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BSU-8242 As-Run Thermal Analysis

July 2021

Cody Hale

Changing the World's Energy Future

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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1. Effective Date	07/22/2021	**Professional Engineer's Stamp** N/A *per LWP-10010, Sec 4.1, par. cc*
2. Does this ECAR involve a Safety SSC?	NO	
3. Safety SSC Determination Document ID	N/A	
4. SSC ID	N/A	
5. Project No.	32349	
6. Engineering Job (EJ) No.	N/A	
7. Building	TRA-670	
8. Site Area	ATR Complex	

9. Objective / Purpose

This Engineering Calculations and Analysis Report (ECAR) documents the calculated as-run thermal analysis using the calculated as-run heat rates. The heat rates were calculated using as-run reactor data for the average lobe powers over the given operating cycle. The heat rates were then input into the thermal models that were generated during the design phase for the experiment (See ECAR-3575 [1]). No as-built data was provided and therefore not incorporated into the models. Nominal gas gaps and dimensions were used. For gas gap sensitivities, refer to ECAR-3575 [1].

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

N/A

11. Conclusion / Recommendations

As-run heating rates calculated in ECAR-4341 [2] and ECAR-4951 [3] were input into the models created during the design of the experiment to evaluate the as-run temperatures. The models used are described in ECAR-3575 [1]. The results are shown in Section 8.2. Melt wires were used in the experiment and a comparison has been made to the calculated design and calculated as-run temperatures which can be found in Section 8.3.

CONTENTS

TABLES

FIGURES

1 PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	Cody Hale	C140	All
Checker[a]	Dan Chapman	C130	All
Independent Reviewer	N/A	N/A	N/A
CUI Reviewer[c]	Katie Anderson	C640	All
Manager[d]	Richard Howard	C140	All
Requestor[e]	Donna Guillen	B611	All
Nuclear Safety[e]	N/A	N/A	N/A
Document Owner[e]	Donna Guillen	B611	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

This Engineering Calculations and Analysis Report (ECAR) documents the calculated as-run thermal analysis using the calculated as-run heat rates. The heat rates were calculated using as-run reactor data for the average lobe powers over the given operating cycle. The heat rates were then input into the thermal models that were generated during the design phase for the experiment (See ECAR-3575 [1]). No as-built data was provided and therefore not incorporated into the models. Nominal gas gaps and dimensions were used. For gas gap sensitivities, refer to ECAR-3575 [1].

3 EXPERIMENT OVERVIEW

The objective of this experiment is to assess the viability of using alloys manufactured by powder metallurgy and hot isostatic pressing (PM-HIP) as nuclear reactor internals, to enhance the weldability and inspectability of these components. The superior properties of PM-HIP alloys make them potential candidates for structural materials in nuclear reactor technologies, including light water reactors (LWRs), advanced light water reactors (ALWRs), small modular reactors (SMRs), and advanced (e.g. Generation IV) reactor designs. However, little is known about the irradiation response of PM-HIP alloys, particularly in comparison to that of conventionally manufactured alloys. The purpose of this experiment is to test and understand the irradiation effect on PM-HIP alloys.

To test these alloys, the experiment sponsor has provided INL with three different types of specimens. The first type of specimen is a round “dog bone” shaped tensile specimen with an overall length of 3 in. and a gauge diameter of 0.25 in. The second specimen type is a Compact Tensile (CT) specimen which is cube shaped with the dimension of 0.394 in. X 0.378 in. X 0.157 in. The third type of specimen is a round Transmission Electron Microscope (TEM) disk with a diameter of 0.118 in. All the TEM’s have a thickness of 0.006 in. except for the hafnium-aluminum materials which have a thickness of 0.012 in (twice as thick as the other TEM materials).

In order to house the desired quantity of materials, some of the specimens had to be distributed between two capsules with the same desired irradiation condition. The specimens that have been split into two capsules are the 300°C 1 dpa specimens, 400°C 1 dpa specimens, and the 400°C 3 dpa specimens. This brings the total number of capsules to seven. However, the 300°C and 400°C 1 dpa capsules are combined into two experiment assemblies for a total of five assemblies. To distinguish between the two capsules of the same type, an “X” or “Y” designator has been assigned to them. For the remainder of this ECAR the seven capsules will be referred to as 300C 1 dpa X, 300C 1 dpa Y, 400C 1 dpa X, 400C 1 dpa Y, 400C 3 dpa X, 400C 3 dpa Y, and 300C 3 dpa. The five experiment assemblies will be referred to as 400C/300C 1 dpa X, 400C/300C 1 dpa Y, 400C 3 dpa X, 400C 3 dpa Y, and 300C 3 dpa.

4 DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

The models used in this analysis were developed during the design phase of this experiment. Information regarding those models can be found in ECAR-3575 [1]. Two different ECAR’s were created to document the heating rates; one for the 1 dpa capsules which is ECAR-4341 [2], and one for the 3 dpa capsules which is ECAR-4951 [3].

5 RESULTS OF LITERATURE SEARCHES AND OTHER BACKGROUND DATA

The drawings used in these analyses are referenced below in Table 1.

Table 5-1. Drawing List

Drawing Number	Rev.	Description
602380	1	UTAH STATE UNIVERSITY SPECIMEN DETAILS
605765	2	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE COMPONENT ASSEMBLIES AND DETAILS
605766	0	ATR NSUF BOISE EXPERIMENT 8242 300C-1 DPA X INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605767	1	ATR NSUF BOISE EXPERIMENT 8242 300C-1 DPA Y INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605768	1	ATR NSUF BOISE EXPERIMENT 8242 300C-3 DPA INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605769	1	ATR NSUF BOISE EXPERIMENT 8242 400C-1 DPA X INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605770	0	ATR NSUF BOISE EXPERIMENT 8242 400C-1 DPA Y INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605771	2	ATR NSUF BOISE EXPERIMENT 8242 400C-3 DPA X INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605772	1	ATR NSUF BOISE EXPERIMENT 8242 400C-3 DPA Y INBOARD A CAPSULE CT AND TEM SPECIMEN ASSEMBLY
605773	1	ATR BSU-8242 Experiment Inboard A Capsule Drawing Tree
605774	2	ATR NSUF BOISE EXPERIMENT 8242 SPECIMEN ASSEMBLY AND DETAILS
605775	0	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE TENSILE SPECIMEN ASSEMBLIES
605776	0	ATR NSUF BOISE EXPERIMENT 8242 300C-1 DPA X INBOARD A CAPSULE ASSEMBLY
605777	0	ATR NSUF BOISE EXPERIMENT 8242 300C-3 DPA INBOARD A CAPSULE ASSEMBLY
605778	0	ATR NSUF BOISE EXPERIMENT 8242 300C-1 DPA Y INBOARD A CAPSULE ASSEMBLY
605779	1	ATR NSUF BOISE EXPERIMENT 8242 400C-1 DPA X INBOARD A CAPSULE ASSEMBLY
605780	0	ATR NSUF BOISE EXPERIMENT 8242 400C-1 DPA Y INBOARD A CAPSULE ASSEMBLY
605781	0	ATR NSUF BOISE EXPERIMENT 8242 400C-3 DPA Y INBOARD A CAPSULE ASSEMBLY
605782	1	ATR NSUF BOISE EXPERIMENT 8242 400C-3 DPA X INBOARD A CAPSULE ASSEMBLY
605824	1	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE 300C-1 DPA X AND 400C-1 DPA X TEST TRAIN ASSEMBLY
605825	1	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE 300C-1 DPA Y AND 400C-1 DPA Y TEST TRAIN ASSEMBLY

Drawing Number	Rev.	Description
605826	2	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE 300C-3 DPA TEST TRAIN ASSEMBLY
605827	2	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE 400C-3 DPA X TEST TRAIN ASSEMBLY
605828	1	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE 400C-3 DPA Y TEST TRAIN ASSEMBLY
605829	0	ATR NSUF BOISE EXPERIMENT 8242 INBOARD A CAPSULE TEST TRAIN INSTALLATION

6 ASSUMPTIONS

1. All dimensions are based on nominal drawing values.
2. Heat rates input into the models are the calculated average heat rates for the given cycle.

7 COMPUTER CODE VALIDATION

A finite element heat transfer analysis of the BSU-8242 experiment was performed using ABAQUS version 6.14-2 on a SGI ICE X distributed memory cluster with 972 compute nodes (“falcon” on the INL network). The operating system is SUSE Linux Enterprise Server 12 Service Pack 4, and each compute node has two 18-core 2.10 GHz Intel Xeon processors. ABAQUS has been validated for thermal analysis 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. Scripts were developed to automate the execution, data collection, and relative error calculation for each test problem. The scripts were run on computer “falcon” and a report file containing the results of validation testing was automatically generated (Appendix C). The test results meet the acceptance criterion that the relative error is less than 3%. Formal validation of Mathcad 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.

8 DISCUSSION/ANALYSIS

8.1 Modeling Information

For modeling information refer to ECAR-3575 [1]. The only difference is the heating rates input into the models which are shown in Appendix B.

8.2 Analysis Results

The following results are provided for each capsule in its respective section. The results are provided graphically to give an overall view of the specimen temperatures and how they compare to the target temperature. However, some of the capsules have a large number of specimens making it difficult to see what the temperatures are for a given specimen; therefore, they have also been provided in a table form. The maximum temperature refers to the maximum nodal temperature using the cycle-average heat rate. The average temperature refers to the volume weighted average temperature using the cycle-average heat rate. The maximum and average temperature for the tensile bars is taken in the gauge section only.

8.2.1 300C 1 DPA X Results

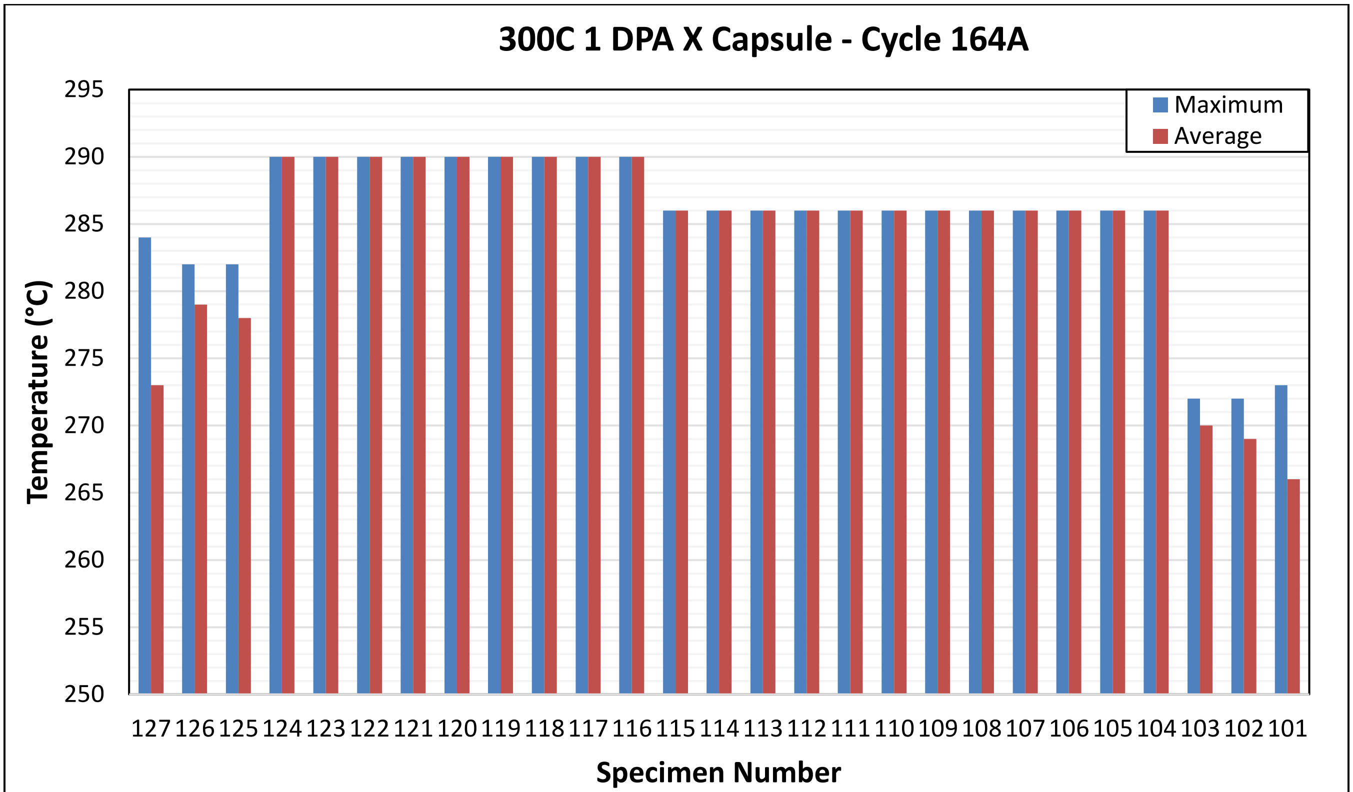

Figure 8-1: Specimen Temperatures for Capsule 300C 1 DPA X in Cycle 164A

Table 8-1: Specimen Temperatures for Capsule 300C 1 DPA X in Cycle 164A

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
RT-SA508 PM-HIP	127	284	273
CT-SA508 Forged	126	282	279
CT-SA508 PM-HIP	125	282	278
TEM-USU-300-1-20	124	290	290
TEM-USU-300-1-20	123	290	290
TEM-USU-300-1-20	122	290	290
TEM-USU-300-1-28	121	290	290

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
TEM-USU-300-1-28	120	290	290
TEM-USU-300-1-28	119	290	290
TEM-USU-300-1-36	118	290	290
TEM-USU-300-1-36	117	290	290
TEM-USU-300-1-36	116	290	290
TEM-SA508 Forged	115	286	286
TEM-SA508 Forged	114	286	286
TEM-SA508 Forged	113	286	286
TEM-SA508 Forged	112	286	286
TEM-SA508 Forged	111	286	286
TEM-SA508 Forged	110	286	286
TEM-SA508 PM-HIP	109	286	286
TEM-SA508 PM-HIP	108	286	286
TEM-SA508 PM-HIP	107	286	286
TEM-SA508 PM-HIP	106	286	286
TEM-SA508 PM-HIP	105	286	286
TEM-SA508 PM-HIP	104	286	286
CT-SA508 PM-HIP	103	272	270
CT-SA508 PM-HIP	102	272	269
RT-SA508 PM-HIP	101	273	266

8.2.2 300C 1 DPA Y Results

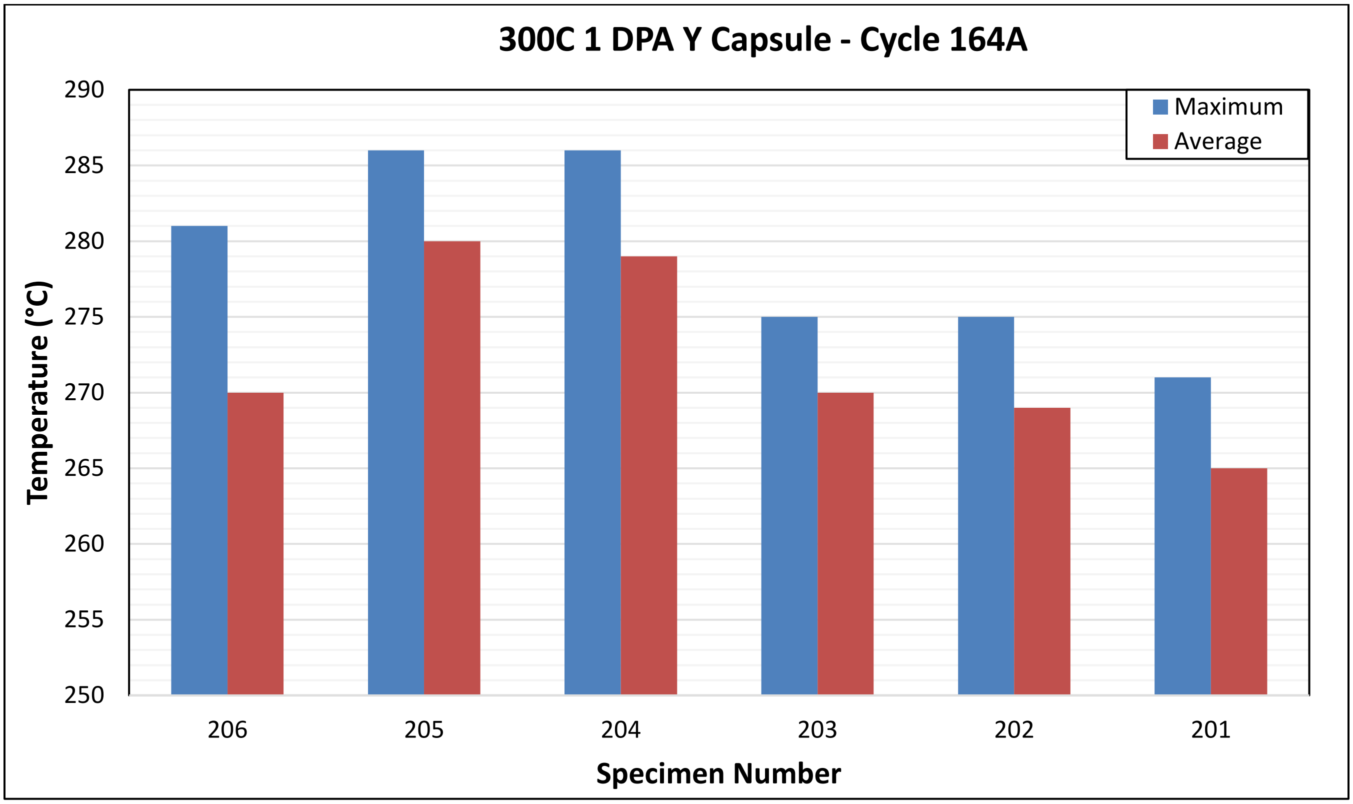

Figure 8-2: Specimen Temperatures for Capsule 300C 1 DPA Y in Cycle 164A

Table 8-2: Specimen Temperatures for Capsule 300C 1 DPA Y in Cycle 164A

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
RT-SA508 Forged	206	281	270
CT-316L Cast	205	286	280
CT-316L Cast	204	286	279
CT-316L PM-HIP	203	275	270
CT-316L PM-HIP	202	275	269
RT-SA508 Forged	201	271	265

8.2.3 300C 3 DPA Results

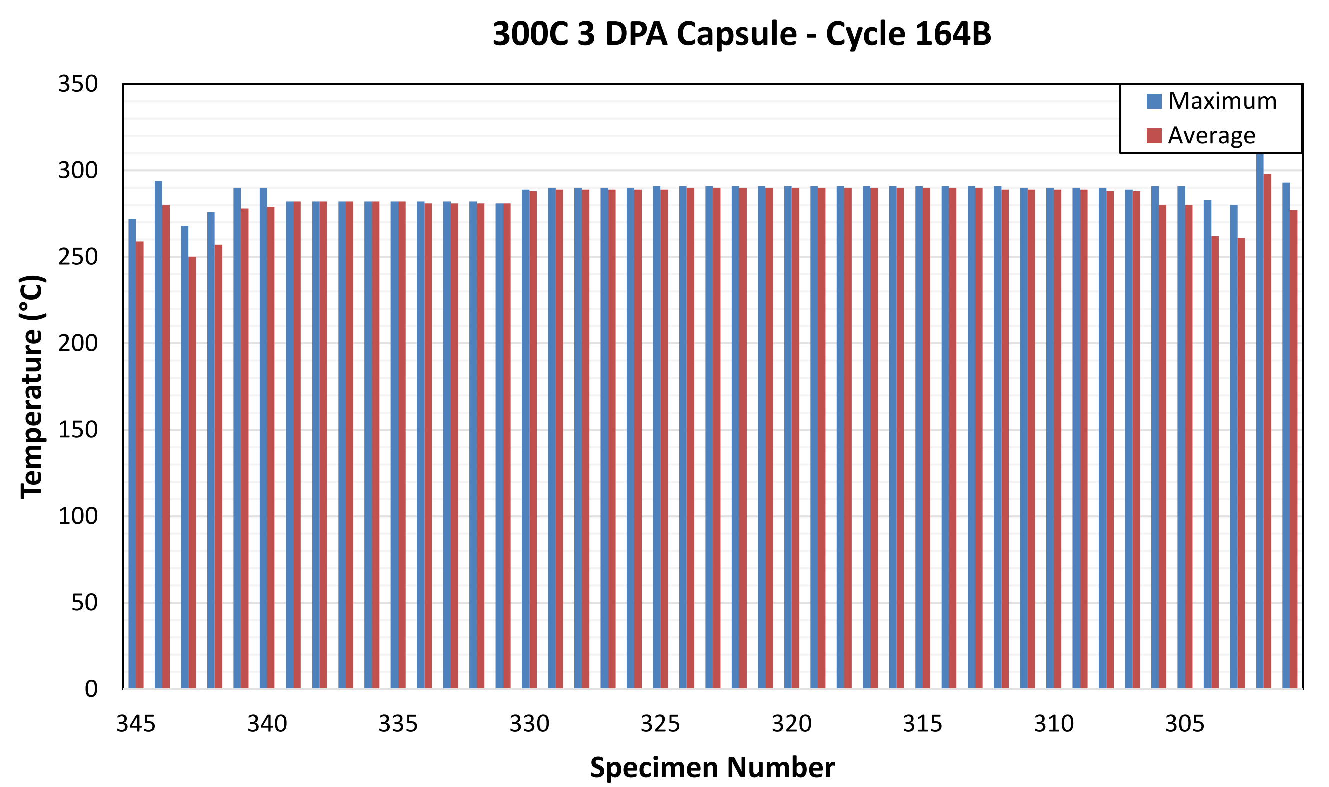

Figure 8-3: Specimen Temperatures for Capsule 300C 3 DPA in Cycle 164B

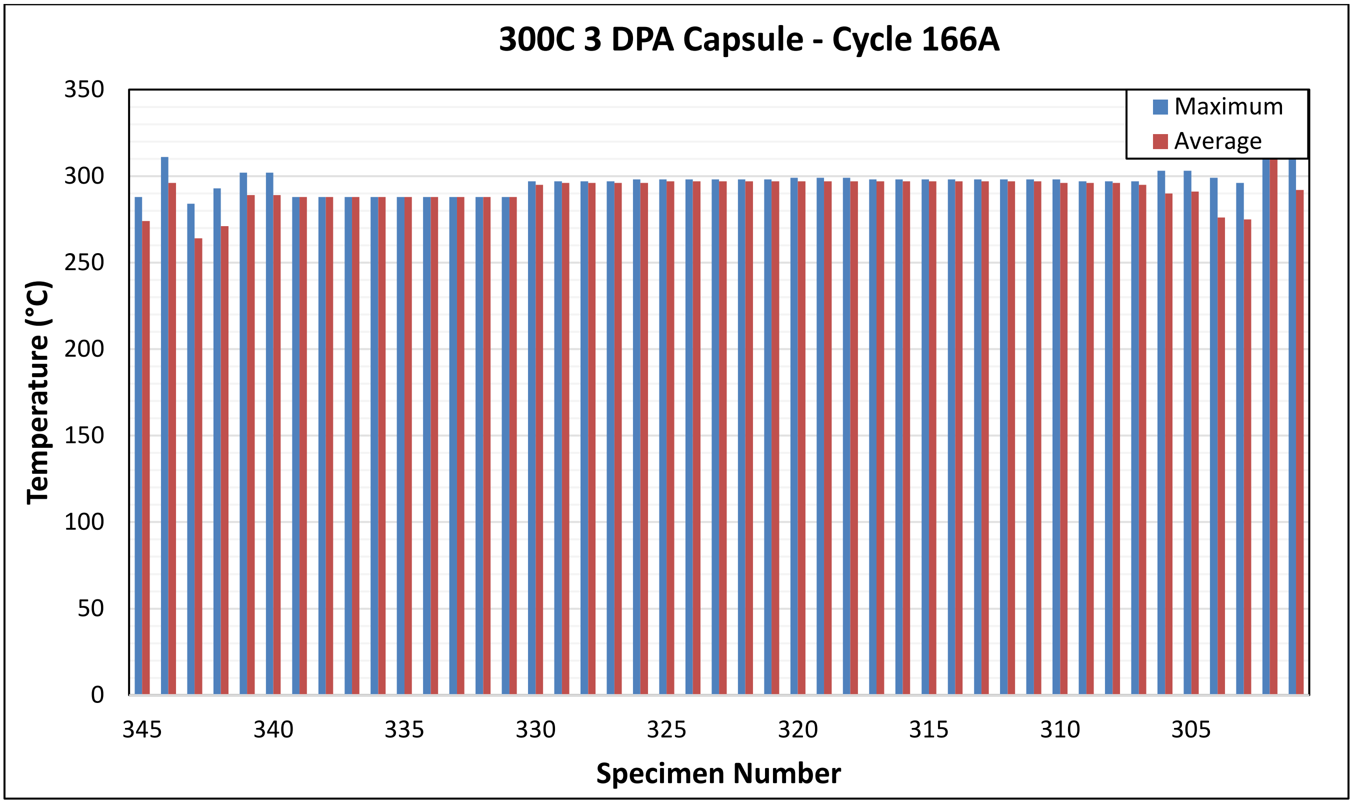

Figure 8-4: Specimen Temperatures for Capsule 300C 3 DPA in Cycle 166A

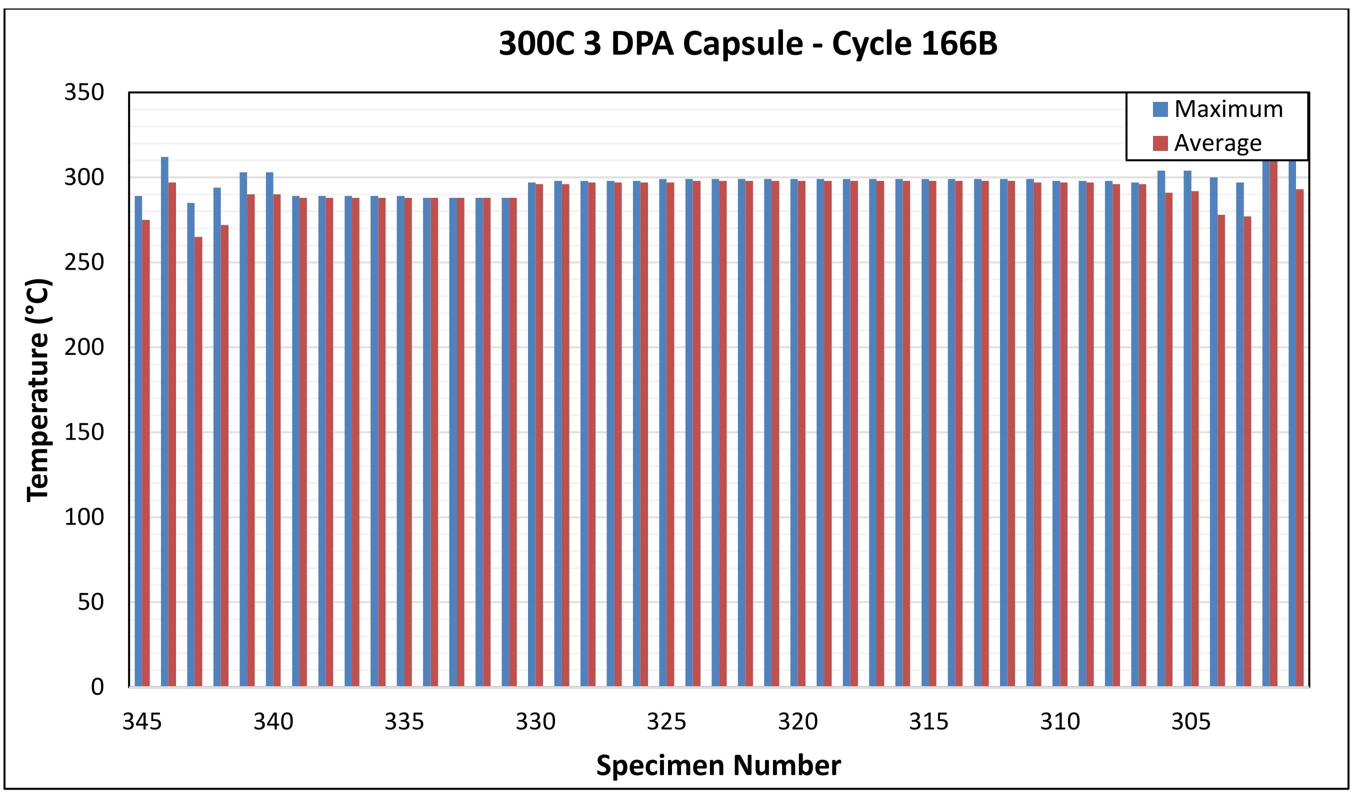

Figure 8-5: Specimen Temperatures for Capsule 300C 3 DPA in Cycle 166B

Table 8-3: Specimen Temperatures for Capsule 300C 3 DPA in Cycles 164B, 166A, and 166B

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
RT-690 PM-HIP	345	272	259	288	274	289	275
RT-690 PM-HIP	344	294	280	311	296	312	297
RT-625 PM-HIP	343	268	250	284	264	285	265
RT-625 PM-HIP	342	276	257	293	271	294	272
CT-625 PM-HIP	341	290	278	302	289	303	290
CT-625 PM-HIP	340	290	279	302	289	303	290
TEM-USU-300-3-20	339	282	282	288	288	289	288
TEM-USU-300-3-20	338	282	282	288	288	289	288
TEM-USU-300-3-20	337	282	282	288	288	289	288
TEM-USU-300-3-28	336	282	282	288	288	289	288
TEM-USU-300-3-28	335	282	282	288	288	289	288
TEM-USU-300-3-28	334	282	281	288	288	288	288
TEM-USU-300-3-36	333	282	281	288	288	288	288
TEM-USU-300-3-36	332	282	281	288	288	288	288
TEM-USU-300-3-36	331	281	281	288	288	288	288
TEM-690 Forged	330	289	288	297	295	297	296
TEM-690 Forged	329	290	289	297	296	298	296
TEM-690 Forged	328	290	289	297	296	298	297
TEM-690 Forged	327	290	289	297	296	298	297
TEM-690 Forged	326	290	289	298	296	298	297
TEM-690 Forged	325	291	289	298	297	299	297
TEM-625 Forged	324	291	290	298	297	299	298
TEM-625 Forged	323	291	290	298	297	299	298
TEM-625 Forged	322	291	290	298	297	299	298
TEM-625 Forged	321	291	290	298	297	299	298
TEM-625 Forged	320	291	290	299	297	299	298
TEM-625 Forged	319	291	290	299	297	299	298
TEM-690 PM-HIP	318	291	290	299	297	299	298
TEM-690 PM-HIP	317	291	290	298	297	299	298
TEM-690 PM-HIP	316	291	290	298	297	299	298
TEM-690 PM-HIP	315	291	290	298	297	299	298
TEM-690 PM-HIP	314	291	290	298	297	299	298
TEM-690 PM-HIP	313	291	290	298	297	299	298
TEM-625 PM-HIP	312	291	289	298	297	299	298
TEM-625 PM-HIP	311	290	289	298	297	299	297
TEM-625 PM-HIP	310	290	289	298	296	298	297

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
TEM-625 PM-HIP	309	290	289	297	296	298	297
TEM-625 PM-HIP	308	290	288	297	296	298	296
TEM-625 PM-HIP	307	289	288	297	295	297	296
CT-625 Cast	306	291	280	303	290	304	291
CT-625 Cast	305	291	280	303	291	304	292
RT-625 Forged	304	283	262	299	276	300	278
RT-625 Forged	303	280	261	296	275	297	277
RT-690 Forged	302	312	298	329	315	331	316
RT-690 Forged	301	293	277	310	292	311	293

8.2.4 400C 1 DPA X Results

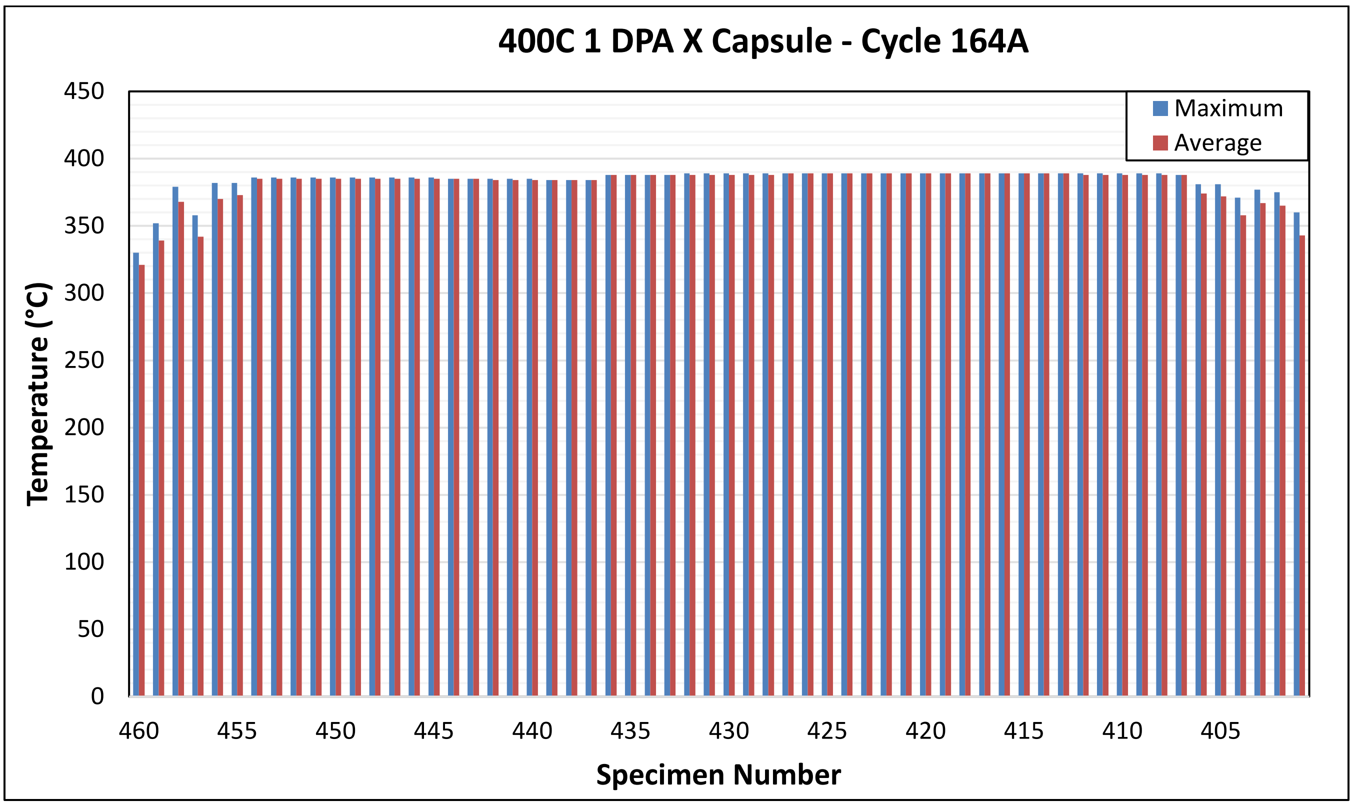

Figure 8-6: Specimen Temperatures for Capsule 400C 1 DPA X in Cycle 164A

Table 8-4: Specimen Temperatures for Capsule 400C 1 DPA X in Cycle 164A

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
RT-625 PM-HIP	460	330	321
RT-625 PM-HIP	459	352	339
RT-690 PM-HIP	458	379	368
RT-690 PM-HIP	457	358	342
CT-625 PM-HIP	456	382	370
CT-625 Cast	455	382	373
TEM-625 PM-HIP	454	386	385
TEM-625 PM-HIP	453	386	385
TEM-625 PM-HIP	452	386	385
TEM-625 PM-HIP	451	386	385
TEM-625 PM-HIP	450	386	385
TEM-625 PM-HIP	449	386	385
TEM-625 Forged	448	386	385
TEM-625 Forged	447	386	385
TEM-625 Forged	446	386	385
TEM-625 Forged	445	386	385
TEM-625 Forged	444	385	385
TEM-625 Forged	443	385	385
TEM-SA508 Forged	442	385	384
TEM-SA508 Forged	441	385	384
TEM-SA508 Forged	440	385	384
TEM-SA508 Forged	439	384	384
TEM-SA508 Forged	438	384	384
TEM-SA508 Forged	437	384	384
TEM-SA508 PM-HIP	436	388	388
TEM-SA508 PM-HIP	435	388	388
TEM-SA508 PM-HIP	434	388	388
TEM-SA508 PM-HIP	433	388	388
TEM-SA508 PM-HIP	432	389	388

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
TEM-SA508 PM-HIP	431	389	388
TEM-91 Cast	430	389	388
TEM-91 Cast	429	389	388
TEM-91 Cast	428	389	388
TEM-91 Cast	427	389	389
TEM-91 Cast	426	389	389
TEM-91 Cast	425	389	389
TEM-91 PM-HIP	424	389	389
TEM-91 PM-HIP	423	389	389
TEM-91 PM-HIP	422	389	389
TEM-91 PM-HIP	421	389	389
TEM-91 PM-HIP	420	389	389
TEM-91 PM-HIP	419	389	389
TEM-690 Forged	418	389	389
TEM-690 Forged	417	389	389
TEM-690 Forged	416	389	389
TEM-690 Forged	415	389	389
TEM-690 Forged	414	389	389
TEM-690 Forged	413	389	389
TEM-690 PM-HIP	412	389	388
TEM-690 PM-HIP	411	389	388
TEM-690 PM-HIP	410	389	388
TEM-690 PM-HIP	409	389	388
TEM-690 PM-HIP	408	389	388
TEM-690 PM-HIP	407	388	388
CT-690 PM-HIP	406	381	374
CT-690 PM-HIP	405	381	372
RT-91 PM-HIP	404	371	358
RT-91 PM-HIP	403	377	367
RT-SA508 PM-HIP	402	375	365
RT-SA508 PM-HIP	401	360	343

8.2.5 400C 1 DPA Y Results

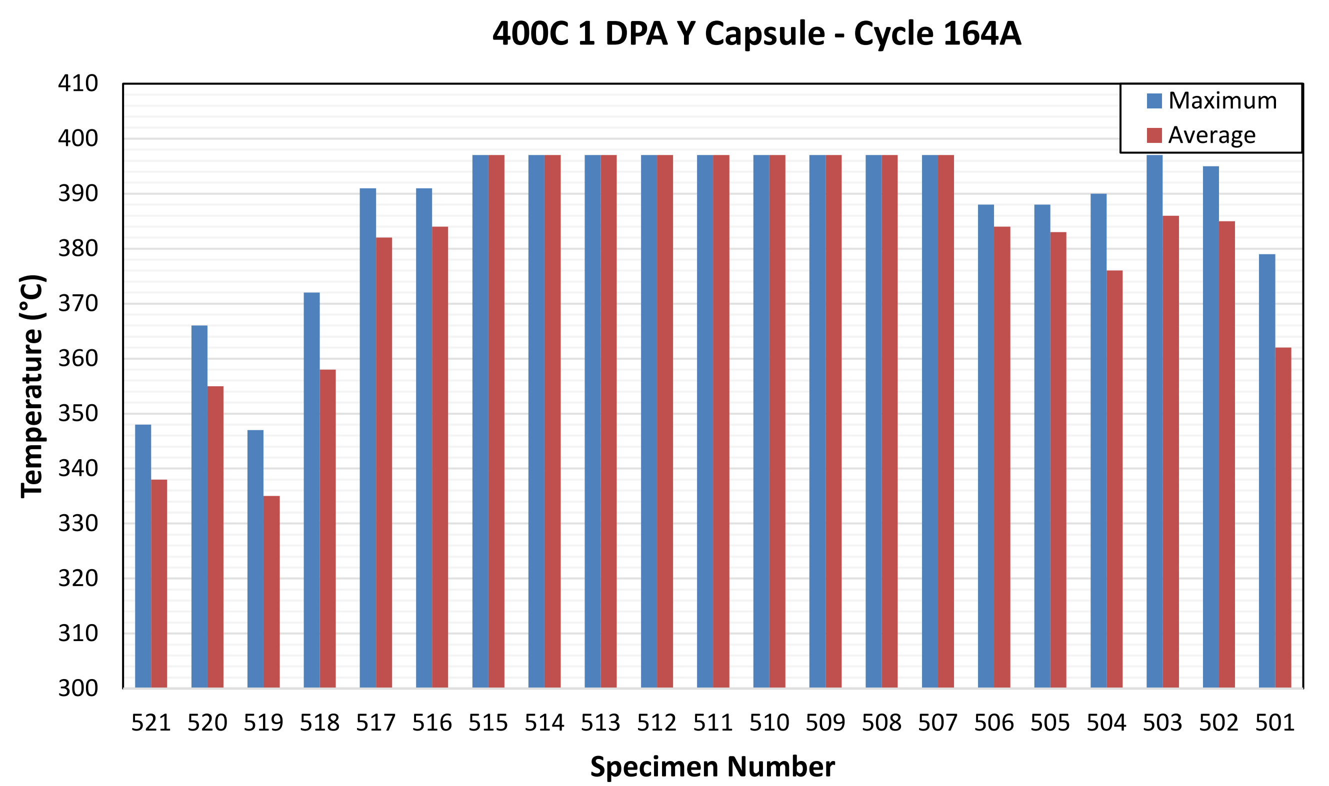

Figure 8-7: Specimen Temperatures for Capsule 400C 1 DPA Y in Cycle 164A

Table 8-5: Specimen Temperatures for Capsule 400C 1 DPA Y in Cycle 164A

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
RT-625 Forged	521	348	338
RT-625 Forged	520	366	355
RT-690 Forged	519	347	335
RT-690 Forged	518	372	358
CT-690 Forged	517	391	382
CT-690 Forged	516	391	384
TEM-USU-400-1-20	515	397	397
TEM-USU-400-1-20	514	397	397
TEM-USU-400-1-20	513	397	397
TEM-USU-400-1-28	512	397	397

Specimen/Material	Specimen Number	Cycle 164A Temperature [°C]	
		Max	Avg
TEM-USU-400-1-28	511	397	397
TEM-USU-400-1-28	510	397	397
TEM-USU-400-1-36	509	397	397
TEM-USU-400-1-36	508	397	397
TEM-USU-400-1-36	507	397	397
CT-91 PM-HIP	506	388	384
CT-91 PM-HIP	505	388	383
RT-91 Cast	504	390	376
RT-91 Cast	503	397	386
RT-SA508 Forged	502	395	385
RT-SA508 Forged	501	379	362

8.2.6 400C 3 DPA X Results

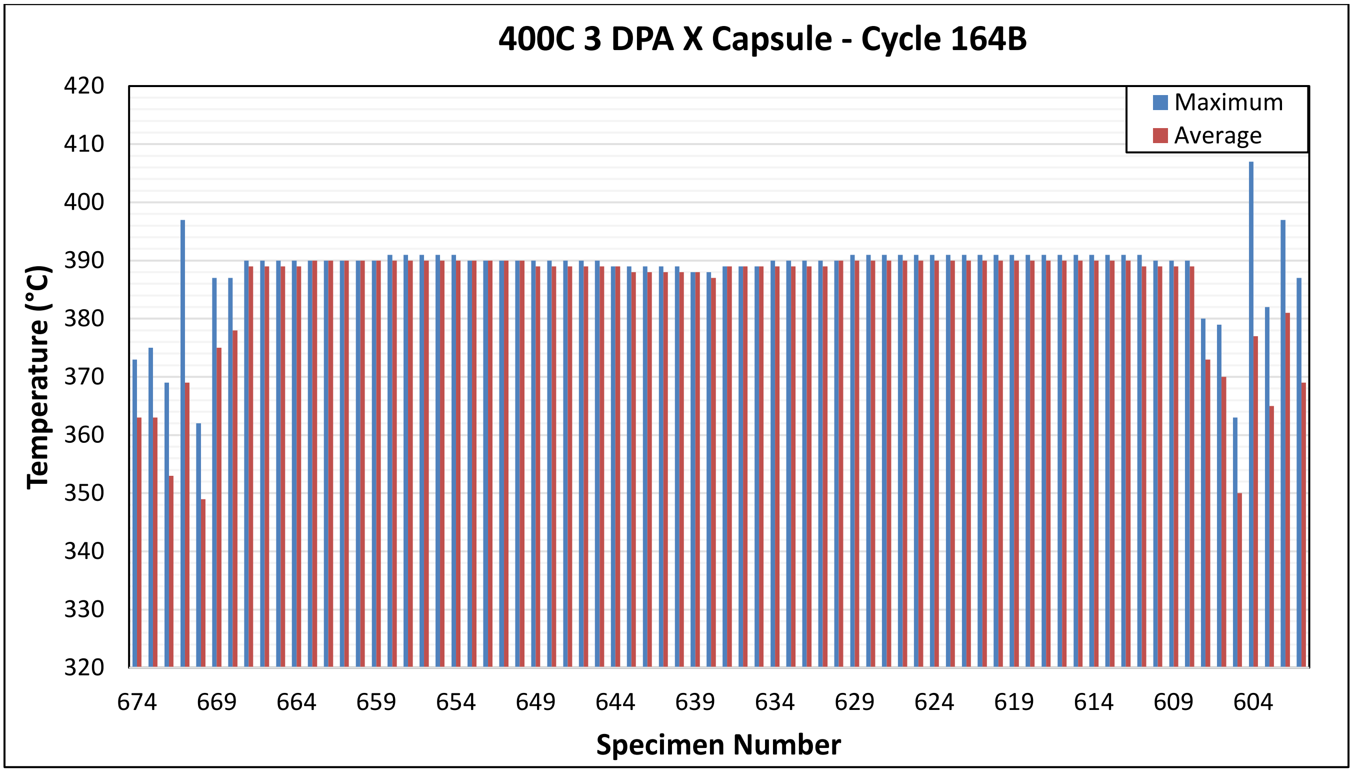

Figure 8-8: Specimen Temperatures for Capsule 400C 3 DPA X in Cycle 164B

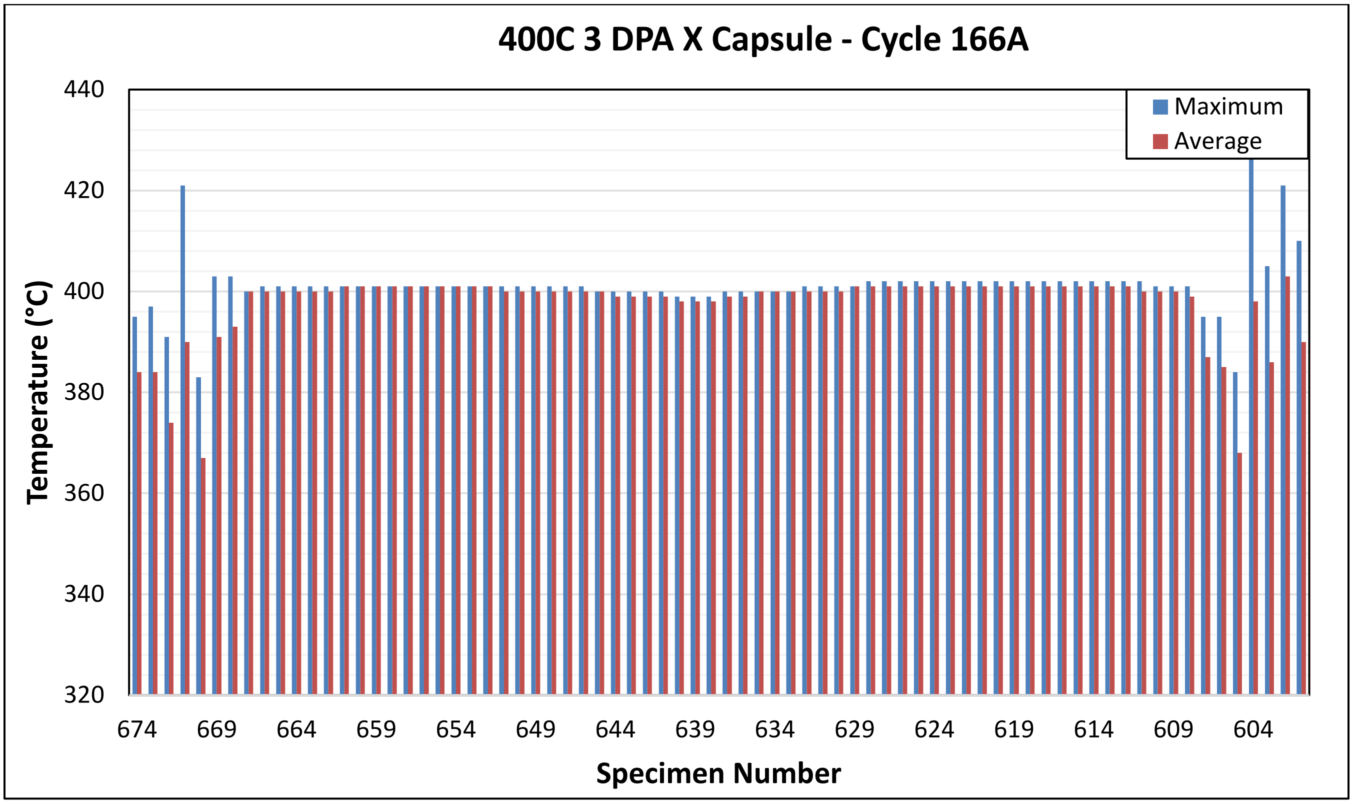

Figure 8-9: Specimen Temperatures for Capsule 400C 3 DPA X in Cycle 166A

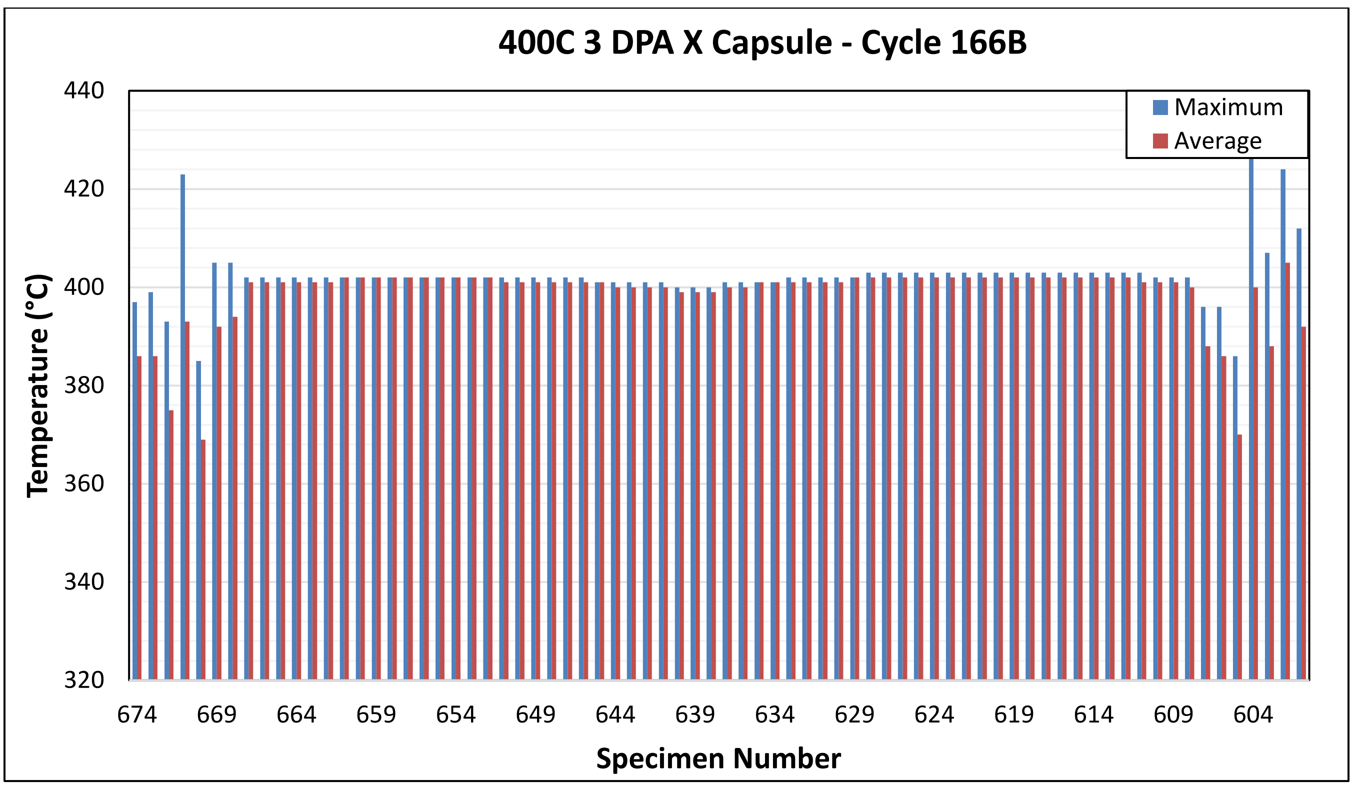

Figure 8-10: Specimen Temperatures for Capsule 400C 3 DPA X in Cycle 166B

Table 8-6: Specimen Temperatures for Capsule 400C 3 DPA X in Cycles 164B, 166A, and 166B

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
RT-690 PM-HIP	674	373	363	395	384	397	386
RT-690 PM-HIP	673	375	363	397	384	399	386
RT-625 PM-HIP	672	369	353	391	374	393	375
RT-625 PM-HIP	671	397	369	421	390	423	393
RT-91 PM-HIP	670	362	349	383	367	385	369
CT-625 PM-HIP	669	387	375	403	391	405	392
CT-625 Cast	668	387	378	403	393	405	394
TEM-91 Cast	667	390	389	400	400	402	401
TEM-91 Cast	666	390	389	401	400	402	401
TEM-91 Cast	665	390	389	401	400	402	401
TEM-91 Cast	664	390	389	401	400	402	401
TEM-91 Cast	663	390	390	401	400	402	401
TEM-91 Cast	662	390	390	401	400	402	401
TEM-304L Forged	661	390	390	401	401	402	402
TEM-304L Forged	660	390	390	401	401	402	402
TEM-304L Forged	659	390	390	401	401	402	402
TEM-304L Forged	658	391	390	401	401	402	402
TEM-304L Forged	657	391	390	401	401	402	402
TEM-304L Forged	656	391	390	401	401	402	402
TEM-304L Forged	655	391	390	401	401	402	402
TEM-304L Forged	654	391	390	401	401	402	402
TEM-304L Forged	653	390	390	401	401	402	402
TEM-304L Forged	652	390	390	401	401	402	402
TEM-304L Forged	651	390	390	401	400	402	401
TEM-304L Forged	650	390	390	401	400	402	401
TEM-316L PM-HIP	649	390	389	401	400	402	401
TEM-316L PM-HIP	648	390	389	401	400	402	401
TEM-316L PM-HIP	647	390	389	401	400	402	401
TEM-316L PM-HIP	646	390	389	401	400	402	401
TEM-316L PM-HIP	645	390	389	400	400	401	401
TEM-316L PM-HIP	644	389	389	400	399	401	400
TEM-316L Forged	643	389	388	400	399	401	400
TEM-316L Forged	642	389	388	400	399	401	400
TEM-316L Forged	641	389	388	400	399	401	400
TEM-316L Forged	640	389	388	399	398	400	399
TEM-316L Forged	639	388	388	399	398	400	399

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
TEM-316L Forged	638	388	387	399	398	400	399
TEM-91 PM-HIP	637	389	389	400	399	401	400
TEM-91 PM-HIP	636	389	389	400	399	401	400
TEM-91 PM-HIP	635	389	389	400	400	401	401
TEM-91 PM-HIP	634	390	389	400	400	401	401
TEM-91 PM-HIP	633	390	389	400	400	402	401
TEM-91 PM-HIP	632	390	389	401	400	402	401
TEM-690 Forged	631	390	389	401	400	402	401
TEM-690 Forged	630	390	390	401	400	402	401
TEM-690 Forged	629	391	390	401	401	402	402
TEM-690 Forged	628	391	390	402	401	403	402
TEM-690 Forged	627	391	390	402	401	403	402
TEM-690 Forged	626	391	390	402	401	403	402
TEM-690 PM-HIP	625	391	390	402	401	403	402
TEM-690 PM-HIP	624	391	390	402	401	403	402
TEM-690 PM-HIP	623	391	390	402	401	403	402
TEM-690 PM-HIP	622	391	390	402	401	403	402
TEM-690 PM-HIP	621	391	390	402	401	403	402
TEM-690 PM-HIP	620	391	390	402	401	403	402
TEM-625 Forged	619	391	390	402	401	403	402
TEM-625 Forged	618	391	390	402	401	403	402
TEM-625 Forged	617	391	390	402	401	403	402
TEM-625 Forged	616	391	390	402	401	403	402
TEM-625 Forged	615	391	390	402	401	403	402
TEM-625 Forged	614	391	390	402	401	403	402
TEM-625 PM-HIP	613	391	390	402	401	403	402
TEM-625 PM-HIP	612	391	390	402	401	403	402
TEM-625 PM-HIP	611	391	389	402	400	403	401
TEM-625 PM-HIP	610	390	389	401	400	402	401
TEM-625 PM-HIP	609	390	389	401	400	402	401
TEM-625 PM-HIP	608	390	389	401	399	402	400
CT-690 PM-HIP	607	380	373	395	387	396	388
CT-690 PM-HIP	606	379	370	395	385	396	386
RT-91 Cast	605	363	350	384	368	386	370
RT-625 Forged	604	407	377	431	398	434	400
RT-625 Forged	603	382	365	405	386	407	388
RT-690 Forged	602	387	370	411	392	413	394

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
RT-690 Forged	601	376	358	400	380	402	382

8.2.7 400C 3 DPA Y Results

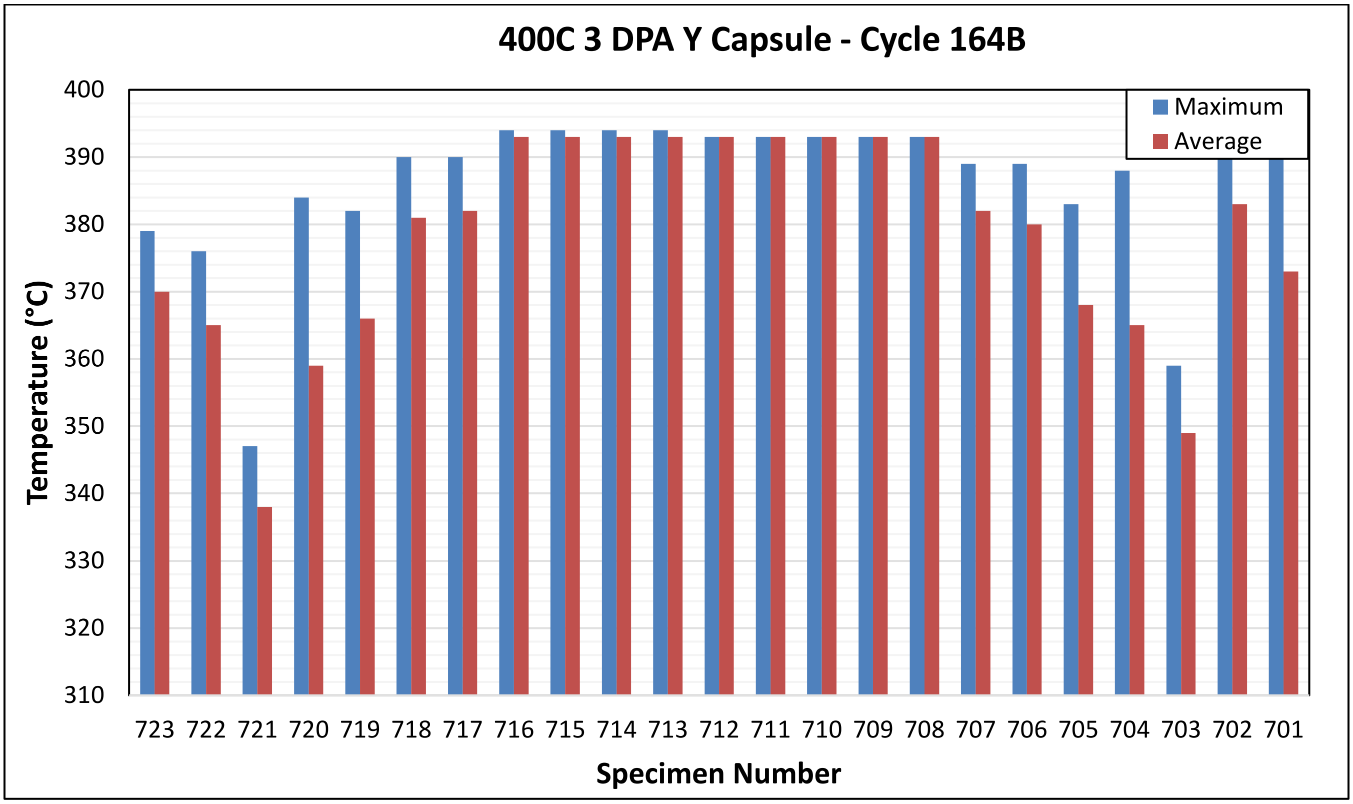

Figure 8-11: Specimen Temperatures for Capsule 400C 3 DPA Y in Cycle 164B

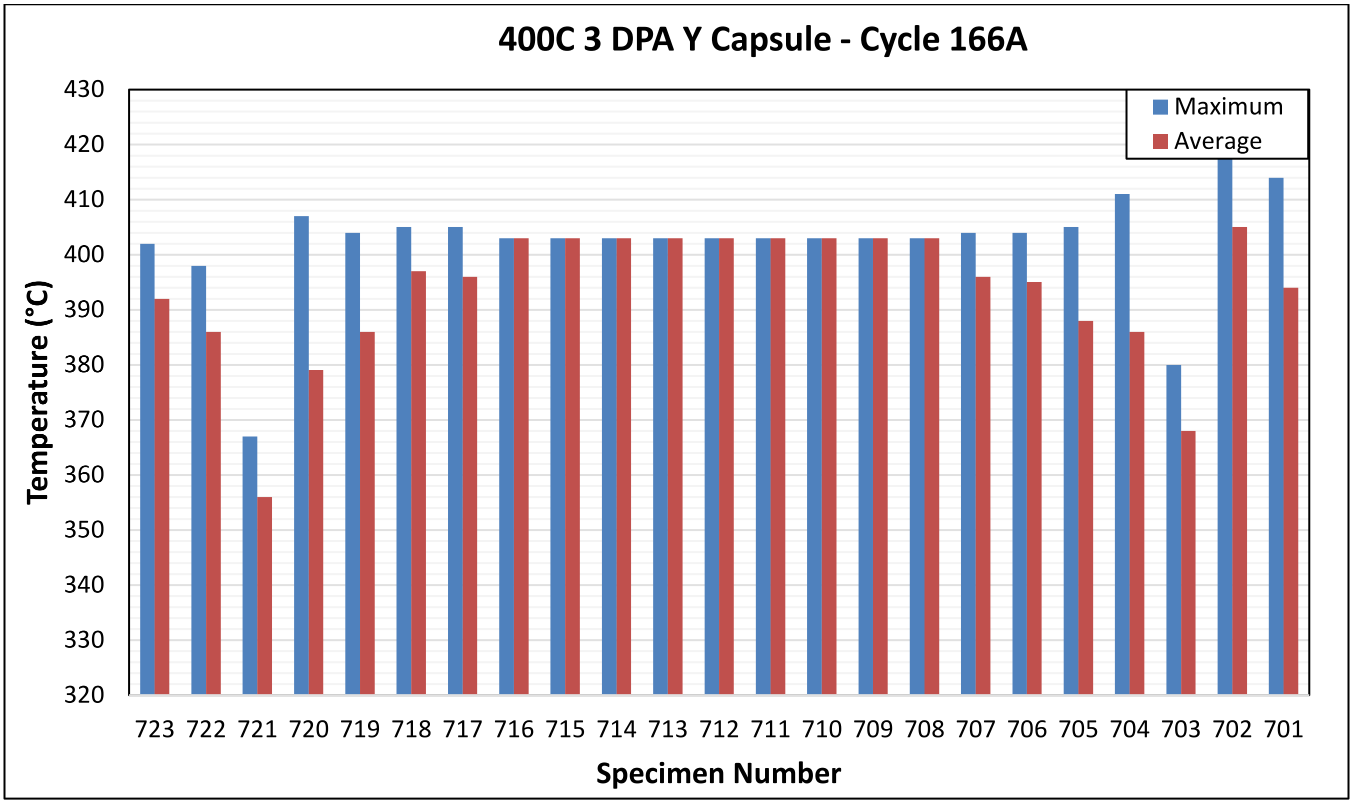

Figure 8-12: Specimen Temperatures for Capsule 400C 3 DPA Y in Cycle 166A

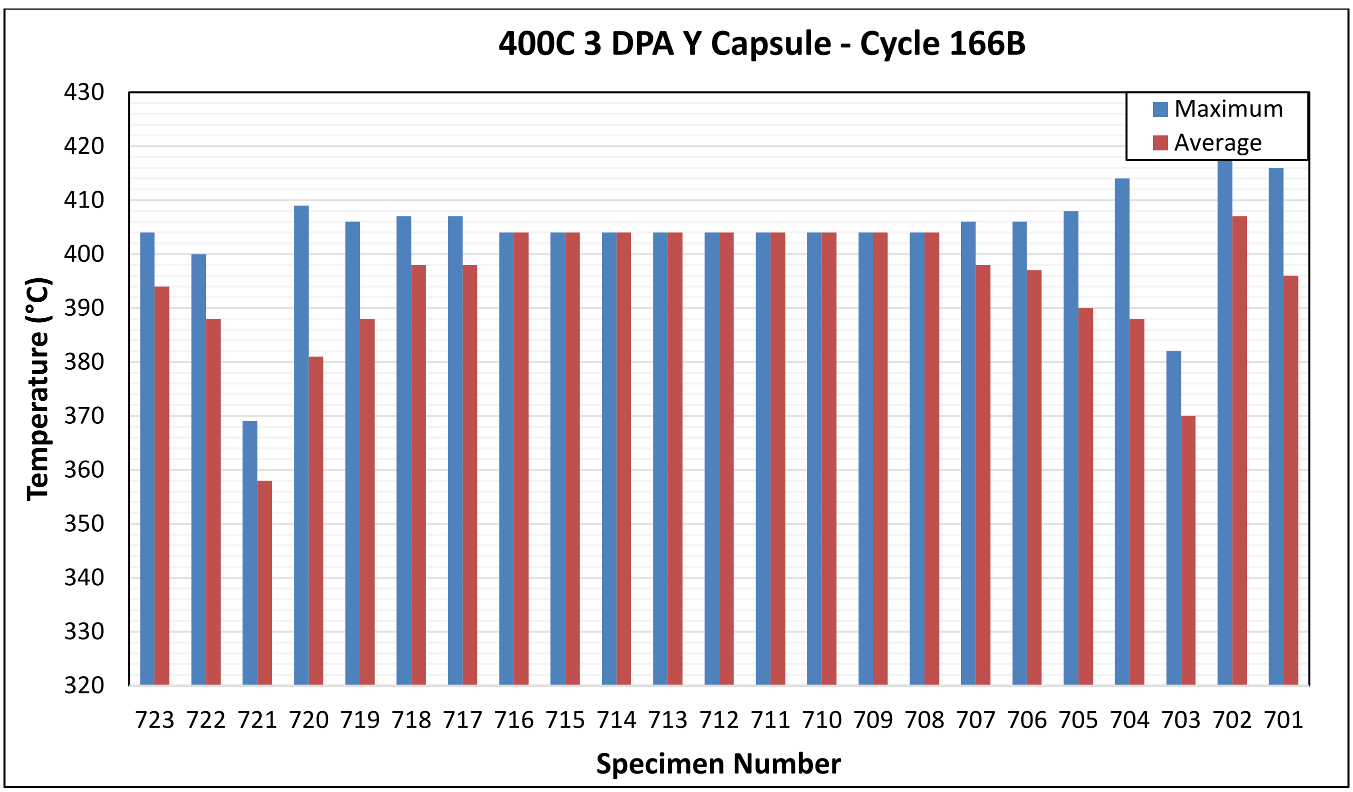

Figure 8-13: Specimen Temperatures for Capsule 400C 3 DPA Y in Cycle 166B

Table 8-7: Specimen Temperatures for Capsule 400C 3 DPA Y in Cycle 164B, 166A, and 166B

Specimen/Material	Specimen Number	Cycle 164B Temperature [°C]		Cycle 166A Temperature [°C]		Cycle 166B Temperature [°C]	
		Max	Avg	Max	Avg	Max	Avg
RT-304L Forged	723	379	370	402	392	404	394
RT-304L Forged	722	376	365	398	386	400	388
RT-91 PM-HIP	721	347	338	367	356	369	358
RT-316L PM-HIP	720	384	359	407	379	409	381
RT-316L PM-HIP	719	382	366	404	386	406	388
CT-690 Forged	718	390	381	405	397	407	398
CT-316 Cast	717	390	382	405	396	407	398
TEM-USU-400-3-36	716	394	393	403	403	404	404
TEM-USU-400-3-36	715	394	393	403	403	404	404
TEM-USU-400-3-36	714	394	393	403	403	404	404
TEM-USU-400-3-28	713	394	393	403	403	404	404
TEM-USU-400-3-28	712	393	393	403	403	404	404
TEM-USU-400-3-28	711	393	393	403	403	404	404
TEM-USU-400-3-20	710	393	393	403	403	404	404
TEM-USU-400-3-20	709	393	393	403	403	404	404
TEM-USU-400-3-20	708	393	393	403	403	404	404
CT-316 PM-HIP	707	389	382	404	396	406	398
CT-316 PM-HIP	706	389	380	404	395	406	397
RT-316L Forged	705	383	368	405	388	408	390
RT-316L Forged	704	388	365	411	386	414	388
RT-91 Cast	703	359	349	380	368	382	370
RT-304L Forged	702	394	383	418	405	420	407
RT-304L Forged	701	391	373	414	394	416	396

8.3 Melt Wire Comparison

At the time of this ECAR, the only melt wire evaluation that had been performed was on the 1 dpa capsules. This evaluation can be found in INL EXT-20-58375 [4]. The following table shows a summary of the melt wire evaluation and was created using Table 1 in INL EXT-20-58375.

Table 8-8: Melt Wire Evaluation Table From INL EXT-20-58375 Table 1

Melt Wire Pack Serial Number	Experiment/HFEF Sample ID	% Weight Each Wire in Package and (Melt Temperature)	Temperature Range
400C-1DPA-X	BSU/MELTWRE4	100 Pb (327.5°C), 85 Te 15 Sn(399.4°C), 100 Te (449.5°C).	327.5°C < T 399.4°C
300C-1DPA-X	BSU/MELTWRE1	95 Sn 5 Sb (238.6°C), 100 Bi (271.5°C), 100 Pb (327.5°C)	T < 238.6°C
300C-1DPA-Y	BSU/MELTWRE2	95 Sn 5 Sb (238.6°C), 100 Bi (271.5°C), 100 Pb (327.5°C).	238.6°C < T <271.5°C
400C-1DPA-Y	BSU/MELTWRE5	100 Pb (327.5°C), 85 Te 15 Sn(399.4°C), 100 Te (449.5°C).	399.4°C < T < 449.5°C

The following table (Table 8-9) is from ECAR-3575 [1] (Table 13) which shows what the melt wire temperature would be if the specimen temperatures were what was calculated in ECAR-3575. Because of the location of the melt wires, the temperature is slightly lower than what the specimens would see.

Table 8-9: Melt Wire Temperature Based on Specimen Temperatures Calculated in ECAR-3575

Capsule	Melt Wire Temperature [°C]
400C 1 dpa X	352
300C 1 dpa X	258
300C 1 dpa Y	257
400C 1 dpa Y	367

Table 8-10: Summary of Average Calculated As-Run Temperatures

Capsule	Temperature [°C]		Temperature Deviation from Target [°C]
	Target	Average	
300C 1 dpa X	300	276	-24
300C 1 dpa Y	300	272	-28
300C 3 dpa*	300	287	-13
400C 1 dpa X	400	362	-38
400C 1 dpa Y	400	371	-29
400C 3 dpa X*	400	389	-11
400C 3 dpa Y*	400	390	-10
*The average temperatures were based on the cycle that produced the highest calculated temperatures.			

The 400C 1 dpa X melt wire pack showed that the experiments maximum melt wire temperature was between 327.5°C and 399.4°C. According to the model, if the melt wire pack is at 352°C then the average specimen temperature is 397°C (information from ECAR-3575, Table 11). This means the actual temperature based on the melt wires is somewhere between 373°C and 444°C. Comparing this to the calculated as-run temperatures, the average[1] specimen temperature was 362°C.

The 300C 1 dpa X melt wire pack showed no signs of melting indicating the melt wire pack never reached a temperature of 238.6°C. According to the model, if the melt wire pack is at 258°C then the average specimen temperature is 298°C (information from ECAR-3575, Table 11). This means the actual temperature based on the melt wires is below 279°C. Comparing this to the calculated as-run temperatures, the average specimen temperature was 276°C.

The 300C 1 dpa Y melt wire pack showed that the experiments maximum melt wire temperature was between 238.6°C and 271.5°C which shows good agreement with Table 8-9. According to the model, if the melt wire pack is at 257°C then the average specimen temperature is 297°C (information from ECAR-3575, Table 11). This means the actual temperature based on the melt wires is somewhere between 279°C and 312°C. Comparing this to the calculated as-run temperatures, the average specimen temperature was 272°C.

The 400C 1 dpa Y melt wire pack showed that the experiments maximum melt wire temperature was between 399.4°C and 449.5°C. According to the model, if the melt wire pack is at 367°C then the average specimen temperature is 407°C (information from ECAR-3575, Table 11). This means the actual temperature based on the melt wires is somewhere between 439°C and 490°C. Comparing this to the calculated as-run temperatures, the average specimen temperature was 371°C.

9 ACRONYMS

ALWR	Advance Light Water Reactor
ATR	Advanced Test Reactor
BSU	Boise State University
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
LWR	Light Water Reactor
NSH	Neck Shim Housing
NSUF	Nuclear Science user Facilities
PM-HIP	Powder Metallurgy and Hot Isostatic Pressing

[1] The average specimen temperature was calculated by averaging each specimen individually except for the TEM's. The TEM's were averaged for each position and then used in the overall average.

SAR	Safety Analysis Report
SMR	Small Modular Reactor
SSC	System, Structure, or Component
SST	Stainless Steel
TEM	Transmission Electron Microscope
TFR	Technical and Functional Requirements
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:

\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run	
Filename	Description
ECAR-5510.docx	This document
Appendix B - BSU-8242 AR HRs.xmcd	Mathcad file containing material properties and heat rates
\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run\Abaqus\300C_3dpa	
Filename	Description
BSU-8242_300C_3dpa_AsRun.cae	ABAQUS cae file
BSU-8242_300C_3dpa ".inp, .odb"	ABAQUS input and output files for the 300C 3dpa capsule
\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run\Abaqus\400C_3dpa_X	
Filename	Description
BSU-8242_400C_3dpa_X_AsRun.cae	ABAQUS cae file
BSU-8242_400C_3dpa_X ".inp, .odb"	ABAQUS input and output files for the 400C 3dpa X capsule
\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run\Abaqus\400C_3dpa_Y	
Filename	Description
BSU-8242_400C_3dpa_Y_AsRun.cae	ABAQUS cae file
BSU-8242_400C_3dpa_Y ".inp, .odb"	ABAQUS input and output files for the 400C 3dpa Y capsule
\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run\Abaqus\400C-300C_1dpa_X	
Filename	Description
BSU-8242_400C-300C_1dpa_X.cae	ABAQUS cae file
BSU-8242_400C-300C_1dpa_X ".inp, .odb"	ABAQUS input and output files for the 400C-300C 1dpa X capsule
\\fswcb1\projects\USUF\IRRADIATION TESTING\NSUF\BSU-8242\As-Run\Abaqus\400C-300C_1dpa_Y	
Filename	Description
BSU-8242_400C-300C_1dpa_Y.cae	ABAQUS cae file
BSU-8242_400C-300C_1dpa_Y ".inp, .odb"	ABAQUS input and output files for the 400C-300C 1dpa Y capsule

11 CONCLUSIONS

See cover page Section 11 for Conclusions

12 REFERENCES

[1] C. Hale, *ECAR-3575, Rev. 3, "BSU-8242 Programmatic and Safety Compliance Structural and Thermal Analysis",* 05/02/2018.

[2] J. Brookman, *ECAR-4341, Rev. 1, "BSU-8242 1 DPA As-Run Physics Analysis",* 5/28/2020.

[3] J. Brookman, *ECAR-4951, Rev. 1, "BSU-8242 3 DPA As-Run Physics Analysis,* 07/02/2020.

[4] K. L. Davis and L. A. Hone, *INL EXT-20-58375, Rev. 0, "NSUF Melt Wire Evaluation for BSU-8242 and GE Hitachi-10393 Irradiation Experiments",* April 2020.

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

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

[7] Idaho National Laboratory, *LWP-10200, Rev 11, "Engineering Calculations and Analysis Report",* 02/06/2018.

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

13 APPENDICES

Appendix A – Engineering Inputs

Appendix B – Heat Rates

Appendix C – Computer Code Validation

Appendix A

Engineering Inputs

Perform an as-run thermal analysis of the BSU-8242 experiment using physics results from ECAR-4341 and ECAR-4951. Temperature reported for each specimen shall be the specimen average and specimen maximum using the cycle average heating rates.

Appendix B

Heat Rates

B.1 Material Densities:

In order to convert specimen heat rates into values used in ABAQUS, the densities for each specimen is needed. The densites for each specime are obtained from ECAR-3575, Appendix C.

$$\rho_{625} := 8.44 \frac{gm}{cm^3}$$

$$\rho_{690} := 8.19 \frac{gm}{cm^3}$$

$$\rho_{G91} := 7.805 \frac{gm}{cm^3}$$

$$\rho_{304L} := 8.03 \frac{gm}{cm^3}$$

$$\rho_{316L} := 7.99 \frac{gm}{cm^3}$$

$$\rho_{508} := 0.283 \frac{lb}{in^3}$$

$$\rho_{Al3Hf20} := 3.428 \frac{gm}{cm^3}$$

$$\rho_{Al3Hf28} := 3.74 \frac{gm}{cm^3}$$

$$\rho_{Al3Hf36} := 3.95 \frac{gm}{cm^3}$$

B.2 Heating Rates for Capsule 300C 1 DPA (X):

Heating rates given in ECAR-4341 are given in specimen order starting from the top and going to the bottom. This same scheme will be kept here. During the neutronics modeling of this capsule the TEM's in position 2 (the USU specimens) were flipped so that the Al3Hf20's were on top instead of the Al3Hf36's. Since the TEM's are so small the heating rate difference would be negligible if the model was corrected and reran. Instead, the heat rates from the neutronics analysis will be flipped so the heat rates associated for the right material type is used.

$$HR_{Splits} := \begin{pmatrix} 6.27 & 6.38 & 6.56 & 6.53 \\ 5.8 & 5.95 & 6.12 & 6.12 \\ 5.68 & 5.81 & 6.01 & 5.99 \\ 8.82 & 10.08 & 11.06 & 11.48 \\ 9.83 & 10.23 & 11.2 & 11.6 \\ 9.71 & 10.24 & 11.29 & 11.49 \\ 9.01 & 9.33 & 10.13 & 10.71 \\ 9.03 & 9.49 & 10.04 & 10.35 \\ 9.07 & 9.44 & 10.01 & 10.18 \\ 8.06 & 8.13 & 9 & 9.17 \\ 8.11 & 8.11 & 8.9 & 9.18 \\ 7.99 & 8.43 & 8.79 & 9.1 \\ 5.07 & 5.35 & 5.57 & 5.58 \\ 4.9 & 5.17 & 5.32 & 5.35 \\ 4.88 & 5.18 & 5.33 & 5.42 \\ 5.04 & 5.19 & 5.26 & 5.41 \\ 5.14 & 5.37 & 5.38 & 5.43 \\ 5.08 & 5.17 & 5.33 & 5.45 \\ 5.01 & 5.09 & 5.17 & 5.36 \\ 5.02 & 5.16 & 5.32 & 5.32 \\ 5.01 & 5.1 & 5.36 & 5.48 \\ 5.04 & 5.17 & 5.24 & 5.45 \\ 5.11 & 5.12 & 5.4 & 5.53 \\ 5.14 & 5.15 & 5.24 & 5.5 \\ 4.96 & 5.11 & 5.34 & 5.39 \\ 4.79 & 4.98 & 5.15 & 5.16 \\ 3.87 & 4.02 & 4.23 & 4.26 \end{pmatrix} \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 127 \\ 126 \\ 125 \\ 124 \\ 123 \\ 122 \\ 121 \\ 120 \\ 119 \\ 118 \\ 117 \\ 116 \\ 115 \\ 114 \\ 113 \\ 112 \\ 111 \\ 110 \\ 109 \\ 108 \\ 107 \\ 106 \\ 105 \\ 104 \\ 103 \\ 102 \\ 101 \end{pmatrix} \end{array}$$

$$i := 0 .. \text{length}\left(HR_{Splits}^{\langle 0 \rangle}\right) - 1$$

$$HR_{300C.1dpa.X_i} := \text{mean}\left(HR_{Splits_{i,0}}, HR_{Splits_{i,1}}, HR_{Splits_{i,2}}, HR_{Splits_{i,3}}\right)$$

$$HR_{300C.1dpa.X} = \begin{pmatrix} 6.435 \\ 5.997 \\ 5.872 \\ 10.36 \\ 10.715 \\ 10.682 \\ 9.795 \\ 9.727 \\ 9.675 \\ 8.59 \\ 8.575 \\ 8.578 \\ 5.393 \\ 5.185 \\ 5.202 \\ 5.225 \\ 5.33 \\ 5.258 \\ 5.157 \\ 5.205 \\ 5.237 \\ 5.225 \\ 5.29 \\ 5.258 \\ 5.2 \\ 5.02 \\ 4.095 \end{pmatrix} \cdot \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 127 \\ 126 \\ 125 \\ 124 \\ 123 \\ 122 \\ 121 \\ 120 \\ 119 \\ 118 \\ 117 \\ 116 \\ 115 \\ 114 \\ 113 \\ 112 \\ 111 \\ 110 \\ 109 \\ 108 \\ 107 \\ 106 \\ 105 \\ 104 \\ 103 \\ 102 \\ 101 \end{pmatrix} \end{array}$$

$$\rho_{300C.1dpa.X} := \begin{pmatrix} \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \end{pmatrix}$$

$$Q_{300C.1dpa.X_i} := \rho_{300C.1dpa.X_i} \cdot HR_{300C.1dpa.X_i}$$

Specimen Number

$$Q_{300C.1dpa.X} = \begin{pmatrix} 7.311E+003 \\ 6.814E+003 \\ 6.672E+003 \\ 5.935E+003 \\ 6.139E+003 \\ 6.12E+003 \\ 5.313E+003 \\ 5.277E+003 \\ 5.248E+003 \\ 4.271E+003 \\ 4.263E+003 \\ 4.265E+003 \\ 6.127E+003 \\ 5.891E+003 \\ 5.911E+003 \\ 5.936E+003 \\ 6.056E+003 \\ 5.973E+003 \\ 5.86E+003 \\ 5.914E+003 \\ 5.951E+003 \\ 5.936E+003 \\ 6.01E+003 \\ 5.973E+003 \\ 5.908E+003 \\ 5.703E+003 \\ 4.652E+003 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{pmatrix} 127 \\ 126 \\ 125 \\ 124 \\ 123 \\ 122 \\ 121 \\ 120 \\ 119 \\ 118 \\ 117 \\ 116 \\ 115 \\ 114 \\ 113 \\ 112 \\ 111 \\ 110 \\ 109 \\ 108 \\ 107 \\ 106 \\ 105 \\ 104 \\ 103 \\ 102 \\ 101 \end{pmatrix}$$

B.3 Heating Rates for Capsule 300C 1 DPA (Y):

$$HR_{Splits} := \begin{pmatrix} 6.17 & 6.28 & 6.42 & 6.39 \\ 5.78 & 5.94 & 6.16 & 6.14 \\ 5.65 & 5.78 & 6.01 & 5.98 \\ 4.94 & 5.09 & 5.3 & 5.33 \\ 4.79 & 4.97 & 5.17 & 5.17 \\ 3.82 & 3.98 & 4.17 & 4.18 \end{pmatrix} \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 206 \\ 205 \\ 204 \\ 203 \\ 202 \\ 201 \end{pmatrix} \end{array}$$

$$i := 0 .. \text{length}\left(HR_{Splits}^{\langle 0 \rangle}\right) - 1$$

$$HR_{300C.1dpa.Y_i} := \text{mean}\left(HR_{Splits_{i,0}}, HR_{Splits_{i,1}}, HR_{Splits_{i,2}}, HR_{Splits_{i,3}}\right)$$

$$HR_{300C.1dpa.Y} = \begin{pmatrix} 6.315 \\ 6.005 \\ 5.855 \\ 5.165 \\ 5.025 \\ 4.037 \end{pmatrix} \cdot \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 206 \\ 205 \\ 204 \\ 203 \\ 202 \\ 201 \end{pmatrix} \end{array}$$

$$\rho_{300C.1dpa.Y} := \begin{pmatrix} \rho_{508} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{508} \end{pmatrix}$$

$$Q_{300C.1dpa.Y_i} := \rho_{300C.1dpa.Y_i} \cdot HR_{300C.1dpa.Y_i}$$

Specimen Number

$$Q_{300C.1dpa.Y} = \begin{pmatrix} 7.175E+003 \\ 6.959E+003 \\ 6.785E+003 \\ 5.985E+003 \\ 5.823E+003 \\ 4.587E+003 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{pmatrix} 206 \\ 205 \\ 204 \\ 203 \\ 202 \\ 201 \end{pmatrix}$$

B.4 Heating Rates for Capsule 300C 3 DPA:

During the neutronics modeling of this capsule the TEM's in position 2 (the USU specimens) were flipped so that the Al3Hf36's were on top instead of the Al3Hf20's. Since the TEM's are so small the heating rate difference would be negligible if the model was corrected and reran. Instead, the heat rates from the neutronics analysis will be flipped so the heat rates associated for the right material type is used.

Specimen Number

$$HR_{300C.3dpa} := \begin{pmatrix} 6.67 & 7.42 & 7.49 \\ 7.54 & 8.38 & 8.46 \\ 8.48 & 9.42 & 9.51 \\ 8.94 & 9.94 & 10.03 \\ 9.39 & 10.44 & 10.54 \\ 9.36 & 10.4 & 10.5 \\ 11.84 & 13.16 & 13.28 \\ 12.14 & 13.5 & 13.63 \\ 12.03 & 13.37 & 13.5 \\ 13.49 & 14.99 & 15.13 \\ 13.24 & 14.72 & 14.86 \\ 13.13 & 14.6 & 14.73 \\ 14.29 & 15.89 & 16.04 \\ 14.49 & 16.11 & 16.26 \\ 14.6 & 16.23 & 16.38 \\ 8.75 & 9.73 & 9.82 \\ 8.73 & 9.71 & 9.8 \\ 8.87 & 9.86 & 9.95 \\ 8.65 & 9.62 & 9.71 \\ 8.56 & 9.51 & 9.6 \\ 8.65 & 9.61 & 9.7 \\ 9.22 & 10.25 & 10.35 \\ 9.2 & 10.23 & 10.33 \\ 9.38 & 10.42 & 10.52 \\ 9.27 & 10.31 & 10.4 \\ 9.2 & 10.23 & 10.33 \\ 9.29 & 10.33 & 10.43 \\ 8.83 & 9.81 & 9.91 \\ 8.87 & 9.86 & 9.96 \\ 8.86 & 9.85 & 9.94 \\ 8.7 & 9.67 & 9.76 \\ 8.66 & 9.63 & 9.72 \\ 8.68 & 9.65 & 9.75 \end{pmatrix} \frac{W}{gm} \qquad \begin{pmatrix} 345 \\ 344 \\ 343 \\ 342 \\ 341 \\ 340 \\ 339 \\ 338 \\ 337 \\ 336 \\ 335 \\ 334 \\ 333 \\ 332 \\ 331 \\ 330 \\ 329 \\ 328 \\ 327 \\ 326 \\ 325 \\ 324 \\ 323 \\ 322 \\ 321 \\ 320 \\ 319 \\ 318 \\ 317 \\ 316 \\ 315 \\ 314 \\ 313 \end{pmatrix}$$

$$\begin{pmatrix} 9.44 & 10.5 & 10.6 \\ 9.38 & 10.43 & 10.53 \\ 9.3 & 10.34 & 10.44 \\ 9.24 & 10.27 & 10.37 \\ 9.3 & 10.34 & 10.44 \\ 9.33 & 10.37 & 10.47 \\ 9.4 & 10.45 & 10.55 \\ 9.38 & 10.43 & 10.52 \\ 9.04 & 10.05 & 10.15 \\ 8.72 & 9.69 & 9.79 \\ 7.9 & 8.78 & 8.86 \\ 7.17 & 7.97 & 8.05 \end{pmatrix} \qquad \begin{pmatrix} 312 \\ 311 \\ 310 \\ 309 \\ 308 \\ 307 \\ 306 \\ 305 \\ 304 \\ 303 \\ 302 \\ 301 \end{pmatrix}$$

$i := 0 .. \text{length}\left(HR_{300C.3dpa}{}^{\langle 0 \rangle}\right) - 1$

$j := 0 .. 2$

$$\begin{pmatrix} \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{690} \end{pmatrix}$$

$$\rho_{300C.3dpa} := \begin{pmatrix} \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \end{pmatrix}$$

$$Q_{300C.3dpa_{i,j}} := \rho_{300C.3dpa_i} \cdot HR_{300C.3dpa_{i,j}}$$

$$Q_{300C.3dpa} = \begin{pmatrix} 7.923E+003 & 8.814E+003 & 8.897E+003 \\ 8.956E+003 & 9.954E+003 & 1.005E+004 \\ 1.038E+004 & 1.153E+004 & 1.164E+004 \\ 1.094E+004 & 1.217E+004 & 1.228E+004 \\ 1.149E+004 & 1.278E+004 & 1.29E+004 \\ 1.146E+004 & 1.273E+004 & 1.285E+004 \\ 5.887E+003 & 6.543E+003 & 6.603E+003 \\ 6.036E+003 & 6.712E+003 & 6.777E+003 \\ 5.981E+003 & 6.647E+003 & 6.712E+003 \\ 7.318E+003 & 8.131E+003 & 8.207E+003 \\ 7.182E+003 & 7.985E+003 & 8.061E+003 \\ 7.122E+003 & 7.92E+003 & 7.99E+003 \\ 8.187E+003 & 9.103E+003 & 9.189E+003 \\ 8.301E+003 & 9.229E+003 & 9.315E+003 \\ 8.364E+003 & 9.298E+003 & 9.384E+003 \\ 1.039E+004 & 1.156E+004 & 1.166E+004 \\ 1.037E+004 & 1.153E+004 & 1.164E+004 \\ 1.054E+004 & 1.171E+004 & 1.182E+004 \\ 1.027E+004 & 1.143E+004 & 1.153E+004 \\ 1.017E+004 & 1.13E+004 & 1.14E+004 \\ 1.027E+004 & 1.142E+004 & 1.152E+004 \\ 1.129E+004 & 1.255E+004 & 1.267E+004 \\ 1.126E+004 & 1.252E+004 & 1.265E+004 \\ 1.148E+004 & 1.276E+004 & 1.288E+004 \\ 1.135E+004 & 1.262E+004 & 1.273E+004 \\ 1.126E+004 & 1.252E+004 & 1.265E+004 \\ 1.137E+004 & 1.265E+004 & 1.277E+004 \\ 1.049E+004 & 1.165E+004 & 1.177E+004 \\ 1.054E+004 & 1.171E+004 & 1.183E+004 \\ 1.052E+004 & 1.17E+004 & 1.181E+004 \\ 1.033E+004 & 1.149E+004 & 1.159E+004 \\ 1.029E+004 & 1.144E+004 & 1.155E+004 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 345 \\ 344 \\ 343 \\ 342 \\ 341 \\ 340 \\ 339 \\ 338 \\ 337 \\ 336 \\ 335 \\ 334 \\ 333 \\ 332 \\ 331 \\ 330 \\ 329 \\ 328 \\ 327 \\ 326 \\ 325 \\ 324 \\ 323 \\ 322 \\ 321 \\ 320 \\ 319 \\ 318 \\ 317 \\ 316 \\ 315 \\ 314 \end{pmatrix} \end{array}$$

$$\begin{pmatrix} 1.031E+004 & 1.146E+004 & 1.158E+004 \\ 1.156E+004 & 1.285E+004 & 1.298E+004 \\ 1.148E+004 & 1.277E+004 & 1.289E+004 \\ 1.138E+004 & 1.266E+004 & 1.278E+004 \\ 1.131E+004 & 1.257E+004 & 1.269E+004 \\ 1.138E+004 & 1.266E+004 & 1.278E+004 \\ 1.142E+004 & 1.269E+004 & 1.282E+004 \\ 1.151E+004 & 1.279E+004 & 1.291E+004 \\ 1.148E+004 & 1.277E+004 & 1.288E+004 \\ 1.107E+004 & 1.23E+004 & 1.242E+004 \\ 1.067E+004 & 1.186E+004 & 1.198E+004 \\ 9.384E+003 & 1.043E+004 & 1.052E+004 \\ 8.517E+003 & 9.467E+003 & 9.562E+003 \end{pmatrix} \qquad \begin{pmatrix} 313 \\ 312 \\ 311 \\ 310 \\ 309 \\ 308 \\ 307 \\ 306 \\ 305 \\ 304 \\ 303 \\ 302 \\ 301 \end{pmatrix}$$

B.5 Heating Rates for Capsule 400C 1 DPA (X):

Specimen Number

$$\begin{pmatrix} 3.71 & 3.8 & 4.09 & 4.11 \\ 5 & 5.11 & 5.42 & 5.44 \\ 5.89 & 5.95 & 6.23 & 6.24 \\ 6.87 & 6.89 & 7.12 & 7.11 \\ 7.91 & 7.91 & 8.12 & 8.09 \\ 7.98 & 7.98 & 8.18 & 8.14 \\ 8.31 & 8.22 & 8.23 & 8.26 \\ 8.05 & 8.1 & 8.1 & 8.23 \\ 8.11 & 8 & 8.19 & 8.34 \\ 8.04 & 7.88 & 8.28 & 8.29 \\ 8.09 & 7.89 & 8.16 & 8.09 \\ 8.1 & 7.95 & 8.2 & 8.26 \\ 7.93 & 7.96 & 8.09 & 8.23 \\ 8.08 & 7.96 & 8.19 & 8.24 \\ 8.26 & 7.87 & 8.23 & 8.35 \\ 8.15 & 7.97 & 8.21 & 8.28 \\ 8.04 & 7.83 & 8.28 & 8.27 \\ 8.12 & 7.9 & 8.24 & 8.2 \end{pmatrix} \qquad \begin{pmatrix} 460 \\ 459 \\ 458 \\ 457 \\ 456 \\ 455 \\ 454 \\ 453 \\ 452 \\ 451 \\ 450 \\ 449 \\ 448 \\ 447 \\ 446 \\ 445 \\ 444 \\ 443 \end{pmatrix}$$

HRSplits := (matrix, units $\frac{W}{gm}$)

7.44	7.33	7.35	7.25		442
7.32	7.12	7.45	7.42		441
7.36	7.17	7.48	7.41		440
7.5	7.26	7.42	7.49		439
7.43	7.39	7.45	7.31		438
7.47	7.24	7.4	7.31		437
7.54	7.46	7.54	7.65		436
7.54	7.54	7.58	7.58		435
7.66	7.48	7.72	7.49		434
7.58	7.5	7.62	7.48		433
7.84	7.51	7.56	7.5		432
7.57	7.56	7.64	7.52	W/gm	431
7.48	7.5	7.55	7.5		430
7.46	7.53	7.49	7.34		429
7.5	7.59	7.44	7.34		428
7.65	7.53	7.49	7.37		427
7.68	7.53	7.71	7.59		426
7.55	7.46	7.78	7.66		425
7.5	7.52	7.76	7.57		424
7.68	7.4	7.66	7.51		423
7.62	7.46	7.62	7.58		422
7.62	7.66	7.52	7.41		421
7.49	7.56	7.53	7.35		420
7.64	7.63	7.71	7.56		419
7.67	7.88	8.18	7.96		418
7.58	7.87	7.91	7.77		417
7.76	7.83	7.83	7.81		416
7.8	7.82	7.95	7.9		415
7.75	7.96	7.95	7.85		414
7.78	7.89	7.92	7.83		413
7.93	7.98	8.14	8.03		412
8.05	7.93	8.37	8.19		411
7.86	7.77	8.28	8.12		410
7.86	7.75	8.18	7.92		409
7.9	7.78	8.07	7.78		408
7.89	7.85	8.04	7.91		407

$$\begin{pmatrix} 8.03 & 7.98 & 8.08 & 8.05 \\ 8.09 & 8.07 & 8.15 & 8.12 \\ 7.81 & 7.75 & 7.78 & 7.72 \\ 7.93 & 7.87 & 7.87 & 7.8 \\ 7.85 & 7.8 & 7.81 & 7.76 \\ 7.56 & 7.57 & 7.6 & 7.55 \end{pmatrix} \qquad \begin{pmatrix} 406 \\ 405 \\ 404 \\ 403 \\ 402 \\ 401 \end{pmatrix}$$

$$i := 0 .. \text{length}\left(HR_{Splits}^{\langle 0 \rangle}\right) - 1$$

$$HR_{400C.1dpa.X_i} := \text{mean}\left(HR_{Splits_{i,0}}, HR_{Splits_{i,1}}, HR_{Splits_{i,2}}, HR_{Splits_{i,3}}\right)$$

Specimen Number

$$\begin{pmatrix} 3.928 \\ 5.242 \\ 6.077 \\ 6.997 \\ 8.008 \\ 8.07 \\ 8.255 \\ 8.12 \\ 8.16 \\ 8.123 \\ 8.057 \\ 8.127 \\ 8.053 \\ 8.117 \\ 8.178 \\ 8.152 \\ 8.105 \\ 8.115 \\ 7.343 \\ 7.327 \\ 7.355 \\ 7.418 \\ 7.395 \\ 7.355 \end{pmatrix} \qquad \begin{pmatrix} 460 \\ 459 \\ 458 \\ 457 \\ 456 \\ 455 \\ 454 \\ 453 \\ 452 \\ 451 \\ 450 \\ 449 \\ 448 \\ 447 \\ 446 \\ 445 \\ 444 \\ 443 \\ 442 \\ 441 \\ 440 \\ 439 \\ 438 \\ 437 \end{pmatrix}$$

$$HR_{400C.1dpa.X} = \begin{pmatrix} 7.548 \\ 7.56 \\ 7.588 \\ 7.545 \\ 7.603 \\ 7.572 \\ 7.508 \\ 7.455 \\ 7.468 \\ 7.51 \\ 7.628 \\ 7.612 \\ 7.588 \\ 7.563 \\ 7.57 \\ 7.553 \\ 7.482 \\ 7.635 \\ 7.923 \\ 7.782 \\ 7.808 \\ 7.867 \\ 7.878 \\ 7.855 \\ 8.02 \\ 8.135 \\ 8.008 \\ 7.928 \\ 7.883 \\ 7.923 \\ 8.035 \\ 8.107 \\ 7.765 \\ 7.867 \\ 7.805 \\ 7.57 \end{pmatrix} \cdot \frac{W}{gm} \qquad \begin{pmatrix} 436 \\ 435 \\ 434 \\ 433 \\ 432 \\ 431 \\ 430 \\ 429 \\ 428 \\ 427 \\ 426 \\ 425 \\ 424 \\ 423 \\ 422 \\ 421 \\ 420 \\ 419 \\ 418 \\ 417 \\ 416 \\ 415 \\ 414 \\ 413 \\ 412 \\ 411 \\ 410 \\ 409 \\ 408 \\ 407 \\ 406 \\ 405 \\ 404 \\ 403 \\ 402 \\ 401 \end{pmatrix}$$

$$\begin{pmatrix} \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \\ \rho_{508} \end{pmatrix}$$

$$\rho_{400C.1dpa.X} := \begin{vmatrix} \rho_{508} \\ \rho_{508} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{G91} \end{vmatrix}$$

$$\begin{pmatrix} \rho_{G91} \\ \rho_{508} \\ \rho_{508} \end{pmatrix}$$

$$Q_{400C.1dpa.X_i} := \rho_{400C.1dpa.X_i} \cdot HR_{400C.1dpa.X_i}$$

	Specimen Number
4.808E+003	460
6.417E+003	459
7.219E+003	458
8.312E+003	457
9.802E+003	456
9.879E+003	455
1.011E+004	454
9.94E+003	453
9.989E+003	452
9.943E+003	451
9.863E+003	450
9.949E+003	449
9.857E+003	448
9.937E+003	447
1.001E+004	446
9.98E+003	445
9.921E+003	444
9.934E+003	443
8.342E+003	442
8.325E+003	441
8.356E+003	440
8.427E+003	439
8.402E+003	438
8.356E+003	437
8.575E+003	436
8.589E+003	435
8.62E+003	434
8.572E+003	433
8.638E+003	432

$$Q_{400C.1dpa.X} = \begin{pmatrix} 8.603E+003 \\ 8.499E+003 \\ 8.439E+003 \\ 8.453E+003 \\ 8.501E+003 \\ 8.634E+003 \\ 8.617E+003 \\ 8.589E+003 \\ 8.561E+003 \\ 8.569E+003 \\ 8.55E+003 \\ 8.47E+003 \\ 8.643E+003 \\ 9.411E+003 \\ 9.245E+003 \\ 9.274E+003 \\ 9.345E+003 \\ 9.357E+003 \\ 9.331E+003 \\ 9.527E+003 \\ 9.663E+003 \\ 9.512E+003 \\ 9.417E+003 \\ 9.363E+003 \\ 9.411E+003 \\ 9.544E+003 \\ 9.631E+003 \\ 8.79E+003 \\ 8.906E+003 \\ 8.868E+003 \\ 8.601E+003 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{pmatrix} 431 \\ 430 \\ 429 \\ 428 \\ 427 \\ 426 \\ 425 \\ 424 \\ 423 \\ 422 \\ 421 \\ 420 \\ 419 \\ 418 \\ 417 \\ 416 \\ 415 \\ 414 \\ 413 \\ 412 \\ 411 \\ 410 \\ 409 \\ 408 \\ 407 \\ 406 \\ 405 \\ 404 \\ 403 \\ 402 \\ 401 \end{pmatrix}$$

B.6 Heating Rates for Capsule 400C 1 DPA (Y):

$$HR_{Splits} := \begin{pmatrix} 3.67 & 3.76 & 4.03 & 4.06 \\ 4.93 & 5.02 & 5.33 & 5.36 \\ 5.78 & 5.86 & 6.12 & 6.12 \\ 6.77 & 6.79 & 7.00 & 6.99 \\ 7.41 & 7.41 & 7.58 & 7.53 \\ 7.44 & 7.47 & 7.63 & 7.60 \\ 10.74 & 10.70 & 11.26 & 11.59 \\ 10.70 & 10.90 & 11.04 & 11.59 \\ 10.75 & 10.79 & 11.10 & 11.65 \\ 12.20 & 12.47 & 12.51 & 12.92 \\ 12.24 & 12.26 & 12.60 & 12.93 \\ 12.18 & 12.47 & 12.60 & 13.05 \\ 13.51 & 13.63 & 13.80 & 14.20 \\ 13.31 & 13.19 & 13.65 & 14.10 \\ 13.18 & 13.14 & 13.92 & 14.27 \\ 7.56 & 7.56 & 7.60 & 7.55 \\ 7.65 & 7.62 & 7.64 & 7.58 \\ 7.66 & 7.62 & 7.61 & 7.56 \\ 7.76 & 7.72 & 7.71 & 7.65 \\ 7.69 & 7.67 & 7.66 & 7.60 \\ 7.42 & 7.44 & 7.47 & 7.44 \end{pmatrix} \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 521 \\ 520 \\ 519 \\ 518 \\ 517 \\ 516 \\ 515 \\ 514 \\ 513 \\ 512 \\ 511 \\ 510 \\ 509 \\ 508 \\ 507 \\ 506 \\ 505 \\ 504 \\ 503 \\ 502 \\ 501 \end{pmatrix} \end{array}$$

$$i := 0 .. \text{length}\left(HR_{Splits}^{\langle 0 \rangle}\right) - 1$$

$$HR_{400C.1dpa.Y_i} := \text{mean}\left(HR_{Splits_{i,0}}, HR_{Splits_{i,1}}, HR_{Splits_{i,2}}, HR_{Splits_{i,3}}\right)$$

$$HR_{400C.1dpa.Y} = \begin{pmatrix} 3.88 \\ 5.16 \\ 5.97 \\ 6.888 \\ 7.482 \\ 7.535 \\ 11.072 \\ 11.057 \\ 11.072 \\ 12.525 \\ 12.508 \\ 12.575 \\ 13.785 \\ 13.563 \\ 13.627 \\ 7.567 \\ 7.622 \\ 7.612 \\ 7.71 \\ 7.655 \\ 7.442 \end{pmatrix} \cdot \frac{W}{gm} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 521 \\ 520 \\ 519 \\ 518 \\ 517 \\ 516 \\ 515 \\ 514 \\ 513 \\ 512 \\ 511 \\ 510 \\ 509 \\ 508 \\ 507 \\ 506 \\ 505 \\ 504 \\ 503 \\ 502 \\ 501 \end{pmatrix} \end{array}$$

$$\rho_{400C.1dpa.Y} := \begin{pmatrix} \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{508} \\ \rho_{508} \end{pmatrix}$$

$$Q_{400C.1dpa.Y_i} := \rho_{400C.1dpa.Y_i} \cdot HR_{400C.1dpa.Y_i}$$

$$Q_{400C.1dpa.Y} = \begin{pmatrix} 4.75E+003 \\ 6.316E+003 \\ 7.092E+003 \\ 8.181E+003 \\ 8.888E+003 \\ 8.951E+003 \\ 5.505E+003 \\ 5.498E+003 \\ 5.505E+003 \\ 6.794E+003 \\ 6.785E+003 \\ 6.821E+003 \\ 7.897E+003 \\ 7.77E+003 \\ 7.807E+003 \\ 8.567E+003 \\ 8.629E+003 \\ 8.617E+003 \\ 8.728E+003 \\ 8.697E+003 \\ 8.456E+003 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 521 \\ 520 \\ 519 \\ 518 \\ 517 \\ 516 \\ 515 \\ 514 \\ 513 \\ 512 \\ 511 \\ 510 \\ 509 \\ 508 \\ 507 \\ 506 \\ 505 \\ 504 \\ 503 \\ 502 \\ 501 \end{pmatrix} \end{array}$$

B.7 Heating Rates for Capsule 400C 3 DPA (X):

			Specimen Number
5.25	5.83	5.89	674
6.23	6.92	6.99	673
7.33	8.15	8.23	672
7.92	8.8	8.89	671
7.63	8.48	8.56	670
8.66	9.63	9.72	669
8.7	9.67	9.77	668
7.77	8.64	8.72	667
7.86	8.73	8.82	666
7.84	8.71	8.8	665
7.94	8.82	8.91	664
8.13	9.04	9.13	663
8.02	8.92	9	662
7.91	8.8	8.88	661
7.92	8.8	8.88	660
8.1	9	9.09	659
8.02	8.92	9	658
7.83	8.71	8.79	657
7.85	8.73	8.81	656
7.72	8.58	8.66	655
7.79	8.66	8.74	654
7.69	8.55	8.63	653
7.73	8.59	8.68	652
7.7	8.56	8.64	651
7.84	8.72	8.8	650
8.01	8.9	8.99	649
7.92	8.8	8.89	648
7.86	8.74	8.82	647
7.85	8.73	8.81	646
7.88	8.76	8.85	645
7.89	8.77	8.85	644
8.06	8.96	9.04	643
8.16	9.07	9.15	642

$HR_{400C.3dpa.X} :=$ (matrix) $\frac{W}{gm}$ (vector)

8.16	9.07	9.16	641
8.23	9.15	9.24	640
8.07	8.97	9.05	639
8.04	8.94	9.02	638
7.86	8.74	8.82	637
7.88	8.76	8.84	636
7.94	8.82	8.91	635
7.86	8.73	8.82	634
7.91	8.79	8.88	633
7.89	8.78	8.86	632
8.06	8.96	9.04	631
8.16	9.07	9.16	630
8.13	9.04	9.13	629
8.05	8.94	9.03	628
8.19	9.11	9.19	627
8.16	9.07	9.15	626
8.2	9.12	9.21	625
8.09	8.99	9.08	624
8.06	8.96	9.05	623
8.16	9.07	9.16	622
8.14	9.05	9.13	621
8.13	9.04	9.12	620
8.62	9.58	9.67	619
8.67	9.64	9.73	618
8.61	9.57	9.66	617
8.73	9.71	9.8	616
8.69	9.66	9.76	615
8.74	9.72	9.81	614
8.63	9.59	9.68	613
8.55	9.51	9.6	612
8.63	9.6	9.69	611
8.53	9.49	9.58	610
8.63	9.59	9.68	609
8.52	9.47	9.56	608
8.3	9.22	9.31	607
8.32	9.25	9.33	606

$$\begin{pmatrix} 7.7 & 8.56 & 8.64 \\ 8.11 & 9.02 & 9.11 \\ 7.66 & 8.52 & 8.6 \\ 6.69 & 7.44 & 7.51 \\ 5.82 & 6.47 & 6.53 \end{pmatrix} \qquad \begin{pmatrix} 605 \\ 604 \\ 603 \\ 602 \\ 601 \end{pmatrix}$$

$i := 0..\,\mathrm{length}\left(HR_{400C.3dpa.X}^{\langle 0\rangle}\right) - 1$

$j := 0..\,2$

$$\begin{pmatrix} \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{G91} \\ \rho_{625} \\ \rho_{625} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \\ \rho_{304L} \end{pmatrix}$$

$$\rho_{400C.3dpa.X} := \begin{vmatrix} \rho_{304L} \\ \rho_{304L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{G91} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{690} \end{vmatrix}$$

$$\begin{pmatrix} \rho_{690} \\ \rho_{690} \\ \rho_{690} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \\ \rho_{G91} \\ \rho_{625} \\ \rho_{625} \\ \rho_{690} \\ \rho_{690} \end{pmatrix}$$

$$Q_{400C.3dpa.X_{i,j}} := \rho_{400C.3dpa.X_i} \cdot HR_{400C.3dpa.X_{i,j}}$$

			Specimen Number
6.236E+003	6.925E+003	6.996E+003	674
7.4E+003	8.22E+003	8.303E+003	673
8.973E+003	9.977E+003	1.007E+004	672
9.695E+003	1.077E+004	1.088E+004	671
8.637E+003	9.6E+003	9.69E+003	670
1.06E+004	1.179E+004	1.19E+004	669
1.065E+004	1.184E+004	1.196E+004	668
8.796E+003	9.781E+003	9.871E+003	667
8.898E+003	9.883E+003	9.984E+003	666
8.875E+003	9.86E+003	9.962E+003	665
8.988E+003	9.984E+003	1.009E+004	664
9.203E+003	1.023E+004	1.034E+004	663
9.079E+003	1.01E+004	1.019E+004	662
9.212E+003	1.025E+004	1.034E+004	661
9.224E+003	1.025E+004	1.034E+004	660
9.434E+003	1.048E+004	1.059E+004	659
9.341E+003	1.039E+004	1.048E+004	658
9.119E+003	1.014E+004	1.024E+004	657
9.143E+003	1.017E+004	1.026E+004	656
8.991E+003	9.993E+003	1.009E+004	655
9.073E+003	1.009E+004	1.018E+004	654
8.956E+003	9.958E+003	1.005E+004	653
9.003E+003	1E+004	1.011E+004	652
8.968E+003	9.969E+003	1.006E+004	651
9.131E+003	1.016E+004	1.025E+004	650
9.282E+003	1.031E+004	1.042E+004	649
9.178E+003	1.02E+004	1.03E+004	648
9.109E+003	1.013E+004	1.022E+004	647
9.097E+003	1.012E+004	1.021E+004	646
9.132E+003	1.015E+004	1.026E+004	645
9.143E+003	1.016E+004	1.026E+004	644
9.34E+003	1.038E+004	1.048E+004	643
9.456E+003	1.051E+004	1.06E+004	642
9.456E+003	1.051E+004	1.062E+004	641
9.537E+003	1.06E+004	1.071E+004	640

$Q_{400C.3dpa.X} =$ (units: $\frac{lbf}{in^2 \cdot s}$)

9.352E+003	1.039E+004	1.049E+004	639
9.317E+003	1.036E+004	1.045E+004	638
8.898E+003	9.894E+003	9.984E+003	637
8.92E+003	9.916E+003	1.001E+004	636
8.988E+003	9.984E+003	1.009E+004	635
8.898E+003	9.883E+003	9.984E+003	634
8.954E+003	9.95E+003	1.005E+004	633
8.932E+003	9.939E+003	1.003E+004	632
9.574E+003	1.064E+004	1.074E+004	631
9.693E+003	1.077E+004	1.088E+004	630
9.657E+003	1.074E+004	1.085E+004	629
9.562E+003	1.062E+004	1.073E+004	628
9.729E+003	1.082E+004	1.092E+004	627
9.693E+003	1.077E+004	1.087E+004	626
9.74E+003	1.083E+004	1.094E+004	625
9.61E+003	1.068E+004	1.079E+004	624
9.574E+003	1.064E+004	1.075E+004	623
9.693E+003	1.077E+004	1.088E+004	622
9.669E+003	1.075E+004	1.085E+004	621
9.657E+003	1.074E+004	1.083E+004	620
1.055E+004	1.173E+004	1.184E+004	619
1.061E+004	1.18E+004	1.191E+004	618
1.054E+004	1.171E+004	1.182E+004	617
1.069E+004	1.189E+004	1.2E+004	616
1.064E+004	1.182E+004	1.195E+004	615
1.07E+004	1.19E+004	1.201E+004	614
1.056E+004	1.174E+004	1.185E+004	613
1.047E+004	1.164E+004	1.175E+004	612
1.056E+004	1.175E+004	1.186E+004	611
1.044E+004	1.162E+004	1.173E+004	610
1.056E+004	1.174E+004	1.185E+004	609
1.043E+004	1.159E+004	1.17E+004	608
9.859E+003	1.095E+004	1.106E+004	607
9.883E+003	1.099E+004	1.108E+004	606
8.717E+003	9.69E+003	9.781E+003	605
9.928E+003	1.104E+004	1.115E+004	604

$$\begin{pmatrix} 9.377E+003 & 1.043E+004 & 1.053E+004 \\ 7.947E+003 & 8.838E+003 & 8.921E+003 \\ 6.913E+003 & 7.685E+003 & 7.757E+003 \end{pmatrix} \qquad \begin{pmatrix} 603 \\ 602 \\ 601 \end{pmatrix}$$

B.8 Heating Rates for Capsule 400C 3 DPA (Y):

Specimen Number

$$HR_{400C.3dpa.Y} := \begin{pmatrix} 5.14 & 5.72 & 5.77 \\ 6.1 & 6.78 & 6.84 \\ 6.89 & 7.65 & 7.73 \\ 7.55 & 8.39 & 8.47 \\ 7.94 & 8.82 & 8.91 \\ 8.44 & 9.38 & 9.47 \\ 8.25 & 9.17 & 9.26 \\ 14.6 & 16.23 & 16.38 \\ 14.49 & 16.11 & 16.26 \\ 14.29 & 15.89 & 16.04 \\ 13.13 & 14.6 & 14.73 \\ 13.24 & 14.72 & 14.86 \\ 13.49 & 14.99 & 15.13 \\ 12.03 & 13.37 & 13.5 \\ 12.14 & 13.5 & 13.63 \\ 11.84 & 13.16 & 13.28 \\ 8.31 & 9.24 & 9.33 \\ 8.32 & 9.25 & 9.34 \\ 8.01 & 8.9 & 8.99 \\ 7.73 & 8.6 & 8.68 \\ 7.2 & 8 & 8.08 \\ 6.55 & 7.28 & 7.35 \\ 5.71 & 6.34 & 6.4 \end{pmatrix} \frac{W}{gm} \qquad \begin{pmatrix} 723 \\ 722 \\ 721 \\ 720 \\ 719 \\ 718 \\ 717 \\ 716 \\ 715 \\ 714 \\ 713 \\ 712 \\ 711 \\ 710 \\ 709 \\ 708 \\ 707 \\ 706 \\ 705 \\ 704 \\ 703 \\ 702 \\ 701 \end{pmatrix}$$

$$i := 0 .. \text{length}\left(HR_{400C.3dpa.Y}^{\langle 0 \rangle}\right) - 1$$

$$j := 0 .. 2$$

$$\rho_{400C.3dpa.Y} := \begin{pmatrix} \rho_{304L} \\ \rho_{304L} \\ \rho_{G91} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{690} \\ \rho_{316L} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf36} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf28} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{Al3Hf20} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{316L} \\ \rho_{G91} \\ \rho_{304L} \\ \rho_{304L} \end{pmatrix}$$

$$Q_{400C.3dpa.Y_{i,j}} := \rho_{400C.3dpa.Y_i} \cdot HR_{400C.3dpa.Y_{i,j}}$$

$$Q_{400C.3dpa.Y} = \begin{pmatrix} 5.986E+003 & 6.662E+003 & 6.72E+003 \\ 7.104E+003 & 7.896E+003 & 7.966E+003 \\ 7.8E+003 & 8.66E+003 & 8.751E+003 \\ 8.749E+003 & 9.723E+003 & 9.815E+003 \\ 9.201E+003 & 1.022E+004 & 1.033E+004 \\ 1.003E+004 & 1.114E+004 & 1.125E+004 \\ 9.561E+003 & 1.063E+004 & 1.073E+004 \\ 8.364E+003 & 9.298E+003 & 9.384E+003 \\ 8.301E+003 & 9.229E+003 & 9.315E+003 \\ 8.187E+003 & 9.103E+003 & 9.189E+003 \\ 7.122E+003 & 7.92E+003 & 7.99E+003 \\ 7.182E+003 & 7.985E+003 & 8.061E+003 \\ 7.318E+003 & 8.131E+003 & 8.207E+003 \\ 5.981E+003 & 6.647E+003 & 6.712E+003 \\ 6.036E+003 & 6.712E+003 & 6.777E+003 \\ 5.887E+003 & 6.543E+003 & 6.603E+003 \\ 9.63E+003 & 1.071E+004 & 1.081E+004 \\ 9.642E+003 & 1.072E+004 & 1.082E+004 \\ 9.282E+003 & 1.031E+004 & 1.042E+004 \\ 8.958E+003 & 9.966E+003 & 1.006E+004 \\ 8.151E+003 & 9.056E+003 & 9.147E+003 \\ 7.628E+003 & 8.479E+003 & 8.56E+003 \\ 6.65E+003 & 7.384E+003 & 7.454E+003 \end{pmatrix} \cdot \frac{lbf}{in^2 \cdot s} \qquad \begin{array}{c} \text{Specimen Number} \\ \begin{pmatrix} 723 \\ 722 \\ 721 \\ 720 \\ 719 \\ 718 \\ 717 \\ 716 \\ 715 \\ 714 \\ 713 \\ 712 \\ 711 \\ 710 \\ 709 \\ 708 \\ 707 \\ 706 \\ 705 \\ 704 \\ 703 \\ 702 \\ 701 \end{pmatrix} \end{array}$$

Appendix C

Computer Code Validation

```
ABQ EXE: abq6142
COMPUTER: falcon1
OS: Linux
OS TYPE: 3.0.101-108.77-default
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
================================================================================
```