High Burnup Spent Fuel Dry Storage Research Project

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ABSTRACT

Much is known about high burnup (HBU) fuel from laboratory testing. However, data is needed on the behavior of the fuel-cladding composite system of HBU fuel under typical dry storage conditions to understand the effect of dry storage on HBU cladding. The Department of Energy and the Electric Power Research Institute are conducting a large scale, long term, dry storage cask research and development project for HBU spent fuel to provide data for model validation and improvement, input to future cask designs, support license renewals and new licenses for dry storage facilities, and support transportation licensing for HBU fuel. The project uses a modified TN-32 bolted storage cask with four different cladding types. The cask was loaded in November 2017 at Dominion Energy's North Anna Power Station. Seven thermocouple lances were inserted into the cask and temperatures recorded through the loading and storage operations. Gas samples were collected from the cask cavity and analyzed.

1. Introduction

Storage of low burnup fuel (<45 GWD/MTU) has been going on for decades. The technical basis for storage of low burnup fuel was primarily through the demonstrations at Idaho National Laboratory (INL) in the mid-1980s through early 1990s; and the CASTOR-V/21 Demonstration Cask that was reopened at INL in 2000 [1]. Storage of high burnup (HBU) fuel (> 45 GWD/MTU) in dry storage casks began in 2004 in the US. The technical basis for storage of HBU fuel in dry storage casks is based on laboratory testing and is documented in US NRC Interim Staff Guidance (ISG) 11, Revision 3 [2]. Due to the expanded use of high burnup fuel in dry storage and its different characteristics compared to low burnup fuel, similar data from a demonstration cask is desirable on high burnup fuel to support ISFSI license renewals as well as transportation licenses. Many organizations across the globe saw the need for such a high burnup demonstration cask. In 2013, the US Department of Energy (DOE) initiated a High Burnup Dry Storage Cask Research and Development Project (HDRP) to design and implement a high burnup, large scale, long term, dry storage cask research and development project for spent nuclear fuel. The project is led by the Electric Power Research Institute (EPRI). Participants in the project include utility Dominion Energy Virginia; technology vendors AREVA, Westinghouse, and NAC International; and six DOE national laboratories. A test plan was developed for the project and published in February 2014 [3].

The project loaded a cask with 32 HBU assemblies of four different cladding types; Zircaloy-4, low-tin Zircaloy-4, Zirlo™ and M5® at Dominion Energy's North Anna Power Station. The Zircaloy-4 assembly is a Westinghouse LOPAR fuel design; the low-tin Zircaloy-4 assembly is a Westinghouse NAIF fuel design; the Zirlo assemblies are Westinghouse NAIF/P+Z fuel design and the M5 assemblies are AREVA AMBW fuel design. To understand the behavior of the HBU fuel in the cask, temperature data and gas samples are being collected. In addition, 25 "sister rods" have been shipped to Oak Ridge National Laboratory (ORNL) for pre-characterization to understand the condition of the cladding before dry storage. The sister rods have similar characteristics as rods loaded in the cask. The HBU research project cask was successfully loaded in November 2017 and began collecting data on the performance of HBU fuel under actual dry storage conditions.

This paper will describe the cask and instrumentation used, the high burnup fuel loaded, the sister rods which were extracted to characterize the fuel before storage, the loading and some initial results.

2. Cask and Instrumentation

To load the cask as soon as possible, an existing TN-32B bolted metal cask was used as the starting point. A number of modifications had to be made to accommodate data collection.

To measure the temperature inside the cask, thermocouple lances were designed to be inserted through the lid into a guide tube in the fuel assembly after the fuel was loaded in the cask. The lid was machined to include a penetration sleeve for the thermocouple upper housing. A funnel guide installed in the top of the assembly ensures the thermocouple is inserted in the correct guide tube. Confinement was provided by a double metallic o-ring that was torqued down using a retaining ring, jacking plate and jacking screws. To monitor the seals, the overpressure system from each thermocouple was incorporated into the existing overpressure monitoring system (green tubing in Figure 1).

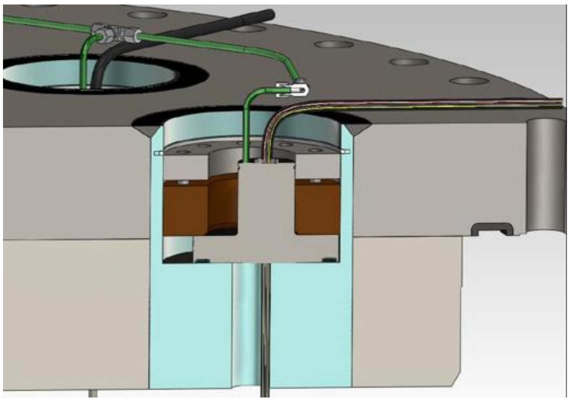


Figure 1. Lid, Penetration sleeve and Thermocouple

The objective for the thermocouples was to provide enough measurements to produce a complete 3-D distribution of temperature inside the cask. This was accomplished using seven thermocouple lances radially distributed (Figure 2), and nine different thermocouples axially distributed within each lance (Table 1) for a total of 63 thermocouples. The radial locations were selected to include locations in the center, middle and periphery of the cask; to have a thermocouple in assemblies of each cladding type with more emphasis on the newer cladding materials (M5® and Zirlo™), to ensure the resultant design would meet the structural requirements with the holes for the seven thermocouples, and not to have any interference for the overpressure tank which must be installed on the lid. The axial locations were chosen to avoid any shadowing from grid spacers and to provide a good axial profile with some thermocouples near the ends and well distributed.

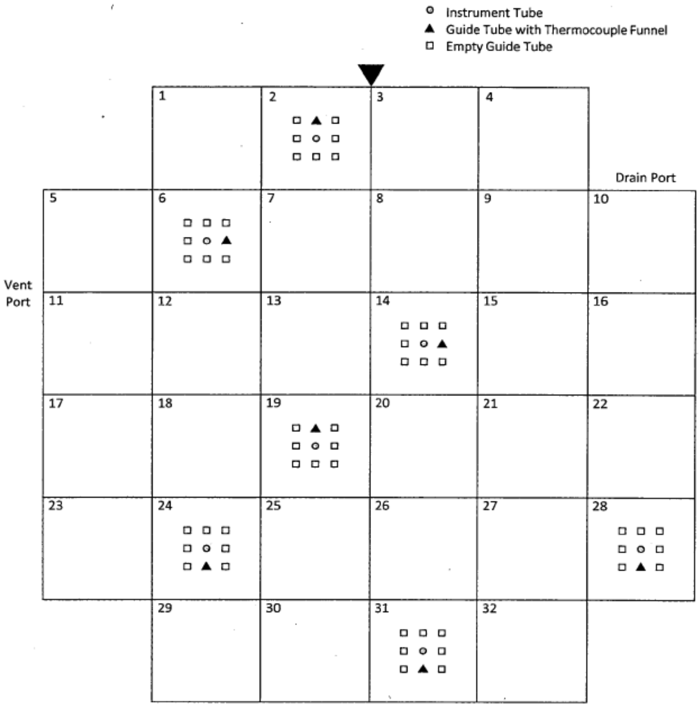


Figure 2: Thermocouple Radial Locations

Thermocouple	Distance from bottom of Assembly (cm)
1	22.9
2	63.5
3	101.6
4	152.4
5	193.0
6	238.8
7	297.2
8	355.6
9	381.0

Table 1: Thermocouple Axial Locations

The thermocouple lance design was based on thermocouples used in reactors. They are Type K thermocouples. A Type B uncertainty estimate using ISO/IEC98-3 was performed and the measurement uncertainty ranges from 1.7°C to 2.11°C for the range of temperatures.

To collect gas samples from the cask interior, a quick connect valve in the existing vent port in the lid provided access to the gas inside the cask cavity. To collect a sample, three separate one liter containers were connected to the vent port quick connect and filled with the gas from the cask interior, one at a time. Prior to use, the sampling containers were purged with ultra-high purity helium, then put under vacuum for at least 12 hours to essentially eliminate any possible contamination of the sample from the container. This purging was done sequentially through the three sample containers and the tubing used to connect the containers. It is also important to note that the vent port is only accessible without the vent port cover plate installed, which provides the confinement boundary.

To allow North Anna to load and store the cask, Dominion Energy Virginia submitted a request to the Nuclear Regulatory Commission (NRC) to amend their dry storage license to include this demonstration cask in August 2015. After a comprehensive review, NRC approved the amendment in September 2017.

3. Fuel Selection

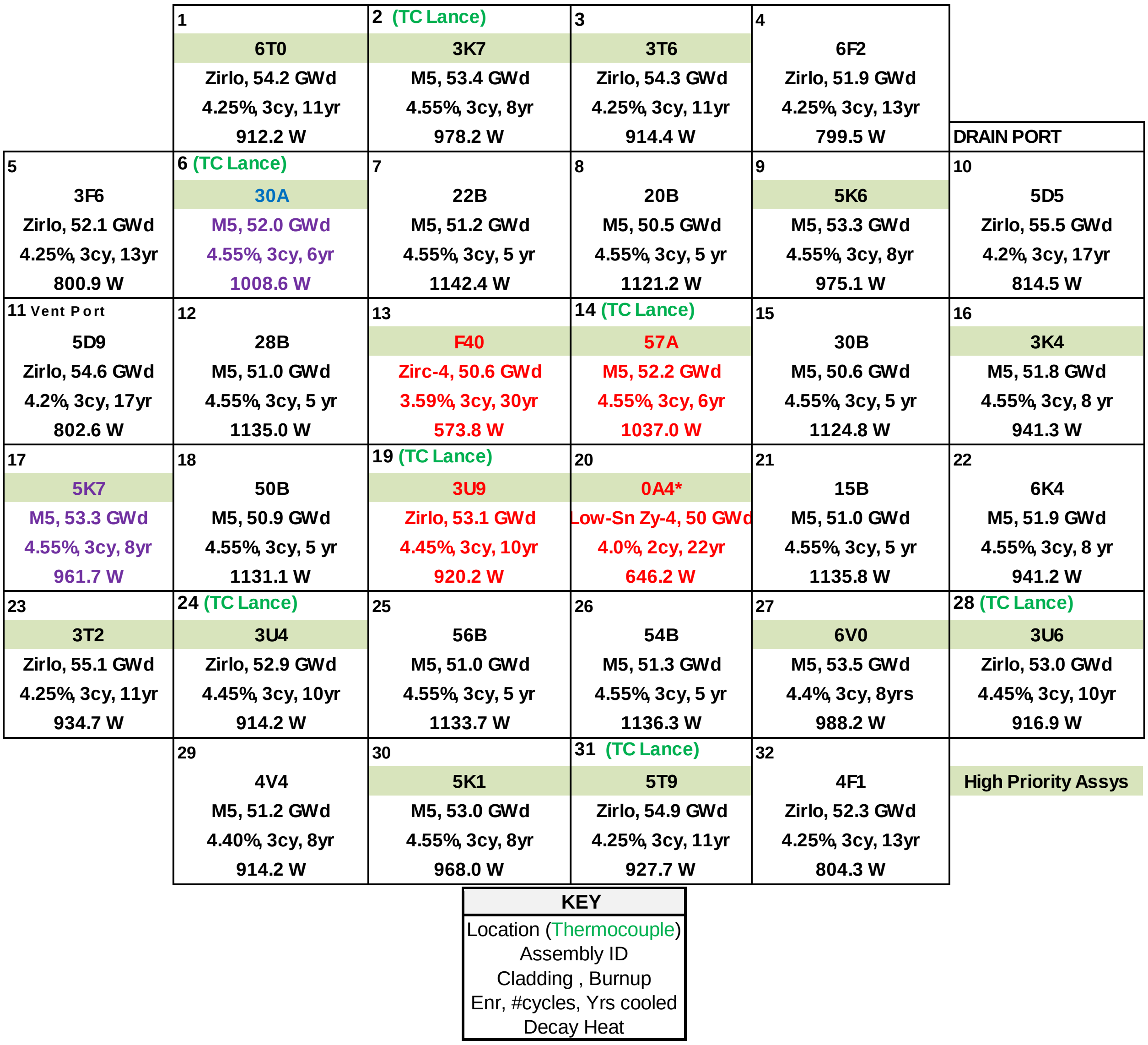
Selection of fuel to load, and location in the cask were important factors to consider in order to maximize the value for this single HBU cask demonstration. Several considerations had to be balanced for the final selection and loading pattern. An overarching factor was to ensure this HBU demo cask was typical of HBU casks in industry. This meant it would not be bounding, but an effort would be made to include fuel that would encompass as broad a range as possible. For the most data from this single cask, as many different cladding materials as possible was desired. Emphasis was given to newer cladding materials with less experimental data. Initially, the goal was to achieve peak cladding temperatures as close to 400°C as possible, however, as discussed below, this was not achievable. It was desired to include the highest burnups, but still typical of HBU fuel being loaded. This excluded very high burnups from lead test assemblies, since it would not be typical. Some fuel with short cooling times would provide added research value as it would produce a wider temperature range due to faster drop off in decay heat. To have a good variation in temperature for each cladding material, fuel in the center, middle and periphery of the cask of each cladding type was desired. Also, cladding integrity was taken into consideration in that no pre-existing failed fuel was allowed.

Using the available fuel from North Anna, and the criteria just described, an initial loading pattern was developed, but the predicted peak clad temperature was only about 300°C. To increase the temperatures, 8 assemblies in the middle of the cask were replaced with 5 year cooled fuel at about 1.6 kW per assembly. This increased the predicted peak cladding temperature to about 320°C and the cask heat load to about 37 kW total. This is significantly below the desire to get close to 400°C. However, with this heat load, the radial neutron resin material was at its maximum design temperature limit of 149°C, so further temperature or heat load increase was not possible.

These temperature predictions assumed the cask would be loaded in July 2017. However delays in the project resulted in the loading occurring in November 2017. The additional 4 month delay yielded about a 1 kW decrease in heat load in addition to a significant drop in ambient temperature from July to November. Furthermore, after these predictions, a more accurate 3-dimensional decay heat calculation was done using detailed fuel history information. The final best estimate peak cladding temperature was 271°C and the total decay heat was 30.5 kW. Table 2 provides a summary of cladding material and burnup ranges for the fuel selected and Figure 3 shows the loading pattern including the calculated decay heat for each assembly.

Cladding Type	Quantity	Burnup Range (GWD/MTU)
Zr-4	1	50.6
low tin Zr-4	1	50.0
Zirlo	12	51.9 - 55.5
M5	18	50.5 - 53.5

Table 2: Fuel Selection Summary



	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 912.2 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 978.2 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 914.4 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 799.5 W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 800.9 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1008.6 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1142.4 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1121.2 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 975.1 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 814.5 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 802.6 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.0 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 573.8 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1037.0 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1124.8 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 941.3 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 961.7 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1131.1 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 920.2 W	20 0A4* Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 646.2 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.8 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 941.2 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 934.7 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 914.2 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1133.7 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1136.3 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 988.2 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 916.9 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 914.2 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 968.0 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 927.7 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 804.3 W	High Priority Assys

KEY
Location (Thermocouple)
Assembly ID
Cladding , Burnup
Enr, #cycles, Yrs cooled
Decay Heat

Figure 3. HBU Research Project Cask Loading Pattern

4. Sister Rods

The overall objective of this project is to understand the behavior of HBU fuel in dry storage, hence it is important to understand the fuel properties before dry storage. To accomplish this, 25 fuel rods were extracted from fuel assemblies either being loaded in the cask, or symmetric partners to assemblies going in the cask. These "sister rods" are undergoing nondestructive and destructive examinations to determine the baseline (t=0) conditions. The rods were selected to provide the best data and considered numerous factors including cladding material, burnup, proximity to a thermocouple, symmetry with other rods at different locations and temperatures in the cask, and proximity to a guide tube. The sister rods selected are summarized in Table 3.

Cladding	Assembly ID	Rod ID	U-235 Enr	F/A Burnup (GWD/MTU)	Sister Assembly in cask
Zr-4	F35	K13	3.59	57.9	none
Zr-4	F35	P17	3.59	57.9	none
low tin Zr-4	3A1	B16	4	50.0	0A4
low tin Zr-4	3A1	F5	4	50.0	0A4
ZIRLO	3D8	B2	4.2	55.0	5D5, 5D9

ZIRLO	3D8	E14	4.2	55.0	5D5, 5D9
ZIRLO	3F9	D7	4.25	52.3	6F2, 3F6, 4F1
ZIRLO	3F9	N5	4.25	52.3	6F2, 3F6, 4F1
ZIRLO	3F9	P2	4.25	52.3	6F2, 3F6, 4F1
ZIRLO	6U3	I7	4.45	52.7	3U9, 3U4, 3U6
ZIRLO	6U3	K9	4.45	52.7	3U9, 3U4, 3U7
ZIRLO	6U3	L8	4.45	52.7	3U9, 3U4, 3U8
ZIRLO	6U3	M3	4.45	52.7	3U9, 3U4, 3U9
ZIRLO	6U3	M9	4.45	52.7	3U9, 3U4, 3U10
ZIRLO	6U3	O5	4.45	52.7	3U9, 3U4, 3U11
ZIRLO	6U3	P16	4.45	52.7	3U9, 3U4, 3U12
M5	30A	G9	4.55	52.0	30A, 57A
M5	30A	K9	4.55	52.0	30A, 57A
M5	30A	D5	4.55	52.0	30A, 57A
M5	30A	E14	4.55	52.0	30A, 57A
M5	30A	P2	4.55	52.0	30A, 57A
M5	5K7	P2	4.55	53.3	3K7, 5K7, 5K6, 5K1
M5	5K7	C5	4.55	53.3	3K7, 5K7, 5K6, 5K2
M5	5K7	K9	4.55	53.3	3K7, 5K7, 5K6, 5K3
M5	5K7	O14	4.55	53.3	3K7, 5K7, 5K6, 5K4

Table 3. Sister Rod Summary

The sister rods were shipped to ORNL in January 2016. DOE and the national laboratories have been developing a detailed test plan for the sister rods. An early overview of the sister rods test plan is available [4]. ORNL has completed the nondestructive examinations [5]. Detailed plans for the destructive examinations to be performed at ORNL, Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL) have been developed. To better understand the complete suite of destructive testing, and to reach some level of consensus, a simplified overview was developed [6]. While a key component of the sister rod testing is to provide baseline data, some of the rods will be heated to higher temperatures to determine the effect on cladding properties. This is a key benefit of having as many as 25 rods given the gap between the actual peak cladding temperature and the desire to be near 400°C.

5. Loading

Loading of the HBU research project cask began on November 14, 2017. The loading closely followed North Anna’s previous experience loading 27 TN-32 casks using standard industry practice for loading, draining, drying and backfilling with helium. All 32 assemblies had previously received a detailed visual inspection. Six poison rod assemblies, necessary to meet the criticality requirements for transportation, were preinstalled in the proper assemblies. The 32 HBU assemblies were loaded, the lid was placed on the cask and the cask moved to the decon bay for processing. About 36 cm of water was removed to prevent thermal expansion of the water from flooding the holes for the thermocouples. To install each thermocouple lance, the temporary shielding in the penetration sleeve hole was removed and the 4.1 meter thermocouple was slowly lowered through the hole in the lid, through the funnel guide in the top of the assembly and into the proper guide tube in the assembly until seated. The 8 jacking screws were torqued to compress the double metallic o-ring to form the seal for confinement. The thermocouples were then connected to the data logger to begin recording temperatures before draining the water. The water was drained from the cask including performing numerous blowdowns to remove as much free water as possible. The cask was vacuum dried for about 8 hours down to a pressure of 55 Pa. The vacuum drying system was secured and the pressure increased to 130 Pa following the required 30 minute hold, verifying the cask was dry. The cask was backfilled with helium to

220,000 Pa on November 16, 2017. The cask then remained in the decon bay for a thermal soak period of 12 days to allow the temperatures to reach equilibrium. During this time three gas samples were collected: the first was shortly after completion of helium backfill, the second was 5 days later, and the third was 7 days after the second (12 days since helium backfill).

As previously discussed, the gas samples were collected by attaching sample containers to the vent port and sequentially filling 3 pre-purged one liter sample containers. It is important to note that no release occurred during sampling. Since the entire sample rig was purged, the only source of contamination from atmospheric air was a very small volume between the male and female quick connect valves. This minimal contamination was confined to a single sample container that was considered a “purge” sample. North Anna analyzed the purge sample along with one other clean sample for each of the 3 samples collected and the results were essentially the same, confirming there was minimal contamination. The third container in each of the samples collected was analyzed by Sandia National Laboratories.

During the thermal soak period external temperature measurements were made using an IR gun at approximately the same time as the gas samples were collected. These measurements were taken to provide information on the boundary conditions for thermal modeling efforts.

Following the 12 day thermal soak period with the loaded cask sitting in the decon bay, the final preparations for storage were made including installing the port covers, performing final helium leak tests and installing the overpressure monitoring system and weather cover. The cask was moved to the truck bay where the heavy haul transporter lifted the cask and transported it about 1.3 km to the Independent Spent Fuel Storage Installation (ISFSI). On November 30, 2017, the cask was placed on the storage pad and the monitoring and temperature measurement instrumentation was reconnected. Figure 4 shows the loaded cask at the North Anna ISFSI.

Figure 4. HBU Research Project Cask at North Anna ISFSI

6. Initial Results

The data being collected in this project to understand the behavior of HBU fuel includes mechanical properties of the cladding, measured temperature data and analysis of the gas inside the cask. The cladding property data is obtained through nondestructive and destructive examinations in hot cells as mentioned in Section 4. Gas samples were collected and analyzed at North Anna. An additional set of analyses on gas samples is being performed at Sandia National Laboratories. Temperature data is being recorded continually. The cladding property data available to date is presented in Reference [5]. The Sandia gas sample results are not yet published. So only the temperature measurement and North Anna gas analysis results will be discussed.

The thermocouples were inserted in the cask before the water was drained to capture the entire thermal transient through draining, drying, helium backfill and reaching thermal equilibrium. The 63 thermocouples recorded the temperature inside the designated guide tube every minute while in the decon bay, then once an hour after it was placed on the storage pad.

The behavior of the temperature measurements was about as expected, except perhaps the magnitude was lower than anticipated. Figure 5 shows the temperature for Cell 14 (near the center of the cask) over the first two weeks. With water in the cask, the slow heatup at a constant slope can be observed. The peak temperature occurs following the rapid heatup from draining and vacuum drying. A sharp drop in temperature with the introduction of helium is observed, followed by a slow rise until the equilibrium temperature is reached. This trend is observed for all thermocouples with the exception of the thermocouples in top part of the assembly where the peak temperature does not occur until later during the thermal soak period. The axial profile is generally cosine shaped with the peak around the center through drying and then slowly shifts to a top peaked shape with the introduction of helium.

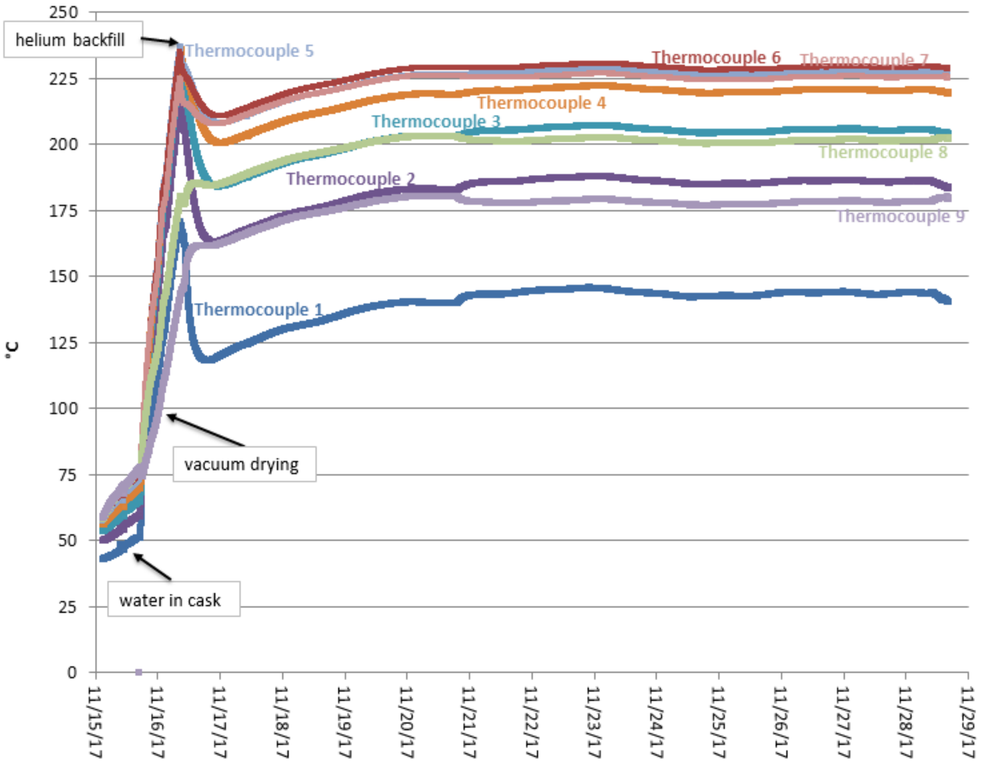


Figure 5. Temperature vs. Time – Cell 14

The peak measured temperature of 237°C occurred in the center of the cask, slightly above the mid-plane (Cell 14, Thermocouple 5). The peak steady state temperature, following helium backfill, rose to within about 8°C of the peak temperature under vacuum conditions.

Gas samples were analyzed for fission gases, hydrogen, oxygen and water. Analysis for fission gas, hydrogen and oxygen was done using standard procedures at North Anna. Fission gas analysis used a mass spectrometer while hydrogen and oxygen used a gas chromatograph with a level of detection of 0.1%. The results indicated no fuel rod failure and minimal amounts of hydrogen and oxygen (below the minimum level of detection). Results are shown in Table 4.

Since water in gas samples is not routinely measured at North Anna, special equipment had to be identified, purchased and training performed. A Water Vapor Isotope Analyzer (WVIA) was selected and used for this analysis. Results of the analysis for water are still inconclusive at this time. Additional work to validate the results with this equipment is ongoing using special gas mixes with known concentrations of water.

Sample	Date	Vessel	Kr-85 (µCi/cc)*	Hydrogen	Oxygen
1	11/16/2017	Purge	<5.45e-4	< 0.1%	Not detected
		Sample	<4.45e-4	< 0.1%	Not detected
2	11/21/2017	Purge	<5.66e-4	< 0.1%	Not detected
		Sample	<4.00e-4	< 0.1%	Not detected
3	11/28/2017	Purge	<4.81e-4	< 0.1%	no peak identified
		Sample	<5.79e-4	< 0.1%	no peak identified

* - All other isotopic activity was below MDA

Table 4. North Anna Gas Sample Results

7. Summary

To validate the technical basis for dry storage of HBU fuel, and to provide data for extended storage of HBU fuel, DOE, EPRI, AREVA and Dominion Energy have begun a large scale, long term, dry storage cask research and development project. Dominion Energy successfully loaded the HBU research project cask in November 2017 at their North Anna Power Station, and data collection has begun. The project is already yielding important results. Through thermal modeling, confirmed by measurements, it has been discovered that HBU fuel is not getting to the temperatures that could impact the mechanical properties of the cladding. Additional data will continue to be collected and analyzed, including data from the sister rods. The project will continue for decades with plans to open the cask after about 10 years of storage to examine the condition of the cladding after storage. At that point, the cask could be reclosed and monitoring continued. The data from the project can be used for model validation and improvement, input to future cask designs, support license renewals and new licenses for dry storage facilities, and support transportation licensing for HBU fuel.

8. References

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