	SS316	554	290	606	319
		PIE TEM 1	SS316	497	258	507	264
		PIE TEM 2	SS316	497	258	507	264
		PIE TEM 3	SS316	496	258	506	263
		PIE TEM 4	SS316	496	258	506	263
	C-2	Tensile	SS316	515	268	604	318
	C-3	Tensile	Inconel	521	272	651	344
	C-4	PIE TPP	Inconel	581	305	660	349
		PIE TEM 1	Inconel	517	269	534	279
		PIE TEM 2	Inconel	517	269	534	279
		PIE TEM 3	Inconel	516	269	533	278
		PIE TEM 4	Inconel	516	269	534	279
D	D-1	PIE TPP	SS316	566	297	601	316
		PIE TEM 1	SS316	492	256	496	258
		PIE TEM 2	SS316	492	256	496	258
		PIE TEM 3	SS316	491	255	495	257
		PIE TEM 4	SS316	491	255	496	258
	D-2	PIE TPP	Inconel	551	288	598	314
		PIE TEM 1	Inconel	481	249	488	253
		PIE TEM 2	Inconel	482	250	489	254
		PIE TEM 3	Inconel	480	249	487	253
		PIE TEM 4	Inconel	481	249	487	253
E	E-1	PIE TPP	SS316	---	---	---	---
		PIE TEM 1	SS316	---	---	---	---
		PIE TEM 2	SS316	---	---	---	---
		PIE TEM 3	SS316	---	---	---	---
		PIE TEM 4	SS316	---	---	---	---
	E-2	PIE TPP	Inconel	---	---	---	---
		PIE TEM 1	Inconel	---	---	---	---
		PIE TEM 2	Inconel	---	---	---	---
		PIE TEM 3	Inconel	---	---	---	---
		PIE TEM 4	Inconel	---	---	---	---

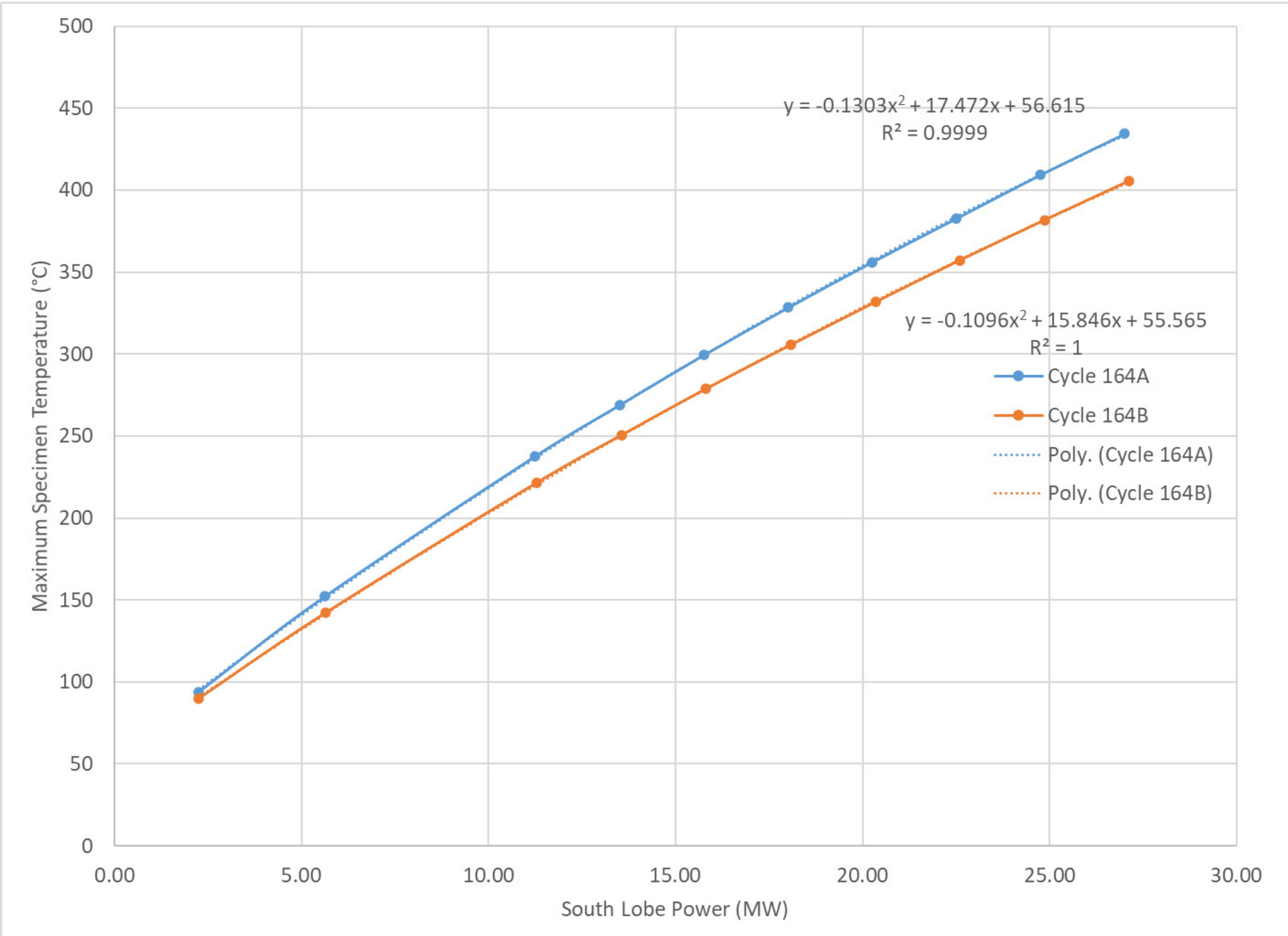

Figure E2 – Maximum Specimen Temperature at Various Power Levels for Each Cycle

Table E5 – Specimen Stacks and Corresponding Specimen Numbers

Capsule	Holder	Specimen Stack	Material	Specimen Numbers
A	A-1	Tensile	SS316	1, 2, 3, 4, 145, 146, 147, 148, 161, 162, 163, 164, 217, 218, 219, 220
	A-2	Tensile	Inconel	13, 14, 15, 16, 73, 74, 75, 76, 89, 90, 91, 92, 229, 230, 231, 232
B	B-1	Tensile	SS316	5, 6, 7, 8, 153, 154, 155, 156, 157, 158, 159, 160, 221, 222, 223, 224
	B-2	Tensile	Inconel	17, 18, 19, 20, 81, 82, 83, 84, 85, 86, 87, 88, 233, 234, 235, 236
C	C-1	PIE TPP	SS316	25, 26, 27, 28, 177, 178, 179, 180, 181, 182, 183, 184, 241, 242, 243, 244
		PIE TEM 1	SS316	49, 50, 51, 52
		PIE TEM 2	SS316	289, 291, 206, 208
		PIE TEM 3	SS316	201, 202, 203, 204
		PIE TEM 4	SS316	265, 266, 267, 268
	C-2	Tensile	SS316	9, 10, 11, 12, 149, 150, 151, 152, 165, 166, 167, 168, 225, 226, 227, 228
	C-3	Tensile	Inconel	21, 22, 23, 24, 77, 78, 79, 80, 93, 94, 95, 96, 237, 238, 239, 240
	C-4	PIE TPP	Inconel	37, 38, 39, 40, 97, 98, 99, 100, 113, 114, 115, 116, 253, 254, 255, 256
		PIE TEM 1	Inconel	61, 62, 63, 64
		PIE TEM 2	Inconel	121, 122, 123, 124
		PIE TEM 3	Inconel	137, 138, 139, 140
		PIE TEM 4	Inconel	281, 282, 283, 284
D	D-1	PIE TPP	SS316	29, 30, 31, 32, 169, 170, 171, 172, 185, 186, 187, 188, 245, 246, 247, 248
		PIE TEM 1	SS316	53, 54, 55, 56
		PIE TEM 2	SS316	193, 194, 195, 196
		PIE TEM 3	SS316	209, 210, 211, 212
		PIE TEM 4	SS316	269, 270, 271, 272
	D-2	PIE TPP	Inconel	41, 42, 43, 44, 101, 102, 103, 104, 117, 118, 119, 120, 257, 258, 259, 260
		PIE TEM 1	Inconel	65, 66, 67, 68
		PIE TEM 2	Inconel	125, 126, 127, 128
		PIE TEM 3	Inconel	141, 142, 143, 144
		PIE TEM 4	Inconel	277, 278, 279, 280
E	E-1	PIE TPP	SS316	33, 34, 35, 36, 173, 174, 175, 176, 189, 190, 191, 192, 249, 250, 251, 252
		PIE TEM 1	SS316	57, 58, 59, 60
		PIE TEM 2	SS316	197, 198, 199, 200
		PIE TEM 3	SS316	213, 214, 215, 216
		PIE TEM 4	SS316	273, 274, 275, 276
	E-2	PIE TPP	Inconel	45, 46, 47, 48, 105, 106, 107, 108, 109, 110, 111, 112, 261, 262, 263, 264
		PIE TEM 1	Inconel	69, 70, 71, 72
		PIE TEM 2	Inconel	129, 130, 131, 132
		PIE TEM 3	Inconel	133, 134, 135, 136
		PIE TEM 4	Inconel	285, 286, 287, 288

Appendix F – Analysis Request

Stacey M. Wilson

From: Donna P. Guillen
Sent: Monday, December 16, 2019 4:32 PM
To: Katie A. Anderson; Stacey M. Wilson
Cc: Misti A. Lillo
Subject: RE: CSM Thermal As-Run

Follow Up Flag: Follow up
Flag Status: Completed

Thanks, Stacey. The PI has requested the as-run temperatures by specimen, as well as a thermal history for the specimens. It will be good enough if you can estimate the thermal history without the need for a detailed neutronics analysis for the history.

Katie – The thermal history might take a bit more hours.

From: Katie A. Anderson <katie.anderson@inl.gov>
Sent: Monday, December 16, 2019 1:47 PM
To: Stacey M. Wilson <stacey.wilson@inl.gov>
Cc: Misti A. Lillo <misti.lillo@inl.gov>; Donna P. Guillen <donna.guillen@inl.gov>
Subject: RE: CSM Thermal As-Run

Hi Stacey,

That sounds great! I will plan on 80 hours to include your time as well as a tech checker. There should be two cycles of as-run results: cycle 164A and 164B for the B-5 position. You can use charge number 1027406A0 and you can start any time you want. I don't think we have a specific "need by" date, just at your earliest convenience. Let me know if you have any other questions.

Thanks!
Katie

Idaho National Laboratory

KATIE ANDERSON | Experiment Manager
Irradiation Testing

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