Design and Fabrication of a Heat Treatment Oven for Full-Length Spent Nuclear Fuel Rods

Rose Montgomery,[1] Nesrin Cetiner,[2] Charles Blue,[3] Randall Blue,[3] Bruce Bevard[1]

[1]Used Fuel Systems, Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN, 37831-6170
[2]Thermal Hydraulics and Irradiation Engineering Group, Oak Ridge National Laboratory
[3]Infrared Heating Technology, 2010 TN-58 Ste 2120, Oak Ridge, TN 37830.
865-576-1381 and montgomeryra@ornl.gov

INTRODUCTION

The US Department of Energy (DOE) Office of Nuclear Energy (NE) is experimentally evaluating the effects of long-term storage and transportation on high burnup (HBU) (defined as >45 gigawatt days per metric ton uranium) spent nuclear fuel (SNF) through the High Burnup Spent Fuel Data Project [1]. In the fall of 2017, an instrumented bolted-lid cask (project cask) at the North Anna Power Station (NAPS) was loaded with intact HBU pressurized water reactor (PWR) fuel assemblies (project assemblies) with four different kinds of cladding. The cask will be reopened in approximately 10 years for inspection. Prior to cask loading, 25 sister rods that are similar to the project cask rods were extracted from NAPS fuel assemblies for post-irradiation examination (PIE).

Destructive examination (DE) of the sister rods will be completed to facilitate an understanding of overall SNF rod strength and durability. Both composite fuel and defueled clad will be tested. While the data generated can be used for multiple purposes, a primary objective for obtaining the sister rod PIE data is to support existing fuel storage licensing and relicensing activities. This will be accomplished by addressing identified knowledge gaps, enhancing the technical bases for post-storage transportation, handling, and consolidation activities [2,3]. An area to be addressed is the effects of dry storage thermal conditions on the HBU fuel rods. 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 either during the drying sequence or just following drying during transfer of the canister to the storage pad.

To gain a better understanding of the effects of the drying and transfer sequence, selected full-length sister rods will be subjected to a simulated dry storage vacuum drying temperature distribution to examine the rod condition induced by the increased fuel rod temperature as compared with the rod condition prior to dry storage [4]. This paper discusses the design and fabrication of a spent fuel rod heat treatment oven (SFRHTO), shown in Fig.1, that is capable of imposing a variety of expected axial temperature profiles and peak cladding temperatures up to 600 °C on a full-length fuel rod.

In contrast with heat treatment of rod segments where the full-length rod is depressurized and segments are cut, 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. Heat treatment of the full-length rods is also expected to maximize time and cost efficiencies in the hot cell and to reduce experimental uncertainties related to sealing and pressurizing short rod segments.

The peak temperature to be applied to the full-length rods will be determined based on both field measurements taken during dry storage vacuum drying and regulatory guidance regarding maximum allowable dry storage temperatures. The peak cladding temperature is currently limited to 400 °C. The full-length rods will be heated slowly and held at temperature for several days, and then they will be slowly cooled to ambient temperature. Since the project assembly cask-stored rods will not be examined immediately

Fig. 1. 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.

after drying and before dry storage, the sister rods offer the only opportunity to discern the separate effects due to the thermal transient imposed by the canister drying procedure.

OPERATIONAL CONFIGURATION

The SFRHTO is intended to house a single full-length SNF rod centered within the SFRHTO cavity. The SFRHTO is a custom-designed piece of equipment that will be installed in the Oak Ridge National Laboratory (ORNL) Irradiated Fuels Examination Laboratory (IFEL). It is composed of two primary components: an in-cell tube shell with heat blankets, and an out-of-cell equipment cabinet housing the electronics, as illustrated in Fig. 2.

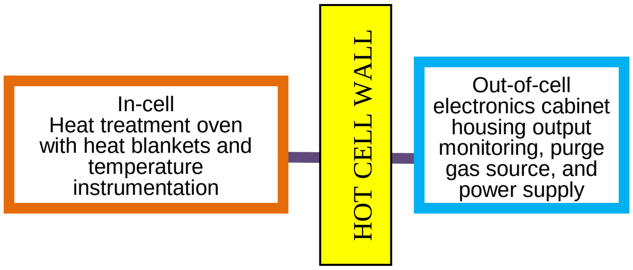

Fig. 2. General placement of the SFRHTO components for operation in ORNL IFEL.

The SFRHTO will be used to heat-treat SNF rods and must therefore be remotely operated inside a hot cell. The cell background radiation dose rate is ~50 R/hr, and the fuel rod dose rate is $\sim 2 \times 10^4$ R/hr at one inch from the rod's surface. Therefore, the SFRHTO design must consider high radiation doses and must also accommodate remote handling operations.

The SFRHTO is approximately 16 feet long, and the outer envelope of the assembled SFRHTO is less than 9.75 inches in diameter to accommodate insertion into the hot cell via a 10-inch diameter port. The SFRHTO is designed to accept full- and part-length boiling water and PWR fuel rods. It uses seven modular segments to allow for economical refurbishment. The seven zones in the oven allow the variable application of heat to approximate the expected dry storage fuel rod axial temperature profile, which may also be varied with time.

The oven tube shell is constructed from 3-inch 304 stainless steel schedule 40 pipe. Seven 24-inch long flanged pipe segments have been cut in half lengthwise and hinged. Each of the short segments is bolted to its neighbor, with the ends using blind flanges cut in half. The lower blind flange includes a ¼-inch FNPT connection fitted with quick-disconnects to allow heated purge gas flow that will originate outside the hot cell. Each oven segment is fitted with an external insulated heat blanket that provides the main source of heat for the oven. The blankets provide the capability of achieving ~600 °C at the external surface of the oven, and each blanket is equipped with power control so the heat output can be modified as needed to achieve the target rod temperature. An integral thermocouple is provided with each heat blanket to monitor the blanket temperature. Blanket controls will be located outside the hot cell to avoid irradiation exposure.

The heat blankets fabricated primarily from fiberglass, and they include an inner fabric liner and an integral knitted heat tape element. The knitted heat tapes are designed for use in high-temperature applications and are constructed from stranded nickel alloy wire. The amount of heat provided by the heat blanket can range between 0 and 250 W/m^2. The external surfaces of the heat blankets are over-wrapped with perforated aluminum to maintain good contact with the oven tube shell, to reduce the potential for loosening or damage during handling, and to facilitate decontamination during decommissioning.

Fourteen (14) simple rod supports, two in each of the seven oven zones, are located along the axis of the oven to support the fuel rod during heat treatment. The rod supports are fabricated from stainless steel strip in a simple bridge configuration with a v-notch to center the rod, as shown in Fig. 3. Gravity serves to keep the rod in position on the rod support in the oven. Thermocouples are attached to the rod support strips below the rod contact points to monitor the local temperature.

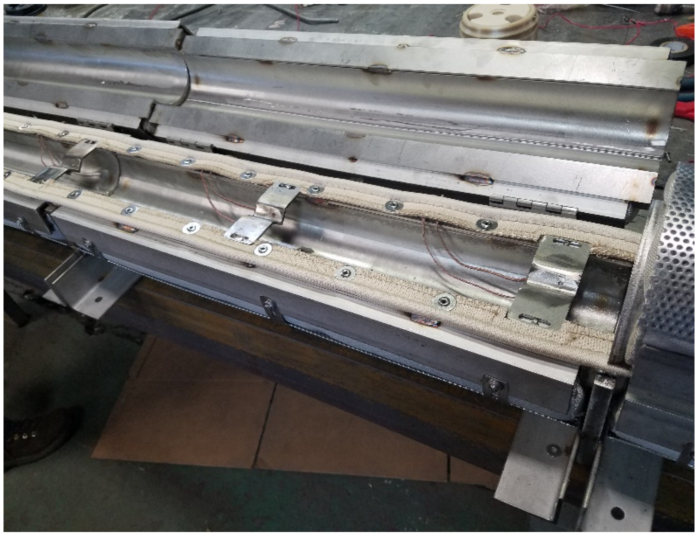

Fig. 3. Two zones of the tube shell with the lid open and the rod supports visible.

The external surfaces of the SFRHTO are expected to be about the same temperature as that of the heat treatment: ~400 °C during operation. This is not an issue, since no personnel will be near the SFRHTO during operation. The SFRHTO includes as much insulation as possible given the cell entry dimensional restrictions. This is mainly to reduce heat loss from the oven.

The SFRHTO is designed to avoid inducing local hot spots, circumferential temperature variations, or unintended axial temperature variations. A slow inert gas purge is applied to eliminate natural convection effects and to remove any off-gassing from the rod. During the decades of dry storage, the fuel rods cool very slowly (<<1 °C/hr). The cooldown rate after vacuum drying is on the order of 5 °C/hr. For the sister rod heat treatments, the cooling rate will be held at 5 °C/hr or less. The SFRHTO must be capable of imposing and maintaining a temperature up to 400 ± 10 °C over a one-week duration. The current plan for heat treatment of the sister rods is to apply a static temperature profile to each rod, meaning that the temperature at each rod axial elevation is not expected to vary with time over the heat treatment period [1]. Therefore, the heat input from the heat blankets is expected to be static over the heat treatment period and, once set, will remain at approximately the same power throughout the heat treatment process. The appropriate blanket power settings to achieve the desired temperature profiles are expected to be determined during qualification testing.

An evaluation of the design was performed using ANSYS to estimate the amount of heat (power) required to achieve the expected axial profile to be applied to the sister rods [5].

CONTROL SYSTEM

As shown in Fig. 4, instrumentation is provided outside the hot cell to monitor and control the heat blankets, to monitor the fuel rod temperatures at discrete locations along the axis, to monitor purge gas temperature and flow rate, to control heating of the purge gas, and to monitor exiting purge gas for fission gases. The control system records the controller-reported temperatures during the heat treatment. The SFRHTO incorporates one thermocouple for each heat blanket controller for each control zone. Each rod support is instrumented on its underside with two K-type thermocouples. Two thermocouples per rod support provide redundancy in the event of a thermocouple failure.

Fig. 4. The main control cabinet is placed out-of-cell to avoid radiation damage to the electronics. Cabling to the oven in cell is routed through the hot cell wall.

Both the primary and redundant rod support thermocouples are monitored manually and inform the manual adjustment of the heat blanket power and temperature in each control zone. The temperatures reported by the rod support thermocouples are recorded for each heat treatment cycle using chart recorders. Each heat blanket is supplied with integral temperature sensors and power control. The leads from the heat blankets are fed through the same external conduit used for the rod support thermocouples, through the hot cell alpha plug, and to a dedicated control unit.

To avoid radiation damage, electronics are not placed in the hot cell. The signal from the sensor is routed from the hot cell to the controller located in the electronics cabinet, and the resulting power change is routed back in. Electrical noise and signal loss are not expected to be an issue for this application. All wiring, cables, thermocouple leads, and cabling insulation near the oven tube shell are rated for temperatures well above 400 °C.

PURGE GAS FLOW ESTIMATE

The oven design includes a gas purge for use in fine-tuning the rod axial temperature distribution and to monitor the exit gases for fuel rod breach. Dry nitrogen helium or argon is planned for use with the sister rods, but other noncombustible gas atmospheres (e.g., air) could be applied. The gas flow is controlled and delivered through piping from outside the hot cell to the inlet of the oven. Outside the hot cell, a control valve is used to manually adjust the flow rate, and a heater is provided to preheat the gas to achieve any desired supplementary heat or cooling input to the fuel rod. Quick-disconnect fittings are provided to allow easy connect/disconnect of the oven for purge. Although the purge gas is expected to be provided by a pressurized Dewar vessel, the heat treatment oven is not designed as a sealed system, so it cannot be pressurized. The exit of the SFRHTO vents to the hot cell, nominally at atmospheric pressure.

The nominal flow rate necessary to eliminate natural convection effects in the 3-inch tube shell is calculated based on standard pipe flow equations. The flow velocity is expected to be relatively constant over the duration of the heat treatment, and changes in flow velocity are expected to be slow. The purge gas flow velocity required to achieve a fully developed laminar flow prior to the first rod support assembly can be derived based on the Reynold’s number for gas temperatures ranging from 27 to 227 °C (Eq. 1) [6].

$$(x / D)_{lam} \approx 0.05\, Re_D \qquad (1)$$

where:

x is the desired length where flow is fully developed, at the first rod support, ~12 inches;

D is the inner diameter of the pipe, 3.26 inches; and

Re_D is the Reynold's number, $\rho V D/\mu$, where: ρ is the fluid density, V is the fluid velocity, D is the pipe inner diameter, and μ is the fluid viscosity.

Given the material properties for nitrogen or helium as listed in Table I and the preceding equations, the velocity range required to produce fully developed laminar flow at all fuel rod locations for the proposed fluids is estimated as 0.014–0.258 m/s. To maintain the flow in the laminar range, the Reynold's number should be maintained below 2,300 [6].

TABLE I. Calculated Purge Gas Velocity to Ensure Fully Developed Flow at the Fuel Rod

	27°C		227°C	
	N	He	N	He
ρ, kg/m^3 [6]	1.1233	0.1625	0.6739	0.0975
μ, N-s/m^2 [6]	1.78E-05	1.99E-05	2.58E-05	2.83E-05
V fully developed, m/s	0.014	0.109	0.034	0.258
V max, laminar, m/s	0.44	3.40	1.06	8.05

QUALIFICATION TESTING

Out-of-cell testing will be completed to demonstrate that the oven performs as expected, that it can be operated remotely, and that a rod can be successfully moved in and out of the oven. The fuel rod will be simulated using a solid stainless-steel rod that is similar in diameter and length to those being tested. The simulated fuel rod will be instrumented with several thermocouples for comparison with the oven rod support thermocouples.

The following qualification tests will be performed to demonstrate the SFRHTO expected performance:

- Heating element performance, capability of achieving and holding 400 ± 10 °C at constant purge gas flow
- Maximum SFRHTO temperature measurement at full power with no purge gas flow
- Temperature profile of the fuel rod under various operating conditions
- Maximum rod temperature at full power with no purge gas flow
- Purge gas flow rate and effect on temperature distribution
- Rod support thermocouple performance and observed differential from dummy rod reported temperatures

PLANNED FUTURE WORK

Qualification testing will be completed in late January 2018 and is expected to demonstrate the thermal performance characteristics, remote operation of the SFRHTO, and fuel rod insertion/withdrawal capabilities.

Once qualification testing is complete, modifications and follow up testing (as needed) will be completed. The furnace will be moved into the hot cell by the 3rd quarter of FY18 for the sister rod heat treatment and puncture tests. The results from the out of cell and in-cell testing are expected to be published early in FY2019.

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