ORNL/TM-2024/3626

Summary of FY 2024 A709 Code Case Testing at ANL, INL and ORNL

Yanli Wang
Xuesong Fan

September 2024

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OAK RIDGE National Laboratory

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Materials Science and Technology Division

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CONTENTS

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LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ANL	Argonne National Laboratory
AOD	Argon-Oxygen-Decarburization
ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATI	Allegheny Technologies Incorporated
DOE	US Department of Energy
ESR	Electroslag Remelting
FR	Fast Reactors
FY	Fiscal Year
GTAW	Gas Tungsten Arc Welding
INL	Idaho National Laboratory
LMP	Larson-Miller parameter
NE	Office of Nuclear Energy
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PT	Precipitation Treatment
RT	Room temperature
SFR	Sodium-Cooled Fast Reactor
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 (ASME) Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors is being carried out at Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), and Argonne National Laboratory (ANL).

Key testing data for the Alloy 709 100,000-hr near-term Code Case submittal to ASME is expected to be completed by the end of 2024, with design parameters anticipated to be finalized in FY 2025. This report summarizes the testing results for three commercial heats of Alloy 709 conducted across three laboratories, reviews the current testing status, and outlines the remaining data needed to support the first Alloy 709 Code Case submittal to ASME. The Alloy 709 Code Case plan remains on schedule.

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1. INTRODUCTION

The objective of the Advanced Materials activities within the Advanced Reactor Technologies (ART) Program of U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) is to provide the technical basis needed to support regulatory requirements for structural materials required for advanced reactors that could be deployed in the near-to-mid-term by the U.S. nuclear industry. Enhancements in the mechanical performance of structural materials are crucial for improving the economics of advanced reactors.

Through a DOE-NE ART material down-selection and intermediate testing program, Alloy 709, an advanced austenitic stainless steel, has been recommended as a Class A construction material for the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 5, in support of sodium-cooled fast reactor (SFR) structural applications due to its superior structural strength (Sham et al., 2022). A comprehensive Code qualification plan has been developed to create the necessary data package and to establish material-specific design parameters for Class A component design in ASME Section III, Division 5.

A collaborative advanced materials development effort involving Oak Ridge National Laboratory (ORNL), Idaho National Laboratory (INL), and Argonne National Laboratory (ANL) is underway to investigate the mechanical performance of Alloy 709 in support of its codification process.

The data package for the ASME Code Cases necessitates an evaluation of mechanical properties, including tensile strength, creep resistance, fatigue behavior, and creep-fatigue performance for both the base metal and its weldments. This report summarizes the progress made in generating Code Case data for three commercial heats of Alloy 709 and their welds, covering data collected across three laboratories. The Code Case testing data from INL is detailed in Mahanjan (2024), while the data from ANL is summarized in Zhang and Listwan (2024).

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, the DOE-NE ART Program has successfully scaled up the production of Alloy 709 in rolled plate product form from a laboratory heat of 500 lb to three Alloy 709 commercial heats, with heat sizes of 45,000, 41,000 and 38,000 lb. The first commercial heat plates were fabricated by G.O. Carlson Inc of Pennsylvania, whereas the second and third heats were both fabricated by Allegheny Technologies Incorporated (ATI) Flat Rolled Products.

The plates used in the Code Case testing were produced by argon-oxygen-decarburization (AOD) followed by electroslag remelted (ESR). The plates were hot rolled, and solution annealed at a minimum temperature of 1150°C. An additional precipitation heat treatment of the plates was performed to ensure a balanced creep and creep-fatigue performance (McMurtrey, et al, 2019). The precipitation heat treatment protocol is 775°C for 10 h in air, followed by air cooling.

Table 1 summarizes the information regarding the Alloy 709 Code Case plates and Table 2 lists the chemical compositions of the three heats of Alloy 709 with the heat numbers of 58776, 529900 and, 530843. In FY 2024, specifications for Alloy 709 plate product have been approved and incorporated into ASTM A240/A240M and ASTM A480/A480M (ASTM, 2023a, ASTM, 2023b). For comparison, the specifications for the chemical requirements of Alloy 709 with a UNS number of S31025 in ASME SA-213 and ASTM A240/A240M (ASME, 2023a; ASTM, 2023a) are also listed in Table 2. The three commercial heats Alloy 709 plates meet the specified UNS S31025 chemical requirements.

Table 1. Three commercial heats of Alloy 709 in plate form for Code Case testing

Fabricator	Master heat number	Plate IDs for base metal Code Case testing	Nominal ASTM grain size number	Plate thickness, (in)
G.O. Carlson Inc	58776	58776-3RBC1	7	1.10
Allegheny Technologies Incorporated	529900	CG05455; CG05368	7	1.81
		CG05453	4	2.00
	530843	CG45192	4	1.82

Table 2. Chemical compositions of the three commercial heats of Alloy 709 plates (wt %).

Element	Commercial Heat 1 heat number 58776	Commercial Heat 2 heat number 529900	Commercial Heat 3 heat number 530843	ASME SA-213, ASTM A240/240M UNS-S31025 Specification ---
C	0.066	0.08	0.07	0.10 max
Cr	20.05	19.9	19.8	19.5–23.0
Co	0.02	0.02	0.01	–
Ni	25.14	24.6	25	23.0–26.0
Mn	0.9	0.9	0.9	1.50 max
Mo	1.51	1.5	1.5	1.0–2.0
N	0.152	0.15	0.15	0.10–0.25
Si	0.38	0.39	0.44	1.00 max
P	0.014	0.003	0.008	0.030 max
S	0.001	<0.001	0.001	0.030 max
Ti	0.01	<0.01	< 0.01	0.20 max
Nb	0.26	0.17	0.18	0.10–0.40
Al	0.02	0.02	0.02	–
B	0.003	0.004	0.005	0.002–0.010
Cu	0.06	0.06	0.04	–
Fe	balance	balance	balance	balance

The specimens used for Code Case testing were machined at the mid-thickness for the Heat 58776 plates and at the 1/4-thickness for both ATI heats plates. All specimens were along the rolling direction.

Table 3 summarizes the room temperature (RT) mechanical properties of the three heats of Alloy 709 plates, which had a minimum solution annealing temperature of 1150°C. The tensile properties are evaluated for both the as-annealed condition and the precipitation-treated (PT) condition at 775°C for 10 hours. The results show that the three heats of Alloy 709 plates used for Code Case testing meet the heat treatment requirements of ASTM A480/A480M (ASTM, 2023b), and the minimum mechanical properties specified in ASTM A240/240M (ASTM, 2023a).

Table 3. Summary of RT properties of solution-annealed and precipitation treated Alloy 709 plates (wt %).

Manufacture	G.O Carlson	ATI	ATI	G.O Carlson	ATI	ATI	ASTM 240/240M UNS-S31025 minimum
Master heat number	Heat 58776	Heat 529900	Heat 530843	Heat 58776	Heat 529900	Heat 530843	
Melt practice	AOD, ESR, ESR + homogenization	ESR	ESR	ESR	ESR	ESR	–
Total number of tensile test data	18	10	2	2	2	2	–
Material heat treatment condition	Minimum solution-anneal temperature of 1150 °C			Solution annealed at a minimum temperature of 1150 °C; and PT at 775 °C for 10-hr.			–
Test Temperature, °C	RT (22°C)						–
Yield Strength, MPa	335.4 ± 34.8	314.6 ± 10.2	313.2 296.4	359.1 345.3	327.0 324.8	304.7 306.1	270
Tensile Strength, MPa	709.3 ± 25.0	689.5 ± 5.8	688.0 681.1	737.4 738.9	694.0 694.6	694.3 690.8	640
Elongation, %	46.6 ± 2.5	53.6 ± 3.3	46.1 49.0	40.0 38.5	43.3 43.4	44.0 43.5	30
Reduction of area, %	71.6 ± 2.9	71.2 ± 1.7	67.9 67.8	51.9 50.6	48.2 44.7	46.5 46.0	–
Grain size No. per ASTM E112	6, 7	4, 7	4, 7	6, 7	4, 7	4, 7	–

Alloy 709 Code Case welds were fabricated at ORNL (Feng et al., 2022). A key focus of the Alloy 709 welding development at ORNL was addressing the solidification cracking issues associated with high phosphorus (P) content in Alloy 709. ORNL has successfully demonstrated the welding of commercial Alloy 709 plates (Heat 58776) with a high phosphorus level of 140 wppm using the gas tungsten arc welding (GTAW) process.

The Alloy 709 welds for Code Case testing were produced on two commercial heats of Alloy 709 plates, and information on these welds is listed in Table 4. The Alloy 709 welds were fabricated used a matching filler metal weld wire with a low phosphorus (P) content of less than 20 wppm. A single V-groove with a 20-degree bevel was used for welding the base metal plates (Heat 58776) with a nominal thickness of 1.125-in, while a double V-groove was used for the plates (Heat 529900) with a nominal thickness of 2.05-in.

All Code Case testing Alloy 709 welds successfully passed X-ray inspection, RT side-bend testing, and tensile testing per ASME Section IX weld qualification requirements. No post-weld heat treatment was performed. The Alloy 709 welds Code Case testing used cross-weld specimens (Feng et al., 2022).

Table 4. Alloy 709 welds fabricated at ORNL in support of Code Case testing

<table>
<tr><th colspan="2">Alloy 709 welds</th><th>Weld No. W6 and W10</th><th>Weld No. W11</th></tr>
<tr><td rowspan="3">Weld Wire</td><td>P Level (wppm)</td><td>< 20</td><td>< 20</td></tr>
<tr><td>Heat No. of the supply material for weld wire</td><td>011367-08</td><td>011367-08</td></tr>
<tr><td>Wire dia. (in)</td><td>0.035</td><td>0.035</td></tr>
<tr><td colspan="2">Base Metal Plate</td><td>Heat No. 58776.
PT at 775 °C for 10-hr.</td><td>Heat No. 529900.
PT at 775 °C for 10-hr.</td></tr>
<tr><td colspan="2">Base metal plate thickness (in)</td><td>1.12</td><td>2.05</td></tr>
<tr><td colspan="2">Length of the weld (in)</td><td>8 and 15</td><td>27.5</td></tr>
<tr><td colspan="2">Weld joint geometry</td><td>20° single V</td><td>20° double V</td></tr>
<tr><td rowspan="3">ASME Sec. IX Weld Qualification</td><td>X-Ray</td><td>Pass</td><td>Pass</td></tr>
<tr><td>Side Bend</td><td>Pass</td><td>Pass</td></tr>
<tr><td>Room Temperature Tensile Testing</td><td>Pass</td><td>Pass</td></tr>
</table>

3. ALLOY 709 CODE CASE TESTING STATUS

3.1 TENSILE CODE CASE TESTING

The full tensile Code Case testing matrix on three heats of Alloy 709 base metal plates with the PT condition has been completed at ORNL in FY 2024. The testing temperature was ranging from RT to 1000 °C with a 50 °C interval, per Code Case data requirement. The tensile testing procedure followed ASMT E8/E8M (ASTM, 2022a) at RT and ASTM E21 (ASTM, 2021) at elevated temperatures.

The tensile properties as a function of the testing temperature are presented in Figure 1 and Figure 2. Generally, Heat 58776 exhibited slightly higher yield and ultimate tensile strength (UTS), along with lower elongation at temperatures below 700 °C, compared to Heat 529900 and Heat 530843. All three heats demonstrated good elongation and ductility across the entire tested temperature range.

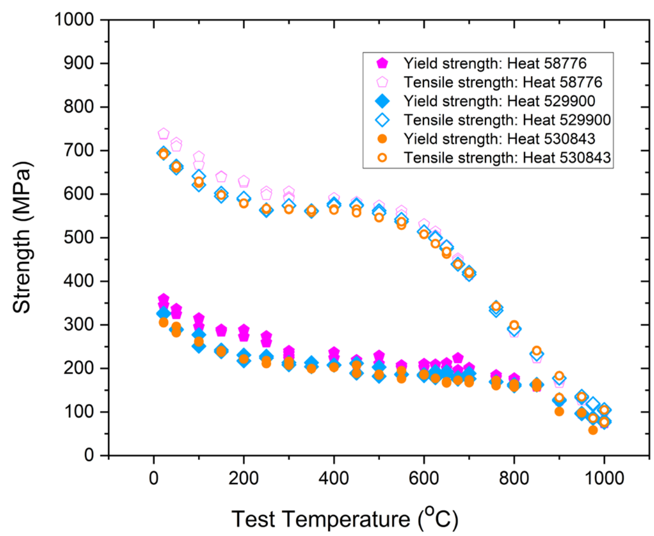

Figure 1. Yield strength and UTS of Alloy 709 with the PT condition

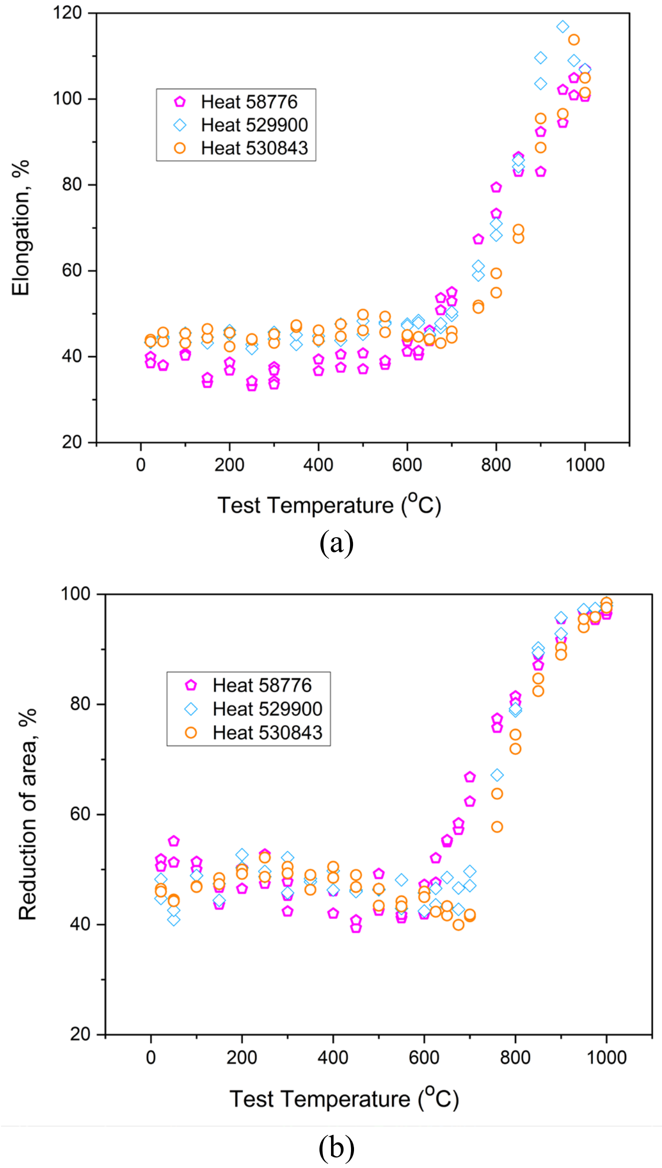

Figure 2. Tensile total elongation (a) and reduction of area (b) of Alloy 709 with the PT condition.

3.2 FATIGUE AND CREEP-FATIGUE CODE CASE TESTING

In FY 2024, a significant portion of the Code Case testing effort has been focused on strain-controlled fatigue and creep-fatigue tests at ORNL and INL. This work supports the development of temperature-dependent fatigue design curves and the construction of the creep-fatigue interaction diagram, which are essential components of the data package and design parameters for the Alloy 709 Code Case. In this Alloy 709 Code Case testing program,

- The pure fatigue testing followed the ASTM E606/E606M (ASTM, 2021b) standard for conducting strain-controlled fatigue tests. The strain rate was controlled at 1E-3 s^{-1}. A triangular loading waveform with a fully reversed profile, i.e., a loading ratio in strain of $R = -1$, was employed.

- The creep-fatigue testing followed the ASTM E606/E606M (ASTM, 2021b) and/or ASTM E2714-13 (ASTM, 2020) standards for conducting creep-fatigue testing under strain-controlled condition. The loading waveform was fully reversed with various hold-times applied at the peak tensile strain. The loading and unloading strain rates were controlled at 1E-3 s^{-1}.

- To develop the temperature-dependent fatigue design curves and creep-fatigue interaction damage diagram, the cycles to failure are required to be extracted from the test data. The failure criterion in the Alloy 709 Code Case cyclic testing data is defined as a 20% drop in the ratio of the maximum stress to the minimum stress as a function of the applied cycles.

There were cases where the specimens failed to meet the 20% drop criterion, and the recorded failure cycle count is reported as a reference. For the final data package in developing the Alloy 709 Code Case, the fatigue and creep-fatigue test results will be further screened to exclude data that are not qualified for ASME code development.

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

3.2.1 Low Temperature Fatigue Curve

The fatigue design curves below creep region for austenitic stainless steels and nickel alloys are for temperatures not exceeding 425°C/800°F from ASME Code Section III, Mandatory Appendix I. The background data that were used to determine the fatigue design curve I-9.2 for austenitic steels, Nickel-Chromium-Iron alloys, and Nickel-Copper alloys are documented in Jaske and O'Donnell (1977), where multiple sources of fatigue data at various temperatures below the creep region were gathered. They consolidated the data into a single plot by converting the strain range, $\Delta\varepsilon_t$, into a fictitious stress amplitude, S_a. This was achieved by multiplying the strain range by the elastic modulus, *E*, as described in equation (1) below.

$$S_a = \frac{1}{2}\Delta\varepsilon_t \times E \tag{1}$$

This approach assumes that temperature has a negligible effect on the strain range versus cycles to failure relationship below the creep region.

Strain-controlled fatigue tests on Alloy 709 at RT and 427 °C are ongoing at ORNL. Data generated in FY 2024 are collected and superimposed to the mean best-fit fatigue curve plot by Jaske and O'Donnell (1977) in Figure 3. The best-fit average fatigue curve, along with two reduction curves—one with a factor of 20 for cycles to failure and another with a factor of 2 for stress amplitude from Jaske and O'Donnell (1977)—are highlighted with red lines.

While cycles to failure are generally below the average curve at large strain ranges, the Alloy 709 data fall within envelopes defined by the two reduction curves. Once additional testing data become available, a proposal for finalizing the low-temperature fatigue curve for Alloy 709 will be submitted to the ASME committees for approval.

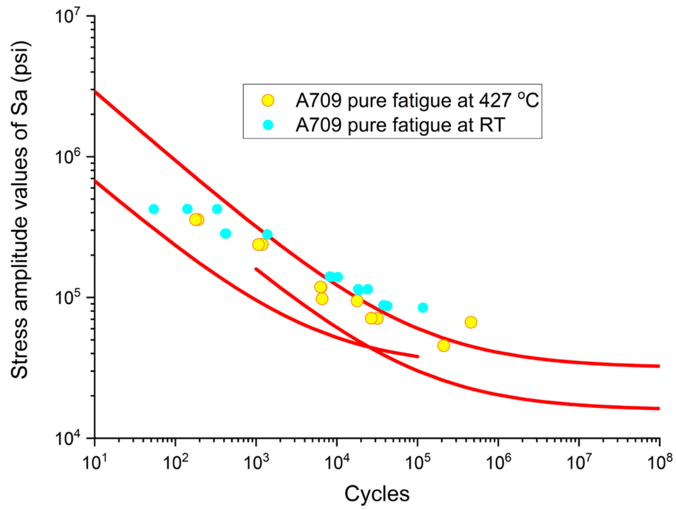

Figure 3. Interim Alloy 709 fatigue test results at RT and 427 °C

3.2.2 Temperature Dependent Fatigue Curves

Strain-controlled fatigue data are being generated at elevated temperatures by ORNL and INL. The focus of FY 2024 testing was at testing temperatures of 1200 °F (649 °C), 1400 °F (760 °C), 1500 °F (816 °C), and 1750 °F (954 °C).

Fatigue testing on three heats of the Alloy 709 with the PT condition at 1400 °F (760 °C) and 1500 °F (816 °C) is nearly complete (Wang and Sham, 2024), and the preliminary fatigue curves at these two temperatures are generated and summarized below.

3.2.2.1 Preliminary fatigue curves at 1500 °F (760 °C) and 1600 °F (816 °C)

The fatigue data generated on the three heats of Alloy 709 in the PT condition were analyzed by decomposing the total strain range, $\Delta\varepsilon_t$, into two components where $\Delta\varepsilon_e$ represents the elastic strain range and $\Delta\varepsilon_{in}$ represents the inelastic strain range:

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_{in} \quad (2)$$

The value of $\Delta\varepsilon_e$ is calculated from the mid-life hysteresis loop and is equal to $\left(\frac{\Delta\sigma}{E}\right)$, where $\Delta\sigma$ represents the stress range. In strain-controlled fatigue testing, the stress range varies with applied cycles. In this study, the stress range at the mid-life cycle is used for the retrogression analyses. The elastic modulus of Alloy 709 was based on the results from Reese et al. (2021), and it equals to 138 GPa at 760 ºC and 134 GPa at 816 ºC. The value of $\Delta\varepsilon_{in}$ is obtained from the difference between $\Delta\varepsilon_t$ and $\Delta\varepsilon_e$. These parameters are schematically shown in Figure 4.

A modified Coffin-Manson equation was used to analyze the interim fatigue data using a power law representation for the two strain ranges as follows:

$$\Delta\varepsilon_e = AN_f{}^a \tag{3}$$

$$\Delta\varepsilon_{in} = BN_f{}^b \tag{4}$$

where N_f is the cycles to failure and A, a, B, and b are fitting parameters. The fatigue curve can therefore be represented as:

$$\Delta\varepsilon_t = AN_f{}^a + BN_f{}^b \tag{5}$$

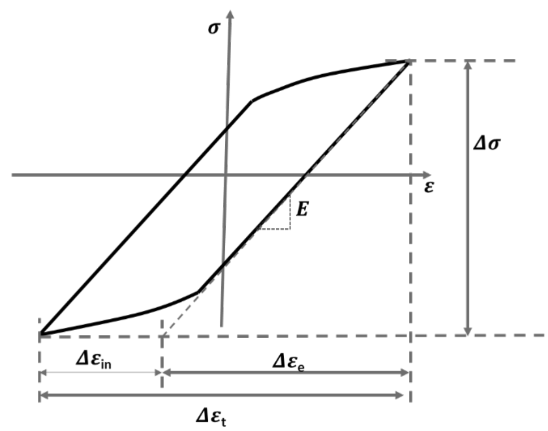

Figure 4. Definition of the stress and strain parameters.

Regression analyses of the fatigue data generated from the three heats of Alloy 709 at 760 and 816 °C were performed using equations (3) and (4), and the results are plotted in Figure 5 and Figure 6. The values of the fitting parameters at the two temperatures are listed in Table 5.

Table 5. Preliminary fatigue curve fitting parameters of Alloy 709 at 760 and 816 °C

Temperature, °C	A	a	R^2 of the fit for $\Delta\varepsilon_e$	B	b	R^2 of the fit for $\Delta\varepsilon_{in}$
760	0.007598	-0.09563	0.95	0.30443	-0.56394	0.93
816	0.005809	-0.08198	0.97	0.47376	-0.64841	0.94

It is observed that at 816 °C, there is a lack of data between failure cycles of 100,000 to 1,000,000, and the three data points beyond 1,000,000 cycles were generated under load-controlled mode where the strain ranges increased with increasing applied cycles. Therefore, the data fit for the fatigue curve at 816°C in the high-cycle range may need adjustment as more data points are generated.

The preliminary fatigue design curves are formulated based on the best-fit curves using the conventional approach, i.e., the fatigue design curves are determined as the lower of the two curves obtained with a reduction factor of two (2) on the strain range and a reduction factor of twenty (20) on the cycles to failure. It is expressed in the following equation:

$$\Delta\varepsilon_t = \text{lower of } [A(20\times N_d)^a + B(20\times N_d)^b] \text{ and } \left[\frac{1}{2}\times\left(AN_d{}^a + BN_d{}^b\right)\right] \tag{6}$$

where N_d is the design allowable cycles.

The preliminary best fit fatigue curves and the corresponding fatigue design curves for 760 and 816 °C are shown in Figure 7.

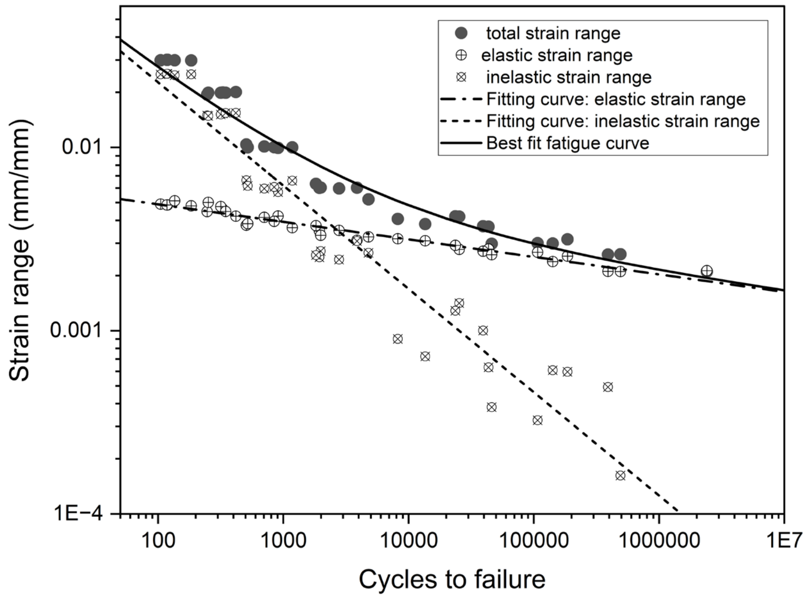

Figure 5. Interim fatigue data and best fit curve on Alloy 709 at 1400 °F (760 °C).

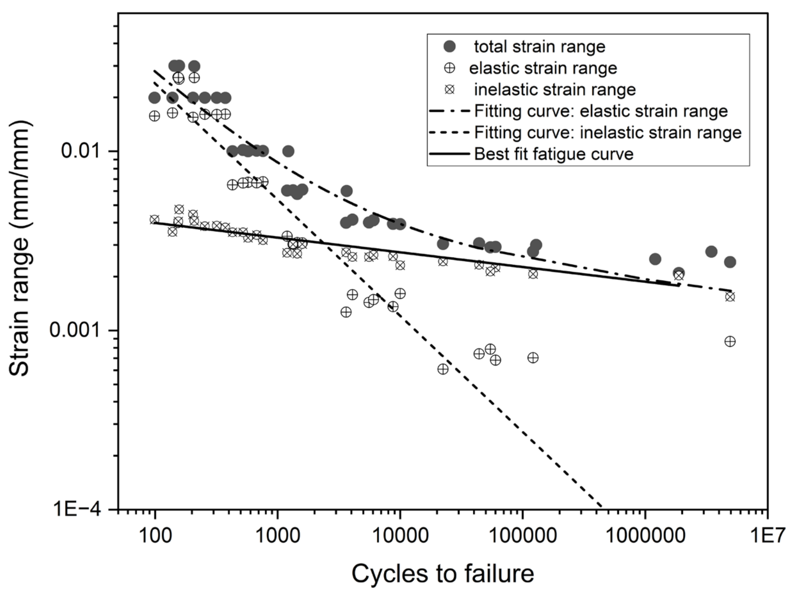

Figure 6. Interim fatigue data and best fit curve on Alloy 709 at 1500 °F (816 °C).

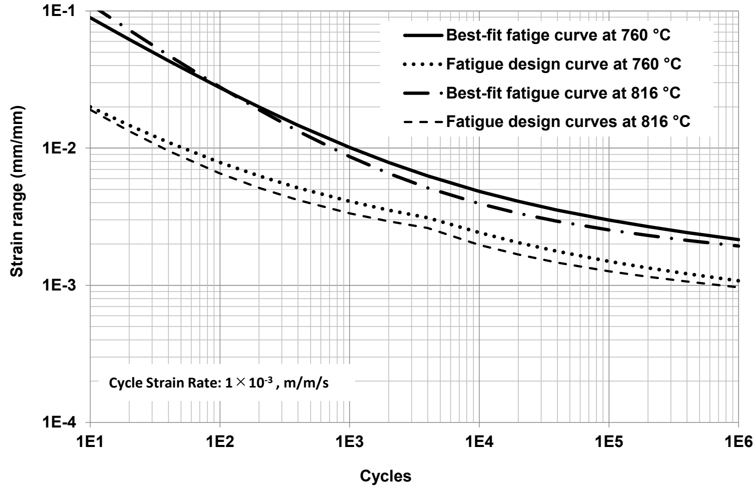

Figure 7. Preliminary best fit fatigue curves and fatigue design curves at 760 and 816 ºC for Alloy 709 with the PT condition.

3.2.2.2 Additional fatigue data generated on Alloy 709 at various elevated temperatures

Fatigue testing data for Alloy 709 are being collected at various high temperatures in addition to the two temperatures discussed above, and the fatigue data obtained from the three heats of Alloy 709 with the PT condition are presented in Figure 8. INL is progressing in generating the necessary data for constructing fatigue design curves at 1200 °F (649 °C) and 1750 °F (954 °C) (Mahanjan, 2024). The completion of the temperature-dependent fatigue design curves is scheduled for FY 2025 and will be included as part of the design parameters for the Code Case.

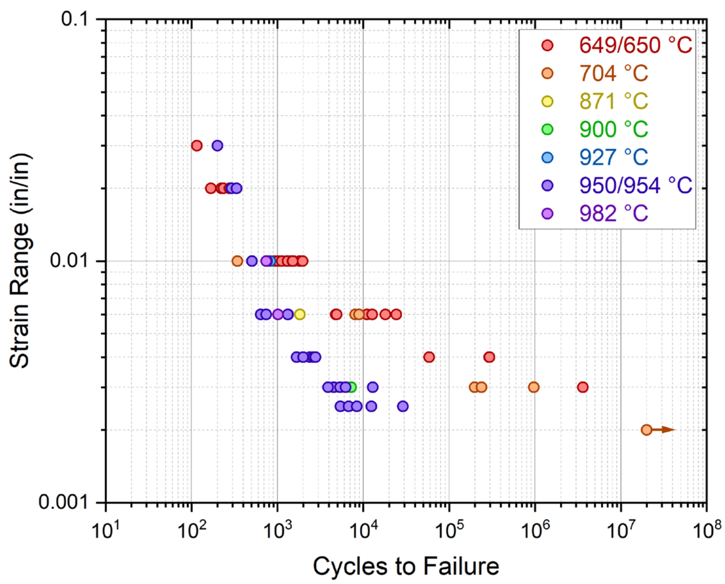

Figure 8. Strain-controlled fatigue data generated on Alloy 709 in the PT condition at various elevated temperatures.

3.3 CREEP-FATIGUE TESTING AND CREEP-FATIGUE INTERACTION DIAGRAM

Creep-fatigue data are collected at INL and ORNL for the three heats of Alloy 709 with the PT condition to evaluate its creep-fatigue performance and in support of the construction of the creep-fatigue interaction diagram. The creep-fatigue testing matrices were updated by Sham et al. (2022) based the interim data results in FY 2023.

Creep fatigue data generated to date at 1200 °F (649 °C), 1500 °F (816 °C) and 1750 °F (954 °C) on three heats of Alloy 709 with the PT condition are summarized in Figure 9 and Figure 11. Based on the available data, the impact of hold time effect on the reduction of cycles to failure is not significant at 1750 °F (954 °C), but generally decreased the cycle lives at 1200 °F (649 °C) and 1500 °F (816 °C).

The preliminary creep-fatigue interaction diagram is generated using the following approach:

- The fatigue-damage fraction is calculated as the ratio of the cycles to failure of the creep-fatigue tests to those of the pure fatigue tests conducted under the same strain range, strain rate, and temperature. Note that the average cycles to failure from duplicate tests are adopted for the calculation of the fatigue-damage, although there are limited number duplicates generated so far.

- The creep damage fraction is determined based on the time-fraction method using the stress relaxation curve at each cycle 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 in Wright, et al (2021).

The results are presented in Figure 12 with the damage fractions in logarithmic scale. In this plot, three bi-linear creep-fatigue interaction envelopes are added for reference. It should be noted that the bi-linear envelope does not represent a lower bound of the creep-fatigue interaction data from lab scale test specimens, but as a trend of the creep-fatigue interaction for use in the ASME Section III Division 5 creep-fatigue evaluation procedure. The design margins are embedded in other parts of the creep-fatigue evaluation procedure. Based on the data analyzed so far for these two temperatures, both interaction points of (0.2, 0.2) and (0.3,0.3) are reasonable.

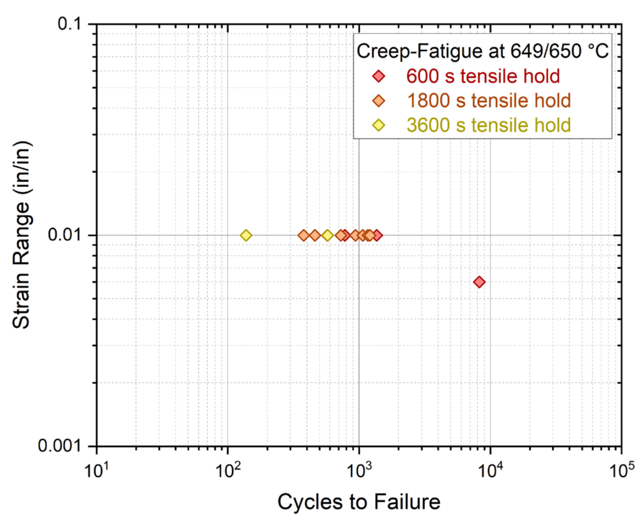

Figure 9. Interim creep-fatigue results for Alloy 709 with the PT condition at 649/650 °C

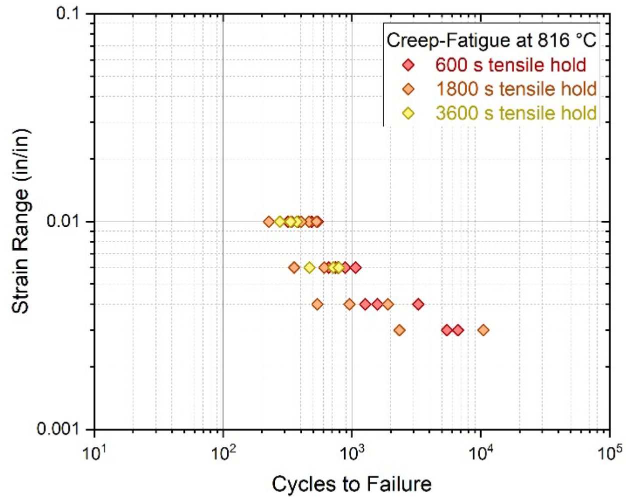

Figure 10. Interim creep-fatigue results for Alloy 709 with the PT condition at 816 °C

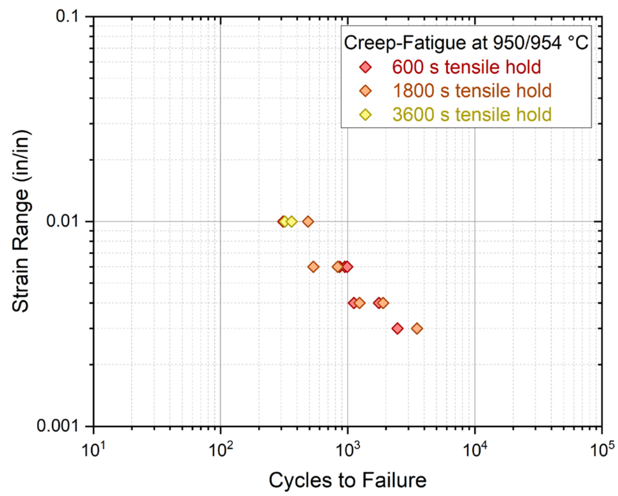

Figure 11. Interim creep-fatigue results for Alloy 709 with the PT condition at 950/954 °C

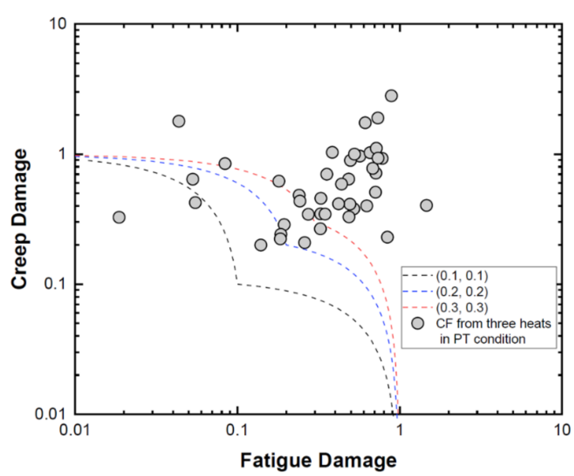

Figure 12. Preliminary creep-fatigue interaction diagram for Alloy 709 with the PT condition.

3.4 CREEP CODE CASE TESTING ON ALLOY 709 AND ITS WELDS

A comprehensive master creep testing matrix for Alloy 709 Code Case testing was developed for the three commercial heats of Alloy 709 in the PT condition and the Alloy 709 welds. The testing activities and research to support the qualification of Alloy 709 are being carried out at ANL, INL, and ORNL.

The creep testing matrix was used to generate data in support of the development of a series of Code Cases including 100,000-hr Code Case, 300,000-hr Code Case, and 500,000-hr Code Case. The creep Code Case testing plan, the corresponding supporting creep rupture data and responsible laboratories are summarized in Table 6.

Table 6. Creep Code Case testing plan on Alloy 709 base metal with the PT condition and Alloy 709 welds

Target Code Case	Supporting creep rupture data, (hr)	Labs involved	
100, 000-hr Code Case	~24,000	Alloy 709 base metal	ANL/INL/ ORNL
		Alloy 709 welds	ORNL
300, 000-hr Code Case	25,000–68,000	Alloy 709 base metal Alloy 709 welds	ORNL
500, 000-hr Code Case	91,000–109,000		

The creep Code Case testing procedure followed ASTM E139 (ASTM, 2018), *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials*. The creep test schedule was arranged to best utilize the individual creep machine capacity and estimated testing duration.

To perform a preliminary assessment of the creep resistance of Alloy 709, rupture data from three heats of Alloy 709 plates with the PT condition were compiled. The results are presented in the form of a Larson-Miller (LM) relationship in Figure 13. A total of 116 rupture data points has been generated to date. Notably, data with longer rupture times were produced during FY 2024, including the longest test for 33,835 hours on Heat 58776 with the PT condition at 700 °C and 90 MPa.

This analysis is consistent with previous findings, showing that Heat 530843 exhibits slightly stronger creep strength than Heat 58776, particularly at lower stress levels.

Creep rupture test results for the Alloy 709 cross-welds, primarily generated in FY 2024, are included in the same figure for comparison. The new data at low stress levels indicate a moderate reduction in creep rupture strength compared to the base metal, necessitating stress reduction factors for Alloy 709. Additional cross-weld rupture data will be collected to establish temperature- and time-dependent stress rupture factors, which will be included as design parameters in the Alloy 709 Code Case.

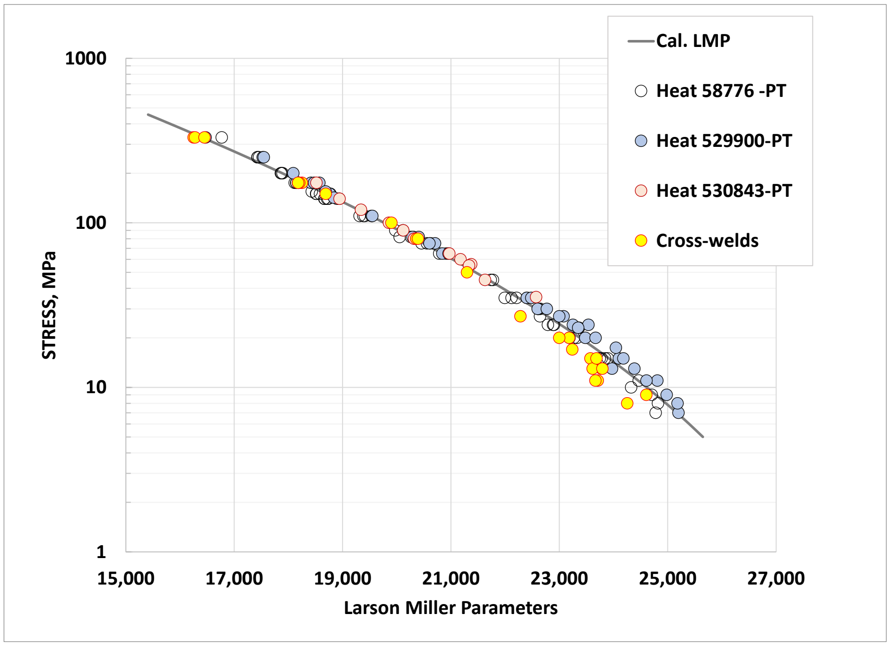

Figure 13. Interim creep rupture results from Alloy 709 with the PT condition and Alloy 709 cross-welds.

3.5 CODE CASE TESTING DATA TO BE GENERATED BY FY 2025

Ongoing Code Case testing experiments are being conducted at three laboratories, generating data that includes additional creep rupture data for both Alloy 709 base metal and its welds, remaining fatigue and creep-fatigue testing, thermal aging tests and aging factor evaluations, and experiments to support the incorporation of Alloy 709 into elastic-perfectly plastic analysis methods. Additionally, experiments are underway to develop an inelastic model for Alloy 709, as part of the Alloy 709 Code Case. All of these activities are planned and scheduled for completion to support the Alloy 709 Code Case submittal to ASME.

4. SUMMARY

The Code Case testing effort to qualify Alloy 709 as a Class A construction material in the ASME Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors is ongoing. This report summarizes the Alloy 709 Code Case testing conducted on three commercial heats of Alloy 709 plates with the PT condition at ORNL, INL, and ANL. The data generated to date supports the recommendation for ASME Code qualification of Alloy 709, aimed at reducing construction and operating costs for advanced reactor deployment.

Key Code Case testing data on Alloy 709 plates is on schedule for completion by the end of 2024, with design parameters expected to be finalized in FY 2025. The Alloy 709 100,000-hr Code Case remains on track for submission to ASME.

REFERENCES

ASME (2023a), Boiler and Pressure Vessel Code, Section III Division 5, *Rules for Construction of Nuclear Facility Components,* Subsection HB Subpart B, American Society of Mechanical Engineers, New York, NY (2021 Edition).

ASME SA-213 (2023b), *Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes,* ASME Coiler and Pressure Vessel Code, Section II Materials, American Society of Mechanical Engineers, New York, NY (2021 Edition).

ASTM E8-2022 (2022), *Standard Test Methods for Tension Testing of Metallic Materials*, ASTM International, West Conshohocken, PA, 2022, www.astm.org

ASTM E139-11 (2018), *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials*. ASTM International, West Conshohocken, PA, 2018, www.astm.org

ASTM E21-20 (2021a), *Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials,* ASTM International, West Conshohocken, PA, 2021, www.astm.org

ASTM E2714-13 (2020), *Standard Test Method for Creep-Fatigue Testing,* ASTM International, West Conshohocken, PA, 2020, www.astm.org

ASTM E606/E606M-21 (2021b), *Standard Test Method for Strain-Controlled Fatigue Testing,* ASTM International, West Conshohocken, PA, 2021, www.astm.org

ASTM A240/A240M REV. A (2023a), *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications,* ASTM International, West Conshohocken, PA, 2023, www.astm.org

ASTM A0480/A0480M-23 REV. B (2023b), *Standard Specification for General Requirements for Flat-Rolled Stainless and Heat- Resisting Steel Plate, Sheet, and Strip*, ASTM International, West Conshohocken, PA, 2023, www.astm.org

ASTM E112 − 13 (2021), *Standard Test Methods for Determining Average Grain Size,* ASTM International, West Conshohocken, PA, 2023, www.astm.org

C.E. Jaske and W. J. O'Donnell, *Fatigue Design Criteria for Pressure Vessel Alloys*, Journal of Pressure Vessel Technology, the American Society of Mechanical Engineers, 1997, 584-592.

Heramb Mahajan, *FY-24 Progress Report on A709 Mechanical Properties Data Development and A709 Thermal Aging Status,* INL/RPT-24-80439, Idaho National Laboratory, Idaho Falls, ID.

M. McMurtrey (2019), *Report on FY-19 Scoping Creep and Creep-Fatigue Testing on Heat Treated Alloy 709 Base Metal,* INL/EXT-19-55502, Idaho National Laboratory, Idaho Falls, ID.

R. N. Wright (2021), *Draft ASME Boiler and Pressure Vessel Code Cases and Technical Bases for Use of Alloy 617 for Construction of Nuclear Components Under Section Ill, Division 5,* INL/EXT-15-36305, Revision 2, Idaho National Laboratory, Idaho Falls, ID.

S.J. Reese, D.S. Smith, R.E. Rupp, J.K. Wright, A.R. Khanolkar, R.N. Wright, and D.H. Hurley (2021), *Elevated-Temperature Elastic Properties of Alloys 709 and 617 Measured by Laser Ultrasound*, JMEPEG (2021) 30:1513–1520.

T.-L. Sham, Y. Wang, R. Bass, X. Zhang, (2022) *A709 Qualification Plan Update and Mechanical Properties Data Assessment, INL/RPT-22-67641*, Idaho National Laboratory, Idaho Falls, ID.

Wang, Y. and Hou, P. (2023), *Progress Report on Alloy 709 Base Metal Code Case Testing at ORNL in FY 2023,* ORNL/TM-2023/2947, Oak Ridge National Laboratory, Oak Ridge, TN.

Wang, Y and T.-L. Sham (2024), *Fatigue and Creep-Fatigue Evaluation of Alloy 709 at 760 and 816°C,* Proceeding of 10th International Conference on Advances in Materials, Manufacturing & Repair for Power Plants, Bonita Springs, Florida, ASM International.

X. Zhang and E. Listwan, *FY24 progress report on A709 creep rupture testing in ANL,* ANL-ART-282, Argonne National Laboratory, Lemont, IL.