ORNL/TM-2022/2593

Interim Mechanical Properties Data from FY22 ORNL Testing of A709 with Precipitation Treatment for ASME Code Case Data Package

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Materials Science and Technology Division

INTERIM MECHANICAL PROPERTIES DATA FROM FY22 ORNL TESTING OF A709 WITH PRECIPITATION TREATMENT FOR ASME CODE CASE DATA PACKAGE

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

Argonne	Argonne National Laboratory
ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
ASTM	ASTM International (formerly American Society for Testing and Materials)
CC	Code Case
CF	creep-fatigue
DOE	US Department of Energy
FR	Fast Reactors
INL	Idaho National Laboratory
LMP	Larson-Miller parameter
MCR	minimum creep rate
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory
PT	precipitation treatment
RT	room temperature
UTS	ultimate tensile strength

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ABSTRACT

A collaborative research and development effort in support of the Alloy 709 Code Case qualification in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors is being conducted at the US Department of Energy's Oak Ridge National Laboratory, Idaho National Laboratory, and Argonne National Laboratory. A recent assessment on the Alloy 709 development and testing effort concluded that the mechanical properties of Alloy 709 with the precipitation treatment continued to outperform those of Type 316 stainless steel. The assessment also affirmed the recommendation for its Code qualification. This report provides the detailed integrated data generated to date on the two commercial heats of Alloy 709 in plate product form with precipitation treatment condition that were used as the basis for this assessment.

Oak Ridge National Laboratory has continued to perform a subset of the Code Case testing for tensile properties, creep rupture, fatigue, and creep-fatigue. This report also updates the key Alloy 709 Code Case testing status and results in FY 2022 at Oak Ridge National Laboratory.

1. INTRODUCTION

Nuclear energy has great potential as an energy source to reduce carbon emissions. It can be used to produce electricity and facilitate a carbon-zero electric-industry sector. The sodium-cooled fast reactor (SFR) can improve thermal effectiveness and is becoming one of the leading advanced reactor concepts. Although SFR technology is relatively mature, its capital cost and economic return must be improved before the private sector invests in large-scale commercial deployment of SFRs. Advances in the mechanical performance of its structural materials are critical to improve the economics of fast reactors. One objective of the advanced materials development activities of the US Department of Energy (DOE) Office of Nuclear Energy (NE) Advanced Reactor Technologies (ART) Program is to provide the technical basis needed to support the regulatory requirements for structural materials for advanced reactors that could be deployed in the near- to mid-term by the US nuclear industry.

Through a DOE-NE ART material down-selection and intermediate term testing program, Alloy 709, an advanced austenitic stainless steel alloy, was recommended as a Class A structural material for the SFR because of its overall superior structural strength advantage (Sham et al. 2022). A comprehensive Code qualification plan was developed to generate the data package and to develop material-specific design parameters required for Class A component design in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 5. A multi-laboratory advanced materials development effort involving the DOE's Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), and Argonne National Laboratory (Argonne) is being conducted to investigate the mechanical performance of Alloy 709 in support of its codification process.

The ASME Code Cases data package requires evaluation of mechanical properties, including tensile properties, creep, fatigue, and creep-fatigue (CF) from base metal as well as additional tests on its welds. To this end, this report summarized the progress at ORNL in FY 2022 and integrates results of Alloy 709 Code Cases testing effort from the three labs.

2. MATERIAL

The data package for code qualification must contain a minimum of three commercial heats, which represent the anticipated compositional ranges. In collaboration with two US steel fabricators, DOE-NE ART successfully scaled up the production of Alloy 709 in plate form from a laboratory heat of 500 lb to three commercial heats of the Alloy 709: commercial heat 1 of 45,000 lb, commercial heat 2 of 41,000 lb, and commercial heat 3 of 38,000 lb. The commercial heat 1 plates were fabricated by G.O. Carlson Inc of Pennsylvania, and the heats 2 and 3 were both fabricated by Allegheny Technologies Incorporated.

The plates used in the Code Case testing were produced by argon-oxygen-decarburization (AOD) followed by electroslag remelting (ESR). The plates were hot rolled, and solution annealed at a minimum temperature 1,150°C. The plates were further heat treated at 775°C for 10 h in air and then air cooled to ensure a balanced creep and CF performance (McMurtrey et al. 2019). This heat treatment protocol was developed by Zhang et al. (2019).

This report summarizes the Code Case testing results from commercial heat 1 and commercial heat 2 with precipitation treatment (PT) condition. The commercial heat 3 plates are being prepared for testing at the time of this report being written, and its results will be added to the Code Case testing matrix in FY 2023.

Table 1 summarizes the information regarding these three commercial heats of Alloy 709 plates. The specimens used for Code Case testing were machined along the rolling direction at the mid-thickness for the commercial heat 1 plates and at the 1/4-thickness for the commercial heat 2 plates.

Table 1. Three commercial heats of Alloy 709 in plate form

Material	Fabricator	Master heat number	Plate ID for base metal Code Case testing	Plate thickness (in.)
Commercial heat 1	G.O. Carlson Inc	58776	58776-3RBC1	1.125
Commercial heat 2	Allegheny Technologies Incorporated	529900	CG05455	1.81
Commercial heat 3	Allegheny Technologies Incorporated	530843	To be determined	1.81

The chemical compositions of Alloy 709 with the heat number 58776 (commercial Heat-1) and 529900 (commercial Heat-2) are listed in Table 2. For comparison, the specifications for the chemical requirements of Nippon Steel NF709, TP310MoCbN, seamless tubing, with a UNS number of S31025 in ASME SA-213 (ASME, 2021) are also listed in Table 2. Both commercial heats met the specified NF709 chemical requirements.

Table 2. Chemical compositions of the two commercial heat Alloy 709 plates with heat number 58776 and 529900 (wt.%)

Element	Commercial heat 1	Commercial heat 2	ASME SA-213 UNS-S31025 specification
	(wt.%)	(wt.%)	(wt.%)
C	0.066	0.08	0.10 max
Cr	20.05	19.9	19.5–23.0
Co	0.02	0.02	—
Ni	25.14	24.6	23.0–26.0
Mn	0.9	0.9	1.50 max
Mo	1.51	1.5	1.0–2.0
N	0.152	0.15	0.10–0.25
Si	0.38	0.39	1.00 max
P	0.014	0.003	0.030 max
S	0.001	<0.001	0.030 max
Ti	0.01	<0.01	0.20 max
Nb	0.26	0.17	0.10–0.40
Al	0.02	0.02	—
B	0.003	0.004	0.002–0.010
Cu	0.06	0.06	—
Fe	balance	balance	balance

3. TENSILE CODE CASE TESTING

3.1 TENSILE CODE CASE TESTING AT ORNL

The tensile test specimen geometry used at ORNL is shown in Figure 1, and the tensile specimens were machined along the rolling direction of the Alloy 709 plates.

A total of 80 tensile tests on commercial heat 1 and commercial heat 2 in PT condition were completed at ORNL. The testing temperature ranged from room temperature (RT) to 1,000°C. Two duplicated tests were performed at each temperature for each material. The tensile testing procedure followed ASTM International (ASTM) E8/E8M (ASTM, 2022) at RT and ASTM E21 (ASTM, 2020a) at elevated temperatures.

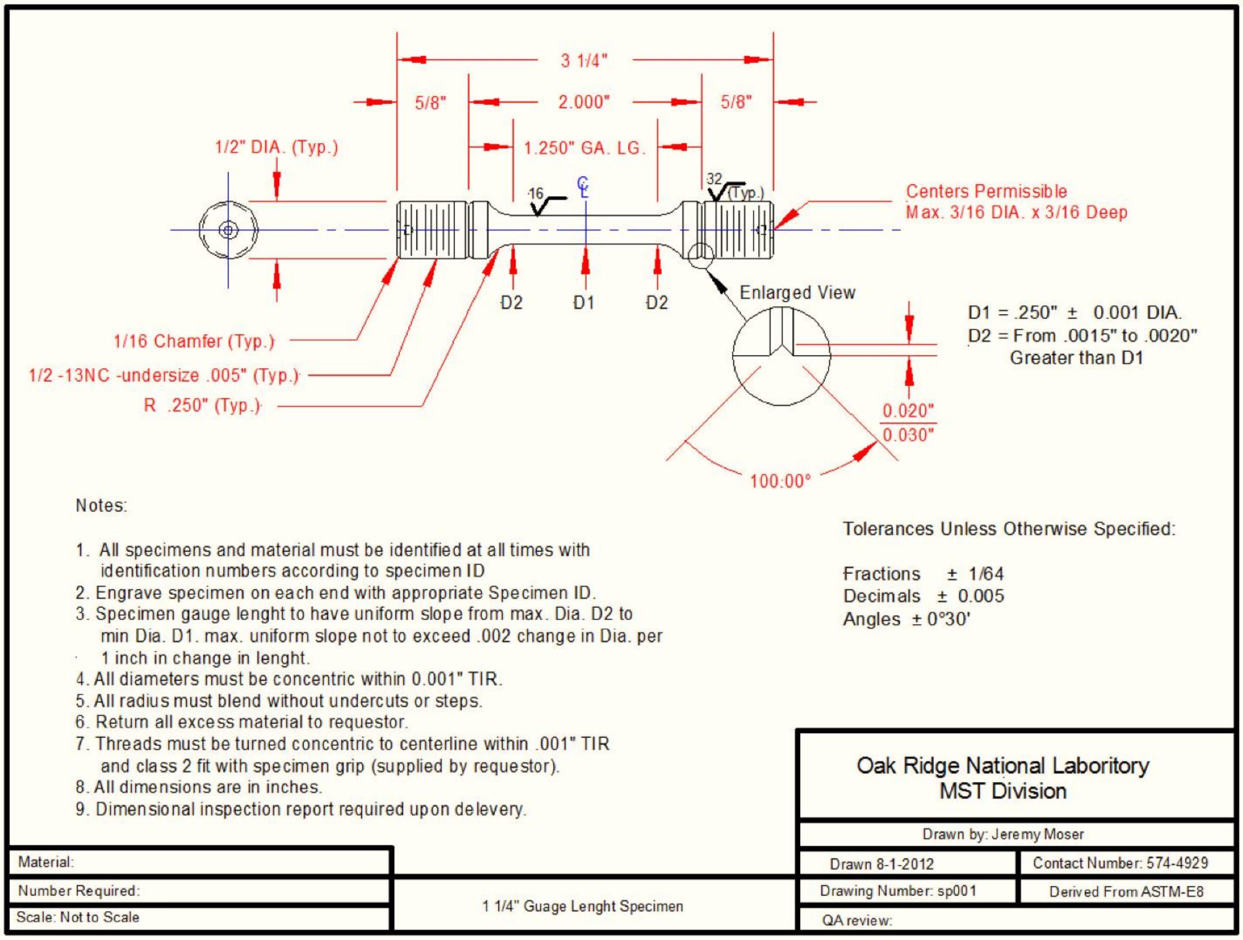

Figure 1. Standard tensile specimen geometry used at ORNL. Dimensions are in inches.

3.2 TENSILE RESULTS

The RT tensile stress–strain curves of commercial heat 1-PT condition (Heat 1-PT) and commercial heat 2-PT condition (Heat 2-PT) are plotted in Figure 2, and the RT tensile properties, including the yield strength, σ_Y, taken as the stress at 0.2% strain offset, the ultimate tensile strength (UTS), and the total elongation, e_t, are summarized in Table 3. The minimum specified RT tensile properties of Alloy 709 per ASME SA-213 UNS-S31025 specification (ASME 2021) are also listed in Table 3. The RT tensile test results confirm that the two commercial heats of Alloy 709 in PT condition meet ASME SA-213 requirements.

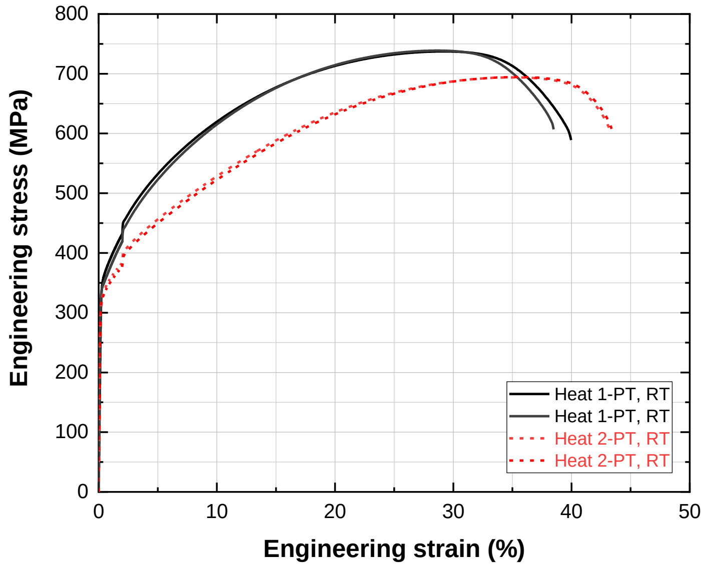

Figure 2. RT tensile stress–strain curves of Alloy 709 in PT condition.

Table 3. RT tensile properties of the two commercial heats Alloy 709-PT condition

Material	RT test number	σ_Y (MPa)	*UTS* (MPa)	e_t (%)
Commercial heat 1-PT condition	1	359	747	40.0
	2	367	748	38.5
Commercial heat 1-PT condition	1	328	701	43.3
	2	330	701	43.4
ASME SA-213 UNS-S31025 specification		270 minimum	640 minimum	30 minimum

In all cases of the tensile tests on both materials, the stress-strain curves for the two sets of tensile tests under the same testing conditions are comparable. For demonstration, one set of tensile stress–strain curves at elevated temperatures for each commercial heat in PT condition are presented in Figure 3. Under the test conditions in this study, the dynamic strain aging behavior was evident at temperatures between 500°C and 625°C for the commercial heat 1-PT condition, and at slightly higher temperatures between 550°C and 675°C for the commercial heat 2-PT condition. At temperatures lower than 700°C, the commercial heat 1-PT condition showed slightly higher yield and tensile strength and lower total elongation than the commercial heat 2-PT condition. No significant differences were observed in the tensile behavior and tensile properties of these two materials at temperatures of 750°C and above.

At test temperatures of 850°C and above, both materials exhibited total elongation larger than 80%, and the specimens did not exhibit discrete tensile fracture load until separation. In these cases, the total elongation is reported as where the applied engineering stress is below 10 MPa.

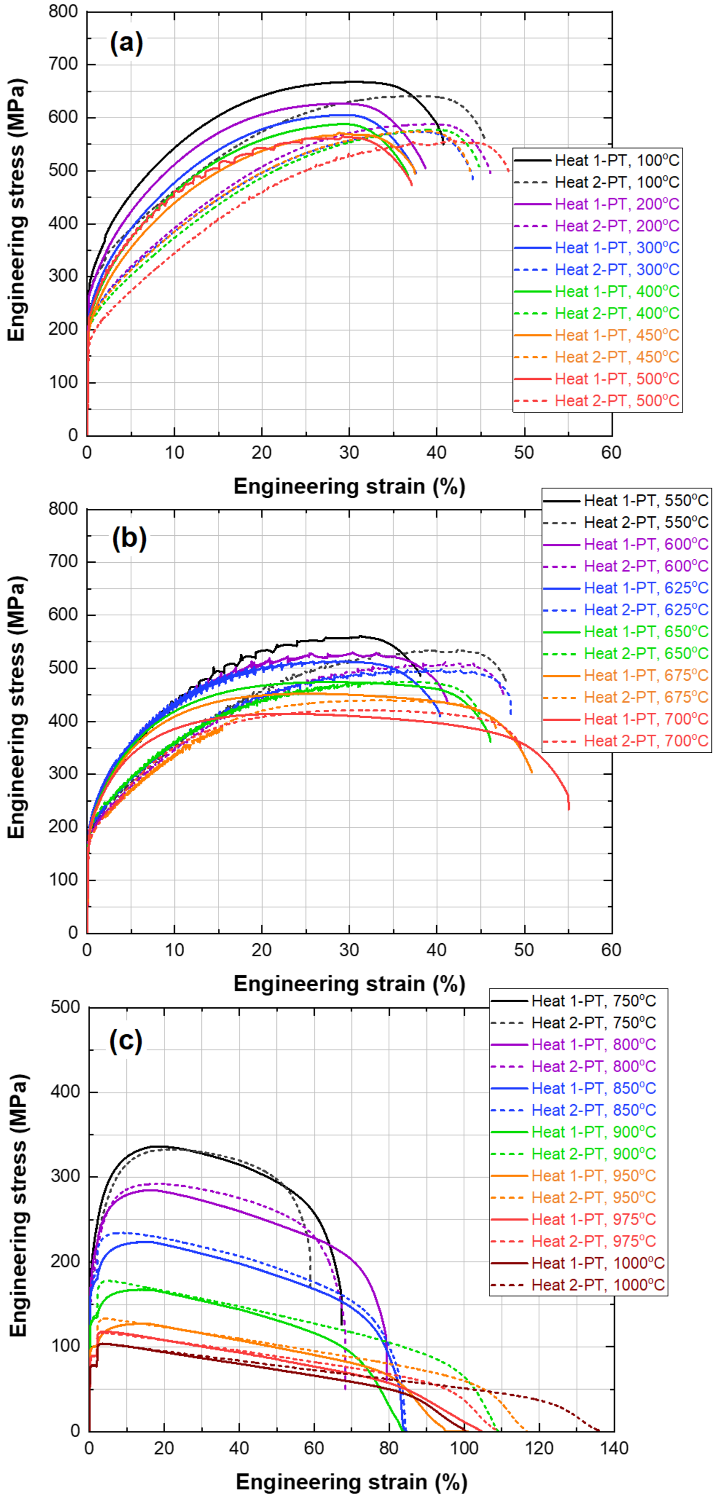

Figure 3. Tensile stress–strain curves of Alloy 709 in PT condition at various temperatures. (a) 100°C to 500 °C, (b) 550°C to 700°C, and (c) 750°C to 1,000°C.

The tensile test parameters and results for the two commercial heats of Alloy 709 in PT condition are summarized in Table 4 and Table 5, respectively. The tensile properties reported in these tables include yield strength at 0.2% strain offset, σ_Y, the UTS, the uniform elongation, e_u, total elongation, e_t, and reduction of area (ROA). The tensile properties as a function of the test temperature are presented in Figure 4.

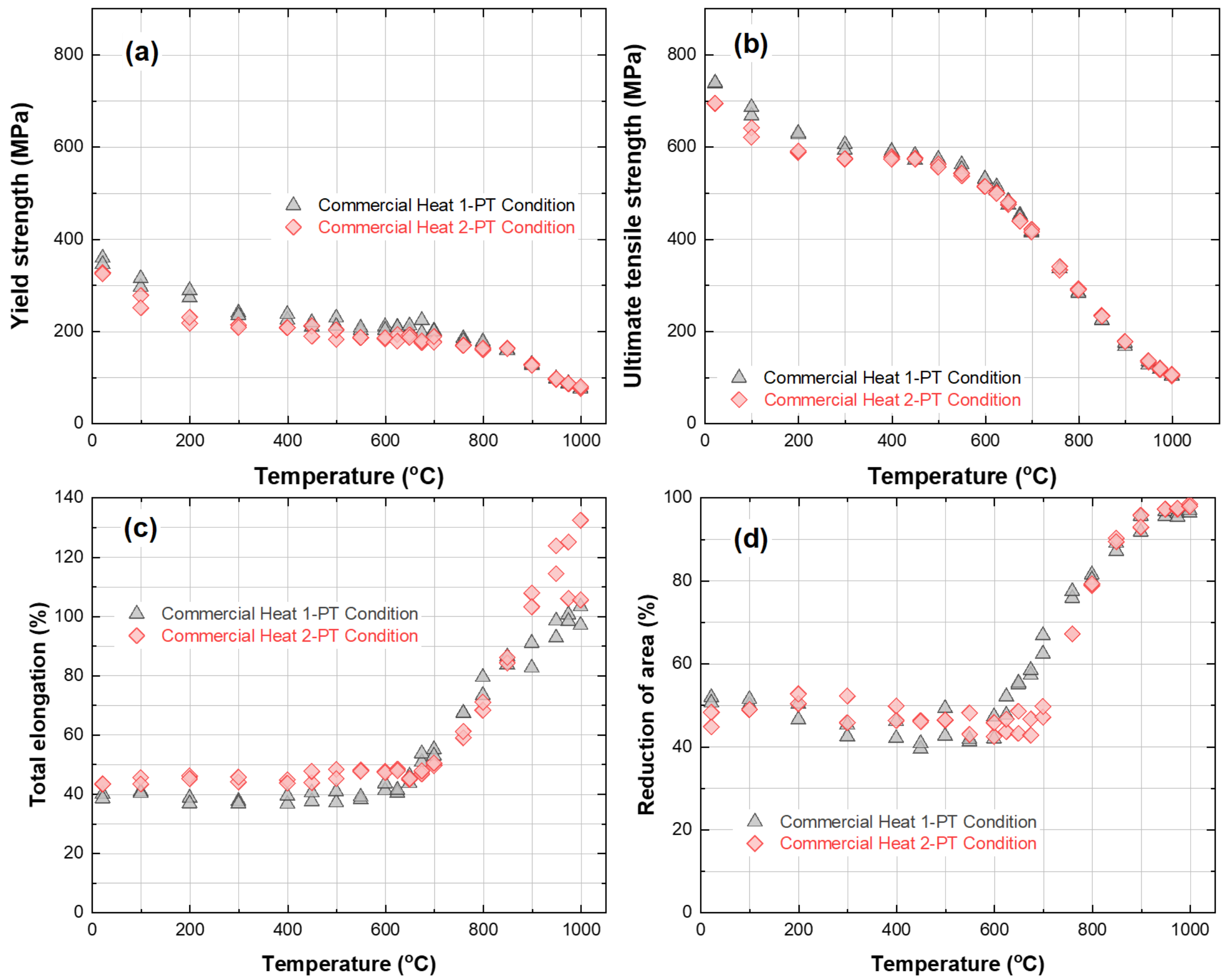

Figure 4. Tensile properties of the two commercial heats of Alloy 709 in PT condition. (a) Yield strength, (b) UTS, (c) total elongation, and (d) ROA.

Table 4. Tensile properties of commercial Heat-1 Alloy 709 in PT condition (Heat number 58776)

Test number	Temperature (°C)	σ_Y (MPa)	UTS (MPa)	e_u (%)	e_t (%)	ROA (%)
1	RT	359	747	26.3	40.0	52.6
2	RT	367	748	26.4	38.5	52.9
3	100	296	668	30.8	40.7	50.0
4	100	315	686	28.6	40.3	51.4
5	200	273	627	29.1	38.7	46.5
6	200	289	630	27.3	36.8	50.3
7	300	240	606	29.6	37.6	45.3
8	300	234	593	29.2	36.8	42.4
9	400	224	588	29.4	36.7	46.0
10	400	237	591	28.0	39.4	42.0
11	450	210	571	28.8	37.5	39.4
12	450	219	582	29.5	40.5	40.8
13	500	229	565	29.3	37.1	42.6
14	500	211	574	27.3	40.8	49.2
15	550	202	562	31.2	38.1	41.2
16	550	207	552	28.6	39.0	41.8
17	600	210	530	30.4	41.2	41.9
18	600	202	531	27.6	43.6	47.2
19	625	209	514	28.4	40.3	47.6
20	625	208	505	27.0	41.3	52.1
21	650	200	474	28.1	46.1	55.0
22	650	212	483	25.9	43.6	55.4
23	675	196	452	25.2	50.8	57.2
24	675	224	448	21.5	53.7	58.4
25	700	201	414	22.2	55.0	62.4
26	700	199	417	22.5	52.9	66.8
27	760	185	336	18.5	67.3	75.8
28	760	179	336	17.3	67.3	77.4
29	800	173	285	16.2	79.4	81.5
30	800	177	283	11.8	73.3	80.2
31	850	161	224	15.1	83.6	87.1
32	850	158	224	7.0	86.4	89.0
33	900	126	167	14.2	82.6	95.5
34	900	129	175	5.2	90.9	91.7
35	950	97	127	14.3	92.7	95.4
36	950	97	135	4.9	98.4	96.7
37	975	87	118	3.7	100.6	96.3
38	975	86	119	3.7	98.3	95.4
39	1,000	77	104	3.7	97.0	96.3
40	1,000	74	102	3.7	103.2	97.0

Table 5. Tensile properties of commercial Heat-2 Alloy 709 in PT condition (Heat number 529900)

Test number	Temperature (°C)	σ_Y (MPa)	UTS (MPa)	e_u (%)	e_t (%)	ROA (%)
41	RT	328	701	38.9	43.3	49.7
42	RT	330	701	39.3	43.4	48.9
43	100	277	641	37.4	45.5	48.9
44	100	251	621	35.9	43.3	48.9
45	200	217	588	39.4	46.1	50.3
46	200	231	591	38.3	45.2	52.7
47	300	213	573	38.3	44.1	52.2
48	300	208	574	40.4	45.7	45.8
49	400	208	578	39.8	44.8	49.8
50	400	208	574	38.4	43.6	46.3
51	450	212	576	35.7	43.8	46.3
52	450	189	573	42.1	47.6	46.0
53	500	182	562	41.5	48.3	46.3
54	500	203	556	40.8	45.2	46.4
55	550	186	537	42.5	48.1	48.1
56	550	186	542	42.7	47.7	42.9
57	600	183	514	41.0	47.6	42.5
58	600	186	514	37.8	47.2	45.8
59	625	193	500	38.7	48.4	43.6
60	625	178	499	37.9	47.9	46.6
61	650	192	475	34.5	44.9	48.6
62	650	187	479	36.4	45.2	43.2
63	675	175	440	33.5	46.8	42.8
64	675	179	439	32.7	47.7	46.6
65	700	176	421	31.7	49.6	47.1
66	700	188	415	29.6	50.4	49.7
67	760	170	333	21.9	59.0	67.2
68	760	169	340	23.4	61.1	67.2
69	800	160	292	18.6	68.3	78.8
70	800	163	289	16.1	71.0	79.2
71	850	164	234	7.6	84.3	90.2
72	850	162	233	8.0	86.1	89.4
73	900	128	178	4.7	107.8	95.8
74	900	126	178	5.1	103.2	92.9
75	950	96	133	4.0	114.4	97.2
76	950	97	136	4.0	123.8	97.2
77	975	86	117	4.0	106.0	97.2
78	975	87	119	3.6	125.0	97.4
79	1,000	76	104	3.5	132.4	98.5
80	1,000	80	106	3.3	105.3	97.9

4. CREEP CODE CASE TESTING

A comprehensive master creep testing matrix for Alloy 709 Code Case testing was developed for commercial heat 1 and commercial heat 2 plates in PT condition. The testing activities and research to support the qualification of Alloy 709 are being carried out at Argonne, INL, and ORNL.

The creep testing matrix was used to generate data in support of the development of a series of Code Cases: preliminary Code Case (prelim CC), 100,000 h Code Case (100K CC), 300,000 h Code Case (300K CC), and 500,000 h Code Case (500K CC). The creep Code Case testing plan, the corresponding supporting creep rupture data, and the responsible laboratories are summarized in Table 6. ORNL is tasked to carry out all the long-term creep rupture tests in support of the 300K CC and 500K CC in addition to a subset of the tests designed for the development of the preliminary CC and 100K CC.

Table 6. Creep Code Case testing on the two commercial heats of Alloy 709 in PT condition

Target Code Case	Supporting creep rupture data (h)	Labs involved
Prelim CC	500–10,000	Argonne/INL/ORNL
100K CC	15,000–24,000	Argonne/INL/ORNL
300K CC	25,000–68,000	ORNL
500K CC	91,000–109,000	ORNL

4.1 CREEP RUPTURE CODE CASE TESTING AT ORNL

The specimen geometry for creep Code Case testing used at ORNL is shown in Figure 5. The creep specimen was designed to have a 9.53 mm (0.375 in.) gage diameter and a nominal gauge length of 47.63 mm (1.875 in.). The larger-than-normal 6.35 mm (0.25 in.) diameter creep specimen geometry was used to reduce the oxidation effect during long-term creep testing. The testing procedure followed ASTM E139-11 (ASTM, 2018), *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials*. The creep tests were arranged to best utilize the individual creep machine capacity and estimated testing duration.

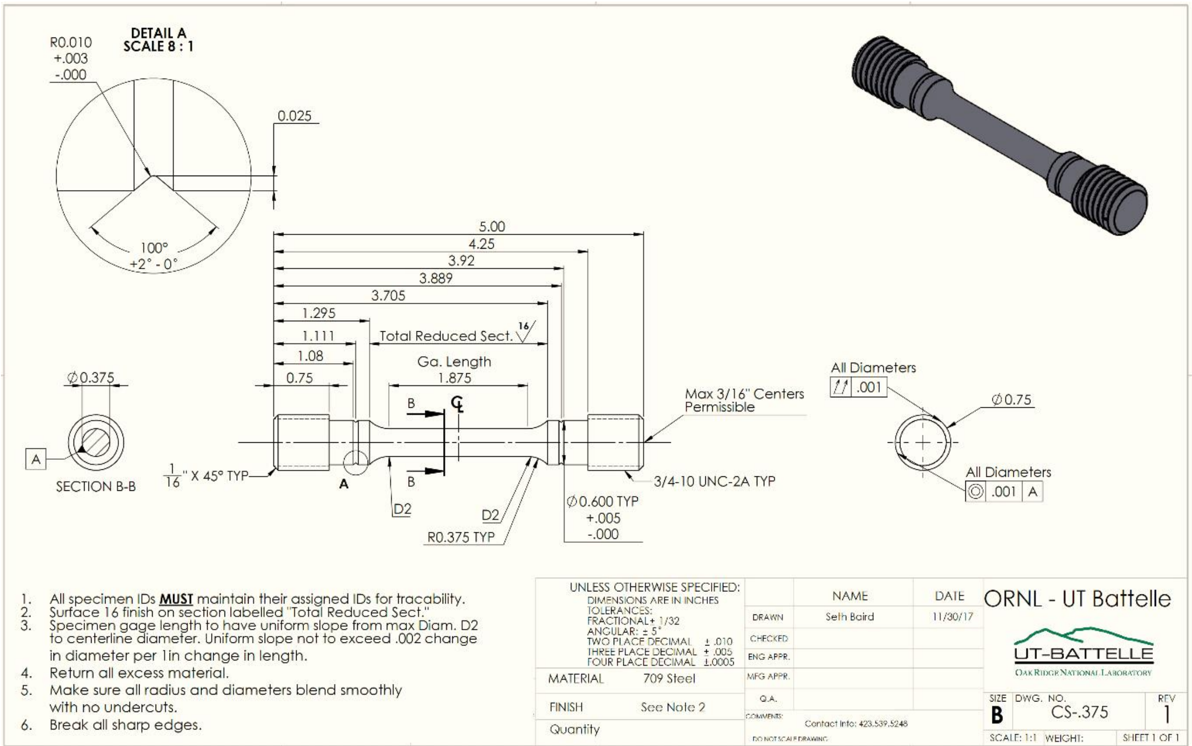

Figure 5. Creep specimen geometry for Alloy 709 Code Case testing used at ORNL. Dimensions are in inches.

In FY 2022, the creep rupture Code Case testing effort on the two commercial heat Ally 709 in PT condition at ORNL is summarized as follows:

- Creep Code Case testing on commercial heat 1-PT condition
  - Two long-term tests in support of 500K CC continued.
  - One new long-term test in support of 500K CC started.
  - Two long-term tests in support of 300K CC continued.
  - Two long-term tests in support of 100K CC continued.
- Creep Code Case testing on commercial heat 2-PT condition
  - All four long-term tests in support of 500K CC started.
  - All three long-term tests in support of 300K CC started.
  - Two long-term tests in support of 100K CC started.
  - Fifteen short-term creep rupture data were generated in support of prelim CC.

The creep rupture Code Case testing parameters and status of the two commercial heats of Alloy 709 in PT condition at ORNL as of FY 2022 are listed in Table 7 and Table 8.

Table 7. FY 2022 creep rupture Code Case testing status on commercial Heat-1-PT condition at ORNL

Temperature (°C)	Stress (MPa)	Code Case	Status
575	200	500K CC	Ongoing
750	45	500K CC	Ongoing
650	110	500K CC	Ongoing
600	175	300K CC	Ongoing
625	140	300K CC	Ongoing
700	90	100K CC	Ongoing
800	35	100K CC	Ongoing
850	30	prelim CC	Ongoing
875	24	prelim CC	Ruptured
900	20	prelim CC	Ruptured
925	15	prelim CC	Ruptured
875	30	prelim CC	Ruptured
975	11	prelim CC	Ruptured
900	24	prelim CC	Ruptured
1,000	7	prelim CC	Ruptured
925	20	prelim CC	Ruptured
950	15	prelim CC	Ruptured
900	30	prelim CC	Ruptured
975	15	prelim CC	Ruptured
1,000	10	prelim CC	Ruptured
975	15	prelim CC	Ruptured
925	24	prelim CC	Ruptured
950	20	prelim CC	Ruptured

Table 8. FY 2022 creep rupture Code Case testing status on commercial Heat-2-PT condition at ORNL

Temperature, (°C)	Stress (MPa)	Code Case	Status
700	70	500K CC	Ongoing
825	21	500K CC	Ongoing
875	12	500K CC	Ongoing
925	8	500K CC	Ongoing
600	175	300K CC	Ongoing
625	150	300K CC	Ongoing
825	24	300K CC	Ongoing
650	140	100K CC	Ongoing
700	90	100K CC	Ongoing
675	140	prelim CC	Ongoing
775	82	prelim CC	Ongoing
850	30	prelim CC	Ongoing
925	27	prelim CC	Ongoing
950	20	prelim CC	Ongoing
1,000	10	prelim CC	Ongoing
1,000	7	prelim CC	Ongoing
975	15	prelim CC	Ruptured
675	175	prelim CC	Ruptured
875	35	prelim CC	Ruptured
975	13	prelim CC	Ruptured
925	24	prelim CC	Ruptured
925	30	prelim CC	Ruptured
900	30	prelim CC	Ruptured
950	24	prelim CC	Ruptured
800	75	prelim CC	Ruptured
900	35	prelim CC	Ruptured
750	110	prelim CC	Ruptured
825	65	prelim CC	Ruptured
725	140	prelim CC	Ruptured
975	20	prelim CC	Ruptured
925	35	prelim CC	Ruptured

4.2 INTEGRATED CREEP RUPTURE RESULTS

As of FY 2022, ORNL, INL, and Argonne have collectively generated a total of 44 creep rupture data on commercial Heat-1-PT condition and 22 on commercial Heat-2-PT condition. The creep rupture life vs. test count for the two commercial heats of Alloy 709 in PT condition is presented in Figure 6.

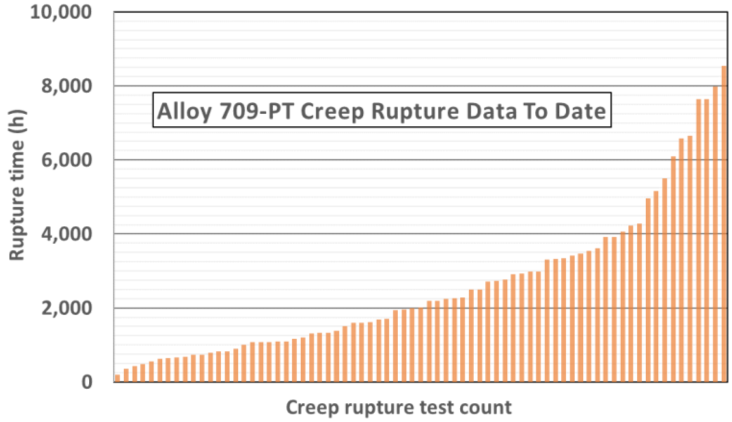

Figure 6. Creep rupture test count for the two commercial heats of Alloy 709 in PT condition.

To make a preliminary assessment of the creep resistance of the Alloy 709 material, the rupture data generated on the two commercial heats of Alloy 709 in PT conditions were assembled and the results are presented in the form of the Larson-Miller relationship in Figure 7. In this plot, the Larson-Miller parameter (LMP) was based on Eq. (1):

$$LMP = (T + 273.15) * (16.6958 + \log t_r), \quad (1)$$

where T is temperature in degrees Celsius and t_r is rupture life in hours.

This preliminary analysis indicates that the commercial heat-2-PT condition has slightly higher creep strength than the commercial heat-1-PT condition.

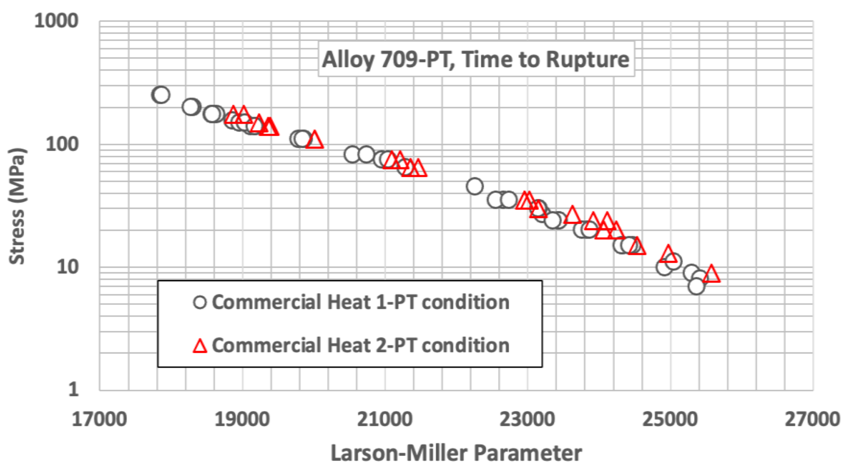

Figure 7. Creep rupture data from the two commercial heats of Alloy 709 in PT condition collected to data on the LMP-stress plot.

To develop the allowable stress tables for codification in ASME Section III Division 5, parameters such as time to 1% strain and time to tertiary are needed to be extracted from the creep curves. The available creep curves collected by ORNL, INL, and Argonne were analyzed. The results, along with the minimum creep rate (MCR), are summarized in Table 9.

Table 9. Creep rupture Code Case testing data to date on commercial Heat 1-PT and commercial Heat 2-PT

Test lab	Material	Temp. (°C)	Stress (MPa)	Time to 1% strain (h)	Time to tertiary (h)	MCR (%/h)
Argonne	Heat 2-PT	775	75	158	2,155	5.61×10^{-3}
Argonne	Heat 2-PT	725	110	191	1,347	6.23×10^{-3}
Argonne	Heat 2-PT	700	140	171	406	5.28×10^{-3}
Argonne	Heat 2-PT	700	150	86	268	6.64×10^{-3}
Argonne	Heat 2-PT	700	175	0	140	1.38×10^{-2}
Argonne	Heat 1-PT	775	82	89	589	1.26×10^{-2}
Argonne	Heat 1-PT	800	75	70	496	1.40×10^{-2}
Argonne	Heat 1-PT	700	110	446	3,985	2.03×10^{-3}
Argonne	Heat 1-PT	750	110	45	174	2.17×10^{-2}
Argonne	Heat 1-PT	725	110	173	928	6.22×10^{-3}
Argonne	Heat 1-PT	725	140	39	135	2.68×10^{-2}
Argonne	Heat 1-PT	675	150	326	719	2.62×10^{-3}
Argonne	Heat 1-PT	700	140	109	243	6.86×10^{-3}
Argonne	Heat 1-PT	700	150	83	238	1.00×10^{-2}
Argonne	Heat 1-PT	650	175	479	1,092	1.57×10^{-3}
Argonne	Heat 1-PT	775	75	267	1,399	2.89×10^{-3}
Argonne	Heat 1-PT	675	140	384	852	1.84×10^{-3}
Argonne	Heat 1-PT	675	175	132	366	6.31×10^{-3}
Argonne	Heat 1-PT	650	200	54	583	2.93×10^{-3}
Argonne	Heat 1-PT	625	200	105	1,949	6.33×10^{-4}
Argonne	Heat 1-PT	625	250	0	938	3.70×10^{-3}
Argonne	Heat 1-PT	600	250	0	3,923	7.13×10^{-4}
INL	Heat 2-PT	1,000	9	1,426	997	9.80×10^{-5}
INL	Heat 2-PT	900	27	1,566	1,232	2.81×10^{-4}
INL	Heat 2-PT	800	65	210	1,390	5.33×10^{-3}
INL	Heat 1-PT	1,000	9	915	678	2.56×10^{-4}
INL	Heat 1-PT	1,000	8	1,002	755	3.27×10^{-4}
INL	Heat 1-PT	875	35	636	527	7.19×10^{-4}
INL	Heat 1-PT	925	35	67	51	5.70×10^{-3}
INL	Heat 1-PT	925	27	288	234	1.40×10^{-3}
INL	Heat 1-PT	850	35	1,997	1,547	2.12×10^{-4}
INL	Heat 1-PT	850	45	709	696	5.63×10^{-4}
INL	Heat 1-PT	800	65	277	876	3.94×10^{-3}
INL	Heat 1-PT	750	82	371	3,354	2.41×10^{-3}
INL	Heat 1-PT	650	155	656	1,798	1.15×10^{-3}

Table 9. (continued)

Test lab	Material	Temp. （°C）	Stress （MPa）	Time to 1% strain （h）	Time to tertiary (h)	MCR (%/h)
INL	Heat 1-PT	700	175	21.0	155	4.46×10^{-2}
INL	Heat 1-PT	650	175	301.0	935	1.09×10^{-3}
ORNL	Heat 2-PT	925	24	1,231.7	766.6	1.93×10^{-4}
ORNL	Heat 2-PT	925	35	68.5	63.8	1.06×10^{-2}
ORNL	Heat 2-PT	975	20	116.9	99.7	4.79×10^{-3}
ORNL	Heat 2-PT	900	30	561.7	392.7	6.39×10^{-4}
ORNL	Heat 2-PT	950	20	763.6	738.0	9.43×10^{-4}
ORNL	Heat 2-PT	975	13	1,168.7	1,535.9	1.89×10^{-3}
ORNL	Heat 2-PT	900	35	194.0	221.8	4.24×10^{-3}
ORNL	Heat 2-PT	800	75	72.5	503.6	1.21×10^{-2}
ORNL	Heat 2-PT	875	35	871.7	848.0	8.36×10^{-4}
ORNL	Heat 2-PT	950	24	449.0	393.6	1.08×10^{-3}
ORNL	Heat 2-PT	750	110	69.8	103.4	1.18×10^{-2}
ORNL	Heat 2-PT	825	65	34.3	184.1	2.62×10^{-2}
ORNL	Heat 2-PT	725	140	41.6	102.9	1.80×10^{-2}
ORNL	Heat 2-PT	675	175	204.8	483.0	2.80×10^{-3}
ORNL	Heat 1-PT	925	20	1,258.6	1,049.5	3.18×10^{-4}
ORNL	Heat 1-PT	1,000	10	521.8	376.4	4.06×10^{-4}
ORNL	Heat 1-PT	975	11	1,592.8	1,434.5	1.04×10^{-3}
ORNL	Heat 1-PT	975	15	638.0	534.4	9.01×10^{-4}
ORNL	Heat 1-PT	1,000	7	1,158.7	822.1	3.31×10^{-6}
ORNL	Heat 1-PT	950	20	343.7	233.7	3.76×10^{-4}
ORNL	Heat 1-PT	900	20	3,714.4	3,516.9	1.82×10^{-4}
ORNL	Heat 1-PT	900	30	645.1	465.7	4.51×10^{-4}
ORNL	Heat 1-PT	900	24	1,529.8	1,273.6	2.41×10^{-4}
ORNL	Heat 1-PT	875	30	1,833.0	1,530.7	2.55×10^{-4}
ORNL	Heat 1-PT	925	15	3,736.7	3,035.1	2.21×10^{-5}
ORNL	Heat 1-PT	875	24	4,514.6	4,686.1	2.07×10^{-4}
ORNL	Heat 1-PT	925	24	393.3	626.7	5.40×10^{-3}
ORNL	Heat 1-PT	950	15	886.6	687.5	2.38×10^{-4}
ORNL	Heat 1-PT	975	15	475.9	406.4	7.34×10^{-4}

5. FATIGUE AND CREEP-FATIGUE CODE CASE TESTING

5.1 FATIGUE AND CREEP-FATIGUE CODE CASE TESTING AT ORNL

A strain-controlled fatigue testing matrix and a CF testing matrix were developed to generate temperature-dependent fatigue design curves and CF interaction damage diagrams as part of the data package to help develop the Code Case for Alloy 709. The fatigue and CF Code Case testing efforts are tasked to ORNL and INL.

The standard fatigue or CF specimen geometry used at ORNL is shown in Figure 8. The specimen has a gage diameter of 6.35 mm (0.25 in.) and a 19.05 mm (0.75 in.) gage length.

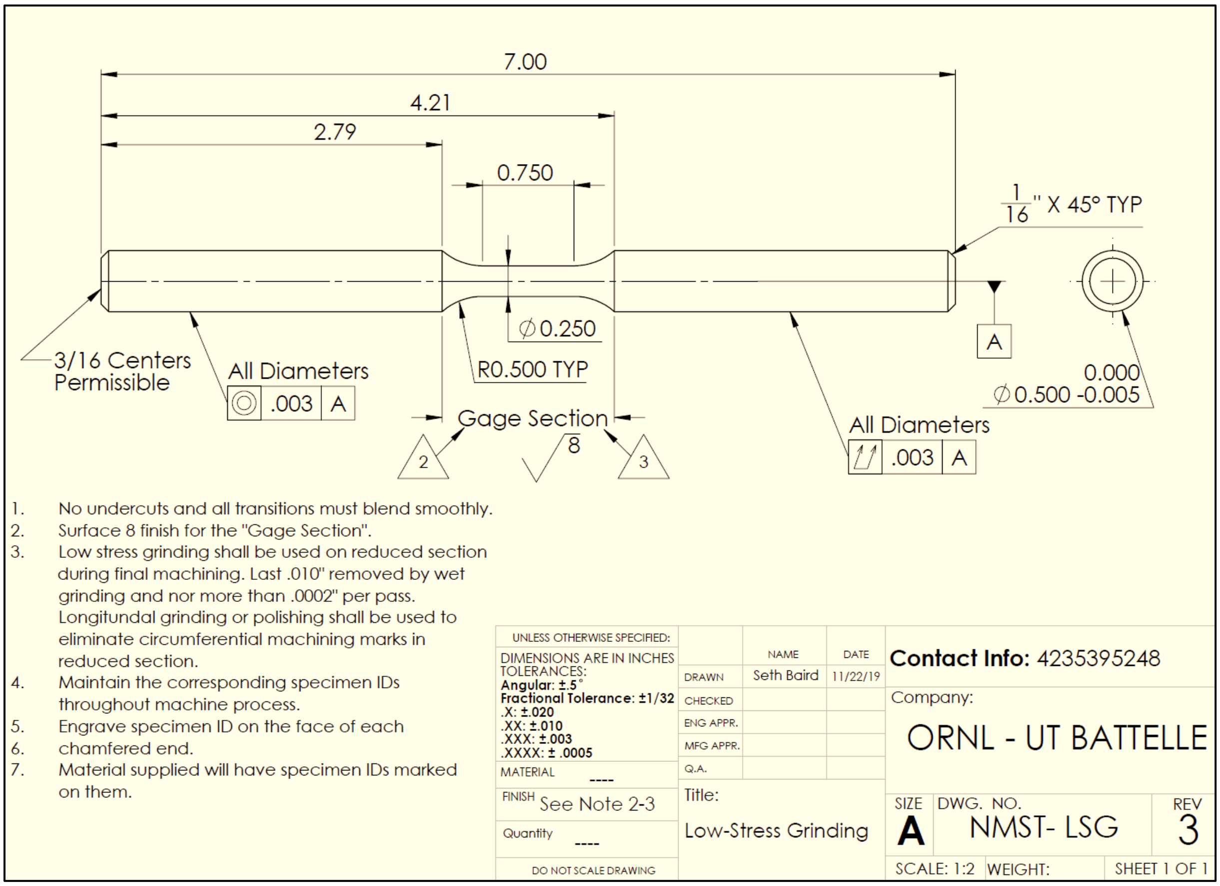

Figure 8. Standard fatigue and CF specimen geometry used at ORNL. Dimensions are in inches.

The testing procedure for strain-controlled fatigue and CF is as follows:

- The fatigue testing followed the ASTM E606 (ASTM, 2021) standard for conducting strain-controlled fatigue tests. The strain rate was controlled at 1×10^{-3} s^{-1}. A triangular loading waveform with a fully reversed profile (i.e., a loading ratio of $R = -1$), was employed.

- The CF testing followed the ASTM E606 (ASTM, 2021) and/or ASTM E2714-13 (ASTM, 2020b) standard for conducting creep fatigue testing under strain-controlled conditions. The loading waveform was fully reversed with various hold times applied at the peak tensile strain. The loading and unloading strain rate were controlled at 1×10^{-3} s^{-1}.

Additionally, at strain ranges below 0.3% and where the material behaves elastically, several fatigue tests were performed under load-controlled mode with the cycling frequency increased to 2.5Hz to generate failure data. The purpose of these tests was to assess the fatigue strength at the low strain ranges and high-cycle region within a reasonable testing duration. Extensometers were used during these loading-controlled tests to record the strain ranges.

To develop the temperature-dependent fatigue design curves and CF interaction damage diagram, the cycles to failure are required to be extracted from the test data. In this report, the failure criteria are defined as the 20% drop in the ratio of the maximum stress to the minimum stress as a function of the applied cycles. Figure 9 schematically illustrates the failure criteria and the approach to determine the 20% drop. In some cases, the specimens failed to meet the 20% drop criteria, and the end-of-test cycles are reported for reference. For the final data package in developing the Alloy 709 Code Case, the fatigue and CF test results will be further screened to exclude data that are not qualified for ASME code development.

A total of 34 fatigue failure data and 23 CF test to failure data were completed on Alloy 709-PT at ORNL. A summary of fatigue and CF tests is provided in the following sections.

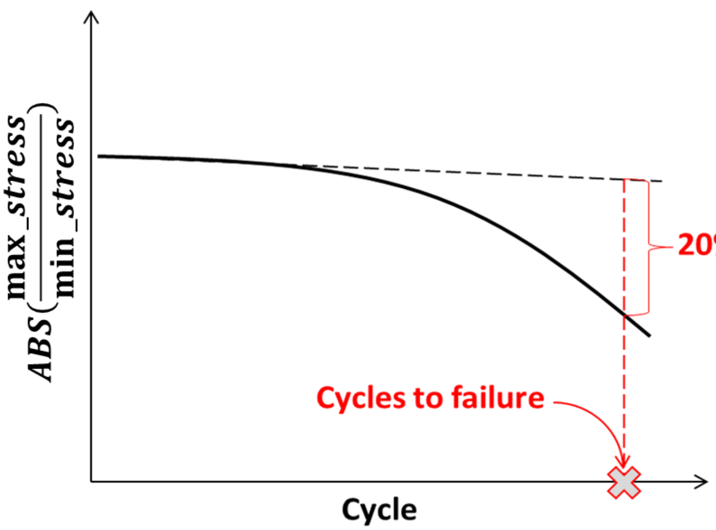

Figure 9. Schematic of the failure criteria in identifying the cycles to failure for fatigue and CF

5.2 CREEP-FATIGUE TESTING RESULTS AT ORNL

In FY 2022, 23 CF tests were completed on the two commercial heats of Alloy 709 in PT condition at ORNL. A summary of CF test parameters and results is provided in Table 11. The evolution of maximum and minimum stresses for these CF tests are presented in Figure 10 and Figure 11. The results also show that the effect of hold time on the evolution and the magnitude of the maximum and minimum stresses is insignificant at a given test temperature and strain range. Figure 12 compares CF test data with different hold times along with the pure fatigue (PF) test at the same strain range. Generally, increasing the hold time led to decreasing CF life cycles, but this effect was not as significant at the higher strain range of 1% than at lower strain ranges of 0.3%.

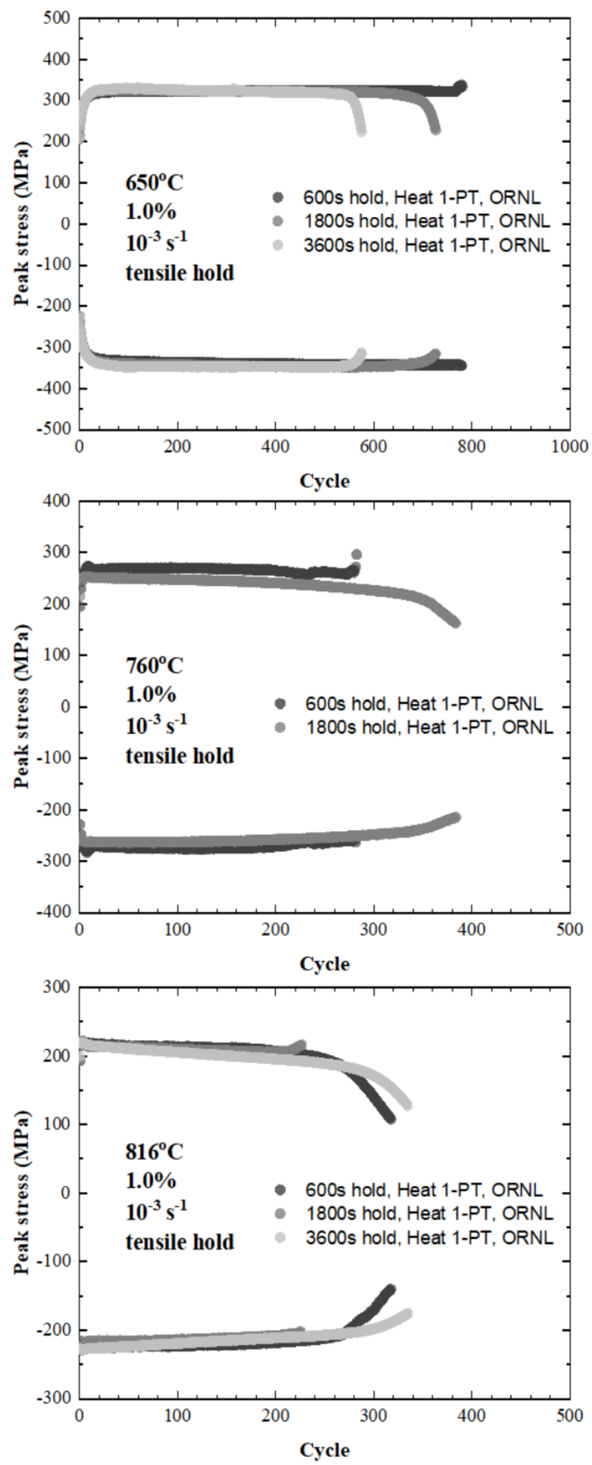

Figure 10. Maximum and minimum stresses in CF cycles at 1% strain range for commercial Heat-1 Alloy 709 in the PT condition. Peak stress at (top) 650°C, (middle) 760°C, and (bottom) 816°C.

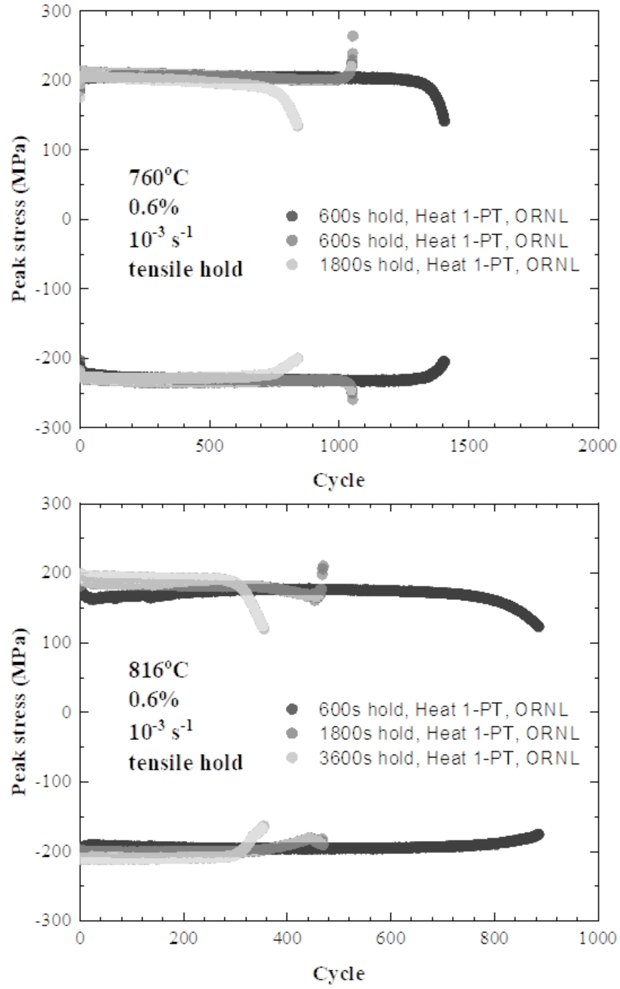

Figure 11. Maximum and minimum stresses in CF cycles at 0.6% strain range for commercial Heat-1 Alloy 709 in the PT condition. Peak stress at (top) 760°C and (bottom) 816°C.

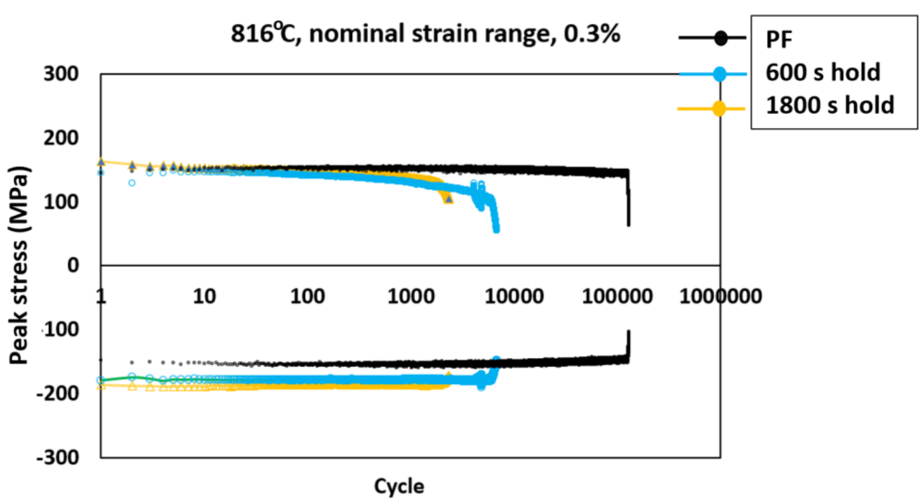

Figure 12. Hold time effect on CF testing at 0.3% strain range and 816°C on commercial Heat-1 Alloy 709 in the PT condition.

The CF test results are compared at test conditions of 3,600 s/1.0% and 1,800 s/0.6% at 950°C for the two commercial heats of Alloy 709, and the results are presented in Figure 13 for the maximum and minimum stresses. In addition, Figure 14 presents the CF mid-life hysteresis loops and their corresponding stress relaxation curves during tension-hold segments at mid-life cycles. Both materials showed comparable peak stresses prior to failure initiation at this high-test temperature of 950°C for both strain ranges. At 1% strain range, no significant differences in CF cycles between the two heats among the available data, and the increase of hold time from 600 s to 3,600 s did not cause reduction of CF life cycles for Heat 2-PT. At 0.6%, commercial Heat 2-PT condition exhibits longer CF life cycles although duplicate tests are needed to have a better comparison. The mid-life hysteresis loops and the stress relaxation characteristics of the two materials are comparable when compared at the same test conditions.

To obtain better assessment of the CF properties of Alloy 709 and to support the Code Case data package, a more detailed comprehensive CF testing plan were developed and updated (Sham et al. 2022). ORNL has adjusted the testing plan accordingly and will continue the Code Case testing studies on the two commercial heats and incorporate the commercial heat 3 in FY 2023.

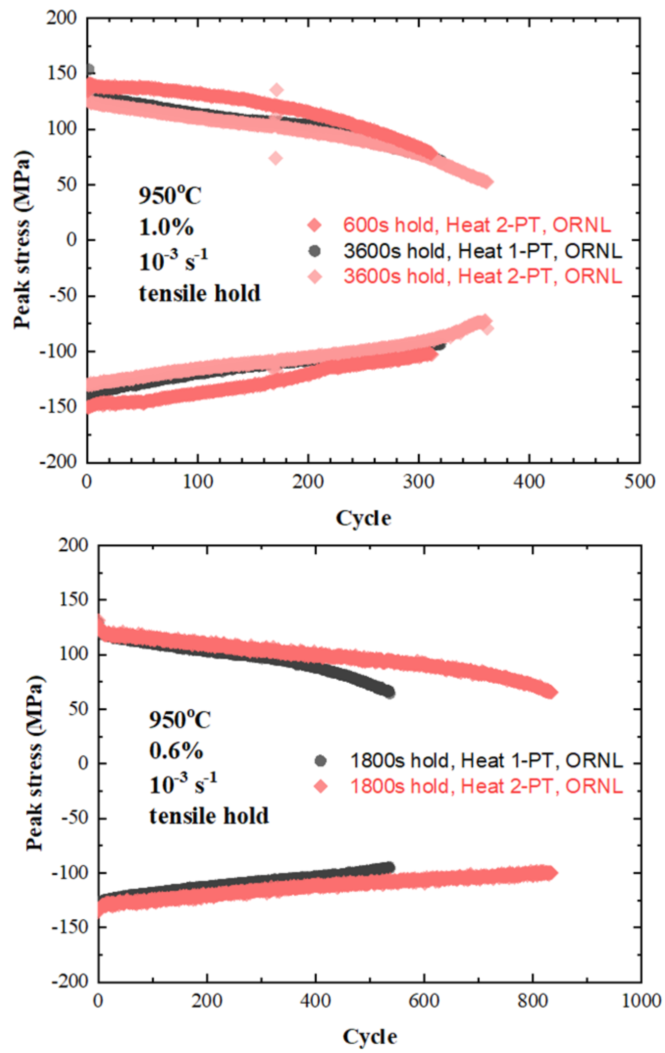

Figure 13. Maximum and minimum stresses in CF cycles for the two commercial heats of Alloy 709 in PT condition. Peak stress at (top) 816°C and (bottom) 950°C.

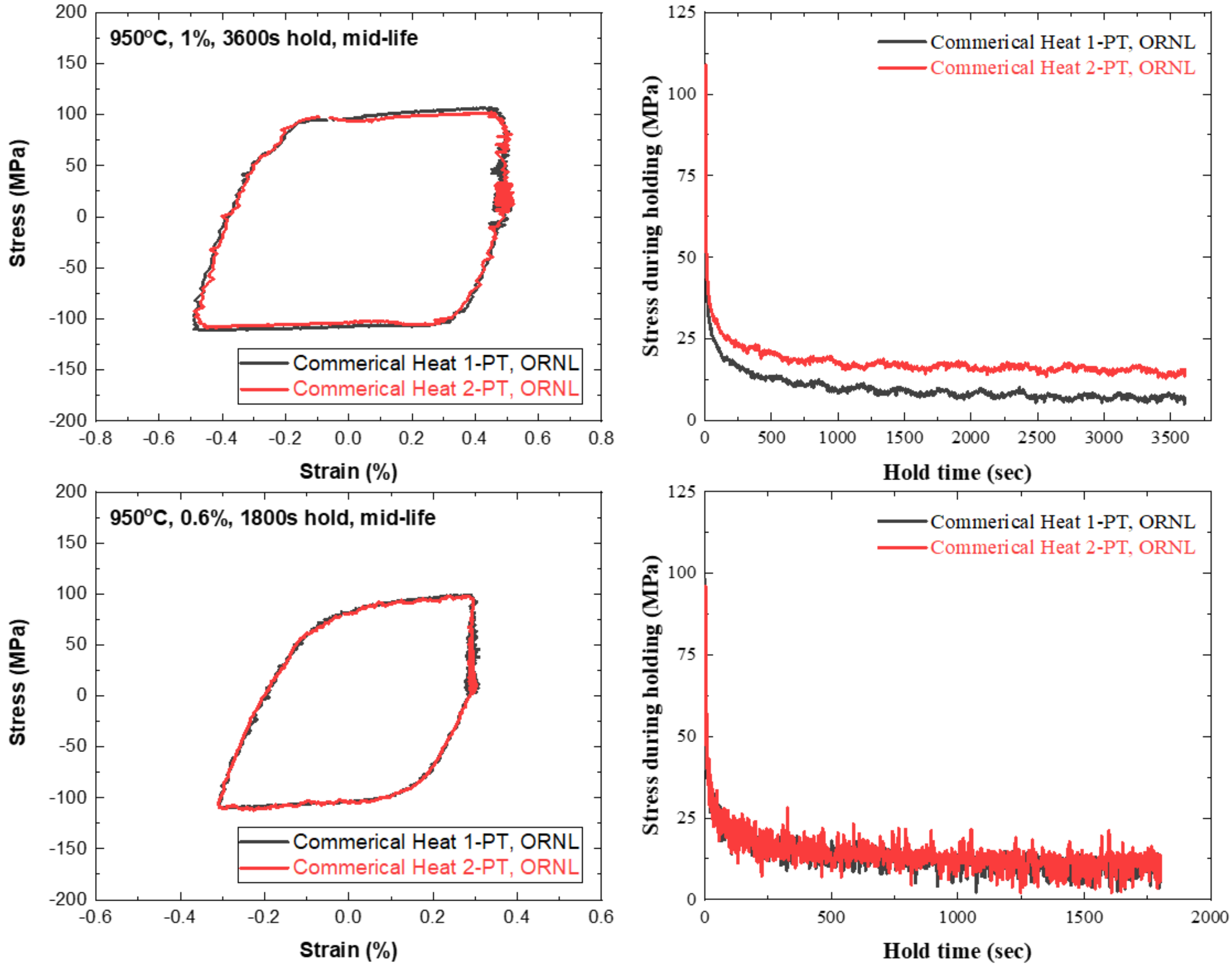

Figure 14. Comparison of the CF mid-life hysteresis loops and stress relaxation curves at 1% and 0.6% strain ranges at 950°C for the two commercial heats of Alloy 709 in PT condition.

5.3 INTEGRATED FATIGUE CODE CASE TESTING RESULTS

Fatigue data generated to date by ORNL and INL on the two commercial heats of Alloy 709 in PT condition are summarized in Table 10, and collectively presented in Figure 15. These fatigue test conditions were selected to establish the general trends of the fatigue curves and shed lights on the fatigue resistance of Alloy709 with PT condition. The fatigue test matrix has been updated by Sham et al. (2022) based on the assessment of these data. ORNL is tasked to continue the fatigue testing effort on the Alloy 709 in PT condition in support of the development of the full fatigue design curves.

From the available data on the two commercial heats of Alloy 709 in PT condition, the effect of the test temperature on fatigue cycles to failure was evaluated at strain ranges of 1.0%, 0.6% and 0.3% and the results are compared in Figure 16. The test temperature did not affect the fatigue failure cycles at 1% strain range, whereas it significantly reduced the fatigue cycles at 0.6% strain range and even more damaging at the low strain range of 0.3%.

Table 10. Fatigue test results to date on the two commercial heats of Alloy 709 in PT condition

Test lab	Material	Temperature (C)	Strain Range (%)	Nf_20
ORNL	Heat 1-PT	650	1.00	1,129
ORNL	Heat 1-PT	650	1.00	1,027
ORNL	Heat 1-PT	650	1.00	1,497
ORNL	Heat 1-PT	760	0.60	3,882
ORNL	Heat 1-PT	760	1.00	1,180
ORNL	Heat 1-PT	760	2.00	418
ORNL	Heat 1-PT	760	3.00	105
ORNL	Heat 1-PT	704	0.60	8,060
ORNL	Heat 1-PT	704	1.00	344
ORNL	Heat 1-PT	704	0.30	238,505
ORNL	Heat 1-PT	704	0.30	197,917
ORNL	Heat 1-PT	950	0.60	640
ORNL	Heat 2-PT	950	0.60	1,333
ORNL	Heat 2-PT	982	0.60	1,017
ORNL	Heat 2-PT	871	0.58	1,830
ORNL	Heat 2-PT	950	0.30	4,542
ORNL	Heat 2-PT	900	0.30	7,212
ORNL	Heat 2-PT	816	1.00	760
ORNL	Heat 2-PT	816	0.60	1,196
ORNL	Heat 2-PT	649	1.00	931
ORNL	Heat 2-PT	760	1.00	521
ORNL	Heat 2-PT	704	1.00	779
ORNL	Heat 2-PT	760	0.60	1,942
ORNL	Heat 2-PT	650	0.54	18,144
ORNL	Heat 2-PT	704	0.49	8,971
ORNL	Heat 2-PT	760	0.60	1,989
ORNL	Heat 2-PT	760	0.37	39,357
ORNL	Heat 1-PT	760	0.52	4,796
ORNL	Heat 1-PT	816	0.60	1,446
ORNL	Heat 2-PT	760	0.26	246,222
ORNL	Heat 2-PT	704	0.28	970,250
ORNL	*Heat 1-PT*	*704*	*0.25*	*20,000,000*[a, b]
ORNL	*Heat 1-PT*	*816*	*0.27*	*3,469,861*[a]
ORNL	*Heat 2-PT*	*816*	*0.24*	*4,932,308*[a]

[a]These three tests were performed under load-controlled mode.
[b]The specimen did not test to failure. The cycles reported are run-out cycle.

Table 10. (continued).

Test lab	Material	Temperature (C)	Strain Range (%)	Nf_20
INL	Heat 2-PT	650	1.00	1,517
INL	Heat 1-PT	650	1.00	1,975
INL	*Heat 1-PT*	*816*	*3.00*	*144*[c]
INL	Heat 1-PT	816	1.00	1,226
INL	Heat 1-PT	816	0.60	3,663
INL	Heat 1-PT	816	0.30	128,666
INL	Heat 1-PT	816	0.25	1,206,978
INL	Heat 1-PT	650	1.00	1,817
INL	Heat 1-PT	650	0.30	3,614,562
INL	Heat 1-PT	650	0.60	24,288
INL	Heat 1-PT	650	2.00	278
INL	Heat 1-PT	650	3.00	116
INL	Heat 2-PT	982	1.00	743
INL	Heat 2-PT	927	1.00	826
INL	Heat 2-PT	871	1.00	754

[c]The specimen buckled. This condition needs to be repeated.

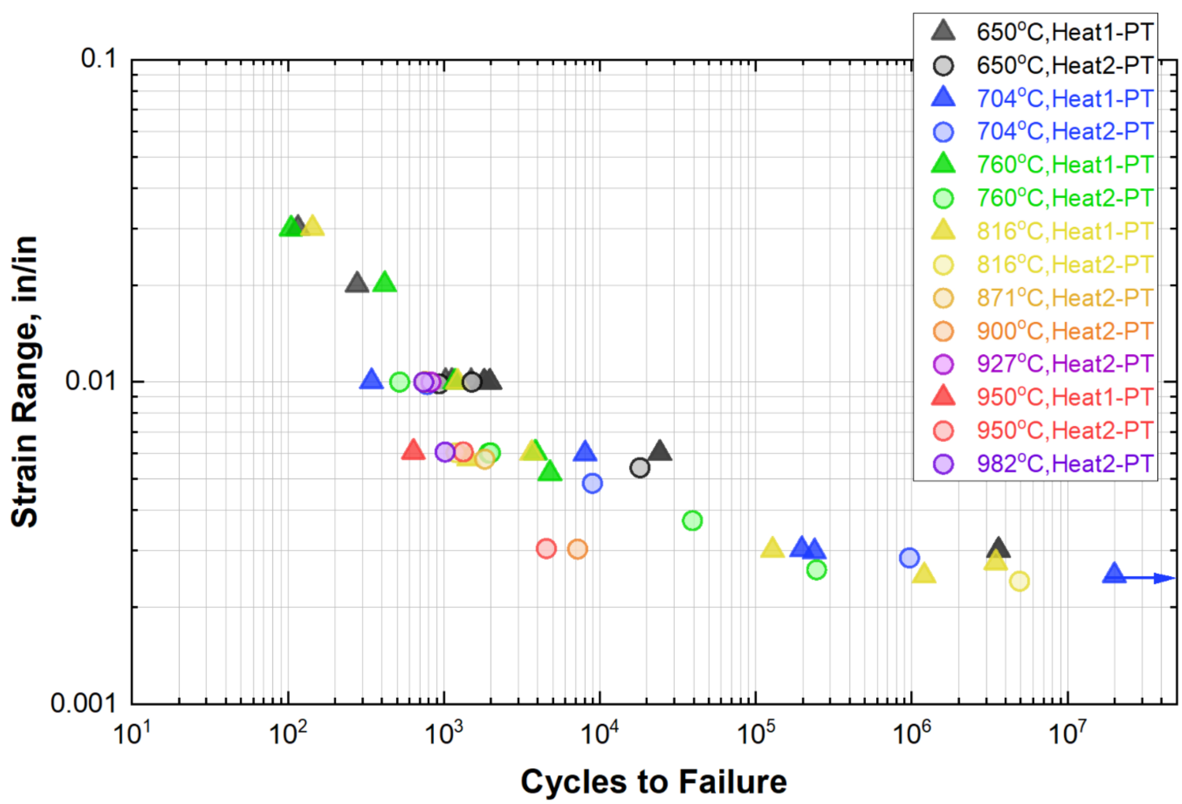

Figure 15. Strain-controlled fatigue data generated on the two commercial heats of Alloy 709 in PT condition.

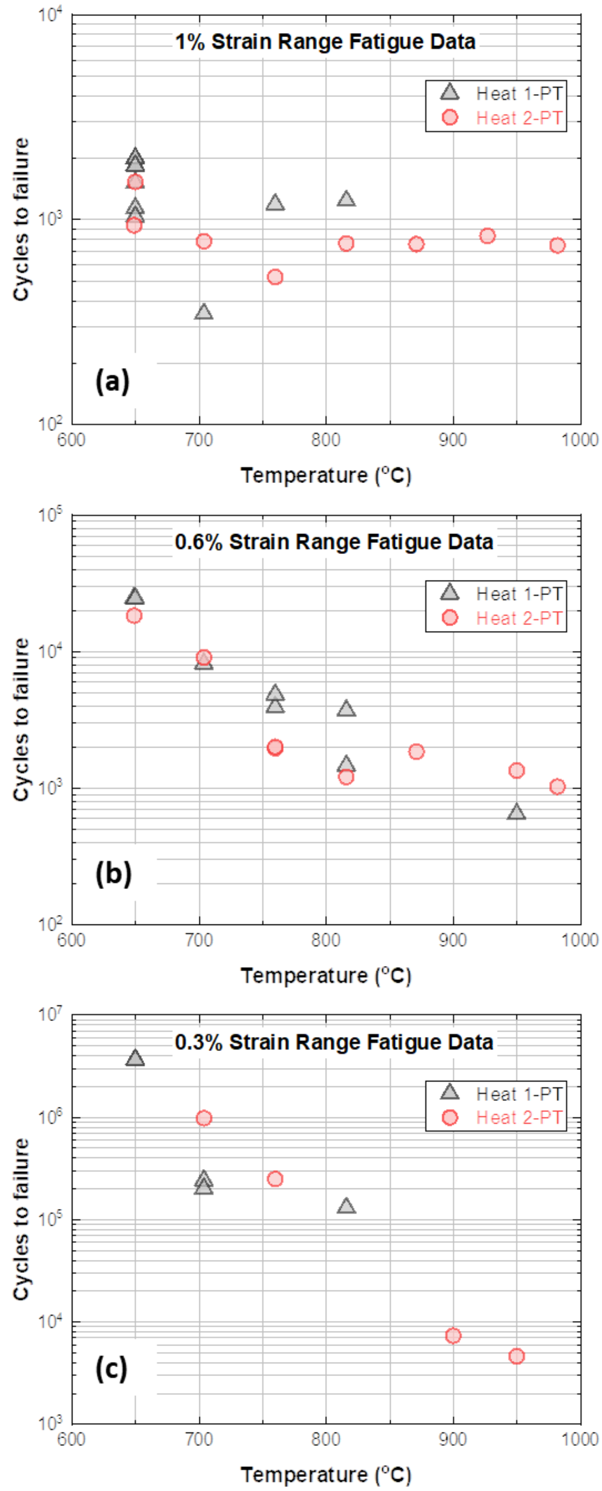

Figure 16. Effect of the test temperature on fatigue cycles at various strain ranges.
(a) 1.0%, (b) 0.6%, and (c) 0.3%.

5.4 INTEGRATED CREEP-FATIGUE TEST RESULTS

Table 9 lists all the CF data from ORNL and INL on the two commercial heats of Alloy 709 in PT condition at the time of writing this report. To provide a preliminary assessment of the of Alloy709-PT material creep and fatigue damage interaction, these test data were analyzed for the fatigue damage fraction and creep damage fraction, and the results are presented in Figure 17 in the form of damage diagram (D-diagram).

Table 11. Creep-fatigue test results to date on the two commercial heats of Alloy 709 in PT condition

Test lab	Material	Temperature (C)	Strain Range (%)	Hold Time (s)	Nf_20
ORNL	Heat 1-PT	650	1.01	600	781
ORNL	Heat 1-PT	650	1.01	1,800	727
ORNL	Heat 1-PT	650	1.00	3,600	576
ORNL	Heat 1-PT	704	0.30	1,800	11,999
ORNL	Heat 1-PT	760	0.63	600	1,408
ORNL	Heat 1-PT	760	1.01	600	283
ORNL	Heat 1-PT	760	0.61	600	1,054
ORNL	Heat 1-PT	760	0.62	1,800	842
ORNL	Heat 1-PT	760	1.01	1,800	384
ORNL	Heat 1-PT	816	0.62	600	886
ORNL	Heat 1-PT	816	1.01	600	318
ORNL	Heat 1-PT	816	0.32	600	6,640
ORNL	Heat 1-PT	816	1.02	1,800	227
ORNL	Heat 1-PT	816	0.62	1,800	356
ORNL	Heat 1-PT	816	0.32	1,800	2,333
ORNL	Heat 1-PT	816	0.62	3,600	470
ORNL	Heat 1-PT	816	1.00	3,600	335
ORNL	Heat 2-PT	950	1.01	600	312
ORNL	Heat 1-PT	950	0.62	1,800	537
ORNL	Heat 1-PT	950	0.31	1,800	3,509
ORNL	Heat 2-PT	950	0.61	1,800	835
ORNL	*Heat 2-PT*	*950*	*0.60*	*1,800*	*517*[a]
ORNL	Heat 1-PT	950	1.02	3,600	320
ORNL	Heat 2-PT	950	1.02	3,600	362
INL	Heat 1-PT	649	0.60	600	8,269
INL	Heat 1-PT	650	1.00	1,800	1,069
INL	Heat 1-PT	650	1.00	1,800	1,169
INL	Heat 1-PT	704	0.60	600	4,005

[a]This specimen did not test to failure.

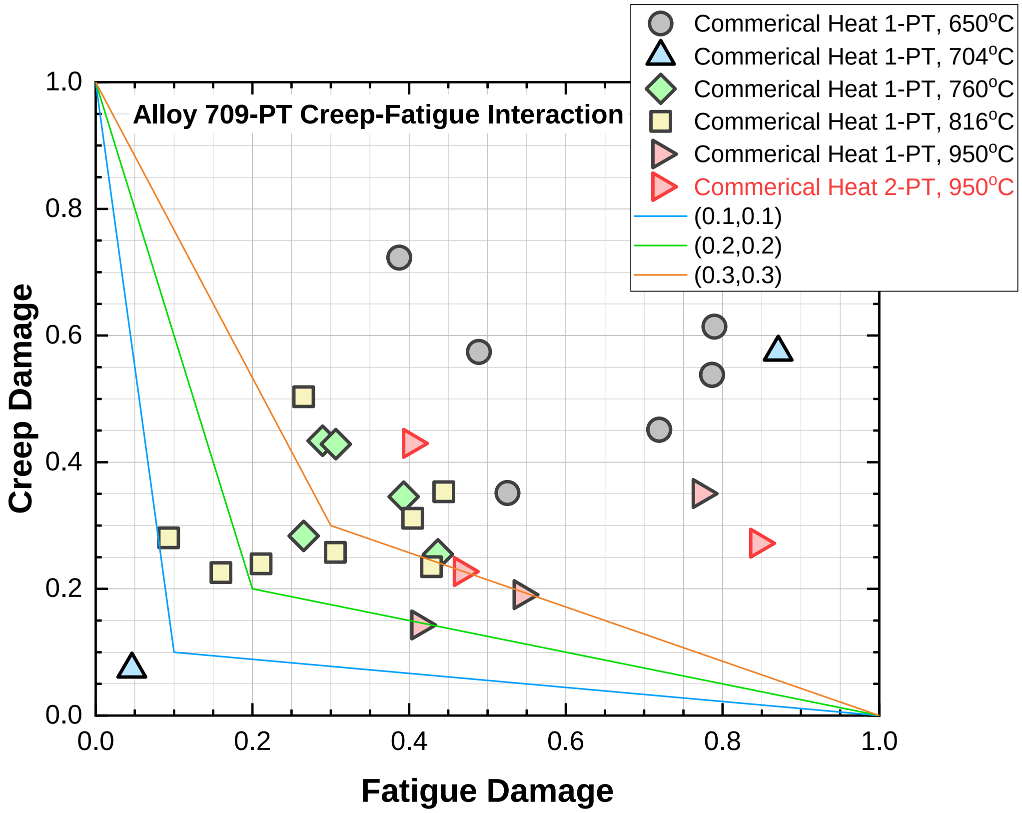

Figure 17. CF interaction diagram for Alloy 709 from the commercial heats in the PT condition.

In this analysis, the fatigue-damage fraction for the D-diagram is calculated as the ratio of the cycles to failure of the CF tests to those of the pure fatigue tests conducted under the same strain range, strain rate, and temperature. The average cycles to failure from duplicate tests are adopted for the calculation of the fatigue-damage fraction, although only a few duplicates have been generated so far. The creep-damage fraction calculation is determined based on the time-fraction method using the mid-life stress relaxation curves during the tensile hold in the CF tests and the time-to-rupture Larson-Miller correlation from the creep-rupture data, similar to the approach used by Wright et al. (2021).

Three bilinear CF interaction envelopes are added to Figure 17 for reference. It should be noted that the bilinear envelope does not represent a lower bound in the Division 5 CF evaluation procedure but rather an envelope of majority of the test data generated from lab scale specimens. It is noted that a new data point generated at 704°C, 0.3% strain range, and 1,800 s tensile hold showed low creep damage and low fatigue damage, and this condition will be assessed in more detail once additional duplicated tests become available.

6. SUMMARY

The Code Case testing effort continued at ORNL, INL, and Argonne in support of the qualification of Alloy 709, an advanced austenitic stainless steel in the ASME Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors. Tensile, creep rupture, fatigue, and CF Code Case testing data generated to date on the precipitation-treated Alloy 709 from two commercial heats in plate product form were collected from the three testing labs and are integrated in this report. The data generated to date on Alloy 709 supports the recommendation for its ASME Code qualification to support the effort to reduce construction and operating costs for advanced reactor deployment.

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