INL/RPT-22-68982
Revision 0

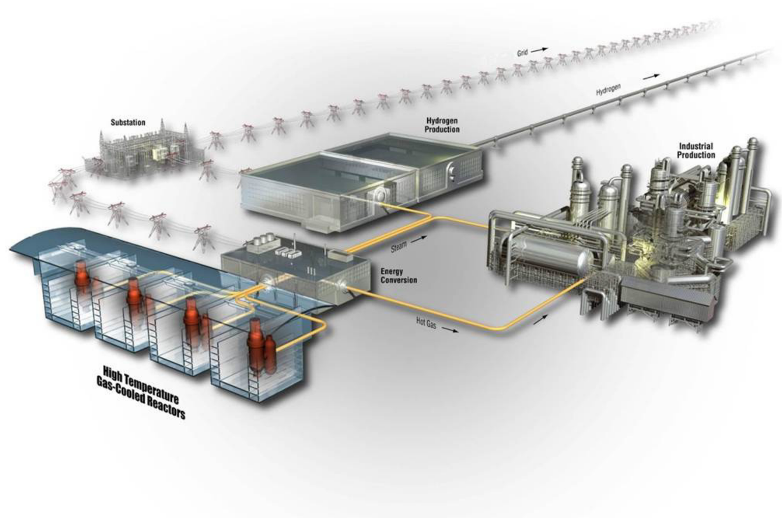
Interim Creep, Fatigue and Creep-Fatigue Data from FY 2022 INL Testing of A709 with Precipitation Treatment for ASME Code Case Data Package

September 2022

Changing the World's Energy Future

Ryann Bass
Idaho National Laboratory

Ting-Leung Sham
Idaho National Laboratory



Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/RPT-22-68982
Revision 0

Interim Creep, Fatigue and Creep-Fatigue Data from FY 2022 INL Testing of A709 with Precipitation Treatment for ASME Code Case Data Package

Ryann Bass
Idaho National Laboratory
Ting-Leung Sham
Idaho National Laboratory

September 2022

Idaho National Laboratory
Originating Organization Advanced Reactor Technologies
Idaho Falls, Idaho 83415

http://www.art.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

INL ART Program

Interim Creep, Fatigue and Creep-Fatigue Data From FY 2022 INL Testing of A709 with Precipitation

INL/RPT-22-68982
Revision 0
September 2022

Technical Reviewer: (Confirmation of mathematical accuracy, and correctness of data and appropriateness of assumptions.)

	9/2/2022
Michael D. McMurtrey ART Elevated-Temperature Metals Lead	Date

Approved by:

M. Davenport	9/6/2022
Michael E. Davenport ART Project Manager	Date
Travis Mitchell	9/6/2022
Travis R. Mitchell ART Program Manager	Date
Michelle Sharp	9/6/2022
Michelle T. Sharp INL Quality Assurance	Date

SUMMARY

This report provides the status of creep, fatigue, and creep-fatigue testing that transpired in fiscal year 2022 at Idaho National Laboratory (INL). This testing is being conducted to develop the data package to qualify A709 in Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC). This would permit the use of A709 for elevated-temperature nuclear construction. Preliminary results continue to demonstrate the improved creep and fatigue resistance of A709 compared to 316H stainless steel.

Page intentionally left blank

ACKNOWLEDGEMENTS

This research was sponsored by the United States (U.S.) Department of Energy (DOE) under Contract No. DE-AC07-05ID14517 with Idaho National Laboratory (INL), which is managed and operated by Battelle Energy Alliance. Programmatic direction was provided by the Office of Nuclear Reactor Deployment of the DOE Office of Nuclear Energy. The authors gratefully acknowledge the support provided by Sue Lesica, Federal Lead for Advanced Materials, Advanced Reactor Technologies (ART) Program; Brian Robinson, Federal Manager, ART Fast Reactors (FR) Campaign; and Bo Feng, ANL, National Technical Director, ART FR Campaign. The authors also acknowledge helpful discussions with Yanli Wang of Oak Ridge National Laboratory, Xuan Zhang of Argonne National Laboratory, Richard Wright of Structural Alloys, Limited Liability Corporation (LLC), and Michael McMurtrey of INL. Finally, the authors thank their support staff: J.W. Jones, M.P. Heighes, and J.A. Simpson of INL for their technical support.

Page intentionally left blank

CONTENTS

TABLES

Page intentionally left blank

ACRONYMS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATI	Allegheny Technologies Incorporated
BPVC	Boiler and Pressure Vessel Code
ESR	electroslag remelting
FY	fiscal year
INL	Idaho National Laboratory
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
SFR	sodium-cooled fast reactor
SS	stainless steel

Page intentionally left blank

Interim Creep, Fatigue and Creep-Fatigue Data from FY 2022 INL Testing of A709 with Precipitation Treatment for ASME Code Case Data Package

1. MOTIVATION

President Biden's Executive Order 14008 issued a federal directive for the development of a plan to facilitate a carbon-zero electric-industry sector by 2035 (Exec. Order No. 14008 2021). Nuclear energy is one potential resource to satisfy this executive order. One of the leading advanced nuclear reactor concepts is the sodium-cooled fast reactor (SFR). Other needs not associated with this executive order but important for clean energy—such as the recycling of spent nuclear fuel—can also be attained with SFRs (Sham and Natesan 2017).

SFR commercialization is dependent upon these reactors being economically viable. A crucial aspect to achieving this commercialization is advanced materials, which can reduce capital constructions costs. Although advanced materials are typically more expensive than traditional steels, they offer advantages that may ultimately lead to savings. Advanced materials may enable higher operating temperatures, which improves thermal efficiency and leads to increased power output. Additionally, advanced materials may offer longer design lifetimes, meaning components may not have to be replaced as regularly. Besides economic savings, advanced materials may offer improved safety margins, material reliability, and design flexibility (Sham and Natesan 2017).

A709, an austenitic stainless steel (SS), has been identified as an advanced material that would improve the viability of SFRs. A709 has better creep properties than 316H SS, the reference construction material for SFRs, but is not as expensive as nickel-based alloys usually used at high temperatures. This enables the construction of thinner walled components, reducing construction costs. A709 has an improved resistance to thermal gradients compared to 316H SS. This eliminates the need for expensive add-on hardware required for construction with 316H SS, further reducing construction costs. There are additional benefits beyond the two examples provided for constructing components with A709 as compared to 316H SS. Potential SFR components to be constructed with A709 are the reactor vessel, piping, core supports, intermediate heat exchanger, and compact heat exchanger. The compact heat exchanger could link the SFR to a supercritical carbon dioxide Brayton energy conversion system as one possible application (Sham and Natesan 2017).

In the United States (U.S.), the U.S. Nuclear Regulatory Commission (NRC) licenses and regulates nuclear reactors and nuclear reactor designs. Nuclear plant owners and operators can take advantage of Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) to reduce the effort needed to license a nuclear reactor or nuclear reactor design. This section of the Code provides design rules for elevated-temperature nuclear construction (ASME 2021b). The NRC is in the process of evaluating the 2017 version of Section III, Division 5 for potential endorsement (Thomas 2018; Nuclear Regulatory Commission 2022). A709 is currently not qualified in Section III, Division 5 of the ASME BPVC. A program comprised of a collaboration between three U.S. Department of Energy (DOE) national laboratories—Argonne National Laboratory (ANL), Idaho National Laboratory (INL), and Oak Ridge National Laboratory (ORNL)—is in progress to qualify A709 in Section III, Division 5 of the ASME BPVC through multiple Code Cases. These Code Cases require conducting tests to collect A709 data and creating data packages from which the design rules will be established.

The purpose of this report is to provide the status of testing conducted in fiscal year (FY) 2022 at INL to generate the data packages for the A709 Code Cases. Focus will be on creep, fatigue, and creep-fatigue testing. Preliminary results are discussed. To date, Code Case testing has been conducted on Commercial

Heat 1 and Commercial Heat 2. The former was fabricated by Electralloy/G.O. Carlson, heat 58776, and Allegheny Technologies Incorporated (ATI) Flat Rolled Products, heat 529900, respectively.

2. BACKGROUND

A709 is an austenitic SS that originated from NF709, which was developed as a tubing material for ultra-supercritical boiler applications by Nippon Steel. NF709 is strengthened by molybdenum and nitrogen in solution as well as carbonitride precipitates. NF709 was designed so that detrimental intermetallics do not precipitate during long-term, elevated-temperature service (Sham and Natesan 2017). NF709 is included in American Society for Testing and Materials (ASTM) specification A213 and ASME specification SA-213. Both specifications are entitled “Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat Exchanger Tubes.” NF709 is designated as grade TP310MoCbN and UNS S31025 (ASTM 2021; ASME 2021c). ASME BPVC Case 2581 qualifies Section I construction of NF709 seamless tubes for temperatures up to 815°C (1500°F) (ASME 2021e).

A collaboration between ANL, INL, and ORNL was initiated in 2013 to develop A709 plate and characterize its properties. This work resulted in the recommendation to qualify A709 in Section III, Division 5 of the ASME BPVC for elevated-temperature nuclear construction. This recommendation was based on the following findings: (1) A709 is stable in an elevated-temperature, liquid-sodium environment; (2) A709 can be successfully welded with Alloy 625 or optimized A709 filler metals by automated gas-tungsten arc welding; (3) the production of A709 can be optimized to improve the creep-fatigue properties while maintaining creep strength; and (4) the properties of A709 are improved compared to 316H SS, which is qualified in Section III, Division 5 of the ASME BPVC (ASME 2021b, Sham and Natesan 2017).

A plan for developing the data package needed to qualify A709 in Section III, Division 5 of the ASME BPVC was formulated. Multiple data packages were devised through a staged qualification approach for A709 to support multiple code cases with increasing design lives. This approach entails qualifying a material for a shorter design life initially using data that can be generated in the near term. The qualified design life is then extended at a later date once the longer-term data needed to support this extension, such as creep and thermal aging, becomes available. This enables accelerated qualification of A709. The alternative, non-accelerated approach, is to wait until all necessary data to support a Code Case for the longest design life is generated. This plan took into consideration the needs of both the ASME BPVC and NRC (Sham and Natesan 2017). This includes Nonmandatory Appendix HBB-Y in Section III, Division 5 of the ASME BPVC, which provides guidelines for qualifying new materials, as well as re-occurring issues flagged by the NRC (Sham and Natesan 2017; ASME 2021b; O’Donnell and Griffin 2007). Nonmandatory Appendix HBB-Y specifies the data package for qualifying new materials must be comprised of data from a minimum of three heats, which need to encompass the composition range, product forms, and size of the components to be used in service (ASME 2021b).

The first commercial heat of A709 was procured in FY 2017 from Electralloy/G.O. Carlson, heat 58776. This heat was procured in a manner that enabled the final processing step and the solution annealing temperature to be independently investigated. The final processing step was either argon oxygen decarburization (AOD), electroslag remelting (ESR), or ESR with a homogenization treatment (ESR + HOMO). The plates were solution annealed at 1050°C (1922°F), 1100°C (2012°F), or 1150°C (2102°F). A total of nine unique groups of plates were fabricated, one for each processing combination (Natesan et al. 2017). Creep, fatigue, and creep-fatigue testing were initiated to down-select the final processing step and solution anneal temperature. Plates that were solution annealed at 1050°C (1922°F) were eliminated from consideration because of a too fine grain size and an unacceptably short creep-rupture lifetime. The ESR final processing condition resulted in longer elongations to failure during creep, establishing it as the best method of manufacturing. A tradeoff between creep and creep-fatigue properties was found between the solution annealing temperatures. The plate with the ESR final processing step, solution annealed at 1150°C (2102°F) had the best creep-rupture properties but inadequate creep-fatigue properties. The processing condition that resulted in the optimal balance in properties was the ESR plate solution annealed at 1100°C (2012°F), although the creep-fatigue properties were worse than desired (McMurtrey 2018; McMurtrey and Rupp 2019; Natesan, Zhang, and Li 2018; Wang et al. 2018). During this time, preliminary results prompted ORNL to start long-term tests of A709 fabricated with AOD and solution annealed at 1100°C (2012°F) (Wang et al. 2018; Wang and Sham 2019; Wang, Hou and Sham 2020; Wang, Hou, and Sham 2021). Later findings resulted in A709 tests with the final processing step of ESR and solution annealed at 1100°C (2012°F) being started at ANL and ORNL (Wang and Sham 2019; Wang, Hou, and Sham 2020; Wang, Hou, and Sham 2021; Zhang and Sham 2019; Zhang and Sham 2020).

A heat treatment referred to as a precipitation treatment for A709 was developed in FY 2019. This precipitation treatment emanated from two questions. The first was concerning whether the beneficial precipitates that form during accelerated testing would form during service at low temperature, low stress conditions. The second was whether the A709 properties, particularly the creep-fatigue properties, could be further improved. Precipitation treating A709 prior to service would ensure the beneficial precipitates would be present during service conditions. The heat treatment needed to precipitate the beneficial MX (Nb, Ti, V: C, N) and Z-phase (CrNbN) without forming the detrimental intermetallics (Fe_2Mo, Fe_2Nb). A 10-hour, 775°C (1427°F) heat treatment protocol followed by air cooling was identified (Zhang, Sham, and Young 2019). This heat treatment promoted the precipitation of the beneficial MX and Z-phase and was observed to improve creep-fatigue properties without significantly impacting creep properties (Rupp and McMurtrey 2020). A709 with ESR as the final processing step, solution annealed at 1150°C (2102°F), and subsequently precipitation treated at 775°C (1427°F) for 10 hours followed by air cooling has been identified as having the best properties. Testing of the A709 material with ESR as the final processing step, solution annealed at 1150°C (2102°F), and precipitation treated was initiated to develop the data package to qualify A709 in Section III, Division 5 of the ASME BPVC (Rupp et al. 2021; Wang, Hou, and Sham 2021; Zhang, Sham, and Li 2021).

In FY 2020, INL placed a purchase order with ATI Flat Rolled Products to procure the second commercial heat of A709 (Wright 2020). The A709 plates, heat 529900, were delivered by ATI in March 2021. This heat was comprised of nine plates, all fabricated by ESR. Of these plates, eight were hot rolled and solution annealed; six of the plates were nominally 1.75 inches thick and the remining two were nominally 2.0 inches thick. The solution anneal was conducted at a minimum of 1149°C (2100°F). The remaining plate was nominally 1.75 inches thick and delivered in the hot-rolled condition. Microstructural characterization and preliminary mechanical testing of this heat has been conducted at INL (Bass and Sham 2022; Mohale and Bass 2022). Testing of material from this heat in the precipitation-treated condition to support the generation of the Code Case data packages was initiated in FY 2022.

In FY 2022, the mechanical properties of the first two commercial heats of plate A709 in the precipitation-treated condition were assessed. This assessment evaluated all tensile, creep, fatigue, and creep-fatigue data generated to date. The mechanical properties of precipitation-treated A709 were determined to outperform those of 316H SS. Consequently, the recommendation to qualify A709 in Section III, Division 5 of the ASME BPVC for elevated-temperature nuclear construction was upheld. This recommendation entails the continuation of the collaboration between ANL, INL, and ORNL to continue development of the data packages needed to qualify A709 in Section III, Division 5 of the ASME BPVC (Sham et al. 2022).

3. MATERIAL

3.1 Commercial Heat 1

The first commercial heat of plate A709, heat 58776, was procured from Electralloy/G.O. Carlson in the solution-annealed condition. In FY 2022, the ESR plate solution annealed at 1150°C (2102°F) and precipitation treated for 10 hours at 775°C (1427°F) and subsequently air cooled was investigated. This plate is 1.1 in. thick with the chemical composition shown in Table 1. The chemistry requirements specified in SA-213 for UNS S31025 are also provided in Table 1 for comparison (ASME 2021c). The microstructure, grain size, hardness, and tensile properties of this plate is available in a 2017 report (Natesan et al. 2017). For the remainder of this report, this plate will be referred to as Commercial Heat 1.

3.2 Commercial Heat 2

The second commercial heat of plate A709, heat 529900, was procured from ATI. In FY 2022, Code Case testing was primarily from plate CG05455 and a single fatigue test from plate CG05453 was conducted. These ESR plates were solution annealed at a minimum of 1149°C (2100°F) and precipitation treated for 10 hours at 775°C (1427°F) and subsequently air cooled. CG05455 is 1.806 in. thick while CG05453 is 2.057” thick. Both plates had the same chemical composition which is provided in Table 1. The chemistry requirements specified in SA-213 for UNS S31025 are also provided in Table 1 for comparison (ASME 2021c). The microstructure, grain size, hardness, and tensile properties of these plates are available in a 2022 report (Bass and Sham 2022). For the remainder of this report, both plates will be referred to as Commercial Heat 2.

Table 1. Chemistry composition, in weight percent, of Commercial Heat 1 and Commercial Heat 2 as well the chemistry requirements specified in ASME SA-213 for UNS S31025 (ASME 2021c).

	C	Mn	Si	P	S	Cr	Ni	Mo
Commercial Heat 1	0.066	0.90	0.38	0.014	0.001	20.05	25.14	1.51
Commercial Heat 2	0.08	0.9	0.39	0.003	< 0.001	19.9	24.6	1.5
UNS S31025	0.10 max	1.50 max	1.00 max	0.030 max	0.030 max	19.5 – 23.0	23.0 – 26.0	1.0 – 2.0

	N	Nb	Ti	Cu	Co	Al	B	Fe
Commercial Heat 1	0.152	0.26	0.01	0.06	0.02	0.02	0.0030	Bal.
Commercial Heat 2	0.15	0.17	< 0.01	0.06	0.02	0.02	0.004	Bal.
ASME SA-213	0.10 – 0.25	0.10 – 0.40	0.20 max	–	–	–	0.002 – 0.010	–

Bal. = Balance

4. FY 2022 CREEP CODE CASE TESTING

In FY 2022, a total of six creep-rupture tests were completed. Another 18 creep-rupture tests are currently in progress at the time of writing this report. These tests can be categorized by the Code Case the test supports; 1) preliminary, 2) 100,000-hour, 3) 300,000-hour, or 4) 500,000-hour. The maximum estimate rupture life for each of these categories is 11,000 hours, 25,000 hours, 68,000 hours, and 110,000 hours, respectively. A breakdown of these tests by category and heat are summarized in Table 2. INL has not been assigned to conduct any creep-ruptures tests to support the 300,000-hour nor the 500,000-hour Code Cases. Consequently, these two categories were not included in Table 2. The test conditions for each of these tests are described in Table 3.

Table 2. Summary of creep-rupture testing during FY 2022.

Category	Commercial Heat	Number of Tests Completed in FY 2022	Number of Tests in Progress at the Time of Writing this Report
Preliminary	1	3	5
	2	3	6
100,000 hours	1	0	3
	2	0	4

Table 3. Creep-rupture tests that transpired during FY 2022.

Commercial Heat	Temperature	Stress	Status	Sample ID
Preliminary				
1	750°C (1382°F)	65 MPa (9.4 ksi)	In progress	BCHT2-IC-02
	775°C (1427°F)	65 MPa (9.4 ksi)	In progress	BCHT3-IC-01
	800°C (1472°F)	45 MPa (6.5 ksi)	In progress	BCHT3-IC-02
	825°C (1517°F)	45 MPa (6.5 ksi)	In progress	BCHT3-IC-03
	850°C (1562°F)	45 MPa (6.5 ksi)	Complete	BCHT2-IC-03
	825°C (1517°F)	35 MPa (5.1 ksi)	In progress	BCHT2-IC-06
	1000°C (1832°F)	9 MPa (1.3 ksi)	Complete	BCHT2-IC-04
	1000°C (1832°F)	8 MPa (1.2 ksi)	Complete	BCHT2-IC-05
2	650°C (1202°F)	175 MPa (25.4 ksi)	In progress	CG05455-11-AT51
	650°C (1202°F)	155 MPa (22.5 ksi)	In progress	CG05455-11-AT52
	800°C (1472°F)	65 MPa (9.4 ksi)	Complete	CG05455-11-AT43
	825°C (1517°F)	35 MPa (5.1 ksi)	In progress	CG05455-11-AT50
	850°C (1562°F)	35 MPa (5.1 ksi)	In progress	CG05455-11-AT44
	900°C (1652°F)	27 MPa (3.9 ksi)	Complete	GC05455-11-AT42
	975°C (1787°F)	11 MPa (1.6 ksi)	In progress	CG05455-11-AT53
	1000°C (1832°F)	9 MPa (1.3 ksi)	Complete	CG05455-11-AT45
	1000°C (1832°F)	8 MPa (1.2 ksi)	In progress	CG05455-11-AT46
100,000 hour				
1	675°C (1247°F)	110 MPa (16.0 ksi)	In progress	BCHT-IC-10
	700°C (1292°F)	82 MPa (11.9 ksi)	In progress	BCHT-IC-09
	775°C (1427°F)	45 MPa (6.5 ksi)	In progress	BCHT2-IC-01
2	675°C (1247°F)	110 MPa (16.0 ksi)	In progress	CG05455-11-AT47
	700°C (1292°F)	82 MPa (11.9 ksi)	In progress	CG05455-11-AT48
	775°C (1427°F)	45 MPa (6.5 ksi)	In progress	CG05455-11-AT49
	875°C (1607°F)	20 MPa (2.9 ksi)	In progress	CG05455-11-AT55

Creep-rupture tests were conducted in accordance with ASTM E139, "Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials" (ASTM 2011). Tests were also in accordance with PLN-3386, "Creep Testing" (Idaho National Laboratory 2016). Cylindrical test specimens were used with the longitudinal direction parallel to the rolling direction of the plate. Specimens were machined from the center of the plate with respect to the plate thickness for Commercial Heat 1. For Commercial Heat 2, specimens were machined from the one-quarter and three-quarters of the plate thickness. The machining of the mechanical test specimens for both commercial heats was in accordance with ASTM guidance (ASTM 2011). Specimens had a 6.35 mm (0.250 in.) minimum diameter and a reduced parallel section that was at minimum 31.75 mm (1.250 in). Test conditions were selected to generate creep-rupture data to cover a wide range of Larson-Miller parameters (Larson, Miller 1952). These conditions also took Section III, Division 5, Nonmandatory Appendix HBB-Y and Section II, Part D, Mandatory Appendix 5 into consideration (ASME 2021b, 2021a). As tests finish and new data becomes available, the growing data package is continuously evaluated for gaps, and if identified, requisite tests are added to the test plan.

5. FY 2022 FATIGUE CODE CASE TESTING

In FY 2022, a total of four fatigue tests were completed. At the time of writing the FY 2021 Code Case testing progress report, two fatigue tests were in progress (Rupp et al. 2021). These two tests finished in FY 2021. A summary of all six of these tests is provided in Table 4. Cycles to failure was determined use N_{20}, which indicates a 20% load drop from the crack initiation point, or the point where load vs. cycle deviates from linear behavior.

Table 4. Summary of fatigue testing that transpired since the reporting of the FY 2021 Code Case testing (Rupp et al. 2021).

Commercial Heat	Temperature	Total Strain Range	Status	Sample ID	Cycles to Failure (N_{20})
1	649°C (1200°F)	0.3%	Complete	BCHT-IF-5	3,614,560
	816°C (1501°F)	0.25%	Complete	BCHT-IF-15	1,206,978
2	650°C (1202°F)	1.0%	Complete	35A7*	1,517
	871°C (1600°F)	1.0%	Complete	CG05455-13-AF26	755
	927°C (1701°F)	1.0%	Complete	CG05455-13-AF23	826
	982°C (1800°F)	1.0%	Complete	CG05455-13-AF22	743

*From plate CG05453

Fatigue tests were conducted in accordance with ASTM E606-12, "Standard Test Method for Strain-Controlled Fatigue Testing" (ASTM 2012). Tests were also in accordance with PLN-3346, "Creep Fatigue Testing" (Idaho National Laboratory 2017). Testing was strain-controlled with a fully reversed (R = -1) triangular strain waveform with a 10^{-3} s^{-1} strain rate. Long tests were an exception to the $10^{-3}s^{-1}$ strain rate, as strain rate was increased when testing exceeded one million cycles. Cylindrical test specimens were used with the longitudinal direction parallel to the rolling direction of the plate.

Specimens were machined from the center of the plate with respect to the plate thickness for Commercial Heat 1. For Commercial Heat 2, specimens were machined from the one-quarter and three-quarters of the plate thickness. Specimens tested at INL had a 7.49 mm (0.29 in.) minimum diameter. The extensometer used at INL had a gauge length of 12 mm (0.47 in.). As fatigue tests finish and new data becomes available, the growing data package is continuously evaluated for gaps, and if identified, requisite tests are added to the test plan.

6. FY 2022 CREEP-FATIGUE CODE CASE TESTING

In FY 2022, one creep-fatigue test was completed. Another test is currently in progress at the time of writing this report. Both tests are from Commercial Heat 1. A summary of these tests is provided in Table 5. Similar to the fatigue tests, N_{20} was used for cycles to failure.

Table 5. Creep-fatigue tests that transpired during FY 2022. Both specimens are from Commercial Heat 1.

Temperature	Total Strain Range	Hold Time	Status	Sample ID	Cycles to Failure (N_{20})
760°C (1400°F)	0.3%	0.5 hr	In progress	BCHT-IF-17	-
816°C (1501°F)	0.3%	0.5 hr	Complete	BCHT-IF-16	10,492

Creep-fatigue tests were conducted in accordance with ASTM E2714-13, "Standard Test Method for Creep-Fatigue Testing," and ASTM E606-12 (ASTM, 2013; 2012). Tests were also in accordance with PLN-3346 (Idaho National Laboratory, 2017). Creep-fatigue testing uses the same setup and procedures as fatigue testing. The difference between creep-fatigue and fatigue testing is the addition of a hold time to the strain waveform at the maximum tensile strain. Test conditions were selected to cover a spectrum of temperatures, total strain ranges, and hold times. This is necessary to establish the creep-fatigue damage envelope. As creep-fatigue tests finish and new data become available, the growing data package is continuously evaluated for gaps, and if identified, requisite tests are added to the test plan.

7. SUMMARY AND ONGOING WORK

A709 is an advanced material that offers many advantages over 316H SS and would improve the viability of SFRs. Consequently, it has been identified as the next alloy to be qualified in Section III, Division 5 of the ASME BPVC. The A709 Code Case data package is currently being developed through a collaboration between ANL, INL, and ORNL. An update is provided on the status of creep, fatigue, and creep-fatigue testing that transpired during FY 2022 at INL. Preliminary results continue to demonstrate the improved creep and fatigue resistance of A709 compared to 316H SS.

In FY 2021, INL placed a purchase order with ATI to procure the third commercial heat of plate A709. The A709 plates, heat 530843, were delivered by ATI to ORNL in April 2022. This heat is currently being sectioned into smaller pieces by waterjet cutting. The heat will then be distributed among ANL, INL, and ORNL. This heat will be characterized and code case testing will be initiated in FY 2023. Code Case testing will include creep, fatigue, and creep-fatigue testing. This testing will be in conjunction with the creep and cyclic tests that are currently in progress at the time of writing this report.

8. REFERENCES

ASME International. 2021a. "Section II, Part D, M: Materials, Properties (Metric)." In *ASME Boiler and Pressure Vessel Code: An International Code*. New York, NY: ASME.

ASME International. 2021b. "Section III, Division 5: Rules for Construction of Nuclear Facility Components, High Temperature Reactors." In *ASME Boiler and Pressure Vessel Code: An International Code*. New York, NY: ASME.

ASME International. 2021c. "Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat Exchanger Tubes." ASME SA-213/SA-213M. New York, NY.

ASME International. 2021e. "20Cr-25Ni-1.5Mo-Cb-N Seamless Austenitic Stainless Steel Tube, Section I." Case 2581. New York, NY.

ASTM International. 2011. "Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials." ASTM E139-06. West Conshohocken, PA.

ASTM International. 2012. "Standard Test Method for Strain-Controlled Fatigue Testing." ASTM E606/E606M-12. West Conshohocken, PA.

ASTM International. 2013. "Standard Test Method for Creep-Fatigue Testing." ASTM E2714-13. West Conshohocken, PA.

ASTM International. 2021. "Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes." ASTM A213/A213M-21a. West Conshohocken, PA.

Bass, Ryann and Ting-Leung Sham. 2022. "Initial Characterization of the Second A709 Commercial Heat." INL/EXT-22-#####-Rev000, Idaho National Laboratory.

Executive Order No. 14,008. 2021. 3 C.F.R 7624. "Tackling the Climate Crisis at Home and Abroad." January 27, 2021.

Idaho National Laboratory. 2016. "Creep Testing." PLN-3386 INL/MIS-16-40783-Rev002, Idaho National Laboratory.

Idaho National Laboratory. 2017. "Creep Fatigue Testing." PLN-3346 INL/MIS-10-18953-Rev009, Idaho National Laboratory.

Larson, F.B. and James Miller. 1952. "A Time-Temperature Relationship for Rupture and Creep Stresses." Transactions of the ASME 74: 765-771.

McMurtrey, Michael. 2018. "Report on the FY-2018 Creep Rupture and Creep-Fatigue Tests on the First Commercial Heat of Alloy 709." INL/EXT-18-46140-Rev000, Idaho National Laboratory. https://doi.org/10.2172/1484686.

McMurtrey, Michael and Ryann Rupp. 2019. "Report on FY-2019 Scoping Creep and Creep-Fatigue Testing on Heat Treated Alloy 709 Base Metal." INL/EXT-19-55502-Rev000, Idaho National Laboratory.

Mohale, Ninad and Ryann Bass. 2022. "Microstructural Characterization of A709 Commercial Heats with Precipitation Treatment." INL/RPT-22-68666-Rev000, Idaho National Laboratory.

Natesan, Krishnamurti, Xuan Zhang, Ting-Leung Sham, and Hong Wang. 2017. "Report on the Completion of the Procurement of the First Heat of Alloy 709." ANL-ART-89, Argonne National Laboratory. https://doi.org/10.2172/1364649.

Natesan, Krishnamurti, Xuan Zhang, and Meimei Li. 2018. "Report on the initiation of planned FY18 short and intermediate term creep rupture tests and creep-fatigue tests on the first commercial heat of Alloy 709." ANL-ART-51, Argonne National Laboratory. https://doi.org/10.2172/1485134.

Nuclear Regulatory Commission. 2022. "Acceptability of ASME Code Section III, Division 5, High Temperature Reactors." NRC-2021-0117. 87 Fed. Reg. 11,490. March 1, 2022.

O'Donnell, William J. and Donald S. Griffin. 2007. "Regulatory Safety Issues in the Structural Design Criteria of ASME Section III Subsection NH and for Very High Temperatures for VHTR & GEN IV." DOE/ID14712-2, ASME Standards Technology, LLC. https://doi.org/10.2172/974279.

Rupp, Ryann E. and Michael D. McMurtrey. 2020. "Mechanical Properties of Aged A709." INL/EXT-20-59630-Rev000, Idaho National Laboratory.

Rupp, Ryann, Yanli Wang, Xuan Zhang, and Ting-Leung Sham. 2021. "Integrated FY-2021 Elevated-Temperature Mechanical-Testing Results for Alloy 709 Code Case." INL/EXT-21-64314-REV000, Idaho National Laboratory.

Sham, Ting-Leung and Krishnamurti Natesan. 2017. "Code Qualification Plan for an Advanced Austenitic Stainless Steel, Alloy 709, for Sodium Fast Reactor Structural Applications." International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear for Sustainable Development (FR17), Yekaterinburg, Russia, IAEA-CN-245-74.

Sham, Ting-Leung, Yanli Wang, Ryann Bass, and Xuan Zhang. 2022. "A709 Qualification Plan Update and Mechanical Properties Data Assessment." INL/RPT-22-67641, Idaho National Laboratory.

Thomas, Brian E. 2018. "NRC Response to ASME Letter of Request for NRC Endorsement of ASME Boiler and Pressure Vessel Code, Section III, Division 5". ML18211A571, United States Nuclear Regulatory Commission.

Wang, Hong, C. Shane Hawkins, Eric C. Disney, and Jeremy L. Moser. 2018. "The Initiation of Long-Term Creep Rupture Tests on the First Alloy 709 Commercial Heat." ORNL/TM-2018/985, Oak Ridge National Laboratory. https://doi.org/10.2172/1476397.

Wang, Yanli and Ting-Leung Sham. 2019. "Planned FY-2019 Creep and Fatigue Design Curve Testing of Alloy 709 Base Metal." ORNL/TM-2019/1303, Oak Ridge National Laboratory. https://doi.org/10.2172/1569365.

Wang, Yanli, Peijun Hou, and Ting-Leung Sham. 2020. "Report on FY-2020 Creep, Fatigue, and Creep-Fatigue Testing of Alloy 709 Base Metal at ORNL." ORNL/TM-2020/1622, Oak Ridge National Laboratory. https://doi.org/10.2172/1671410.

Wang, Yanli, Peijun Hou, and Ting-Leung Sham. 2021. "Report on FY 2021 Creep, Fatigue, and Creep Fatigue Testing of Alloy 709 Base Metal at ORNL." ORNL/TM-2021/2120, Oak Ridge National Laboratory.

Wright, Richard N. 2020. "Report Documenting Activity for Second Alloy 709 Commercial Heat." INL/EXT-20-59880-Rev000, Idaho National Laboratory.

Zhang, Xuan, and Ting-Leung Sham. 2019. "FY-2019 Status Report on Creep Test Data on Commercial Heat of Alloy 709." ANL-ART-172, Argonne National Laboratory. https://doi.org/10.2172/1601809.

Zhang, Xuan, Ting-Leung Sham, and George A. Young. 2019. "Microstructural Characterization of Alloy 709 Plate Materials with Additional Heat Treatment Protocol." ANL-ART-170, Argonne National Laboratory. https://doi.org/10.2172/1601459.

Zhang, Xuan, and Ting-Leung Sham. 2020. "FY-2020 Status Report on Creep Rupture Testing to Support the Development of Alloy 709 Code Case." ANL-ART-193, Argonne National Laboratory. https://doi.org/10.2172/1656611.

Zhang, Xuan, Ting-Leung Sham, and Meimei Li. 2021. "FY21 Status Report on Creep Rupture Testing at ANL to Support the Development of Alloy 709 Code Case." ANL-ART-231, Argonne National Laboratory. https://doi.org/10.2172/1810715.