# High Burnup Spent Fuel Dry Storage Research Project

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## ABSTRACT

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 high burnup spent fuel. Dominion Energy loaded the cask in November 2017 at the North Anna Power Station. Internal temperatures are being recorded at 63 different radial and axial locations. An initial set of gas samples were collected from the cask cavity and analyzed during the first two weeks after loading. Temperature data is planned to be collected over the next 10 years while the cask remains in storage. To complete the project, examinations of the fuel after about 10 years of storage will be performed to determine any effects from the loading and storage operations. To perform these examinations, the cask will need to be shipped to a fuel examination facility with a large hot cell capable of opening the cask and removing the fuel. This transportation effort is the focus of the next phase of the project and this paper. The design for transportation of the High Burnup Research Project Cask will be competed including addressing any needed modifications to the cask in its storage condition to prepare for transportation. A transportation license application for the cask will be submitted to NRC. The remaining equipment necessary for transportation will be fabricated, such as impact limiters. The transportation plan will initially be developed in a generic sense and will be finalized once the destination is determined. The High Burnup Research Project Cask will be transported from its storage location to the fuel building at North Anna and prepared for transportation. This will include preparing the lid for transportation, placing the cask on the transport conveyance and installing the impact limiters.

## 1. INTRODUCTION

The technical basis for storage of low burnup fuel was primarily established 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]. The technical basis for storage of high burnup 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 world saw the need for such a high burnup demonstration project. In 2013, the US Department of Energy (DOE) initiated a High Burnup Dry Storage Cask Research and Development Project 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; technology vendors Orano, Framatome, Westinghouse, and NAC International; and six DOE national laboratories. A test plan was developed for the project and published in February 2014 [3].

The purpose of the project is to collect data on high burnup spent fuel under actual dry storage conditions to better understand the behavior of high burnup spent fuel to support license renewals and transportation. To accomplish this, the overall project includes designing, fabricating and licensing a specially instrumented cask for storage of high burnup spent fuel; loading and storing the cask using standard industry practices; collecting data during the loading and storage period; obtaining baseline data of the fuel before storage; opening and examining the fuel after about 10 years of storage to determine the effects of the loading and storage on the cladding properties.

An existing TN-32B cask was modified to accommodate the instrumentation and licensed for storage. The cask was loaded with 32 high burnup assemblies of four different cladding types; Zircaloy-4, low-tin Zircaloy-4, Zirlo™ and M5® at Dominion Energy's North Anna Power Station in November 2017. Data was collected through the loading process and will continue to be collected during storage for about 10 years.

To obtain the baseline characteristics of the high burnup fuel stored in the cask, 25 sister rods with similar characteristics to rods stored in the cask were shipped to Oak Ridge National Laboratory (ORNL) for pre-characterization to understand the condition of the cladding before dry storage. The pre-characterization includes a suite of nondestructive and destructive examinations of the sister rods [4].

To quantitatively identify the effects of the loading and storage on the high burnup fuel rods, the same suite of tests will be performed on the rods stored in the cask for about 10 years. To examine the rods after storage requires opening the cask and extracting the fuel rods to be examined. Typically, the cask would be opened in a spent fuel pool, using the existing facilities at the power plant, however opening the cask wet would quench the fuel rods and may alter the very characteristics being measured. Therefore, the cask needs to be opened in a dry environment, in a hot cell large enough to accommodate the cask and removing the fuel. This requires transporting the High Burnup Research Project Cask from the storage location at the North Anna Independent Spent Fuel Storage Installation (ISFSI) to an examination facility to be identified.

This paper will describe the instrumentation installed, the loading, initial results from the loading, the planned approach for shipping the cask and other consideration for transportation.

## 2. INSTRUMENTATION

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 specific pre-selected guide tube. Confinement was provided by a double metallic o-ring that was compressed by tightening eight jacking screws through a retaining ring and jacking plate. To monitor the seals, the overpressure system from each thermocouple was incorporated into the existing overpressure monitoring system (green tubing in Figure 1).

To provide sufficient measurements to produce a complete 3-D distribution of temperature inside the cask, 63 thermocouples were installed using seven thermocouple lances radially distributed (Figure 2), and nine different thermocouples axially distributed within each lance (Table 1). The radial locations had to ensure the resultant design would meet the structural requirements with the seven penetration sleeves welded in the holes in the lid, and not to interfere with the overpressure tank which must also be installed on the lid. The axial locations were chosen to avoid any shadowing from grid spacers and to provide a good well distributed axial profile with some thermocouples near the ends. 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.

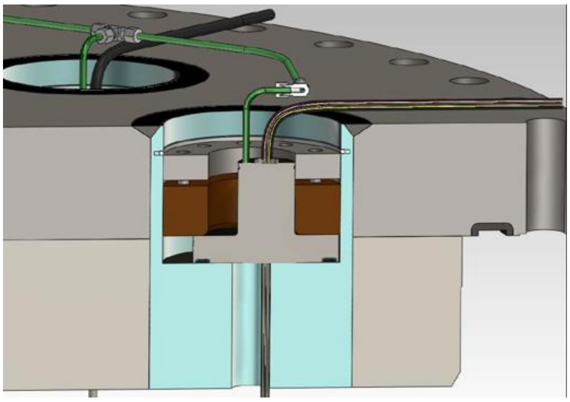

**Figure 1. Lid, Penetration sleeve and Thermocouple**

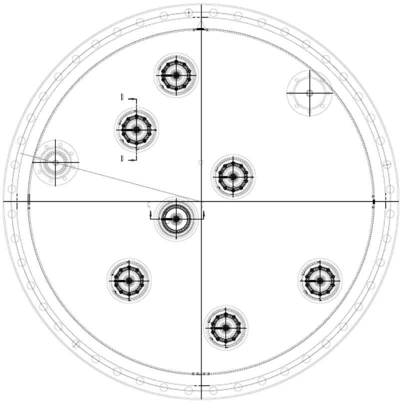

**Figure 2. Thermocouple Radial Locations**

**Table 1. Thermocouple Axial 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 |

## 3. LOADING

Loading of the High Burnup Research Project Cask was completed in November 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. Six poison rod assemblies, necessary to meet the criticality requirements for transportation, were preinstalled in the proper assemblies. The 32 high burnup 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. Each of the 4.1 meter thermocouple lances were 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 record temperatures through the draining, drying and storage operations. 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 0.22 MPa. 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).

Gas samples were collected by attaching sample containers to the vent port and sequentially filling 3 pre-purged one liter sample containers. A very small volume between the male and female quick connect valves introduced a small amount of air into the sample collection. 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.

Following the 12 day thermal soak period 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 ISFSI. The monitoring and temperature measurement instrumentation were reconnected. Figure 4 shows the loaded cask at the North Anna ISFSI.

**Figure 4. High Burnup Research Project Cask at North Anna ISFSI**

## 4. INITIAL RESULTS

The data being collected in this project to understand the behavior of high burnup 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 to determine the pre-storage and post-storage conditions. The cladding property data available to date is presented in Reference [5] and will not be discussed further here.

The peak measured thermocouple temperature was 237°C and occurred at the end of vacuum drying in the center of the cask, slightly above the mid-plane (Cell 14, Thermocouple 5) (Figure 5). The temperatures then dropped sharply with the introduction of helium, followed by a slow rise until the equilibrium temperature was reached. The peak steady state temperature was within about 8°C of the peak temperature under vacuum conditions. 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.

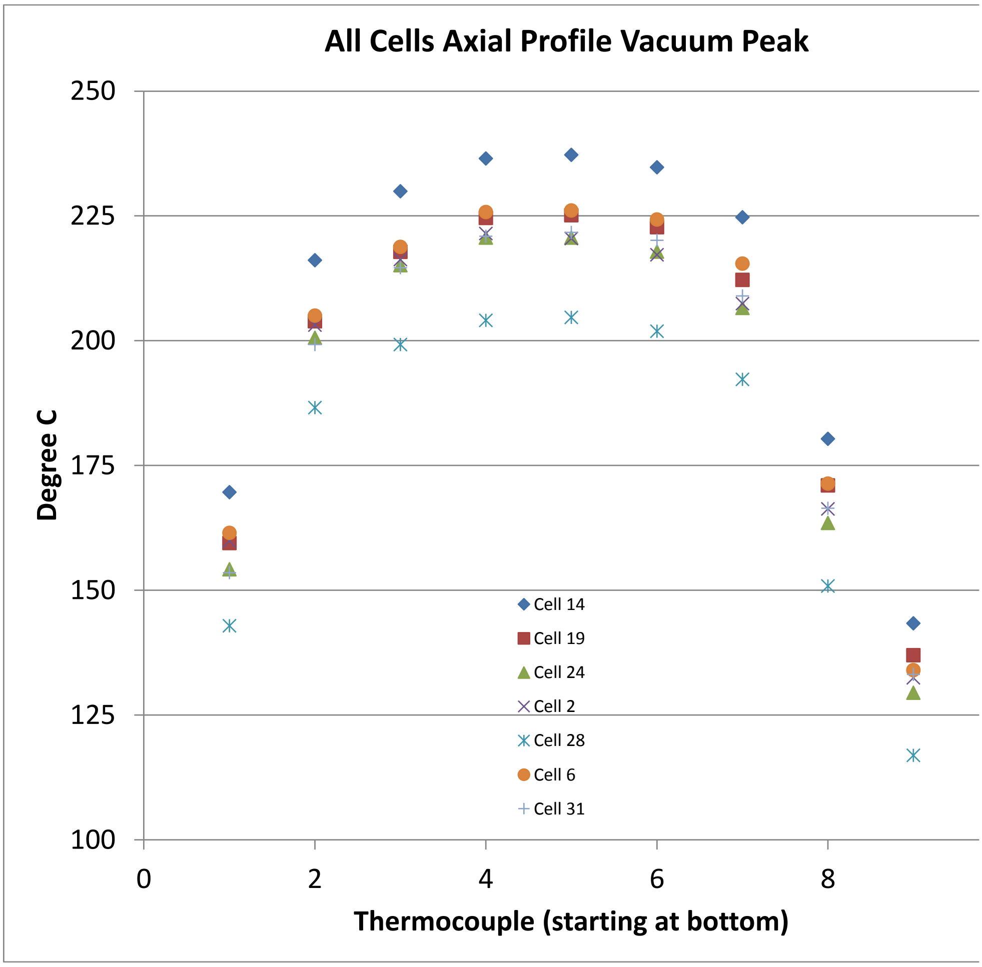

**Figure 5. Peak Temperatures in Vacuum Drying**

Gas samples were analyzed for fission gases, hydrogen, oxygen and water by both North Anna and Sandia National Laboratories [6]. Fission gas analysis used a mass spectrometer at North Anna and a gamma ray spectrometer at Sandia. Hydrogen and oxygen used a gas chromatograph at North Anna and a mass spectrometer at Sandia. Analysis of the water content proved to be challenging. North Anna used a Water Vapor Isotope Analyzer (WVIA). Some changes to the technique to use the WVIA for the water analysis were needed to determine the best method. This was done before analyzing the cask gas samples. Also, special gas samples of known moisture contents were used to calibrate the results. Sandia tried several methods before selecting a final method using a Vaisala humidity probe in a heated environment.

The results for fission gases indicated no fuel rod failure and minimal amounts of hydrogen and oxygen were detected. From the results from the water analysis, it is difficult to draw any solid conclusions, however it is clear that the water content in the gas increased substantially from the first sample at 5 hours after backfill to the second sample 5 days later. Results are shown in Table 4.

**Table 4. Gas Sample Results**

| Sample | Date | Vessel | Kr-85 (µCi/cc)* | Hydrogen (ppmv) | Oxygen (ppmv) | Water (ppmv) |
|---|---|---|---|---|---|---|
| 1 | 11/16/2017 | Purge | <5.45e-4 | 300 | Not detected | NA |
| | | Sample | <4.45e-4 | 400 | Not detected | 1633 |
| | | Sandia | Not detected | 46 | 680 | 2097 |
| 2 | 11/21/2017 | Purge | <5.66e-4 | 200 | Not detected | NA |
| | | Sample | <4.00e-4 | 300 | Not detected | 8896 |
| | | Sandia | Not detected | 287 | 38 | 9605 |
| 3 | 11/28/2017 | Purge | <4.81e-4 | 700 | no peak identified | NA |
| | | Sample | <5.79e-4 | 600 | no peak identified | 8300 |
| | | Sandia | Not detected | 498 | 134 | 17,400 |

* - All other isotopic activity was below the minimum detectable activity

## 5. PLANNED APPROACH FOR TRANSPORTATION

As mentioned previously, a key element to the overall project is to open the cask and examine the fuel after storage to determine the effects of loading and storage on the cladding properties. To accomplish this, the cask will need to be shipped to an examination facility with a large hot cell. Obtaining a transportation license for this shipment is the next major focus of the project.

Although the cask has been loaded and placed in storage before obtaining a transportation license, an evaluation was performed before loading to provide confidence a transportation license could be obtained. The TN-32B cask is similar to the TN-40 cask which has a transportation license [7]. The TN-40 licensing included one-third scale drop tests. Due to the similarity between the TN-40 and the TN-32B, the results from the TN-40 drop tests will be applied to the transportation licensing of the High Burnup Research Project Cask. This will necessitate using the same impact limiter design. Many of the calculations for transportation were performed to confirm the cask would meet the acceptance criteria for normal conditions of transport (NCT) and hypothetical accident conditions (HAC) prior to loading the High Burnup Research Project Cask. Preliminary criticality calculations were performed for transportation, and it was determined that poison rod assemblies would be needed to meet the criticality acceptance criteria using the NRC accepted analytical approach. Therefore, six poison rod assemblies were included in the plans for the initial loading of the cask for storage. The poison rod assemblies were fabricated and placed in six assemblies near the center of the cask. Initial structural analysis was performed for the two most severe drop accidents. The analysis included conservative assumptions for the properties of the high burnup cladding and determined the cladding would not fail. Preliminary shielding analysis using a single worst case bounding assembly as well as the shortest decay time for all 32 assemblies determined the transportation dose rate limits were met except for the 0.1 mSV/hr (10 mrem/hr) at 2 meters limit. The final transport configuration including the railcar, conveyance and personnel barrier can be designed to ensure the 2 meter dose rate limit will be met. Also, the analysis can be rerun to gain additional margin using the information for each specific assembly as loaded instead of bounding assumptions for all 32 assemblies.

Despite the similarities between the TN-40 and the base TN-32B model, the High Burnup Research Project Cask includes penetrations in the lid for the seven thermocouples, which present a challenge for maintaining the containment boundary. The penetration sleeve includes a 17.8 cm (7.00 inches) diameter well for housing the thermocouple lance. One of the HAC tests is a drop onto a 15.2 cm (6 inch) diameter steel bar. Should the steel bar be oriented toward the lid, the steel bar could directly impact the top of the thermocouple housing and breach the containment boundary provided by the thermocouple lance. To protect against this scenario, an approach was developed to reinforce this area to preserve the containment boundary. Since the thermocouple lances are not required for transportation, the thermocouples can be essentially abandoned in place by cutting the thermocouple cables and overpressure monitoring tubing, and welding a 2.54 cm (1 inch) thick plate over each penetration sleeve opening. Due to the vulnerability of the single plate with a partial penetration weld from a direct hit of the 15.2 cm (6 inch) diameter steel bar, an additional 2.54 cm (1 inch) thick by 202 cm (79.5 inch) diameter plate will be installed over the entire lid. These two plates provide the necessary puncture resistance to maintain the containment boundary for this HAC.

With this approach, temperature monitoring will end at the end of the storage period. While the collection of temperature measurements over the approximate 10 year storage period should provide sufficient information as to the thermal behavior of the fuel, it is desired to be able to continue temperature monitoring after the cask is received at the examination facility. Several possible options will be evaluated in future work. One option is to cut the cable as in the existing approach and then reconnect the thermocouple cable by splicing connections between the remaining cable with a new cable. The likelihood of being able to reconnect the thermocouple cable is not known and needs to be investigated and proven before pursuing this option. Another option is to not cut the existing cable, but coil the cable up and store it under a larger plate installed over the existing lid. However the size of larger plate needed for the structural capacity to maintain containment through the HAC may not be compatible with the existing impact limiter design. Another option is to demonstrate compliance using alternative environmental and test conditions, or a one-time shipment authorization for this special demonstration cask. This would allow using the existing storage configuration for transport, with no other changes other than installation of impact limiters. Finally, the thermocouples could be still abandoned in place as in the current approach, but replaced with new thermocouples installed in the cask while in the hot cell after the cask is opened and the fuel examined.

It is important to ensure any changes observed in the cladding properties are from the loading and storage process and not caused by an inadvertent change in the cask internal conditions. Hence the initial loading needed to account for the transportation conditions to avoid having to open the cask, or replace any components related to the confinement as this has the potential to alter the cask cavity environment from its as loaded storage condition. For this reason, additional considerations had to be made for the lid bolts such that they would be acceptable for transportation. Structural analysis of the free drop condition determined a higher strength bolt material and a reduced lid bolt shank were needed. These changes were included in the fabrication and initial loading configuration. One other important difference is that a transportation cask typically would replace the metallic lid seals and perform a leak rate test to determine the conditions immediately prior to transport. However, replacing the lid seal prior to shipment from North Anna would require re-flooding the cask in the spent fuel pool to remove the lid and replace the seal. Re-flooding the cask and quenching the fuel rods could alter the mechanical properties of the cladding. Therefore, the transportation license will need to verify the condition of the seals based primarily on the initial leak test done at the beginning of the storage period. Additional leak tests to the sensitivity necessary are problematic in the current storage configuration due to trace amounts of residual helium that cannot be fully removed once the interseal space has been filled with helium.

Finally, leak rate testing was not performed on the base material of the containment boundary of the High Burnup Research Project Cask, as specified in ANSI N14.5-2014 [8]. The original fabrication of the TN-32B cask which was used as the starting point for the High Burnup Research Project Cask was completed in 2004. The leak rate testing performed at that time was in accordance with the then current version of the standard, ANSI N14.5-1997 [9]. A key change between the 1997 and 2014 versions of ANSI N14.5 is that the 2014 version revised the requirements in Table 1 to clarify that the requirement to test the entire containment boundary included base material. However, the containment boundary is no longer accessible to perform a leak test in accordance with ANS N14.5-2014 as the construction of the cask includes shrink fitting a gamma shield around the inner containment boundary. To address the issue, a pre-application meeting was held with NRC and the staff suggested performing an evacuated envelope test. Due to the inaccessibility of the entire containment boundary, a best-effort evacuated envelope test was performed. Two penetrations were drilled on opposite sides to access the space between the inner shell (containment boundary) and the outer shield shell just below the shield shell flange. While these penetrations provided access to the outer surface of the containment boundary, it is not known how much of the surface may have been obstructed and not in communication with the access penetrations due to the shrink fit of the shield shell onto the inner shell. The results of the evacuated envelope test met the leaktight acceptance criteria, but the vessel cannot be declared leaktight due to the best effort nature of the test. While the leak testing of the High Burnup Research Project Cask is not in full compliance with ANSI N14.5-2014 [8], the results of the best effort test will be provided as a basis for demonstrating the cask meets the release limit criteria.

The remaining calculations to support an application for a transportation license, including preparing the Safety Analysis Report (SAR) will be completed and submitted to NRC for review. The transportation license application will include the factors discussed above that are unique to the High Burnup Research Project Cask. Assuming the transportation license is approved by NRC, additional transportation ancillary equipment will need to be fabricated (shipping skid, conveyance, impact limiters). The destination will need to be identified, a transportation and security plan will be developed and the necessary arrangements for shipment of spent nuclear fuel will be executed.

Once all the necessary conditions and plans for transportation are completed, the cask will be prepared for shipment. The data loggers will be disconnected and the High Burnup Research Project Cask will be transported from the ISFSI to the fuel building and placed in the decon bay. A final gas sample will be collected for analysis. Using the current approach, the thermocouple cables and overpressure monitoring tubing will be cut and plates will be welded over the penetration sleeve opening. An additional lid will be placed over the main lid. The cask will be placed on the shipping conveyance and the impact limiters installed. Once all the ancillary shipping equipment is installed, the cask will be moved to the North Anna gate, title and custody will be transferred to DOE and the cask will be shipped to the fuel examination facility, which has yet to be determined.

## 6. SUMMARY

To validate the technical basis for dry storage of high burnup fuel, and to provide data for extended storage and transportation of high burnup fuel, DOE, EPRI, Dominion Energy, Orano and Framatome have begun a large scale, long term, dry storage cask research and development project. Dominion Energy successfully loaded the High Burnup Research Project Cask in November 2017 at their North Anna Power Station, and began data collection. The project is already yielding important results. Through thermal modeling, confirmed by measurements, it has been discovered that high burnup 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. To support opening the cask and examining the fuel after about 10 years of storage, the cask will need to be shipped to an examination facility with a large hot cell. An application for a transportation license that addresses the unique aspects of the High Burnup Research Project Cask will be prepared and submitted to NRC. Design and fabrication of the transportation ancillary equipment will need to be completed. Once the examination facility is identified, and assuming the transportation license is approved, the cask will be brought back into the fuel building and prepared for shipment. The cask will be loaded onto the conveyance and shipped to the examination facility where the cask will be opened and the same suite of examinations for pre-characterization of the sister rods will be performed on the rods after about 10 years of storage to quantify the effect of loading, storage and transportation on high burnup fuel. 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 high burnup fuel.

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