FY19 Status Report on Creep Test Data on Commercial Heat of Alloy 709

Applied Materials Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see <http://www.anl.gov>.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (<http://www.osti.gov/>), a service of the US Dept. of Energy's Office of Scientific and Technical Information.

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information
Service 5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

FY19 Status Report on Creep Test Data on Commercial Heat of Alloy 709

Prepared by

X. Zhang

Nuclear Science and Engineering Division
Argonne National Laboratory

T.-L. Sham

Applied Materials Division
Argonne National Laboratory

September 2019

ERRATA

Location	Error	Correction
Title page	Typo in title	Changed “790” to “709”

ABSTRACT

This report provides an update on the status of the creep rupture testing on the first commercial heat of Alloy 709 in support of the Alloy 709 Code Case development. The report is a Level 3 deliverable in FY19 (M3AT-19AN020502041), under the Work Package AT-19AN0205204, “A709 Code Case Testing” performed by Argonne National Laboratory (ANL), as part of the Advanced Reactor Technologies Program.

A creep test laboratory has been set up at ANL that comprises of 15 indirectly loaded test frames capable of testing ASTM standard-size specimens of the commercial heat of Alloy 709. The systems are equipped with high temperature furnaces capable of operation up to 1000°C in an air environment. In FY19, 15 creep-rupture tests of the ESR-1100°C solution annealed material, requiring the use of Type K thermocouples, were initiated to support the 100,000-hour Code Case. At the time of writing this report, eight tests were completed. This report presents the data from those completed tests and also microstructural characterization of the fractured specimens. During FY19, efforts were being made to add Type S thermocouples to five of the creep test frames, for performing longer term tests at higher temperatures.

TABLE OF CONTENTS

ABSTRACT.....	i
Table of Contents	ii
List of Tables	iii
List of Figures	iv
1 Introduction	1
2 Material Specifications and Mechanical test facilities	3
2.1 Materials and specimens	3
2.2 Creep test facilities.....	3
2.3 Creep test procedure	6
3 Creep Test Data on Alloy 709 Commercial Heat ESR-1100°C Condition.....	8
4 Microstructural Analysis of Creep-Tested Specimens	12
4.1 Fracture surfaces	12
4.2 Grain structures and deformation defects	15
5 Addition of Type S thermocouple measurement capability	20
6 Summary and Future Work	20
Acknowledgements.....	21
References	21

LIST OF TABLES

Table 2-1.	Chemical composition of melt of Alloy 709 heat # 58776 (in wt.%).....	3
Table 3-1.	FY19 Alloy 709 code case testing progress.....	9

LIST OF FIGURES

Figure 2-1. Schematic drawing of ASTM standard-sized creep specimens.....	3
Figure 2-2. Creep test laboratory set up at ANL for testing of Alloy 709.....	5
Figure 2-3. Photograph of a machine with furnace and a specimen loaded for the test.....	6
Figure 2-4. The loading curve of an Alloy 709 sample being loaded to 330 MPa at 625°C. ..	7
Figure 3-1. The creep rupture time and minimum creep rate plots of the eight completed tests in FY19.. ..	9
Figure 3-2. Plots of elongation and reduction of area as a function of test temperature and applied stress for the ruptured A709 specimens in FY19.....	10
Figure 3-3. Creep strain as a function of time for the commercial heat of Alloy 709 in FY19 code case testing program. The plot only shows the eight completed tests.....	10
Figure 3-4. Larson-Miller plot of the completed tests in FY 18 and FY19 of the commercial heat of Alloy 709 ESR-1100°C condition.	11
Figure 4-1. Photos of the creep-ruptured A709 specimens	12
Figure 4-2. SEM micrographs of fracture surfaces of creep-tested Alloy 709 specimens at low and high magnifications.....	13-14
Figure 4-3. A photo showing the polished surfaces of the cross section and axial section of the crept specimens. The sample IDs were labeled on the right in corresponding positions.. ..	15
Figure 4-4. Top: the cross section view of sample BB2-8, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-8, at lower (5x) and higher (20x) magnifications.	16
Figure 4-5. Top: the cross section view of sample BB2-3, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-3, at lower (5x) and higher (20x) magnifications.	17
Figure 4-6. Top: the cross section view of sample BB2-14, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-14, at lower (5x) and higher (20x) magnifications.	18
Figure 4-7. Top: the cross section view of sample BB2-5, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-5, at lower (5x) and higher (20x) magnifications.	19

1 Introduction

Due to the significant enhancement in mechanical properties of Alloy 709, an austenitic alloy, relative to 316H stainless steel, a reference construction material for Sodium Fast Reactor (SFR) systems, code qualification of Alloy 709 was recommended in FY14. A comprehensive plan for the development of a 500,000-hour, 760°C ASME Code Case and the resolution of structural integrity issues identified by Nuclear Regulatory Commission (NRC) for Alloy 709 was developed in FY15. The maximum use temperature of 760°C also draws interest from molten salt reactor vendors for the potential use of Alloy 709 in their designs.

The execution of the Phase I plan was initiated in FY2016. Creep testing frames at Argonne National Laboratory (ANL), Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) went through upgrade and refurbishment to support the generation of creep rupture data for the Alloy 709 Code Case. In collaboration with the material vendor, G.O. Carlson Inc. of Pennsylvania, the Advanced Reactor Technologies (ART) program successfully scaled the production of Alloy 709 from a laboratory heat of 500 pounds to a commercial heat of 45,000 pounds. The fabrication procedures for the first commercial heat Alloy 709 hot-rolled plates were summarized in Natesan et al. 2017. The master heat of Alloy 709 with heat number 58776 was processed under different processing conditions, namely Argon-Oxygen-Decarburization (AOD), Electroslag Remelting (ESR), and ESR with subsequent Homogenization (ESR-Homogenized), followed by solution annealing (S/A) at three different temperatures. The Alloy 709 plates with these different processing conditions were tested for creep, fatigue and creep-fatigue under selected conditions to screen out the preferred processing condition. Both the AOD with S/A 1100°C and ESR with S/A 1100°C showed good microstructure and combined high temperature mechanical properties.

The test effort for the comprehensive creep test matrix developed to support the preliminary, 100,000-, 300,000-, and 500,000-hour Alloy 709 Code Cases was split among ANL, INL and ORNL. ESR with S/A 1100°C was added to the intermediate and long term testing effort in FY2019. This report documents the status of the planned FY2019 creep testing at ANL.

Alloy 709 is derived from NF709 (Fe-20Cr-25Ni-1.5Mo-Nb,B,N), which was a commercial heat- and corrosion-resistant austenitic stainless steel developed by Nippon Steel Corporation in Japan for boiler tubing applications. The high strength of NF709 is achieved by controlling the carbon content to 0.07–0.10% and precipitation strengthening by NbC and CrNbN (Z phase). NF709 also shows good fabricability properties and weldability. It was regarded as one of the best austenitic steels for elevated temperature applications among commercially-available austenitic alloy classes at the time. Alloy 709 has the same chemical composition as NF709 but is intended for sodium fast reactor applications that include reactor vessel, core supports, primary and secondary piping, and intermediate heat exchanger. Hence development of processing conditions and fabrication scale up for different product forms such as plates, pipes, bars, forgings and sheets, in addition to seamless tubing, are required.

The focus of the FY19 scope at ANL was on the 100,000-hour code case testing. Fifteen creep rupture tests were planned at temperatures at or below 700°C, thus only requiring the use of Type K thermocouples, were initiated. At the time of writing this report, eight tests were

completed. In addition, effort was initiated to add Type S thermocouples to five of the creep test frames at ANL for performing longer term tests at higher temperatures.

2 Material Specifications and Mechanical test facilities

2.1 Materials and specimens

The product chemistry of the first commercial Alloy 709 heat (#58776) conforms to the ranges or maximum values specified in wt.% in Table 2-1. The chemistry targets and the actual melt compositions are also shown in the table.

Table 2-1. Chemical composition of melt of Alloy 709 heat # 58776 (in wt.%)

Alloy 709	C	Cr	Ni	Mn	Mo	N	Si	P	Ti	Nb	B	Fe
Specification range	0.04-0.10	19.5-23	23-26	1.5	1.0-2.0	0.14-0.16	1.0	<0.025	0.2	0.1-0.4	0.002-0.01	Bal
Target	0.07	20	25	0.9	1.5	0.15	0.40	*	0.05	0.25	0.002-0.005	Bal
Actual	0.066	19.93	24.98	0.91	1.51	0.148	0.44	0.014	0.04	0.26	0.0045	Bal

*The P shall not exceed 0.025 wt.%.

Figure 2-1 shows the drawing for the ASTM standard-size specimens used in the creep rupture tests. Since the plate thickness is about 1.1", only one specimen was sampled from the mid-section of the plate per ASTM practice.

Figure 2-1. Schematic drawing of ASTM standard-sized creep specimens.

2.2 Creep test facilities

A creep test laboratory was set up for the project at ANL. Figure 2-2 shows a photograph of the creep test laboratory. The laboratory contains twelve newly procured creep frames and three existing frames that were upgraded to meet the test plan requirements. The creep machines are ATS Series 2300 Lever Arm Creep Testing Systems integrated with WinCCS II computer control and data acquisition software package. ATS systems are precision knife-edge lever arm testers that incorporate a number of enhanced design features. Some of these features include:

- Wide-frame construction, which allows for a variety of environmental chambers, fixtures, and other accessories, while maintaining compact overall dimensions
- Counterbalanced lever arm with precision ratio adjustment and four-position rotatable hardened knife edges
- Precision drawhead guide assembly, providing automatic beam leveling, “weightless” specimen loading, hot-step loading, stress relaxation, constant stress, and more via WinCCS II software
- Durable vibration isolator mounts to prevent disturbance to other sensitive equipment upon specimen breakage
- On-center loading at high load ratio, providing optimum strength and minimum deflection
- Rugged vee-block supports for maximum linear knife-edge contact
- Knife edges of high-strength tool steel, designed for easy replacement of worn edges
- Unique lever arm design permits the construction of high load ratios, e.g., 50:1, with standard arm and machine dimensions

Each creep machine is equipped with a three-zone split-tube furnace capable of operation up to 1100°C. Following the setup of the systems, the furnaces were baked to remove any impurities in the refractory insulation. The temperature in the system is controlled by the ATS temperature control system which regulates the power applied to the resistive heating elements and maintain the desired temperature (setpoint) as measured by a control thermocouple. The systems are also equipped with high-limit alarms and over-temperature controllers. Figure 2-3 shows the photograph of a single machine with a specimen being loaded. Two type-K thermocouples were spot welded to the shoulder sections of the specimen as the furnace temperature feedback. This direct contact method minimizes the errors in temperature readings due to incorrect electrical contact between the thermocouple wires and/or between the wires and the specimen. It also ensures the efficient heat conduction between the thermocouple and the specimen, thus providing an accurate measure of the specimen temperature.

Figure 2-2. Creep test laboratory set up at ANL for testing of Alloy 709.

Figure 2-3. Photograph of a machine with furnace and a specimen loaded for the test.

2.3 Creep test procedure

The creep tests under this project are conducted according to the ASTM Standard E139-11, “Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests on Metallic Materials.” A lever arm ratio of 20:1 was used for all frames. Before test, samples were measured, mounted on individual rigs with LVDTs retrieved to zero position, and loaded to the frames. To initiate a test, the required dead weight was first calculated based on the sample geometry and placed on the pan. Then the furnace was heated up to the set temperature, and soaked for 1 hour. The load was then applied in a step manner and fully loaded in about 5 minutes. A load cell was placed directly above the dead weight to measure the load applied on the sample at each

step. A typical loading curve is shown in Figure 2-4. In this case, the end stress was 330 MPa. During the test, data was recorded by the WinCCS II software. Upon sample failure, the furnace was cooled down in air and the sample was removed with the rig. The samples were then measured for the overall length and the minimum diameter by carefully placing the two broken pieces back together for calculation of the elongation and the reduction of area.

Figure 2-4. The loading curve of an Alloy 709 sample being loaded to 330 MPa at 625°C.

3 Creep Test Data on Alloy 709 Commercial Heat ESR-1100°C Condition

Fifteen creep tests were initiated in FY19 in support of the 100,000-hour code case. The material is the commercial heat of the Alloy 709 ESR-1100°C condition. Table 3-1 lists the test parameters and the progress at the time of writing this report. Eight tests have been completed under 600°C/355 MPa, 600°C/330 MPa, 625°C/330 MPa, 625°C/285 MPa, 650°C/200 MPa, 675°C/200 MPa, 700°C/175 MPa and 700°C/155 MPa conditions. The elongation and area reduction are both calculated from the measurement of the rupture specimens. Figure 3-1 plots the creep rupture life and the minimum creep rate as a function of test temperature and stress. Higher temperature and higher stress level leads to a shorter creep life and a higher minimum creep rate. Figure 3-2 plots the percent elongation and the percent area reduction as a function of test temperature and stress. It is seen that higher temperature and lower stress leads to a more ductile failure. At temperatures at and above 650°C, the elongations are more than 50% and area reductions are more than 70%.

Figure 3-3 plots the creep curves of the eight completed tests. Due to the limited range of the LVDTs, once the creep strain is over ~30%, the reading stops. Therefore, to reflect the real creep strain, in the figure the end creep strains, measured from the ruptured specimens, are plotted for those tests. Tests in progress are not plotted.

Figure 3-4 is the Larson-Miller plot of the eight completed tests, together with the 2 tests in FY18 (600°C/330MPa and 600°C/300MPa) of the same ESR-1100°C material. The Larson-Miller parameter was calculated as

$$LMP = (T + 273.15) \times (\log_{10} t_r + C),$$

where T is the temperature in °C, and C is a constant chosen to be 16.56 because it gives the best linear regression. The fitted line gives

$$LMP = -5034.7 \times \log_{10} \sigma + 29994.88 .$$

From the above two equations, the best-fit creep life t_r of the material can be estimated knowing the stress and the temperature:

$$\log_{10} t_r = \frac{-5034.7 \times \log_{10} \sigma + 29994.88}{T + 273.15} - 16.56 .$$

It is worth to note that as more tests are completed in the future, the parameters in the above equations are subjected to revision.

Table 3-1. FY19 Alloy 709 code case testing progress.

Test # (ANL)	sample ID	Stress (MPa)	Temp (°C)	Status
1	BB2-15	355	550	running
2	BB2-16	200	625	running
3	BB2-23	380	550	running
4	BB2-18	175	650	running
5	BB2-19	355	575	running
6	BB2-20	330	575	running
7	BB2-10	355	600	ruptured
8	BB2-8	330	600	ruptured
9	BB2-12	285	600	running
10	BB2-3	330	625	ruptured
11	BB2-13	285	625	ruptured
12	BB2-14	200	650	ruptured
13	BB2-4	200	675	ruptured
14	BB2-5	175	700	ruptured
15	BB2-6	155	700	ruptured

Figure 3-1. The creep rupture time and minimum creep rate plots of the eight completed tests in FY19.

Figure 3-2. Plots of elongation and reduction of area as a function of test temperature and applied stress for the ruptured A709 specimens in FY19.

Figure 3-3. Creep strain as a function of time for the commercial heat of Alloy 709 in FY19 code case testing program. The plot only shows the eight completed tests.

Figure 3-4. Larson-Miller plot of the completed tests in FY 18 and FY19 of the commercial heat of Alloy 709 ESR-1100°C condition.

4 Microstructural Analysis of Creep-Tested Specimens

Figure 4-1 shows the photos of the creep-ruptured Alloy 709 specimens. All the specimens failed at the gauge section, with the majority failed around the gauge center. The deformation microstructures were studied by scanning electron microscopy and optical microscopy.

Figure 4-1. Photos of the creep-ruptured A709 specimens.

4.1 Fracture surfaces

The fracture surfaces of the A709 specimens were studied by scanning electron microscopy. Figure 4-2 shows the microstructures at low magnification (30×) and moderate magnification (180×) for all the specimens. It is seen that at 600°C, the failure mode is a mixture of ductile (void coalescence at grain boundaries) and brittle, with the higher stress condition (355MPa) being more towards brittle failure than the lower stress condition (330MPa). At 625°C, the failure mode is also a mixture of ductile and brittle, and similarly to 600°C, higher stress condition (330MPa) shows more brittle feature than lower stress condition (285MPa). Above 625°C, the failure mode is mainly ductile.

Figure 4-2. SEM micrographs of fracture surfaces of creep-tested Alloy 709 specimens at low and high magnifications.

4.2 Grain structures and deformation defects

Figure 4-3 shows a photo of polished surfaces near the fracture regions of creep-tested specimens with their IDs labeled in corresponding positions to the right. The cross sections (round pieces) were cut out very close to the fracture surface from one piece of the broken specimen, and the axial sections (long pieces) were the mid-section of the gage region near the fracture surface of the other piece of the broken specimen. Those surfaces were polished to mirror finish and were etched for optical microscopy study. Optical microscopy of the grain structures and deformation defects revealed that as the test temperature and stress varies, drastic differences in microstructures exist. In general, samples BB2-8 (600°C/330MPa), BB2-10 (600°C/355MPa), BB2-13 (625°C/285MPa), and BB2-3 (625°C/330MPa) show large, intergranular pores, while other samples, including BB2-14 (650°C/200MPa), BB2-4 (675°C/200MPa), BB2-6 (700°C/155MPa), and BB2-5 (700°C/175MPa), show small, possibly mixed types of pores. Micrographs from selected samples are shown in Figures 4-4 to 4-7. Figures 4-4 and 4-5 show the microstructures of BB2-8 (600°C/330MPa) and BB2-3 (625°C/330MPa), respectively. Unlike sample BB2-8 which has uniform grain structure, sample BB2-3 has very large grains across the gage which are almost defect-free. Nevertheless, the original grain structure seems to be preserved, despite some elongation in the loading direction. Also, in both samples, cracks present at grain boundaries, and large cracks can be found even millimeters away from the fracture surface. The observations are very different for samples deformed at higher temperatures. Figures 4-6 and 4-7 show the microstructures of BB2-14 (650°C/200MPa) and BB2-5 (700°C/175MPa). In those cases, the original grain structures are not very distinguishable, and the grains are super elongated along the loading direction, indicating the super plasticity. The pores are much smaller compared with those from lower temperature samples, and are likely to be a mixture of intergranular and intragranular types (due to the disappearance of the original grain boundaries, it is hard to define intergranular pores). Also, the pores are mostly concentrated near the fracture surface. The sharp transition of microstructures from 625°C to 650°C is in agreement with the observation from fracture surface analysis in section 4.1, indicating a transition from (more) brittle to (more) ductile failure. Figure 3-2 (elongation and area reduction plot) also agrees with this conclusion.

Figure 4-3. A photo showing the polished surfaces of the cross section and axial section of the creep specimens. The sample IDs were labeled on the right in corresponding positions.

Figure 4-4. Top: the cross section view of sample BB2-8, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-8, at lower (5x) and higher (20x) magnifications.

Figure 4-5. Top: the cross section view of sample BB2-3, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-3, at lower (5x) and higher (20x) magnifications.

Figure 4-6. Top: the cross section view of sample BB2-14, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-14, at lower (5x) and higher (20x) magnifications.

Figure 4-7. Top: the cross section view of sample BB2-5, at lower (5x) and higher (20x) magnifications. Bottom: the axial section view of sample BB2-5, at lower (5x) and higher (20x) magnifications.

5 Addition of Type S thermocouple measurement capability

The 15 creep test frames at ANL in support of the ART work are currently equipped with Type K thermocouples. Type K thermocouples are known to have drift issues during prolonged exposure to very high temperature. In discussions with ORNL, it was recommended that Type S thermocouples should be used for test temperatures higher than 750°C and lifetimes longer than 4,000 hours. Below 650°C, Type K thermocouples can perform indefinitely. All the tests carried out so far work well with Type K thermocouples. There are tests planned at ANL for Alloy 709 code case that will benefit from the use of Type S thermocouple. Therefore, addition of this capability to five of the creep frames are planned. We identified the procedure, purchased the hardware, and obtained the work authorization. It is expected that the installation will be completed by November, 2019.

6 Summary and Future Work

A creep test laboratory has been set up at ANL that comprises of 15 indirectly loaded test frames capable of testing ASTM standard-size specimens of the commercial heat of Alloy 709. The systems are equipped with high temperature furnaces capable of operation up to 1000°C in an air environment. In FY19, 15 creep-rupture tests on the first commercial heat of Alloy 709 with ESR-1100 were initiated to support the 100,000-hour Code Case. Those tests utilized the existing Type K thermocouple measurement capability. At the time of writing this report, 8 tests were completed under 600°C/355 MPa, 600°C/330 MPa, 625°C/330 MPa, 625°C/285 MPa, 650°C/200 MPa, 675°C/200 MPa, 700°C/175 MPa and 700°C/155 MPa.. The results enabled the preliminary construction of the Larson-Miller plot. The deformation microstructures were characterized, and was found that at 600°C and 625°C, the fracture mode was a mixture of ductile (void coalescence) and brittle (cleavage), but above 625°C, the fracture was largely ductile. In addition, an effort was being made to add Type S thermocouples to five of the creep test frames, for performing long-term tests at temperatures higher than 675°C.

Future work involves the testing and characterization of other code-case conditions, and perform a systematic study of the creep performance of the Alloy 709 in a large temperature and stress window. The ultimate goal is to deliver the Alloy 709 code case to ASME.

Acknowledgements

The research was sponsored by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357 with Argonne National Laboratory, managed and operated by UChicago Argonne LLC. Programmatic direction was provided by the Office of Nuclear Reactor Deployment of the Office of Nuclear Energy (NE).

The authors gratefully acknowledge the support provided by Brian Robinson of DOE-NE, Federal Manager, Advanced Reactor Technologies (ART) Program, Fast Reactors Campaign; Sue Lesica of DOE-NE, Federal Manager, ART Advanced Materials; and Robert Hill of Argonne National Laboratory, National Technical Director, ART Fast Reactors Campaign.

Helpful discussions with Meimei Li of Argonne National Laboratory, Richard Wright and Mike McMurtrey of Idaho National Laboratory and Yanli Wang of Oak Ridge National Laboratory are very much appreciated. The authors acknowledge the assistance of E. Listwan and R.L. Rink at Argonne National Laboratory for specimen preparation, test set-up, and data acquisition.

References

Busby, J. T., S. Byun, R. Klueh, P. Maziasz, and J. Vitek, K. Natesan, M. Li, R. Wright, S. Maloy, M. Toloczko, A. Motta, B. D. Wirth, G. R. Odette, and T. Allen, "Candidate Developmental Alloys for Improved Structural Materials for Advanced Fast Reactors," ORNL/GNEP/LTR-2008-023, March 2008.

Natesan, K., X. Zhang, T.-L. Sham, and H. Wang, Argonne National Laboratory Report, ANL-ART-89, June 2017.

Natesan, K., X. Zhang, and M. Li, Argonne National Laboratory Report, ANL-ART-134, August 2018.

Applied Materials Division

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC