Title: As-Run Thermal Analysis of the GE-Hitachi Experiment

ECAR No.: 4771 Rev. No.: 0 Project No.: 32535 Date: 12/05/19

1.	Does this ECAR involve a Safety SSC?	No	**Professional Engineer's Stamp** N/A See LWP-10010 for requirements.
2.	Safety SSC Determination Document ID	N/A	
3.	Engineering Job (EJ) No.	N/A	
4.	SSC ID	N/A	
5.	Building	TRA-670	
6.	Site Area	ATR Complex	

7. Objective/Purpose:

The purpose of this Engineering Calculations and Analysis Report (ECAR) is to document the results from the as-run thermal analysis of the GE-Hitachi experiment. The GE-Hitachi experiment contains compact tension (CT) and tensile specimens of 316L stainless steel and Inconel 718 which was irradiated in a static drop-in style experiment in the ATR position B-11. The ABAQUS model created during the Design phase of the experiment (details outlined in ECAR-3571) was used to perform this as-run analysis. The neutronics analysis, ECAR-4740, documents the as-run heat rates from the four cycles that the experiment was irradiated (162A, 162B, 164A, and 164B).

8. If revision, please state the reason and list sections and/or pages being affected:

N/A

9. Conclusions/Recommendations:

The predicted as-run temperatures for cycles 162A, 162B, 164A, and 164B have been calculated for the GE-Hitachi experiment. These temperatures are shown in Table 2. The heating rates provided as input into the existing ABAQUS models are taken from ECAR-4740 [1]. The calculated results show that the specimens were within the requested target temperature of 290°C ±50°C.

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TABLE OF TABLES

1 PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	Cody Hale	C130	All
Checker[a]	Casey Jesse	C130	All
Independent Reviewer	N/A	N/A	N/A
CUI Reviewer[c]	Matthew Arrowood	C630	All
Manager[d]	Misti Lillo	C130	All
Requestor[e]	Matthew Arrowood	C630	All
Document Owner[e]	John Jackson	C002	All

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

2 SCOPE AND BRIEF DESCRIPTION

The purpose of this Engineering Calculations and Analysis Report (ECAR) is to document the results from the as-run thermal analysis of the GE-Hitachi experiment. The GE-Hitachi experiment contains compact tension (CT) and tensile specimens of 316L stainless steel and Inconel 718 which was irradiated in a static drop-in style experiment in the ATR position B-11. The ABAQUS model created during the Design phase of the experiment (details outlined in ECAR-3571) was used to perform this as-run analysis. The neutronics analysis, ECAR-4740, documents the as-run heat rates from the four cycles that the experiment was irradiated (162A, 162B, 164A, and 164B).

3 EXPERIMENT OVERVIEW

The GE-Hitachi experiment is an irradiation experiment funded by the NSUF (Nuclear Science User Facilities) to provide industry with access to irradiation testing capabilities at the Advanced Test Reactor. This experiment contains rectangular compact tension (CT) and round tensile specimens irradiated in a large B position using gas gap temperature control to maintain the specimen temperature at 290°C ±50°C. The test train consists of twelve CT specimens and eight tensile specimens contained in a stainless steel capsule and aluminum basket that fits the 1.5 inch diameter irradiation position. Capsule internal components include aluminum alloy specimen holders, zirconia spacers that thermally isolate the hotter internal components from the cooler capsule end cap, neutron fluence monitors, silicon carbide temperature indicators, and several melt wires encompassing a range of melting temperature. Design details are from the drawings listed Table 1.

4 DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

Design and technical input can be found in TFR-959 [2].

5 RESULTS OF LITERATURE SEARCHES AND OTHER BACKGROUND DATA

The drawings used in this analysis are referenced below in Table 1.

Table 1. Drawing List

Drawing Number	Rev.	Description
605754	1	ATR GE Hitachi (GEH) Capsule Details and Assembly
605755	1	ATR Ge Hitachi (GEH) Additively Manufactured (AM) Round Tensile Specimen Detail
605756	1	ATR Ge Hitachi (GEH) Additively Manufacture (AM) Compact Tension Specimen Detail
605757	2	ATR Ge Hitachi (GEH) Final Assembly
605758	1	ATR Ge Hitachi (GEH) Basket Details and Assembly
605759	2	ATR Ge Hitachi (GEH) Pressure Boundary and Spacer Details
605760	0	ATR Ge Hitachi (GEH) In-Vessel Installation

6 ASSUMPTIONS

All modeling assumptions can be found in ECAR-3571 [3].

7 COMPUTER CODE VALIDATION

A finite element heat transfer analysis of the GE-Hitachi experiment was performed using ABAQUS version 6.14-2 on a DELL Precision T5810 workstation (“INL603135” on the INL network).The operating system is Windows 10 Enterprise 64-bit operating system, and the processor is an Intel Xenon CPU E5-1607 with a speed of 3.10 GHz. 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 thermal analysis of ATR experiments by solving several test problems and verifying the results against analytical solutions provided in heat transfer textbooks. A complete description of the validation test problems is given in ECAR-131 [4]. It should be noted that ECAR-131 was performed for validating ABAQUS 6.7-3 however the test problem descriptions are still accurate for the test problems run for version 6.14-2. The test problems were run on computer “INL603135” and a report file containing the validation test results was automatically generated (see Appendix C). The results meet the acceptance criterion that the relative error is less than 3%. The Mathcad calculations have been independently verified by visual inspection and random hand calculation checking during the review process as allowed by LWP-10200, Appendix E [5].

8 DISCUSSION/ANALYSIS

8.1 Modeling Information

For modeling information (including material properties, interaction properties, geometric information, meshing and hydrodynamic conditions) refer to ECAR-3571 [3]. The only difference between the model used for the Design of the GE-Hitachi experiment and this model is the heat rates which reflect the calculated as-run heat rates documented in ECAR-4740 [1]. These heat rates can also be found in Appendix B where they have been converted into units acceptable for the ABAQUS model.

8.2 Analysis Results

The following table provides the calculated temperature results for the GE-Hitachi experiment in position B-11 within the ATR during operating cycles 162A, 162B, 164A, and 164B. These temperatures represent the average temperature of the specimen in the region of interest during post-irradiation testing (the region of crack growth and failure).

Table 2: As-Run Temperature Results for the GE-Hitachi Experiment

Specimen Identifier	Specimen Material	Specimen Temperature (°C)			
		162A	162B	164A	164B
CT-1	316L SST	306	285	289	291
CT-2	Inconel 718	310	290	294	296
CT-3	316L SST	300	282	285	287
CT-4	Inconel 718	306	287	290	292
CT-5	316L SST	300	281	284	286
CT-6	Inconel 718	305	286	290	292
CT-7	316L SST	295	278	280	283
CT-8	Inconel 718	304	283	288	288
CT-9	316L SST	296	276	281	280
CT-10	Inconel 718	303	283	287	288
CT-11	316L SST	299	277	283	282
CT-12	Inconel 718	309	288	293	294
Tensile-bot-NE	316L SST	292	274	277	279
Tensile-bot-NW	Inconel 718	296	273	281	279
Tensile-bot-SE	Inconel 718	290	269	275	274
Tensile-bot-SW	316L SST	288	268	272	274
Tensile-top-NE	316L SST	291	274	276	280
Tensile-top-NW	Inconel 718	294	273	279	279
Tensile-top-SE	Inconel 718	289	268	274	274
Tensile-top-SW	316L SST	286	269	271	274

The following contour plots are provided to show a representative temperature profile within the specimen. A quarter section of each specimen is taken out in order to view the location of interest within each specimen.

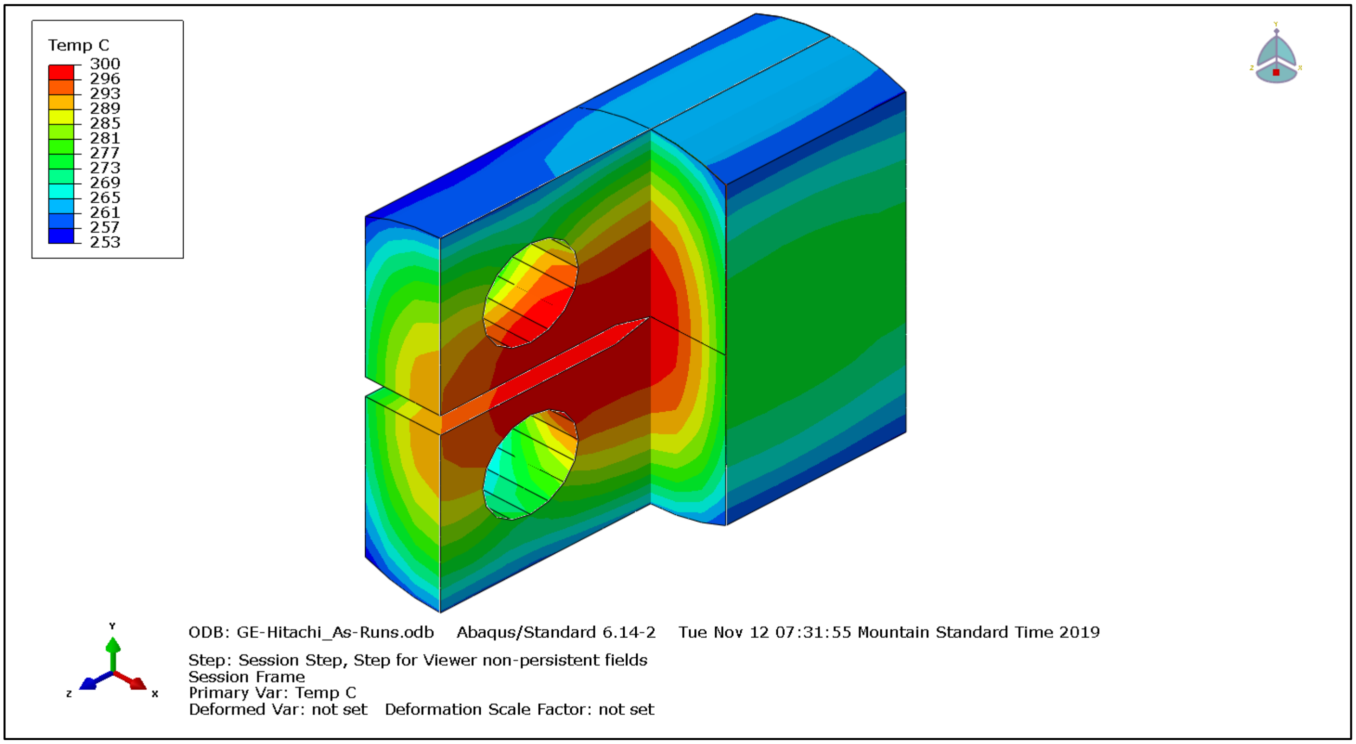

Figure 1: Representative temperature contour plot of an Inconel 718 CT specimen (CT-6) from cycle 164B

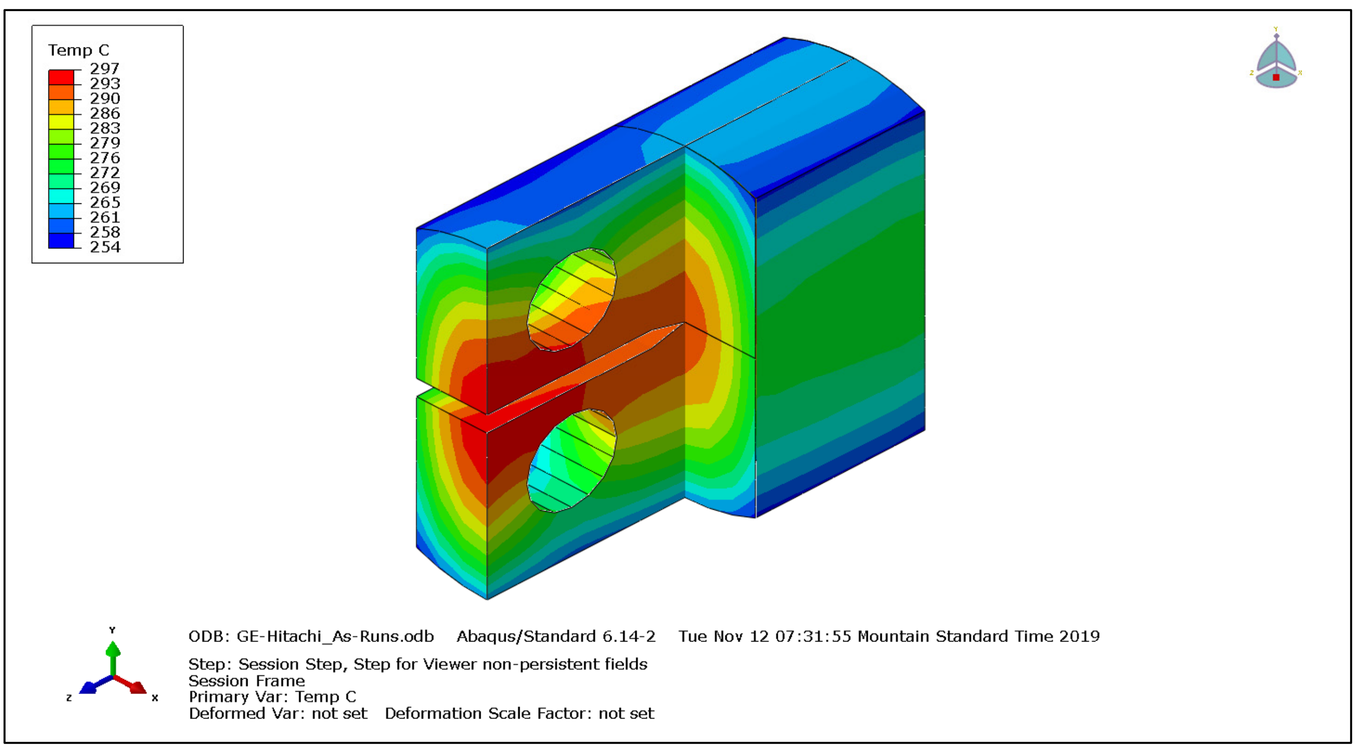

Figure 2: Representative temperature contour plot of a 316 SST CT specimen (CT-5) from cycle 164B

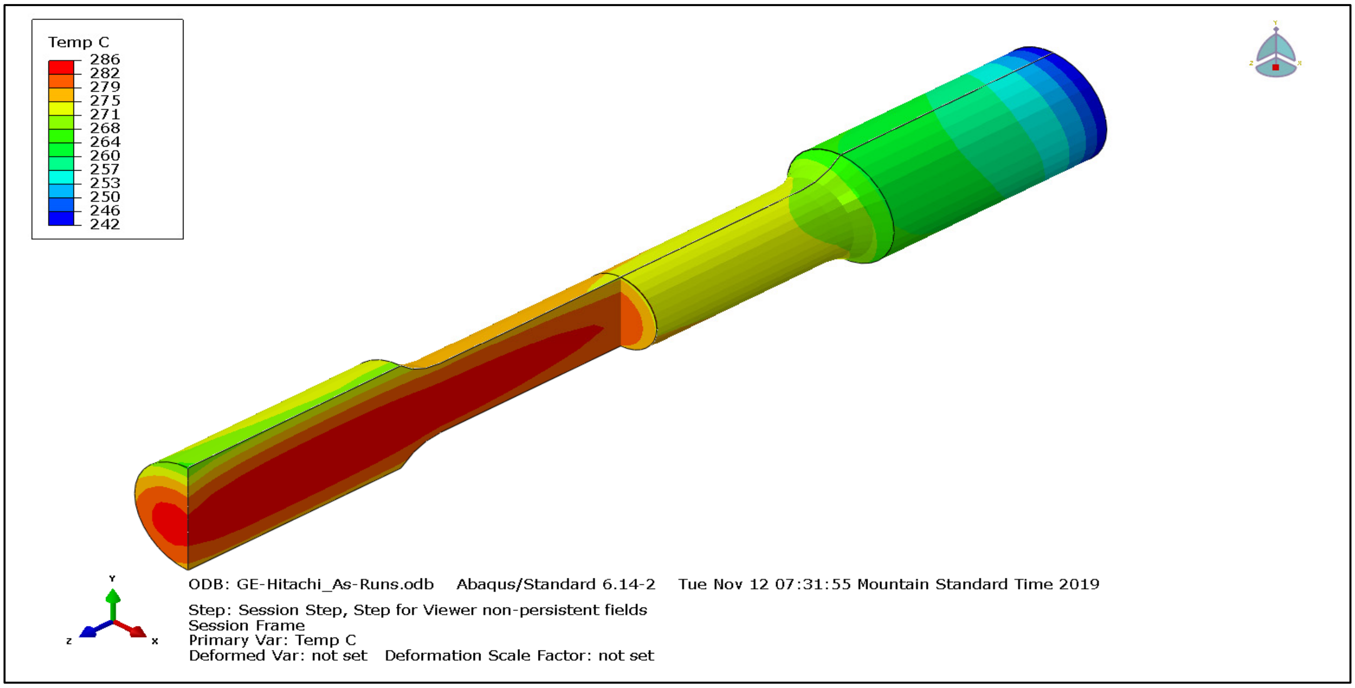

Figure 3: Representative temperature contour plot of an Inconel 718 tensile specimen (Tensile-bot-NW) from cycle 164B

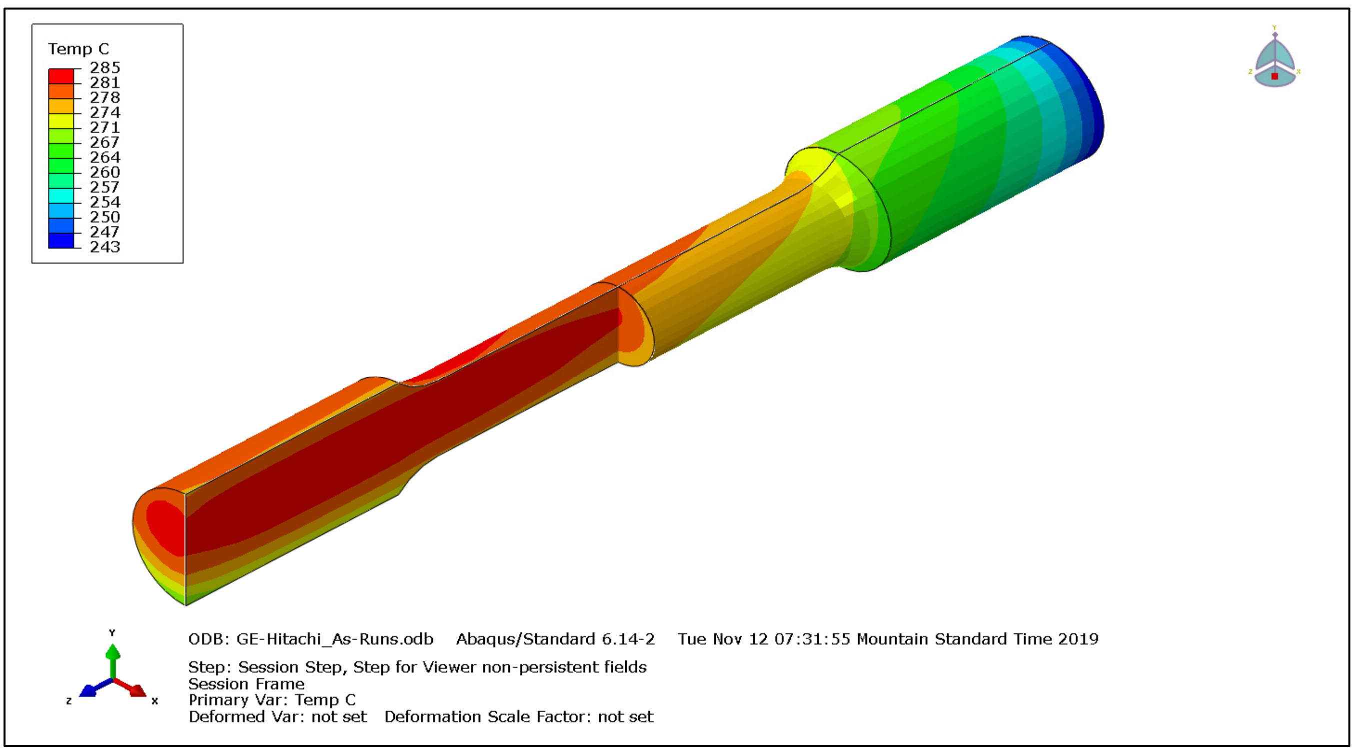

Figure 4: Representative temperature contour plot of a 316 SST tensile specimen (Tensile-bot-NE) from cycle 164B

Figure 5 below is a temperature contour plot of the tensile holders and center CT blank specimen where melt wires are located within the experiment. Cycle 162A exhibited the highest temperatures therefore only this cycles melt wire location temperatures are shown. The melt wires were not explicitly modeled in ABAQUS however their temperature will be close to the temperature of the surrounding materials since the melt wires are so small and the heat generation is low.

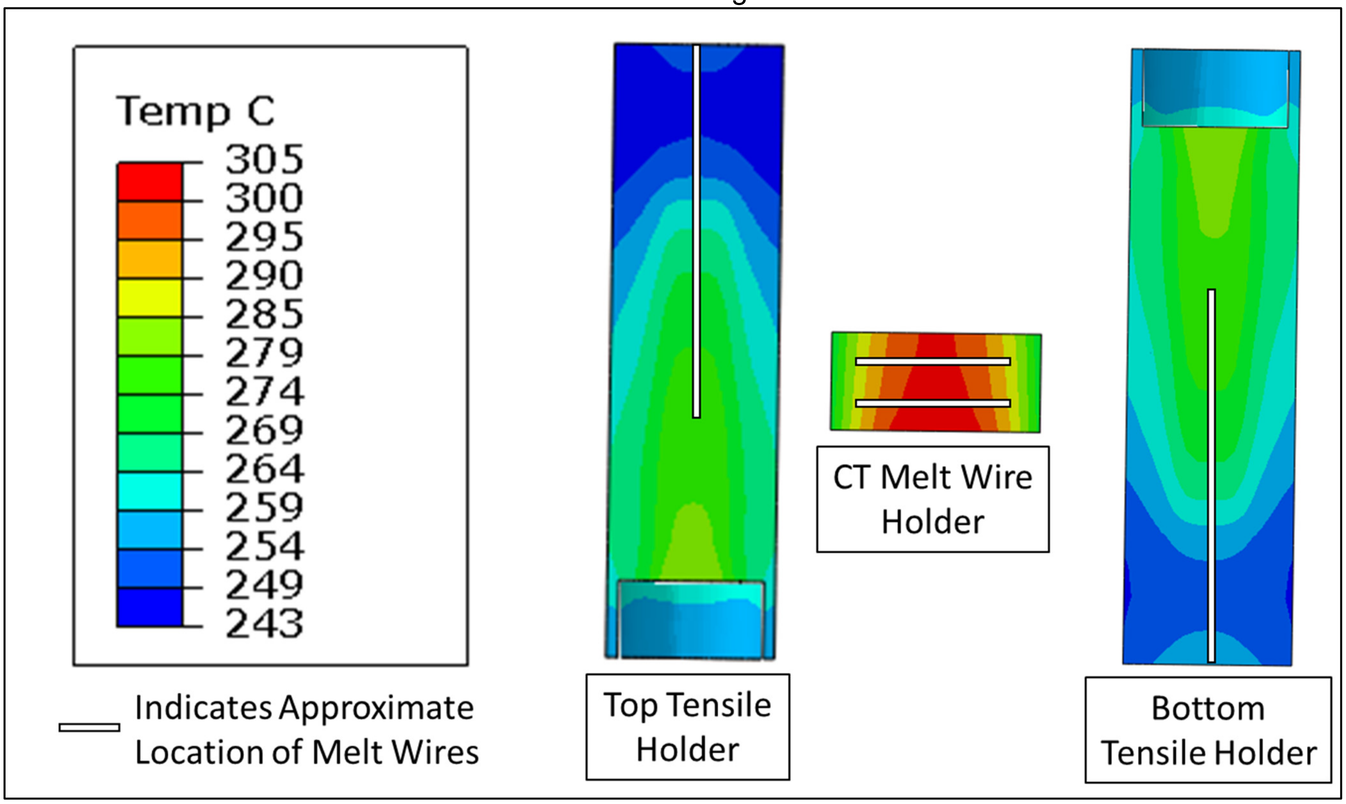

Figure 5: Temperature contour plot of Melt Wire locations during cycle 162A

9 ACRONYMS

ATR	Advanced Test Reactor
CT	Compact Tension
CUI	Controlled Unclassified Information
EA	Enterprise Architecture
ECAR	Engineering Calculations and Analysis Report
EJ	Engineering Job
INL	Idaho National Laboratory
LWP	Laboratory Wide Procedure
NSUF	Nuclear Science User Facilities
SSC	System, Structure, or Component
TRA	Test Reactor Area

10 DATA FILES

The following table contains names and descriptions of the electronic files associated with this analysis that can be found in the following directories:

C:\Users\HALEDD\OneDrive - Idaho National Laboratory\Projects\GE-Hitachi_As-Run	
Filename	Description
ECAR-4771 – Thermal As-Run Final Draft.docx	This document
Appendix B – Heat Rates.xmcd	Mathcad file containing heat rates
Results.xlsx	Excel file containing temperature results

C:\Users\HALEDD\OneDrive - Idaho National Laboratory\Projects\GE-Hitachi_As-Run\Abaqus	
Filename	Description
GE-Hitachi_As-Run.cae, GE-Hitachi_As-Run.jnl	ABAQUS cae and journal files
GE-Hitachi_As-Run.inp, GE-Hitachi_As-Run.odb	ABAQUS input and output files

11 CONCLUSIONS

The predicted as-run temperatures for cycles 162A, 162B, 164A, and 164B have been calculated for the GE-Hitachi experiment. These temperatures are shown in Table 2. The heating rates provided as input into the existing ABAQUS models are taken from ECAR-4740 [1]. The calculated results show that the specimens were within the requested target temperature of 290°C ±50°C.

12 REFERENCES

[1] J. Mitchell, ECAR-4740, Rev. 0, "As-Run Neutronics Evaluation for the GE Hitachi Experiment in ATR", 10/2019.

[2] D. Stacey, TFR-959, Rev. 1 "GE-Hitachi Drop-in Capsule Experiment Technical and Functional Requirements", 04/25/2017.

[3] P. Murray, ECAR-3571, Rev. 1, "Thermal Analysis of the GE-Hitachi Experiment", 05/24/2017.

[4] P. E. Murray, *ECAR-131, Rev 0, "Validation of ABAQUS Standard 6.7-3 Heat Transfer",* 1/30/2008.

[5] Idaho National Laboratory, *LWP-10200, Rev 9, "Engineering Calculations and Analysis Report",* 5/17/2017.

[6] ABAQUS Standard, Version 6.14-2, Dassault Systemes Corp., Inc., Providence, RI, 2014.

13 APPENDIXES

Appendix A – Engineering Inputs
Appendix B – Heat Rates
Appendix C – Computer Code Validation

Appendix A

Engineering Inputs

From: Matthew M. Arrowood
To: Cody D. Hale
Subject: Ge-Hitachi As Run Thermal Analysis Request
Date: Thursday, October 17, 2019 2:38:54 PM

I am requesting an as run analysis of the GE-Hitachi experiment (Project # 32535).

John Jackson will be the document owner and I will perform the CUI review.

Thanks,

Matthew Arrowood
Experiment Manager
Idaho National Laboratory
Office: (208) 526-3527
Mobile: (208) 339-0550

Appendix B

Material Heating Rates

B.1: Material Densities

Densities of the following materials are obtained from Appendix A of ECAR-3571

$\rho_{SST} := 8.0 \dfrac{gm}{cm^3}$ $\rho_{SST} = 0.289 \dfrac{lb}{in^3}$ Density of stainless steel

$\rho_{718} := 8.22 \dfrac{gm}{cm^3}$ $\rho_{718} = 0.297 \dfrac{lb}{in^3}$ Density of Inconel 718

$\rho_{AL} := 2.70 \dfrac{gm}{cm^3}$ $\rho_{AL} = 0.098 \dfrac{lb}{in^3}$ Density of aluminum

$\rho_{ZrO2} := 6.02 \dfrac{gm}{cm^3}$ $\rho_{ZrO2} = 0.217 \dfrac{lb}{in^3}$ Density of zirconium oxide

$\rho_{Be} := 1.850 \dfrac{gm}{cm^3}$ $\rho_{Be} = 0.067 \dfrac{lb}{in^3}$ Density of Beryllium

$\rho_{w} := 981.15 \dfrac{kg}{m^3}$ $\rho_{w} = 0.035 \dfrac{lb}{in^3}$ Density of water at inlet temperature

B.2: Heat Rates

ECAR-3571 calculates axial profiles for the Beryllium, water, capsule, and basket. These same axial profiles will be used for the as-run since the differences will be negligible with respect to specimen temperature. Instead just the maximum value will be input into the load within ABAQUS.

Load-1	Capsule Body	Load-4-6	CT-specimen-6.body	Load-11	spacer-bottom.body
Load-2	Basket Body	Load-4-7	CT-specimen-7.body	Load-12	spacer-top.body
Load-3-1	CT-holder.Set-1	Load-4-8	CT-specimen-8.body	Load-13-1	insulator-bottom.body
Load-3-2	CT-holder.Set-2	Load-4-9	CT-specimen-9.body	Load-13-2	insulator-top.body
Load-3-3	CT-holder.Set-3	Load-4-10	CT-specimen-10.body	Load-14-1	tensile-holder-1.body
Load-3-4	CT-holder.Set-4	Load-4-11	CT-specimen-11.body	Load-14-2	tensile-holder-2.body
Load-3-5	CT-holder.Set-5	Load-4-12	CT-specimen-12.body	Load-15-1	CT-holder.spacer-bot
Load-3-6	CT-holder.Set-6	Load-4-13	specimen-blank.body	Load-15-2	CT-holder.spacer-top
Load-3-7	CT-holder.Set-7	Load-5-1	tensile-specimen-Bot-NW.body		
Load-3-8	CT-holder.Set-8	Load-5-2	tensile-specimen-Bot-SW.body		
Load-3-9	CT-holder.Set-9	Load-5-3	tensile-specimen-Bot-SE.body		
Load-3-10	CT-holder.Set-10	Load-5-4	tensile-specimen-Bot-NE.body		
Load-3-11	CT-holder.Set-11	Load-6-1	tensile-specimen-Top-NW.body		
Load-3-12	CT-holder.Set-12	Load-6-2	tensile-specimen-Top-SW.body		
Load-3-13	CT-holder.Set-13	Load-6-3	tensile-specimen-Top-SE.body		
Load-4-1	CT-specimen-1.body	Load-6-4	tensile-specimen-Top-NE.body		
Load-4-2	CT-specimen-2.body	Load-7	reflector.body		
Load-4-3	CT-specimen-3.body	Load-8	water-inner.body		
Load-4-4	CT-specimen-4.body	Load-9	water-outer.body		
Load-4-5	CT-specimen-5.body	Load-10	water-spacer.body		

For the following heat rates for columns 1, 2, 3, and 4 represent cycles 162A, 162B, 164A, and 164B respectively.

$$q_{Load\_1} := (4.8 \quad 4.3 \quad 4.4 \quad 4.4)\frac{W}{gm}$$

$$q_{Load\_2} := (3.8 \quad 3.5 \quad 3.5 \quad 3.6)\frac{W}{gm}$$

$$q_{Load\_3\_1} := (3.4 \quad 3.2 \quad 3.1 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_2} := (3.5 \quad 3.2 \quad 3.2 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_3} := (3.6 \quad 3.2 \quad 3.3 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_4} := (3.6 \quad 3.2 \quad 3.3 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_5} := (3.6 \quad 3.3 \quad 3.3 \quad 3.4)\frac{W}{gm}$$

$$q_{Load\_3\_6} := (3.6 \quad 3.3 \quad 3.3 \quad 3.4)\frac{W}{gm}$$

$$q_{Load\_3\_7} := (3.5 \quad 3.2 \quad 3.2 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_8} := (3.5 \quad 3.3 \quad 3.2 \quad 3.4)\frac{W}{gm}$$

$$q_{Load\_3\_9} := (3.5 \quad 3.2 \quad 3.2 \quad 3.3)\frac{W}{gm}$$

$$q_{Load\_3\_10} := (3.5 \quad 3.1 \quad 3.2 \quad 3.2)\frac{W}{gm}$$

$$q_{Load\_3\_11} := (3.5 \quad 3.1 \quad 3.2 \quad 3.2)\frac{W}{gm}$$

$$q_{Load\_3\_12} := (3.3 \quad 3.0 \quad 3.1 \quad 3.1)\frac{W}{gm}$$

$$q_{Load\_3\_13} := (3.5 \quad 3.3 \quad 3.2 \quad 3.4)\frac{W}{gm}$$

$q_{Load\_4\_1} := (4.1 \quad 3.7 \quad 3.8 \quad 3.8)\dfrac{W}{gm}$

$q_{Load\_4\_2} := (4.5 \quad 4.1 \quad 4.2 \quad 4.2)\dfrac{W}{gm}$

$q_{Load\_4\_3} := (4.2 \quad 3.9 \quad 3.9 \quad 4.0)\dfrac{W}{gm}$

$q_{Load\_4\_4} := (4.5 \quad 4.1 \quad 4.2 \quad 4.2)\dfrac{W}{gm}$

$q_{Load\_4\_5} := (4.3 \quad 3.9 \quad 4.0 \quad 4.0)\dfrac{W}{gm}$

$q_{Load\_4\_6} := (4.6 \quad 4.2 \quad 4.3 \quad 4.3)\dfrac{W}{gm}$

$q_{Load\_4\_7} := (4.2 \quad 3.9 \quad 3.9 \quad 4.0)\dfrac{W}{gm}$

$q_{Load\_4\_8} := (4.6 \quad 4.1 \quad 4.3 \quad 4.2)\dfrac{W}{gm}$

$q_{Load\_4\_9} := (4.2 \quad 3.7 \quad 3.9 \quad 3.8)\dfrac{W}{gm}$

$q_{Load\_4\_10} := (4.4 \quad 4.1 \quad 4.1 \quad 4.2)\dfrac{W}{gm}$

$q_{Load\_4\_11} := (4.1 \quad 3.6 \quad 3.8 \quad 3.7)\dfrac{W}{gm}$

$q_{Load\_4\_12} := (4.2 \quad 3.8 \quad 3.9 \quad 3.9)\dfrac{W}{gm}$

$q_{Load\_4\_13} := (4.2 \quad 3.9 \quad 3.9 \quad 4.0)\dfrac{W}{gm}$

$q_{Load\_5\_1} := (4.5 \quad 3.8 \quad 4.2 \quad 3.9)\dfrac{W}{gm}$

$q_{Load\_5\_2} := (3.5 \quad 3.3 \quad 3.2 \quad 3.4)\dfrac{W}{gm}$

$$q_{Load\_5\_3} := (3.8\ \ 3.2\ \ 3.5\ \ 3.3)\frac{W}{gm}$$

$$q_{Load\_5\_4} := (4.1\ \ 4.0\ \ 3.8\ \ 4.1)\frac{W}{gm}$$

$$q_{Load\_6\_1} := (4.3\ \ 3.6\ \ 4.0\ \ 3.7)\frac{W}{gm}$$

$$q_{Load\_6\_2} := (3.3\ \ 3.2\ \ 3.1\ \ 3.3)\frac{W}{gm}$$

$$q_{Load\_6\_3} := (3.6\ \ 3.0\ \ 3.3\ \ 3.1)\frac{W}{gm}$$

$$q_{Load\_6\_4} := (4.0\ \ 3.9\ \ 3.7\ \ 4.0)\frac{W}{gm}$$

$$q_{Load\_7} := (3.5\ \ 3.2\ \ 3.2\ \ 3.3)\frac{W}{gm}$$

$$q_{Load\_8} := (6.0\ \ 5.4\ \ 5.5\ \ 5.5)\frac{W}{gm}$$

$$q_{Load\_9} := (6.0\ \ 5.4\ \ 5.5\ \ 5.5)\frac{W}{gm}$$

$$q_{Load\_10} := (6.0\ \ 5.4\ \ 5.5\ \ 5.5)\frac{W}{gm}$$

$$q_{Load\_11} := (2.0\ \ 1.7\ \ 1.8\ \ 1.7)\frac{W}{gm}$$

$$q_{Load\_12} := (1.6\ \ 1.5\ \ 1.5\ \ 1.5)\frac{W}{gm}$$

$$q_{Load\_13\_1} := (3.7\ \ 3.3\ \ 3.4\ \ 3.4)\frac{W}{gm}$$

$$q_{Load\_13\_2} := (3.5\ \ 3.1\ \ 3.2\ \ 3.2)\frac{W}{gm}$$

$$q_{Load\_14\_1} := (3.2\ \ 2.9\ \ 3.0\ \ 3.0)\frac{W}{gm}$$

$$q_{Load\_14\_2} := (3.0\ \ 2.8\ \ 2.8\ \ 2.9)\frac{W}{gm}$$

$$q_{Load\_15\_1} := (3.9 \quad 3.5 \quad 3.6 \quad 3.6)\frac{W}{gm}$$

$$q_{Load\_15\_2} := (3.8 \quad 3.5 \quad 3.5 \quad 3.6)\frac{W}{gm}$$

ABAQUS Input:

$$Q_{Load\_1} := q_{Load\_1} \cdot \rho_{SST} = (2.147E+003 \quad 1.923E+003 \quad 1.968E+003 \quad 1.968E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_2} := q_{Load\_2} \cdot \rho_{AL} = (5.737E+002 \quad 5.284E+002 \quad 5.284E+002 \quad 5.435E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_1} := q_{Load\_3\_1} \cdot \rho_{AL} = (5.133E+002 \quad 4.831E+002 \quad 4.68E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_2} := q_{Load\_3\_2} \cdot \rho_{AL} = (5.284E+002 \quad 4.831E+002 \quad 4.831E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_3} := q_{Load\_3\_3} \cdot \rho_{AL} = (5.435E+002 \quad 4.831E+002 \quad 4.982E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_4} := q_{Load\_3\_4} \cdot \rho_{AL} = (5.435E+002 \quad 4.831E+002 \quad 4.982E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_5} := q_{Load\_3\_5} \cdot \rho_{AL} = (5.435E+002 \quad 4.982E+002 \quad 4.982E+002 \quad 5.133E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_6} := q_{Load\_3\_6} \cdot \rho_{AL} = (5.435E+002 \quad 4.982E+002 \quad 4.982E+002 \quad 5.133E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_7} := q_{Load\_3\_7} \cdot \rho_{AL} = (5.284E+002 \quad 4.831E+002 \quad 4.831E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_8} := q_{Load\_3\_8} \cdot \rho_{AL} = (5.284E+002 \quad 4.982E+002 \quad 4.831E+002 \quad 5.133E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_9} := q_{Load\_3\_9} \cdot \rho_{AL} = (5.284E+002 \quad 4.831E+002 \quad 4.831E+002 \quad 4.982E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_10} := q_{Load\_3\_10} \cdot \rho_{AL} = (5.284E+002 \quad 4.68E+002 \quad 4.831E+002 \quad 4.831E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_11} := q_{Load\_3\_11} \cdot \rho_{AL} = (5.284E{+}002 \quad 4.68E{+}002 \quad 4.831E{+}002 \quad 4.831E{+}002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_12} := q_{Load\_3\_12} \cdot \rho_{AL} = (4.982E{+}002 \quad 4.529E{+}002 \quad 4.68E{+}002 \quad 4.68E{+}002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_3\_13} := q_{Load\_3\_13} \cdot \rho_{AL} = (5.284E{+}002 \quad 4.982E{+}002 \quad 4.831E{+}002 \quad 5.133E{+}002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_1} := q_{Load\_4\_1} \cdot \rho_{SST} = (1.834E{+}003 \quad 1.655E{+}003 \quad 1.7E{+}003 \quad 1.7E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_2} := q_{Load\_4\_2} \cdot \rho_{718} = (2.068E{+}003 \quad 1.884E{+}003 \quad 1.93E{+}003 \quad 1.93E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_3} := q_{Load\_4\_3} \cdot \rho_{SST} = (1.879E{+}003 \quad 1.745E{+}003 \quad 1.745E{+}003 \quad 1.789E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_4} := q_{Load\_4\_4} \cdot \rho_{718} = (2.068E{+}003 \quad 1.884E{+}003 \quad 1.93E{+}003 \quad 1.93E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_5} := q_{Load\_4\_5} \cdot \rho_{SST} = (1.923E{+}003 \quad 1.745E{+}003 \quad 1.789E{+}003 \quad 1.789E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_6} := q_{Load\_4\_6} \cdot \rho_{718} = (2.114E{+}003 \quad 1.93E{+}003 \quad 1.976E{+}003 \quad 1.976E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_7} := q_{Load\_4\_7} \cdot \rho_{SST} = (1.879E{+}003 \quad 1.745E{+}003 \quad 1.745E{+}003 \quad 1.789E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_8} := q_{Load\_4\_8} \cdot \rho_{718} = (2.114E{+}003 \quad 1.884E{+}003 \quad 1.976E{+}003 \quad 1.93E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_9} := q_{Load\_4\_9} \cdot \rho_{SST} = (1.879E{+}003 \quad 1.655E{+}003 \quad 1.745E{+}003 \quad 1.7E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_10} := q_{Load\_4\_10} \cdot \rho_{718} = (2.022E{+}003 \quad 1.884E{+}003 \quad 1.884E{+}003 \quad 1.93E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_11} := q_{Load\_4\_11} \cdot \rho_{SST} = (1.834E{+}003 \quad 1.61E{+}003 \quad 1.7E{+}003 \quad 1.655E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_12} := q_{Load\_4\_12} \cdot \rho_{718} = (1.93E{+}003 \quad 1.747E{+}003 \quad 1.793E{+}003 \quad 1.793E{+}003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_4\_13} := q_{Load\_4\_13} \cdot \rho_{SST} = (1.879E+003 \quad 1.745E+003 \quad 1.745E+003 \quad 1.789E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_5\_1} := q_{Load\_5\_1} \cdot \rho_{718} = (2.068E+003 \quad 1.747E+003 \quad 1.93E+003 \quad 1.793E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_5\_2} := q_{Load\_5\_2} \cdot \rho_{SST} = (1.566E+003 \quad 1.476E+003 \quad 1.431E+003 \quad 1.521E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_5\_3} := q_{Load\_5\_3} \cdot \rho_{718} = (1.747E+003 \quad 1.471E+003 \quad 1.609E+003 \quad 1.517E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_5\_4} := q_{Load\_5\_4} \cdot \rho_{SST} = (1.834E+003 \quad 1.789E+003 \quad 1.7E+003 \quad 1.834E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_6\_1} := q_{Load\_6\_1} \cdot \rho_{718} = (1.976E+003 \quad 1.655E+003 \quad 1.838E+003 \quad 1.701E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_6\_2} := q_{Load\_6\_2} \cdot \rho_{SST} = (1.476E+003 \quad 1.431E+003 \quad 1.387E+003 \quad 1.476E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_6\_3} := q_{Load\_6\_3} \cdot \rho_{718} = (1.655E+003 \quad 1.379E+003 \quad 1.517E+003 \quad 1.425E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_6\_4} := q_{Load\_6\_4} \cdot \rho_{SST} = (1.789E+003 \quad 1.745E+003 \quad 1.655E+003 \quad 1.789E+003) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_7} := q_{Load\_7} \cdot \rho_{Be} = (3.62E+002 \quad 3.31E+002 \quad 3.31E+002 \quad 3.414E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_8} := q_{Load\_8} \cdot \rho_{W} = (3.292E+002 \quad 2.962E+002 \quad 3.017E+002 \quad 3.017E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_9} := q_{Load\_9} \cdot \rho_{W} = (3.292E+002 \quad 2.962E+002 \quad 3.017E+002 \quad 3.017E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_10} := q_{Load\_10} \cdot \rho_{W} = (3.292E+002 \quad 2.962E+002 \quad 3.017E+002 \quad 3.017E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_11} := q_{Load\_11} \cdot \rho_{AL} = (3.019E+002 \quad 2.566E+002 \quad 2.717E+002 \quad 2.566E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_12} := q_{Load\_12} \cdot \rho_{AL} = (2.416E+002 \quad 2.265E+002 \quad 2.265E+002 \quad 2.265E+002) \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_13\_1} := q_{Load\_13\_1} \cdot \rho_{ZrO2} = \begin{pmatrix} 1.245E+003 & 1.111E+003 & 1.144E+003 & 1.144E+003 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_13\_2} := q_{Load\_13\_2} \cdot \rho_{ZrO2} = \begin{pmatrix} 1.178E+003 & 1.043E+003 & 1.077E+003 & 1.077E+003 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_14\_1} := q_{Load\_14\_1} \cdot \rho_{AL} = \begin{pmatrix} 4.831E+002 & 4.378E+002 & 4.529E+002 & 4.529E+002 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_14\_2} := q_{Load\_14\_2} \cdot \rho_{AL} = \begin{pmatrix} 4.529E+002 & 4.227E+002 & 4.227E+002 & 4.378E+002 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_15\_1} := q_{Load\_15\_1} \cdot \rho_{SST} = \begin{pmatrix} 1.745E+003 & 1.566E+003 & 1.61E+003 & 1.61E+003 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

$$Q_{Load\_15\_2} := q_{Load\_15\_2} \cdot \rho_{SST} = \begin{pmatrix} 1.7E+003 & 1.566E+003 & 1.566E+003 & 1.61E+003 \end{pmatrix} \cdot \frac{BTU}{hr \cdot in^3}$$

Appendix C

Computer Code Validation

Validation on INL Computer 603135:

```
ABQ EXE: abq6142
COMPUTER: INL603135
OS: Windows
OS TYPE: 7
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
==============================================================================
===
```