Sister Rod Destructive Examinations (FY23)

Appendix A: Full-Length Rod Heat Treatments

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

Oak Ridge National Laboratory
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SUMMARY

This report documents work performed under the Spent Fuel and Waste Disposition's Spent Fuel and Waste Science and Technology program for the US Department of Energy (DOE) Office of Nuclear Energy (NE). This work was performed to fulfill Level 2 Milestone M2SF-24OR010201024, "FY23 ORNL Testing on Sibling Pins," within work package SF-24OR01020102 and is an update to the work reported in M2SF-23OR010201024, M2SF-22OR010201047, M2SF-21OR010201032, M2SF-19ORO010201026, and M2SF-19OR010201028.

As a part of DOE NE High Burnup Spent Fuel Data Project, Oak Ridge National Laboratory (ORNL) is performing destructive examinations (DEs) of high burnup (HBU) (>45 GWd/MTU) spent nuclear fuel (SNF) rods from the North Anna Nuclear Power Station operated by Dominion Energy. The SNF rods, called *sister rods* or *sibling rods*, are all HBU and include four different kinds of fuel rod cladding: standard Zircaloy-4 (Zirc-4), low-tin Zirc-4, ZIRLO, and M5. The DEs are being conducted to obtain a baseline of the HBU rod's condition before dry storage and are focused on understanding overall SNF rod strength and durability. Composite fuel and defueled cladding will be tested to derive material properties. Although the data generated can be used for multiple purposes, one primary goal for obtaining the post-irradiation examination data and the associated measured mechanical properties is to support SNF dry storage licensing and relicensing activities by (1) addressing identified knowledge gaps and (2) enhancing the technical basis for post-storage transportation, handling, and subsequent disposition.

This report documents the status of the ORNL Phase 1 DE activities related to full-length rod heat treatments (FHT) applied to selected sister rods in Phase 1 of the sister rod test program.

Table SA-1 provides the status of the FHT.

Table SA-1. DE status.

Planned DE		**Status**	**Comments**
FHT	Heat-treat whole rods to 400°C, cool at ≤5°C/h 1 ZIRLO, 1 M5 and 1 Zirc-4 rod	Complete	Three fuel rods were heat-treated: one Zirc-4-clad (F35P17), one ZIRLO-clad (3F9N05), and one M5-clad (30AE14) rod. The target heat-up rates, soak temperatures and times, and cooldown rates were successfully achieved, except for the spent fuel rod heat-treatment oven (SFRHTO) Zone 1 for rod 30AE14 (the upper ~550 mm), which reached temperatures as high as 485°C for approximately 1.75 h during the thermal soak. 30AE14's Zone 1 average temperature during the soak period was 452°C. At the higher average temperature imposed, the pressure was ~7.6 MPa—about 8% higher than planned. The maximum pressure during the soak was estimated as 8.0 MPa at the 485°C peak temperature for ~1.75 h. The rod's temperature was corrected before cooldown, and cooldown was as expected.

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ACKNOWLEDGMENTS

Many thanks to our US Department of Energy Office of Nuclear Energy sponsor, Ned Larson, along with the Spent Fuel and Waste Science and Technology storage and transportation program leadership for their continued support. The sister rod project would not have been possible without the vision and support of the Electric Power Research Institute, Westinghouse, Framatome, and Dominion Energy.

The expertise and fabrication capabilities provided by Charles Blue and Randall Blue of Infrared Heating Technology (Oak Ridge, Tennessee) were vital to the development and deployment of the full-length rod heat-treatment oven.

This work would not have been possible without the support and expertise provided by the leadership and staff members of the Oak Ridge National Laboratory's Irradiated Fuel Examination Laboratory. Special thanks go to Jerid Metcalf and Brian Woody for their assistance with installing and operating the heat-treatment oven and to Lucian Palcu for his work on the oven electrical components.

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REVISION HISTORY

Date	Changes
3/29/2019	Initial release
9/27/2019	Revised to include additional data and incorporate comments from the previously released report.
10/30/2020	Modified as an appendix to the main sister rod report. Minor changes to the text in the body of the document.
11/30/2020	The document numbering was revised to reflect its M2 status and the date was changed.
3/31/2022	The document numbering and date was revised to be consistent with the main document.
1/31/2024	The document ID and date was revised to be consistent with the main document.

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ACRONYMS

DE	destructive examination
DOE	US Department of Energy
FHT	full-length fuel rod heat treatment
HBU	high burnup
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory
RPC	Research Project Cask
SFRHTO	spent fuel rod heat-treatment oven
SFWST	Spent Fuel and Waste Science and Technology
SNF	spent nuclear fuel
UE	uniform elongation

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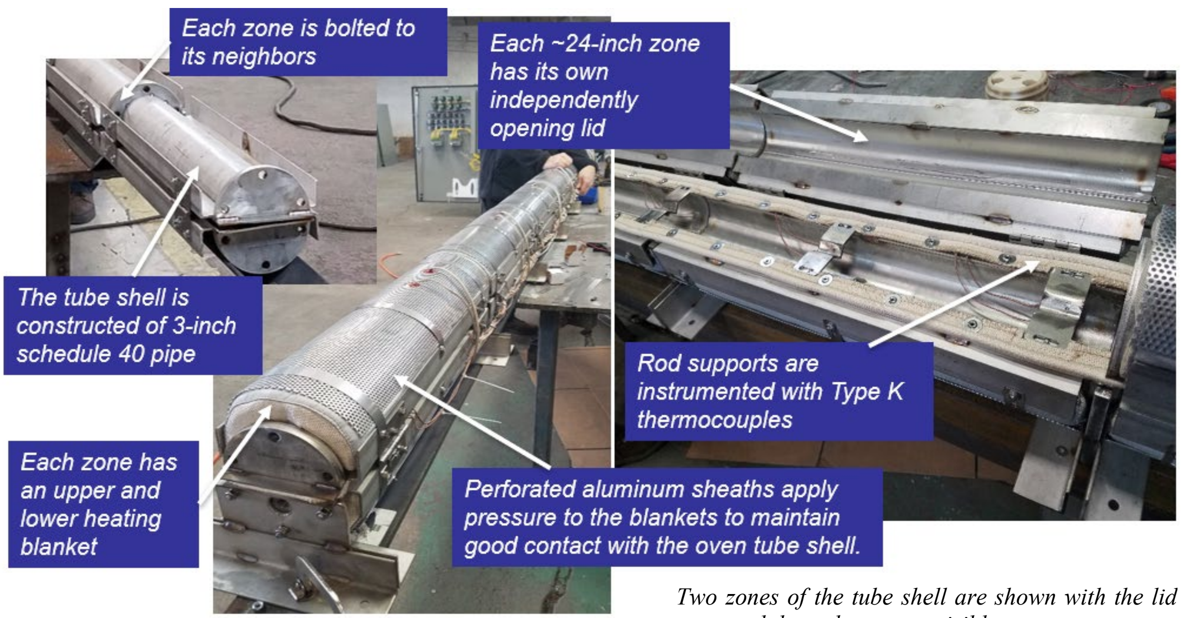
A-1. Full-Length Fuel Rod Heat-Treatment Oven Design

In preparation for dry storage, the fuel assemblies and canister cavity must be drained and dried. Typically, the most challenging thermal condition experienced by the fuel during dry storage occurs during the drying sequence or just after drying during transfer of the canister to the storage pad. To better understand the effects of the drying and transfer sequence, three full-length sister rods were subjected to a simulated dry storage vacuum drying temperature distribution to examine the rod condition induced by the increased fuel rod temperature compared with the rod condition before dry storage [A-1, A-2, A-3].

The spent fuel rod heat-treatment oven (SFRHTO), shown in Figure A-1, was developed for full-length fuel rod heat treatment (FHT). The SFRHTO can impose a variety of normal condition axial temperature profiles and peak cladding temperatures up to 530°C (as limited by the commercially purchased heating blankets) on a full-length fuel rod. In contrast with the heat treatment of rod segments in which the full-length rod is depressurized and segments are cut and repressurized, heat treating full-length fuel rods before depressurization preserves the as-received, as-irradiated internal pressure and induces the representative hoop stresses associated with bounding drying temperature conditions.



The SFRHTO tube shell with its seven modular zones. The power and thermocouple cables for the heating blankets are visible at the top center of each zone.

Two zones of the tube shell are shown with the lid open and the rod supports visible.

Figure A-1. SFRHTO configuration.

A-2. Rod Selections and Temperature Profiles for Phase 1 for FHT

As discussed in the Oak Ridge National Laboratory sister rod test plan [A-3], the sister rods selected for FHT were chosen based on two main criteria: (1) the likelihood of a relatively high amount of hydrogen in the cladding for that cladding type and (2) the predicted rod internal pressure. Past ring compression tests at Argonne National Laboratory [A-4] identified these two parameters as important to hydride reorientation, which can degrade the load-bearing capability of the cladding under some conditions. The completed nondestructive examinations [A-5], particularly the eddy current examinations, confirmed that the selected

FHT rods are expected to have among the highest oxidation and hydrogen pickup for rods of the same cladding type. Since rod internal pressure is not directly correlated to cladding oxidation and hydrogen pickup, the rod with the highest pressure is not necessarily the rod whose cladding has the highest hydrogen content. Therefore, specimen selections considered available analytical predictions of rod internal pressure.

A peak temperature of 400°C was selected to be applied to the full-length rods based on regulatory guidance regarding calculated peak fuel cladding temperatures for normal conditions of dry storage and short-term loading operations [A-6]. The full-length rods were heated slowly and held at temperature for several days, and then they were slowly cooled to ambient temperature.

As illustrated in Figure A-2, the local temperature of the fuel rod cladding varies with axial elevation and based on the dry storage system; however, a flat 400°C was imposed at all axial locations for the FHT. The expected axial temperature distribution in the Research Project Cask (RPC) is also provided in Figure 2 for information [A-7]. The hydrogen content in the fuel rod cladding is expected to vary axially also, with the highest cladding hydrogen concentrations located in the upper elevations at which the cladding and coolant were hottest during reactor operation. Axial rod elevations where high hydrogen cladding concentration coincides with higher temperatures during storage are expected to be the most vulnerable to cladding degradation mechanisms, such as hydride reorientation embrittlement, and those elevations of the sister rods are expected to provide representative performance data for high burnup fuel storage conditions.

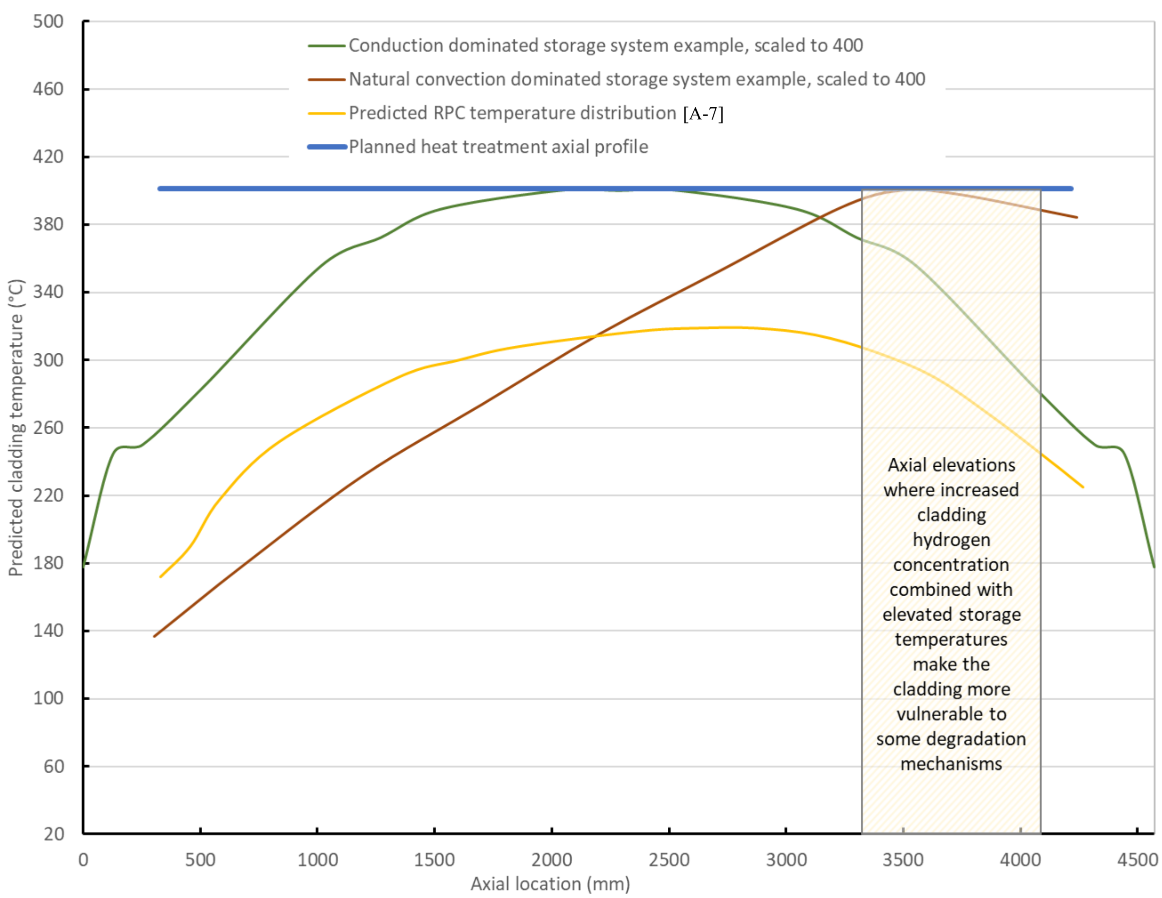


Figure A-2. Illustration of various axial profiles associated with dry storage systems and the fuel rod expected axial hydride density trend.

Although several different types of spent nuclear fuel dry storage systems are available, there are two basic designs with respect to heat transfer modes: a convection-based design and a conduction-based design. As illustrated in Figure A-2, the axial temperature profiles of the fuel in the storage systems differ in the location of the peak temperature and the quantity of fuel in the storage system at or near the peak temperature. As described by Salzstein [A-2], in an effort to reduce the number of variables that could cause variations in the behavior of the hydrides along the axis of the rod, the Spent Fuel and Waste Science and Technology (SFWST) program elected to implement a flat temperature profile for FHTs with all rod elevations subjected to the peak temperature. The peak temperature for the heat treatment (400°C) was selected based on the regulatory limit for the fuel rod cladding.

The target heat-up and cooldown rates selected for the heat treatments are based on the rates measured for the RPC during the cask loading and vacuum drying sequence and are 10°C/h and 3.7°C/h, respectively. The SFWST program specified an 8 h hold time, or *soak*, at peak temperature to ensure that cladding hydrogen dissolution was complete while minimizing the potential for the annealing of irradiation defects that tend to offset any effects of hydride reorientation-induced embrittlement. Figure A-3 provides a graphical representation of the ideal timeline for the selected FHT.

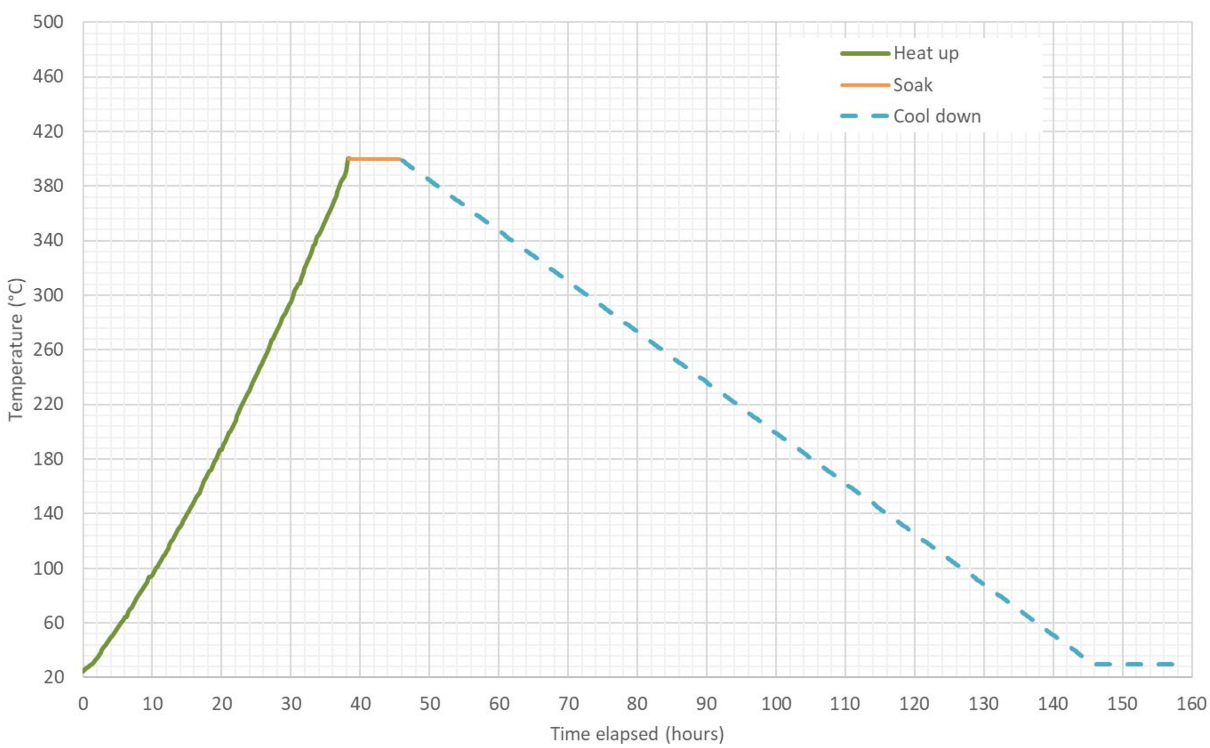


Figure A-3. The selected heat-up and cooldown cycle for the three initial FHT sister rods.

A-3. Heat Treatments Applied

To date, three fuel rods have been heat-treated in the SFRHTO: one Zirc-4-clad (F35P17), one ZIRLO-clad (3F9N05), and one M5-clad (30AE14) unpunctured fuel rod. Figure A-4, Figure A-5, and Figure A-6 provide the heat-treatment history for each of the selected rods. Table A-1 provides a summary of the heat-treatment parameters.

As evidenced by the data, the target heat-up rates, soak temperatures and times, and cooldown rates were successfully achieved, except for the SFRHTO Zone 1 for rod 30AE14. During the heat treatment of 30AE14 (M5 cladding), the Zone 1 heating blanket controller malfunctioned, and that part of the fuel rod (the upper end cap, plenum region, and ~200 mm of fuel stack at the top of the rod) reached temperatures as high as 485°C for approximately 1.75 h during the thermal soak. The average Zone 1 temperature during the 8 h soak period was 452°C (Figure A-6). The Zone 1 heating blanket controller was corrected before the end of the 8 h soak, and the average temperature was 401°C when cooldown began.

Table A-1. Measured rod temperatures and heat-up/cooldown rates during the heat treatments.

Rod	SFRHTO zone	Approximate rod elevations (mm)	Heat-up rate (°C/h)	Cooldown rate (°C/h)	Average soak temperature (°C)
F35P17 (Zirc-4)	1	Bottom of rod–420 mm	10.3	3.9	414.8
	2	420–1,030 mm	10.1	3.8	405.6
	3	1,030–1,640 mm	9.9	3.7	396.0
	4	1,640–2,250 mm	10.2	3.8	406.2
	5	2,250–2,860 mm	10.1	3.8	405.1
	6	2,860–3,470 mm	10.0	3.8	403.7
	7	3,470 mm–top of rod	10.0	3.8	402.7
3F9N05 (ZIRLO)	1	3,470 mm–top of rod	10.2	3.8	408.2
	2	2,860–3,470 mm	10.1	3.8	404.8
	3	2,250–2,860 mm	9.9	3.7	396.2
	4	1,640–2,250 mm	10.1	3.8	406.0
	5	1,030–1,640 mm	10.0	3.8	404.0
	6	420–1,030 mm	10.0	3.8	402.5
	7	Bottom of rod–420 mm	10.0	3.8	401.0
30AE14 (M5)	1	3,470 mm–top of rod	11.2	3.6	451.6
	2	2,860–3,470 mm	10.1	3.6	409.4
	3	2,250–2,860 mm	9.8	3.6	397.8
	4	1,640–2,250 mm	10.1	3.6	407.4
	5	1,030–1,640 mm	10.0	3.6	405.5
	6	420–1,030 mm	9.9	3.6	402.6
	7	Bottom of rod–420 mm	9.9	3.6	402.3
Average, all rods in all zones			10.1	3.7	406.4
Standard deviation, all rods in all zones			0.3	0.1	11.2

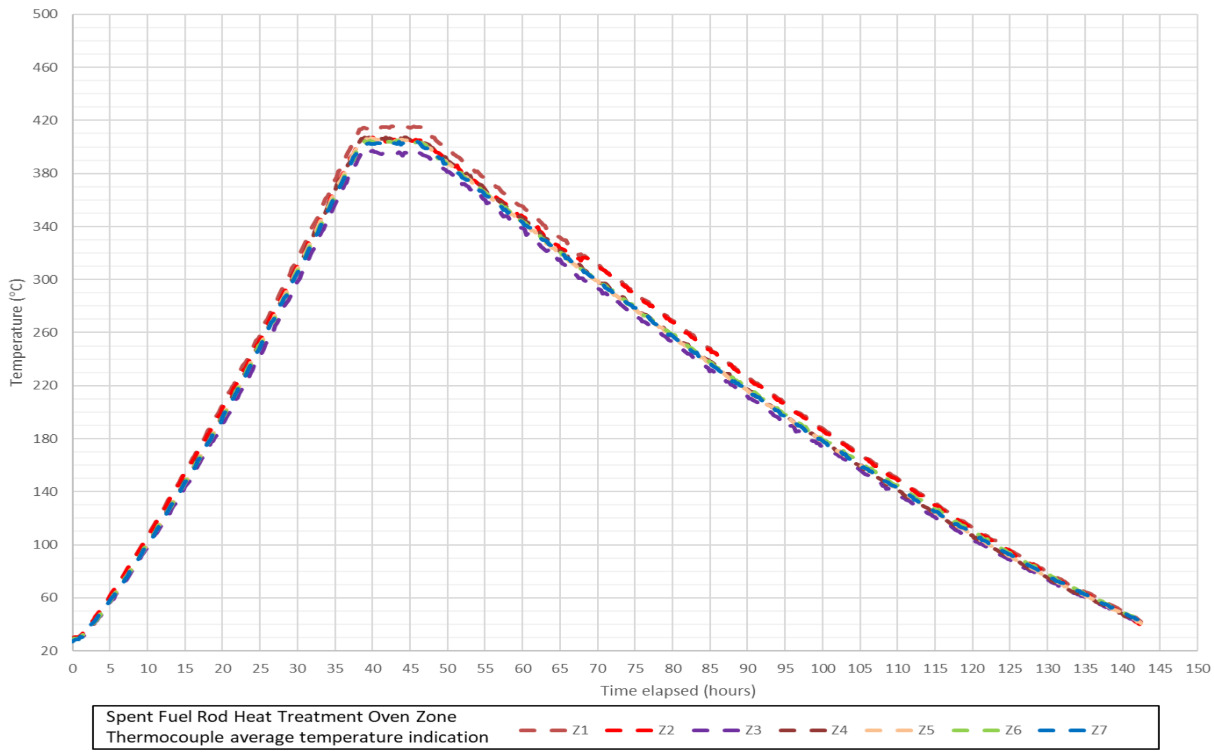


Figure A-4. Heat-treatment zone average rod temperatures for F35P17.

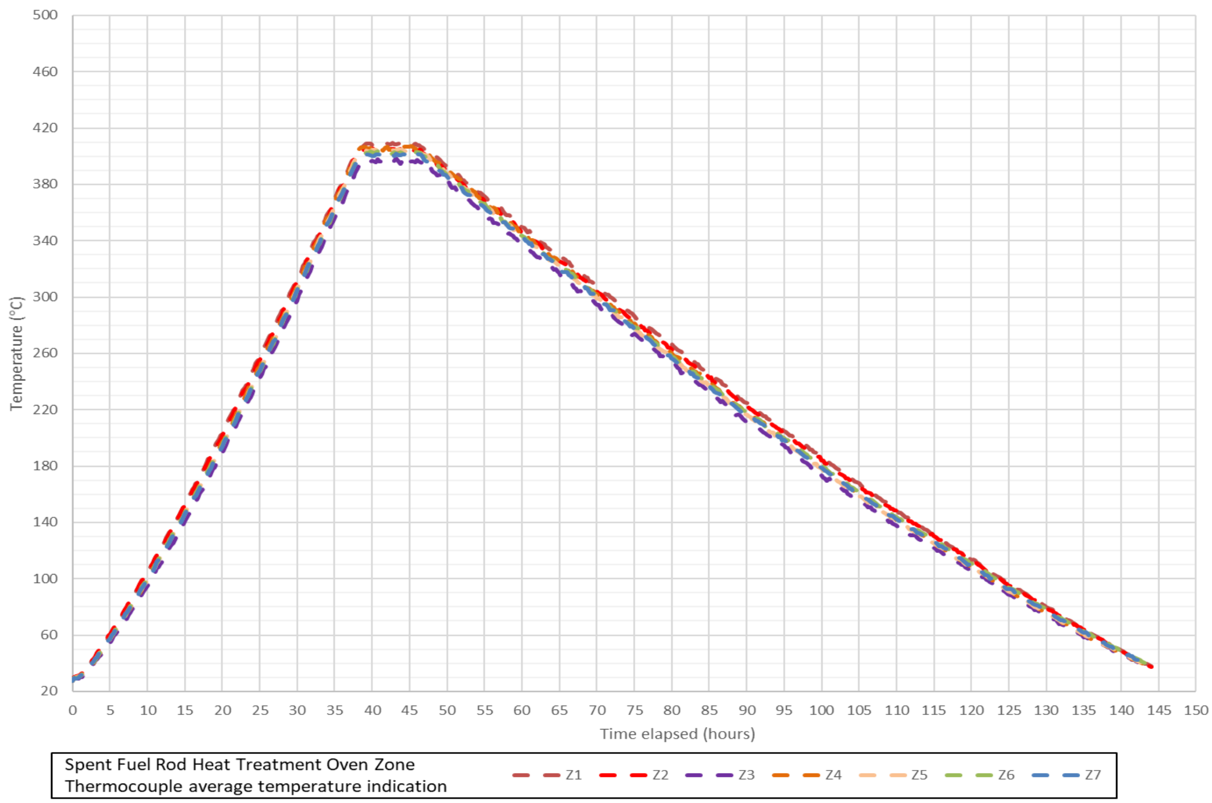


Figure A-5. Heat-treatment zone average rod temperatures for 3F9N05.

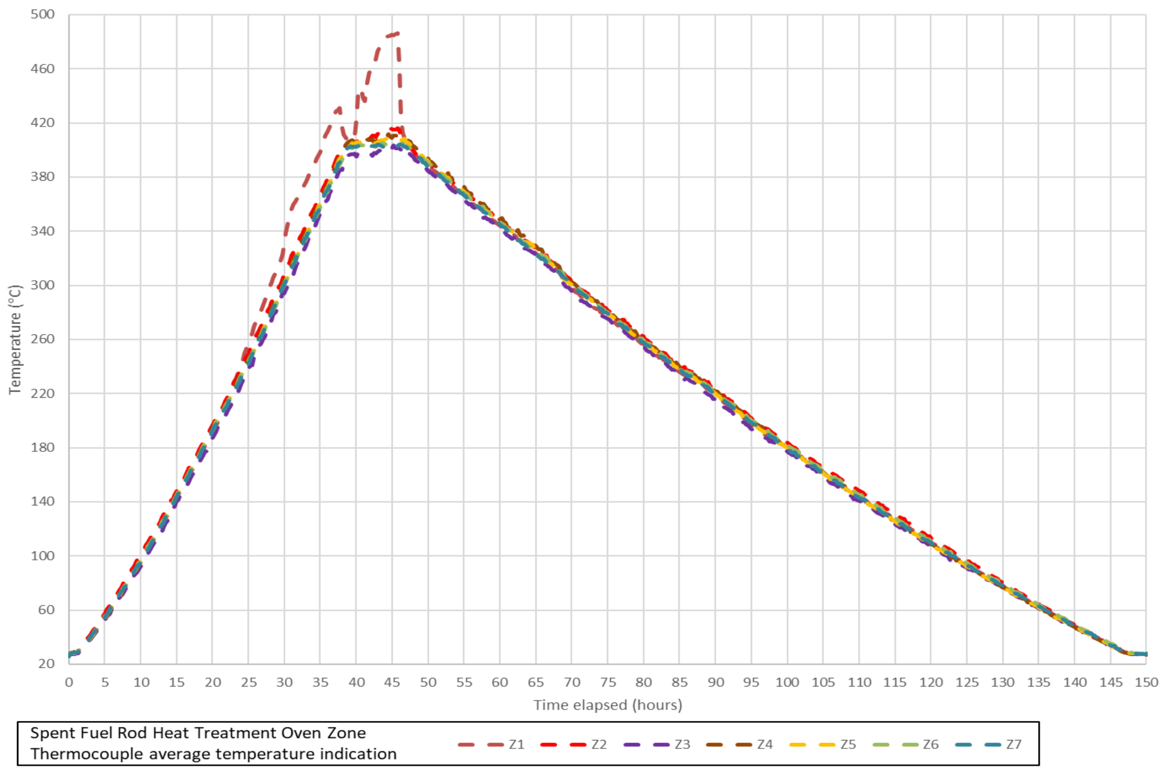


Figure A-6. Heat-treatment zone average rod temperatures for 30AE14.

A-4. Evaluating the Higher-than-Planned Soak Temperature of 30AE14

Although the soak temperature of Zone 1 on rod 30AE14 was corrected before initiating rod cooldown, it is important to assess the potential impacts on the follow-on experiments to be completed on that rod. In particular, the impacts on hydrogen and hydride reorientation, pellet-clad bonding, and annealing of irradiation defects can strongly influence the mechanical strength of the rod.

At room temperature, the measured pressure of 30AE14 was 3.2 MPa (Section 3.2). At the targeted 400°C, the rod pressure would have been ~7.1 MPa. At the higher average temperature of 452°C that was imposed during the heat treatment, the pressure was ~7.6 MPa, which was about 8% higher than planned. The maximum pressure during the soak was estimated as 8.0 MPa at the 485°C peak temperature for ~1.75 h. The impacts of the higher temperature and pressure on pellet clad bonding will be investigated as more testing is completed.

It is unlikely that the higher temperature affected the behavior of the cladding hydrides for the following reasons.

- Based on the eddy current data [A-4], the M5-clad rod has a thin oxide layer (31 µm peak measured lift-off) and is expected to have low hydrogen content.
- At a low hydrogen concentration, all precipitated hydrides are expected to be dissolved in the cladding at 400°C, and no additional dissolution would have occurred as the result of the higher temperature.

- Given the low hydrogen content in the plenum region of the M5-clad rod, any migration of hydrogen from the hotter SFRHTO Zone 1 to the adjacent SFTHTO Zone 2 (<85°C cooler) is expected to be minimal.
- Because the controller was corrected and the temperature was restored to the target range (400°C) before the end of the soak, the cooldown phase proceeded as expected, and the precipitation of the hydrides should not have been affected.

To evaluate the potential effects on irradiation annealing, available data on irradiation defect annealing were collected. Bourdiliau [A-8] provides uniform elongation (UE) data on irradiation defect annealing in the 400–420°C range for Zr-1% Nb specimens (Figure A-7). Cockeram [A-9] provides data on Zirc-2 and Zirc-4 materials annealed over much shorter timescales (1–500 h) and over a range of temperatures. Based on Bourdiliau's data, the increase in UE associated with 1,000 h at approximately 400°C is 4.5%. Given the 8 h soak time for the sister rods, the increase in ductility related to the heat treatment is expected to be <0.1%. Based on Cockeram's results, it appears that there is little change in the irradiation defect annealing rate as the temperature is increased from 400 to ~500°C. Given these data, it is highly unlikely that there was additional annealing of irradiation defects as a result of the higher temperatures imposed on rod 30AE14.

Based on these discussions, it seems unlikely that the short increase in soak temperature will affect the results of the DE; however, the difference in the heat-treatment conditions will be considered with the results of the DE when it becomes available.

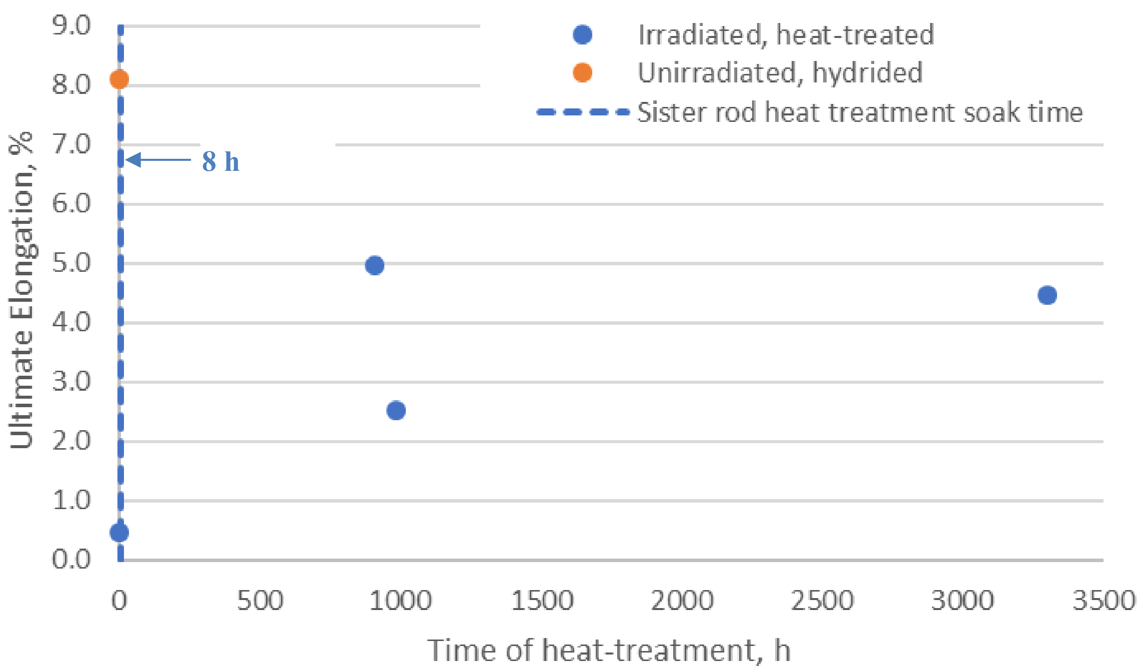


Figure A-7. Data available on ductility for irradiated Zr-1%Nb after heat treatments in the 400–420°C range [A-8] as compared with the 8 h sister rod heat-treatment soak time.

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