INL/EXT-20-57230-Revision-0

# Quarterly Management Document FY20, 1st Quarter, Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications

Thomas M Lillo, Wen Jiang

February 2020

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**February 2020**

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

**Quarterly Management Document – FY20, 1st Quarter, Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications**

**Document #** INL/EXT-20-57230

| WBS Element | Project Title | Contract Number | Contract Start | Contract End |
|---|---|---|---|---|
| C.B.10.02.02.40 | Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications | FEAA90 | 10/01/17 | 09/30/2020 |
| **Performer Name and Address**<br>Thomas Lillo<br>Idaho National Laboratory<br>P.O. Box 1625<br>Idaho Falls, ID 83415 | | | **Principal Investigator(s)**<br>Thomas Lillo | |

BUDGET AND COST REPORT

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Prior Year Funds ($K)** | | | | **10.9** | | | | | | | | |
| **Total Current Year Commitment ($K)** | | | | **10.9** | | | | | | | | |
| **Projected Current Year Costs ($K)** | | | | **10.9** | | | | | | | | |
| | **O** | **N** | **D** | **J** | **F** | **M** | **A** | **M** | **J** | **J** | **A** | **S** |
| **Monthly Planned Costs** | **0.5** | **1.0** | **1.0** | **1.0** | **2.7** | **2.7** | **2.0** | **0** | **0** | **0** | **0** | **0** |
| **Actual Monthly Costs** | **0.6** | **0.1** | **1.1** | | | | | | | | | |
| **Monthly Variance** | **-0.1** | **0.9** | **-0.1** | | | | | | | | | |
| **Total costs – planned** | **0.5** | **1.5** | **2.5** | **3.5** | **6.2** | **8.9** | **10.9** | **10.9** | **10.9** | **10.9** | **10.9** | **10.9** |
| **Total costs - actual** | **0.6** | **0.7** | **1.8** | | | | | | | | | |

MILESTONE REPORT

| Milestone Designation | Milestone Description | Due Date | Revised Due Date | Completion Date |
|---|---|---|---|---|
| A | Evaluate current MOOSE capabilities | 09/30/2015 | | 09/30/2015 |
| B | Complete Alloy 617 weld characterization | 10/30/2015 | | 11/18/2015 |
| C | Receipt of Alloy 740H plates | 10/30/2015 | | 11/05/2015 |
| D | Complete welds in Alloy 740H | 11/16/2015 | 7/31/2016 | 7/31/2016 |

| | | | | |
|---|---|---|---|---|
| E | Characterize Alloy 740H welds | 02/01/2016 | 09/30/2016 | 9/02/2016 |
| F | Creep model development – Stage 1 | 09/30/2016 | | 9/30/2016 |
| G | Creep Model Development – Stage 2 | 8/29/2017 | 2/28/2019 | 1/15/2019 |
| H | Calibration of Secondary creep – Alloy 617 | 9/30/2017 | 3/31/2019 | Eliminated |
| I | Stress Drop Tests | 2/01/2017 | 5/31/2018 | 6/28/2018 |
| J | Characterization of creep failure mechanisms | 4/01/2017 | 04/30/2018 | 5/04/2018 |
| K | Secondary creep calibration for welds – Alloy 617 | 5/30/2018 | 4/15/2019 | Eliminated |
| L | Creep model development – Completion of Stage 3 | 8/30/2018 | 8/16/2019 | 9/9/2019 |
| M | Creep simulation of a welded joint in Alloy 740H | 9/30/2018 | 03/20/2020 | |
| N | Validation of creep simulation model via an Alloy 740H weld consisting of refined microstructure | 9/15/2018 | 04/10/2020 | |

## TECHNICAL HIGHLIGHTS

**Milestone M,** "Creep simulation of a welded joint in Alloy 740H"

Calibration of the model was begun with the creep tests on all-weld-metal, base metal only, and cross weld creep specimens from 740H welds, using synthetic microstructures. The creep conditions at 700, 750 and 800°C were chosen to obtain approximately a 500 hr creep life. Experimental creep tests were previously carried out on all-weld-metal (AWM), base metal and cross-weld (X-Weld) creep specimens using the same creep conditions. Figures 1-3 below show the processed experimental creep data for each type of specimen at temperatures of 700, 750 and 750°C. Only one sample of all-weld-metal and aged base metal was creep tested at each temperature with the exception of 750ºC at which two base metal specimens were tested – one previously aged at 750ºC for 4004 hrs and one previously aged at 750ºC for 8000 hrs. Cross weld creep test were carried out in triplicate to understand the variability in the creep behavior of welded specimens.

Calibration is initially being performed on the base metal creep tests (samples identified with the prefix "SD" in Figs. 1-3). The base metal consists of the most uniform microstructure in terms of grain size and shape as well as γ' distribution and is thus expected to provide the best calibration results. However, creep tests were run only on aged 740H base metal. The effect of aging is to grow the γ' precipitates so that the at the start of the creep test these base metal specimens have a γ' particle size that is significantly larger than in the cross-weld and, likely, the AWM specimens. However, it should be kept in mind that the weld metal was deposited using multiple weld passes which undoubtedly contributed to aging of the previously deposited weld layers and in the heat affect zone of the base metal. Previously, it was found that the average γ' particle radius in the weld metal (with PWHT - 800ºC, 4 hrs) was approximately 14.3 nm compared to 49.3 and 61.6 nm after aging base metal at 750ºC for 4004 and 8000 hrs, respectively. Due to the large γ' particle size in the aged base metal one would expect the creep rate for base metal specimens to be considerably higher than in either AWM or X-Weld samples. This is definitely the case for the tests conducted at 700ºC where the creep rate for the SD-2-05 specimen is much higher than that of either the AWM sample or the cross-weld samples. Interestingly, the X-Weld creep behavior is quite consistent and almost equivalent to the AWM creep behavior, i.e., the cross-weld creep behavior seems to be dictated by the weld creep behavior with little influence from the base metal present in cross-weld creep specimens at 700°C.

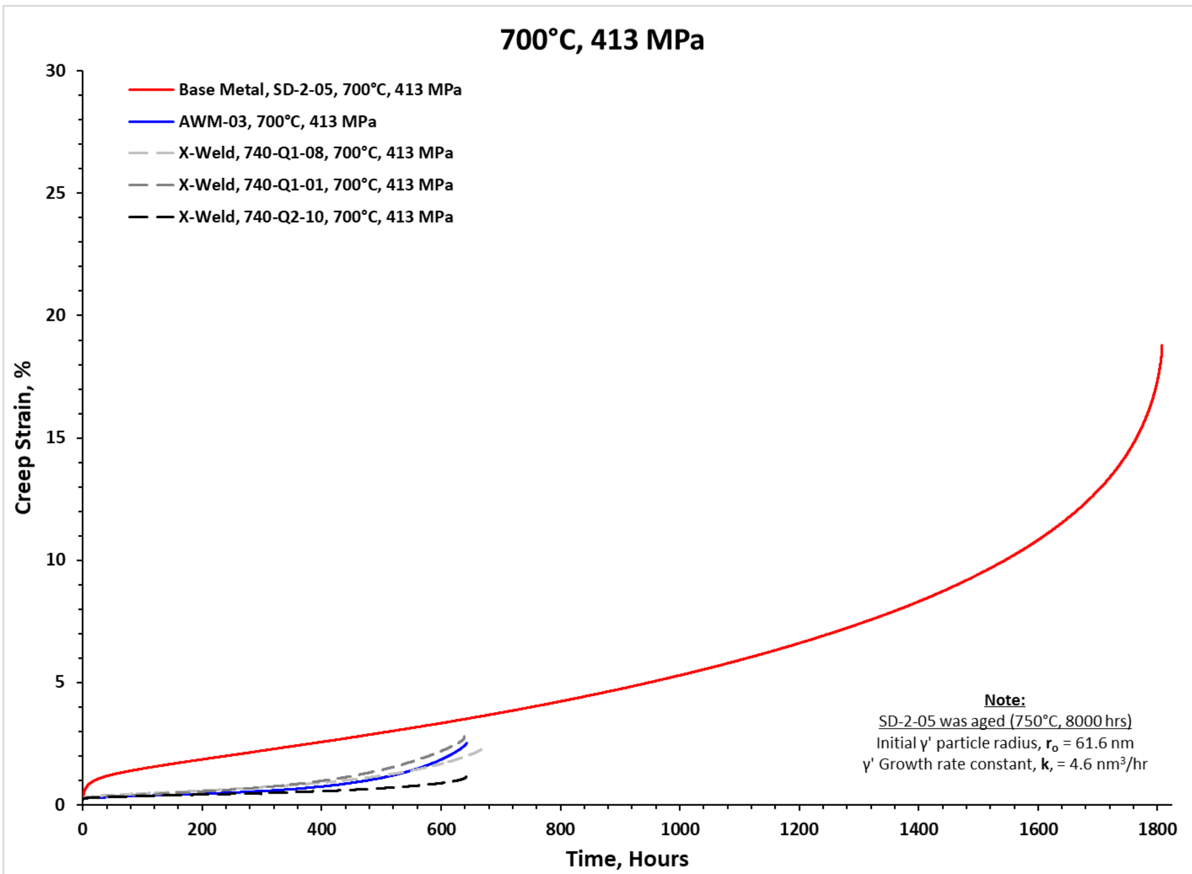



Figure 1. Plots of the experimental creep behavior at 700°C of all-weld-metal (AWM), base metal (Base Metal) and cross-weld (X-Weld) creep specimens. The base metal material for sample SD-2-05 was aged for 8000 hrs at 750°C prior to fabrication of the creep specimen.

At 750ºC, the overall creep behavior of the cross-weld creep specimens seems to have been influenced to a greater extent by the base metal. The creep rates of the cross-weld creep samples tend to be closer to that of the base metal sample aged for only 4004 hrs at 750°C. Creep ductility for all specimens that contain weld metal remains in the single digits.

At 800ºC, the creep behavior, i.e., minimum creep rate, of the AWM and X-Weld samples is on the order of that shown by the aged base metal specimen, although there is considerable variation in the creep behavior at 800ºC. At 800°C, γ’ growth is quite rapid and the growth rate rapidly decreases with increasing time so the average particle size in the various specimens probably become similar in a relatively short time resulting in the similar creep behavior. Creep ductility is considerably lower for AWM and X-Weld specimens compared to the base metal specimen. Presumedly, the weld metal is controlling ductility. The exact mechanism which results in the overall reduction in creep ductility is not clear. However, it is possible that the effect of nucleation of voids on the long grain boundaries in the columnar grains of the weld may be different compared to void nucleation in the finer grained, equiaxed base metal, Fig. 4. In the weld, voids can be expected to nucleate at regular intervals on long grain boundaries oriented perpendicular to the applied creep stress, as shown previously in 3rd quarter report in FY19. This would allow easy link up and, ultimately, short creep lifetimes. In fine, equiaxed grains of the base metal voids still nucleate on the grain boundary segments oriented perpendicular to the applied creep stress, however, they are more widely separated and cannot easily link up, Fig. 4a, leaving more contiguous paths to carry the applied creep load, allowing greater amounts of creep deformation to occur.

Also, previously, there was indications that not all grain boundaries perpendicular to the applied creep stress were not equally susceptible to void nucleation (see 2nd quarter report from FY18). In crept samples, post-test characterization, using Orientation Imaging Microscopy, revealed that random, high-angle grain boundaries were most susceptible to void nucleation. However, some random, high angle grain boundaries exhibited a greater density of creep voids than other random, high-angle grain boundaries similarly oriented to the applied stress (see 3rd quarter report FY18). Thus, it may be quite possible that the texture in the weld lends itself to development of random, high-angle grains boundary that are more susceptible to creep void nucleation and growth compared the randomly oriented, base metal.

In any case, X-Weld samples always fail in the weld metal, regardless of the test temperature, indicating creep ductility is governed by damage accumulation in the weld metal. This is reinforced in Figs. 1-3 where the X-Weld creep ductility is on the same order as the AWM specimen – both of which is considerably less than the aged, base metal specimens.

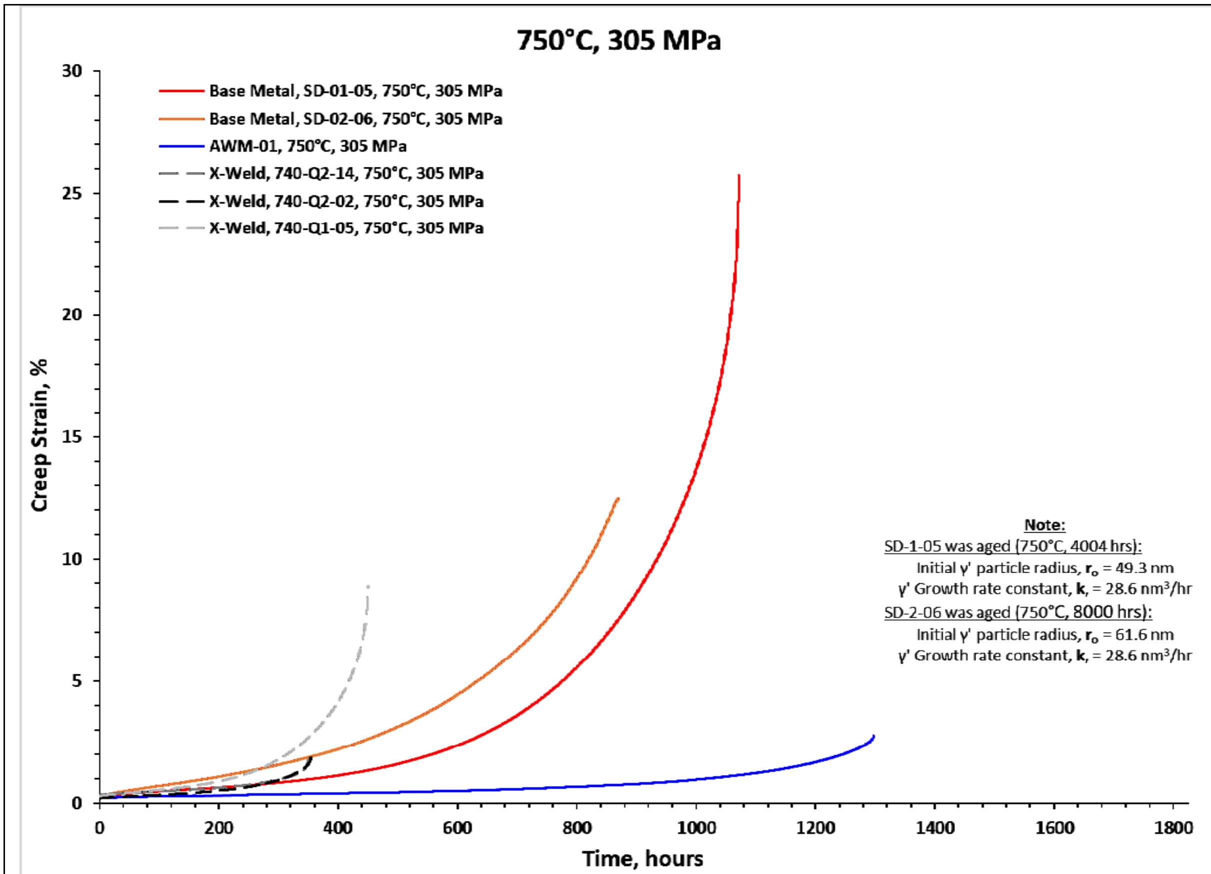



**Figure 2. Plots of the experimental creep behavior at 750°C of all-weld-metal (AWM), base metal (Base Metal) and cross-weld (X-Weld) creep specimens. The material for the base metal sample, SD-1-05, was aged for 4004 hrs at 750°C prior to fabrication of the creep specimen. The material for the base metal sample, SD-2-06, was aged for 8000 hrs at 750°C prior to fabrication of the creep specimen.**

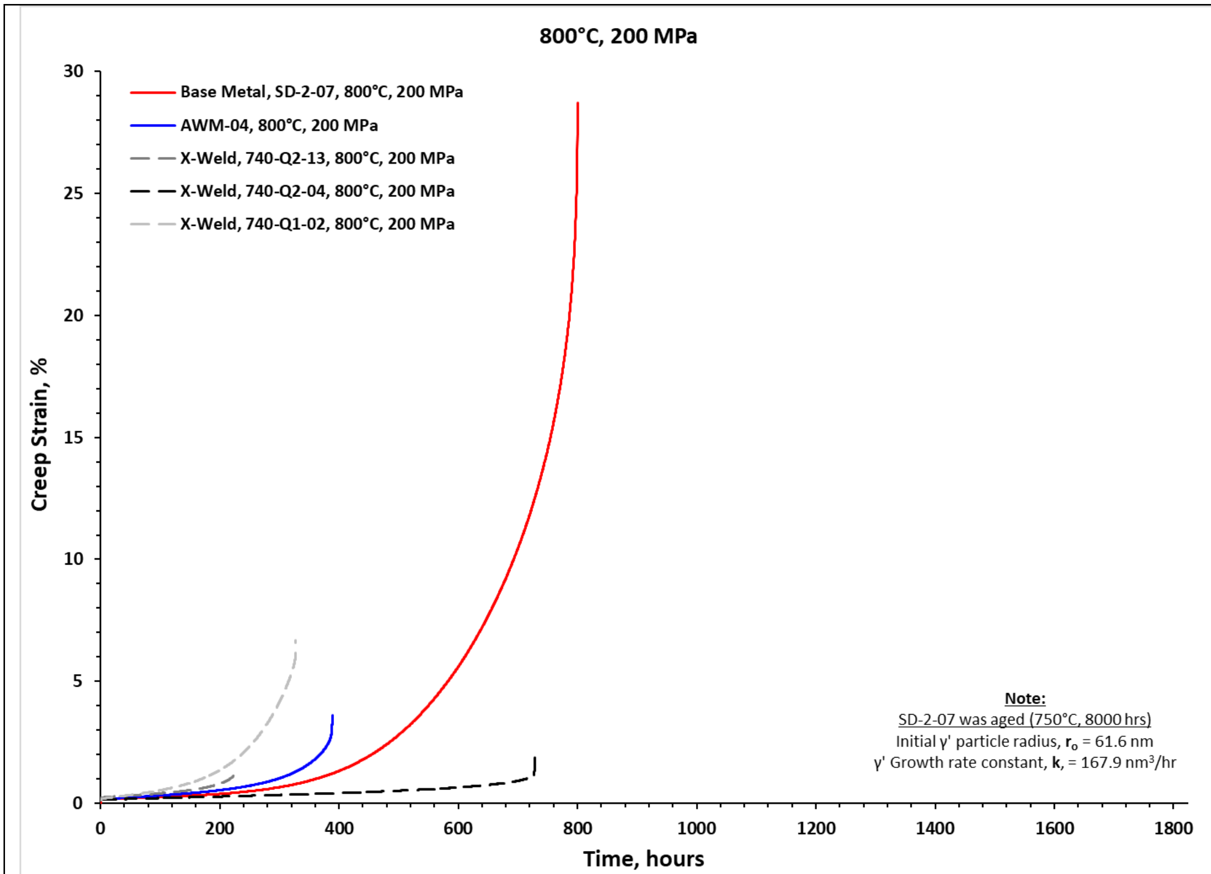
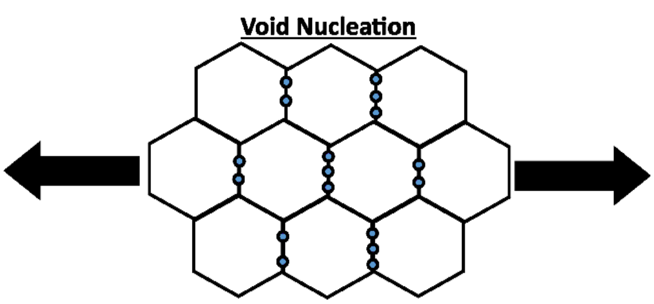



**Figure 3. Plots of the experimental creep behavior at 800°C of all-weld-metal (AWM), base metal (Base Metal) and cross-weld (X-Weld) creep specimens. The material for the base metal sample, SD-2-07, was aged for 8000 hrs at 750°C prior to fabrication of the creep specimen.**

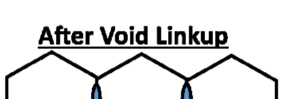
**(**
**a**
**)**
**(a)**

**(**
**b**
**)**




**(**
**c**

**(**
**d**
**)**



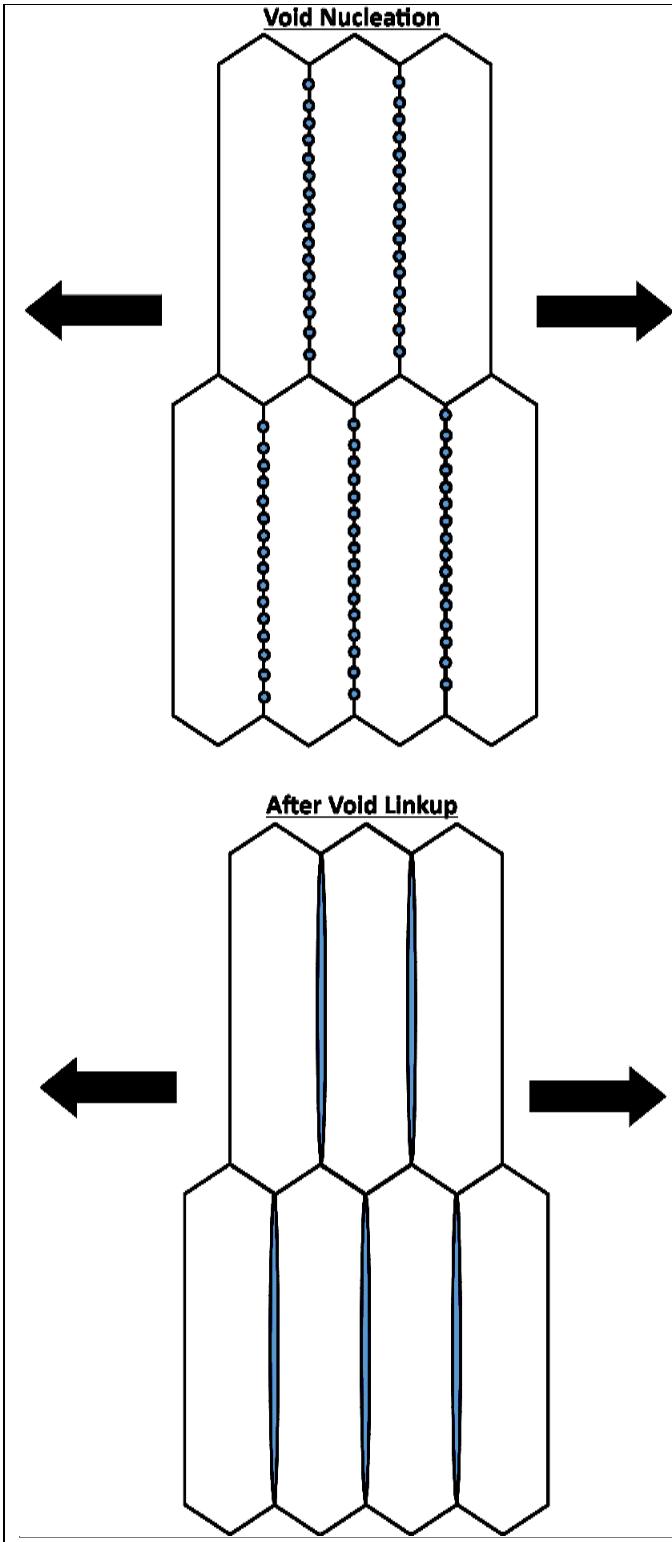



Figure 4. Schematic of void nucleation and link up in (a) fine, equiaxed grain structure versus (b) long, columnar grains of a weld. Note: Drawings are schematic representations only and dimensions are not to scale.

Base metal creep curves are being used to calibrate the model for the base metal while the all-weld metal creep curves are being used to determine model parameters in the weld metal. All-weld-metal creep curves will also be used to calibrate the model for diffusional growth of creep voids in the weld metal and the evolution of the damage parameter. Cross-weld creep behavior will then be modeled as a superposition of the base metal creep behavior plus the creep behavior of the weld metal.

Completion of this task is now targeted for 03/20/2020.

**Milestone N,** "Validation of creep simulation model via an Alloy 740H weld consisting of refined microstructure"

No progress on this task during the 1st quarter of FY20.

The completion date of this task is now targeted for 04/10/2020

ISSUES

Calibration, especially using the all-weld metal creep specimens, has brought to light the variability of creep behavior of the weld metal. Welding defects are most likely present in these specimens to different extents and, therefore, the creep behavior can vary considerably from one sample to the next under the same conditions of temperature and applied stress. In essence, the creep behavior of weld metal is highly statistical. Only one all-weld-metal sample was tested at each temperature due to the amount of weld required to make these samples and this dataset most likely does not capture the variability of the creep behavior in the weld metal. However, in this work we used a relatively large gage diameter and gage length for the creep specimens which help lessen the variability of the creep behavior. However, larger and longer gage diameters and lengths are probably needed to obtain an "average" creep behavior in all-weld-metal and cross-weld creep samples. At this point in the project and with the funds that remain, this is not an option. Therefore, the calibration will proceed with the data we have already obtained from all-weld-metal and cross-weld creep specimens. Comparisons between the model and the experimental data will be made and differences will be discussed as they relate to the variability inherent in the welding process.

The project will be concluded prior to the next FE annual crosscutting review meeting.

| Report Prepared By | Date |
|---|---|
| Thomas M. Lillo and Wen Jiang | 01/24/2020 |