Preliminary Test Design and Plan for a Canister Deposition Field Demonstration

Spent Fuel and Waste Disposition

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ABSTRACT

This report provides a high-level test plan for deploying three commercial 32PTH2 spent nuclear fuel (SNF) canisters inside NUHOMS Advanced Horizontal Storage Modules (AHSM) from Orano (formerly Transnuclear Inc.). The details contained in this report represent the best designs and approaches explored for testing as of this publication. Given the rapidly developing nature of this test program, some of these plans may change to accommodate new objectives or adapt in response to conflicting requirements.

The goal of the testing is to collect highly defensible and detailed surface deposition measurements from the surface of dry storage systems in a marine coastal environment to guide chloride-induced stress corrosion crack (CISCC) research. To facilitate surface sampling, the otherwise highly prototypic dry storage systems will not contain SNF but rather will be electrically heated to mimic the thermal-hydraulic environment. Instrumentation throughout the canister, storage module, and environment will provide an extensive amount of information for the use of model validation. Manual sampling over a comprehensive portion of the canister surface at regular time intervals will offer a high-fidelity quantification of the conditions experienced in a harsh yet realistic environment.

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ACKNOWLEDGEMENTS

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ACRONYMS

AHSM	Advanced Horizontal Storage Module
CFD	computational fluid dynamics
DAQ	data acquisition
DCSS	dry cask storage system
DOE	US Department of Energy
DSC	dry shielded canister
FCRD	Fuel Cycle Research and Development
FY	fiscal year
HLZC	heat load zone configuration
HSM	Horizontal Storage Modules
ISFSI	independent spent fuel storage installation
NE	Office of Nuclear Energy
PNNL	Pacific Northwest National Laboratory
PTB	power test board
PWR	pressurized water reactor
RMS	root mean square
SCC	stress corrosion crack
SCR	silicon controlled rectifier
SFWD	Spent Fuel and Waste Disposition
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TC	thermocouple
UFSAR	Updated Final Safety Analysis Report

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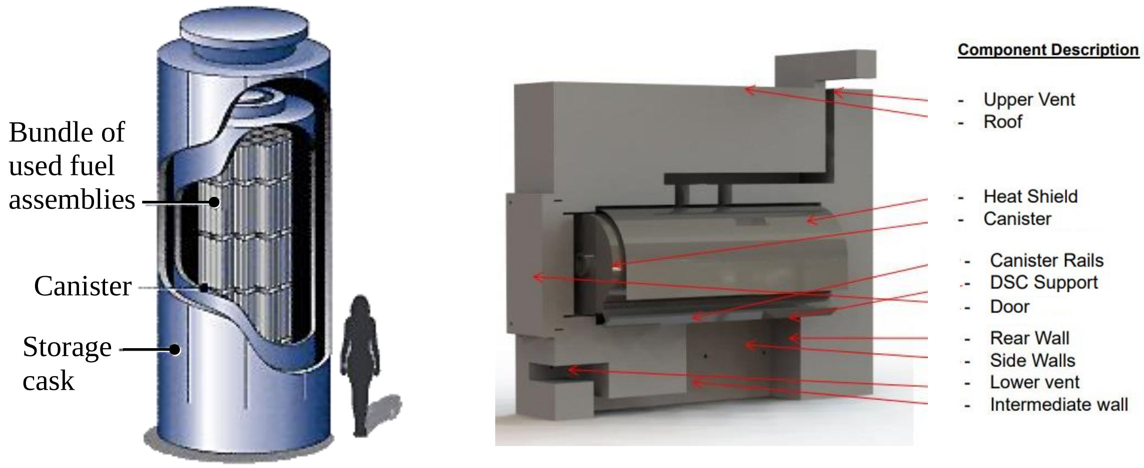
PRELIMINARY TEST DESIGN AND PLAN FOR A CANISTER DEPOSITION FIELD DEMONSTRATION

This report fulfills milestone M3SF-21SN010208032 in the Canister Deposition Field Demonstration work package (SF-21SN01020803). This work was sponsored under the Department of Energy's (DOE) Office of Nuclear Energy (NE) Spent Fuel and Waste Disposition (SFWD) campaign.

1 INTRODUCTION

Dry cask storage systems (DCSSs) for spent nuclear fuel (SNF) are designed to provide a confinement barrier that prevents the release of radioactive material, maintain SNF in an inert environment, provide radiation shielding, and maintain subcriticality conditions. SNF is initially stored in pools of water for cooling where the water also provides radiation shielding. As these pools get closer to capacity, dry storage systems are becoming the primary means of extended storage. After sufficient cooling in pools, SNF is loaded into a canister and placed inside a storage cask, where the canister is welded shut. The DCSS is then decontaminated and dried, and the system is moved to an on-site dry storage location. Figure 1.1 shows the major components of typical vertical and horizontal dry storage cask systems for SNF.



Source: https://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html

Source: https://twitter.com/Orano_usa/status/1174384799181692930/photo/1

Figure 1.1 Typical dry cask storage systems, vertical on left, horizontal on right.

Typically, the canisters are made of stainless steel. The dry storage system is designed with an open volume between the canister and the storage cask or vault. Rejection of the decay heat is accomplished by air flowing from air inlets at the bottom to outlets at the top via natural convection. This passively cooled design also allows dust from the environment into the system. These particulates may then collect on the surfaces of the canister. As the SNF cools, salts contained in the dust may deliquesce in the presence of moisture from the ambient relative humidity to form concentrated brines, which may contain corrosive species such as chlorides. These species can cause localized corrosion, called pitting. With sufficient stresses, these pits can evolve into stress corrosion cracks (SCCs), which could penetrate through the canister wall and allow communication from the interior of the canister to the external environment [Schindelholz, 2017].

1.1 Objective

The objective of the study described in this high-level test plan is to measure the deposition of corrosive species (chloride salts) from marine coastal ambient air onto prototypic spent nuclear fuel (SNF) dry canister storage systems (DCSSs). To facilitate surface sampling, the otherwise highly prototypic DCSS will not contain SNF but rather will be electrically heated to mimic the prototypic thermal environment.

The study will include three identical DCSSs. One system will represent a canister loaded with roughly the maximum allowed heat load, another will represent a canister loaded with one quarter of the maximum heat load, and the third canister will be used as an unheated control.

DOE NE-8 is making available three Orano (formerly Transnuclear Inc.) NUHOMS Advanced Horizontal Storage Module (AHSM) and 32PTH2 dry shielded canisters (DSCs) for use in the study (illustrated in Figure 1.2). The three canisters were delivered to Sandia on November 13, 2020. Figure 1.3 shows a photograph of the three canisters staged in the high bay of Sandia's Building 6630 where they will be fitted with electrical heaters and instrumented with thermocouples. The component weights for the 32PTH2 spent fuel canister are provided in Table 1.1. Discussions are ongoing to locate a suitable facility to host this long-term deposition study. An independent spent fuel storage installation (ISFSI) near a marine coastal environment would be ideal to provide harsh yet realistic conditions.

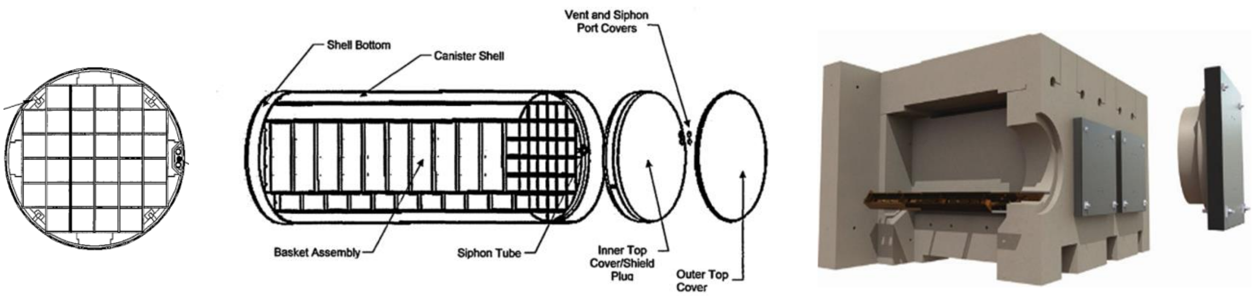


Figure 1.2 32PTH2 spent fuel canister (end view – left, side view – center) and NUHOMS Advanced Horizontal Storage Modules (AHSM – right).

Figure 1.3 Three 32PTH2 spent fuel canisters inside of Sandia's Building 6630 south high bay.

Table 1.1 32PTH2 spent fuel canister component weights [Transnuclear, 2017].

Component	Nominal Weight	
	Pounds	Kilograms
Canister shell	6,060	2,749
Outer top cover plate	2,140	971
Inner top cover plate	2,150	975
Top shield plug and support ring	6,430	2,917
Bottom end assembly	7,200	3,266
Grapple ring	75	34
Total canister assembly	**24,055**	**10,911**
Fuel compartments (32)	11,090	5,030
Aluminum/poison plates	4,920	2,232
Stainless steel plates	2,360	1,070
Small support rails	3,260	1,479
Large support rails	9,370	4,250
Total Fuel Basket	**31,000**	**14,061**
Basket Fuel spacer	1,460	662
Total Empty DSC (Basket and Canister)	56,515	25,635
Fuel assembly weight (32) @ 1610 lb/assembly	51,520	23,369
Total loaded DSC weight	**108,035**	**49,004**

The three canisters will be designed to simulate three decay heats.

1. 0 kW decay heat for control. Canister will be loaded with heater assemblies and insulation to perform as a backup if other systems fail. The control canister should be most susceptible to deliquescence due to having the coolest surface temperatures.
2. 10 kW decay heat to represent canisters that have been stored for a while and more susceptible to deliquescence than the higher-powered canister because of cooler surface temperatures.
3. 40 kW decay heat to represent a freshly loaded system with short cooled fuel. The decay heat will be decreased at various intervals to determine how concentration, composition, and location of deposits vary with decay heat and associated air flow velocities and patterns.

After some period of time, to be determined based on a combination of modeling and sampling at the host location, the canisters will be inspected for salt composition and concentration at various locations on the canister.

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2 APPARATUS AND PROCEDURES

2.1 32PTH2 Canister and Advanced Horizontal Storage Module

The 32PTH2 canisters were selected for testing based on availability and suitability. These canisters were made available to the national laboratories by DOE for research purposes. While the 32PTH2 is not the latest generation of canister designs, the technology contained in this system is representative of the domestic fleet of DCSSs, especially for horizontal storage.

2.1.1 Modifications

Modifications to certain components will be necessary to accommodate testing. Specifically, the canister lids and support ring will need to be altered for testing purposes. These modifications primarily include mechanically mounting the inner lid to the support ring and excluding the shield plug and outer lid. Pass throughs for power, instrumentation, and the lifting lugs will also need to be considered. In addition, modifications to the AHSM will be needed. Insulative walls on the sides and rear of the AHSM will provide better boundary conditions for modeling and prevent the different powered canisters from influencing their neighbors. A rear hatch cut into the AHSM is also needed for cable management.

2.1.1.1 Lid Modification

The electric heaters that simulate the decay heat of spent fuel and the internal temperature sensors that monitor the thermal response will require penetrations in the top canister lid for signal and power wiring. Figure 2.1 illustrates some details of the top shield plug assembly. The shield plug is nominally 14 cm (5.5 in.) thick, weighs about 2,900 kg (6,380 lbs.) and rests on a support ring welded to the inside circumference of the canister. Both the inner and outer top cover plates, or lids, are nominally 5 cm (2 in.) thick and weigh about 1,000 kg (2,200 lbs). In prototypic commercial application, both the inner and outer top cover plates are welded in place to produce a redundant hermetic seal. For the present testing purposes, the top shield plug is not required because the heat source is not radioactive.

The inner top cover plate will be mounted to the shield plug support ring and will serve as the only cover installed. Additional mounts to the support ring may be needed to secure the inner lid. The outer top cover will also not be used. The recessed spaced obtained by locating the inner cover on the shield plug support ring will allow approximately 10 cm (4 in.) of space below the top plane of the canister for junction boxes required for temperature sensor and heater power connections. This design feature ensures the junction boxes will not interfere with the canister installation into the AHSM.

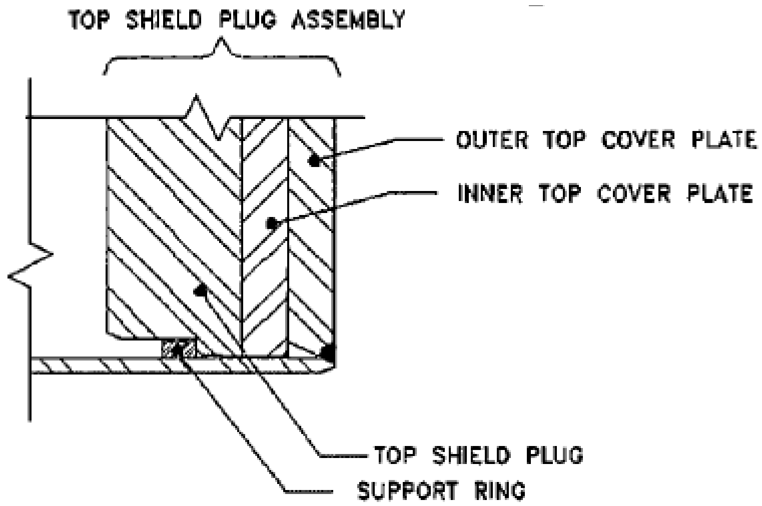

Figure 2.1 Detail of the top shield plug assembly for the 32PTH2 canister. Adapted from Figure B.3.1-1 [Transnuclear, 2016]

2.1.1.2 AHSM modification

The concrete AHSM vault will also be modified to accommodate the testing. Some of the modifications are illustrated in Figure 2.2 and Figure 2.3. A rear hatch will be cut in the back wall of the vault to gain access to the junction boxes recessed into the top of the canister. Internal and external temperature sensor and heater power wiring will exit the vault through this access opening. Temperature sensitive thermocouple (TC) junctions will be made in a junction box outside the vault (see black and white junction box in Figure 2.2). In preparation for canister extraction, the connections going from the junction boxes to the data acquisition and heater power will be disconnected. The TC junction box is then moved from outside the vault to inside the canister next to the heater power junction box as illustrated in Figure 2.3.

Additional modifications will be made to the three AHSMs when they are installed. The envisioned modifications would place a 5 to 10 cm thick layer of appropriate ridged foam insulation into the center of the interior and exterior walls to produce a thermal break between adjacent vaults and the outside environment. The thermal break between adjacent vaults is of particular importance to keep the high-powered test from influencing the adjacent lower powered tests.

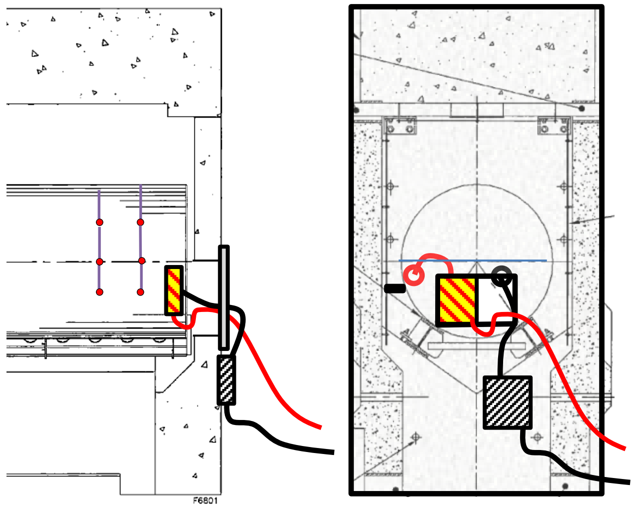

Figure 2.2 AHSM vault modifications (operation mode).

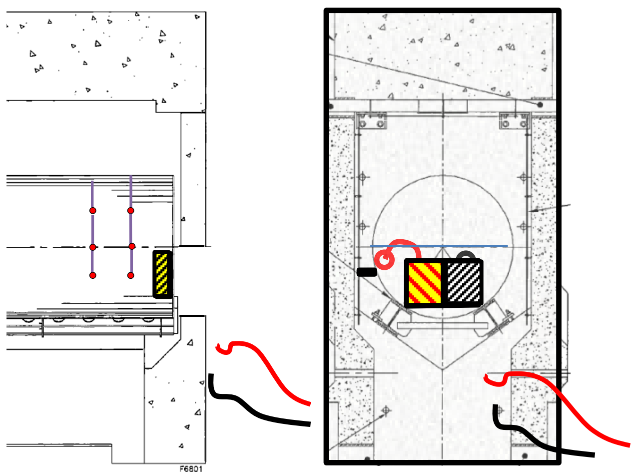

Figure 2.3 AHSM vault modifications (configuration for extraction).

2.1.2 Insertion and Extraction Operations

Depending on the available facilities at the host site, a means for inserting and extracting the canister will need to be devised. The top and bottom lids may need to be designed and rated for the loads of pushing or pulling the canister. As of this writing, option 2 listed below is being explored in further detail and is the preferred choice.

1. Pull the canister out onto a bier, raised track or roller system (aligned with the rails in the AHSM), pulled back via the rear access panel
    a. Versa-Lift
    b. Winch
    c. Crane/pulley
2. Pull/push with modified transfer cask system that provides as much access to the entire canister outer surface as possible (e.g. eliminate the transfer cask)
    a. Rollers on custom trailer frame

b. Rollers instead of rails in AHSM

2.2 Simulated Decay Heat

2.2.1 Power Control

In order to achieve a surface temperature distribution that accurately represents an analogous commercially loaded canister, the power loading pattern of the electric heaters will closely follow the power loading of spent fuel in the commercial canister. The 32PTH2 DSC is designed to store up to 32 fuel assemblies in the four arrangements shown in Figure 2.4. There are three distinct assembly power zones identified. Heat Load Zone Configuration (HLZC) #1 will be scaled to a total power of 10 kW or 40 kW. The heaters will be powered to mimic this loading pattern using Control Concepts Microfusion silicon-controlled rectifiers (SCRs). The total power delivered to each zone will be independently measured using Ohio Semitronics Power Test Boards (PTBs), which provide high-accuracy true RMS measurements for voltage, current, power, and power factor and are specifically designed to accommodate distorted and chopped waveforms typical of SCRs. Electrical power will be supplied using a 112.5 KVA, 480 V 3Ø → 208 V 3Ø, GE Guard II noise isolation transformer for clean power with demonstrated 120 dB common mode noise rejection and 60 dB transverse mode noise rejection. Similar power control systems have been used in previous studies with excellent results [Durbin and Lindgren, 2018; Pulido *et al.*, 2020].

	Zone 3	Zone 3	Zone 3	Zone 3	
Zone 3	Zone 2	Zone 2	Zone 2	Zone 2	Zone 3
Zone 3	Zone 2	Zone 1	Zone 1	Zone 2	Zone 3
Zone 3	Zone 2	Zone 1	Zone 1	Zone 2	Zone 3
Zone 3	Zone 2	Zone 2	Zone 2	Zone 2	Zone 3
	Zone 3	Zone 3	Zone 3	Zone 3	

Number of Fuel Assemblies	4	12	16	
	Zone 1	Zone 2(2)	Zone 3(1)	
HLZC #	Maximum Decay Heat/Fuel Assembly(3), [kW]	Maximum Decay Heat/Fuel Assembly(3), [kW]	Maximum Decay Heat/Fuel Assembly(3), [kW]	Maximum Decay Heat/DSC, [kW]
1	0.8	1.5	1.0	37.2
2	0.9	1.3	1.0	35.2
3	1.0	1.0	1.0	32.0
4	0.8	1.0	1.0	31.2

Notes:

(1) Damaged fuel assemblies, up to 16 damaged (balance intact), shall be placed in Zone 3 only.

(2) Zone 2 is for placement of up to 8 reconstituted fuel assemblies with irradiated stainless steel rods when stored in the Option 1 configuration (the four corner locations of Zone 2 are not allowed for storage of such assemblies). The Option 2 configuration for storage of up to 32 reconstituted fuel assemblies with irradiated stainless steel rods does not have any restriction on placement of fuel assemblies within the DSC. Option 1 and Option 2 are defined in Table B.2.1-1.

(3) Decay heat per fuel assembly shall be determined per Table B.2.1-7.

Figure 2.4 Heat Load Zone Configuration (HLZC) for the 32PTH2 DCS. From Figure B.2.1-1 [Transnuclear, 2016].

A power/instrumentation skid will provide a protected enclosure for power control, instrumentation interfaces, and data acquisition (DAQ). This unit is comprised of an insulated steel storage container (Width × Depth × Height = 8 × 10 × 8.5 ft.) with a top-mounted HVAC unit for climate control. To accommodate clearance and cable management, the final footprint on the ISFSI pad of the power/instrumentation skid is expected to be 10 × 15 ft. The primary power service requirements are estimated to be a total of 80 kW, which allows for continuous use of 50 kW for simulated decay heats (40 and 10 kW) and 15 kW for HVAC and instrumentation. This load represents 81% of the service capacity.

The data acquisition (DAQ) system will be built for reliability and flexibility. A National Instruments PXI-e chassis is the leading candidate for scalable performance. Up to 608 total TCs are currently planned with 192 TCs per system (96 internal and 96 external including the AHSM) and 32 TCs for ambient and component temperatures.

2.2.2 Target Surface Temperatures

The objective of this field demonstration is to deploy an electric heater system that reproduces the surface temperature distribution obtained from an analogously loaded 32PTH2 spent fuel canister. The targeted surface temperatures were calculated via detailed computational fluid dynamics (CFD) modeling using STAR-CCM+ for the 10 kW and 40 kW cases. A summary of the results is presented in Table 2.1. The surface temperature profiles are shown in Figure 2.5 for the 40 kW case and in Figure 2.6 for 10 kW case.

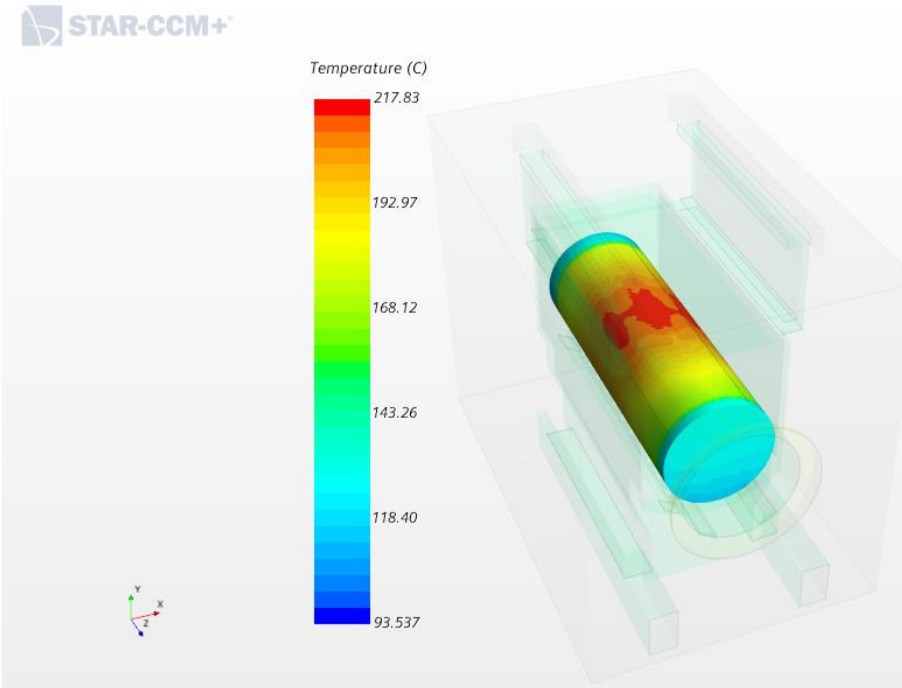

Figure 2.5 Surface temperature distribution of a 32PTH2 canister uniformly loaded with 40 kW of spent fuel.

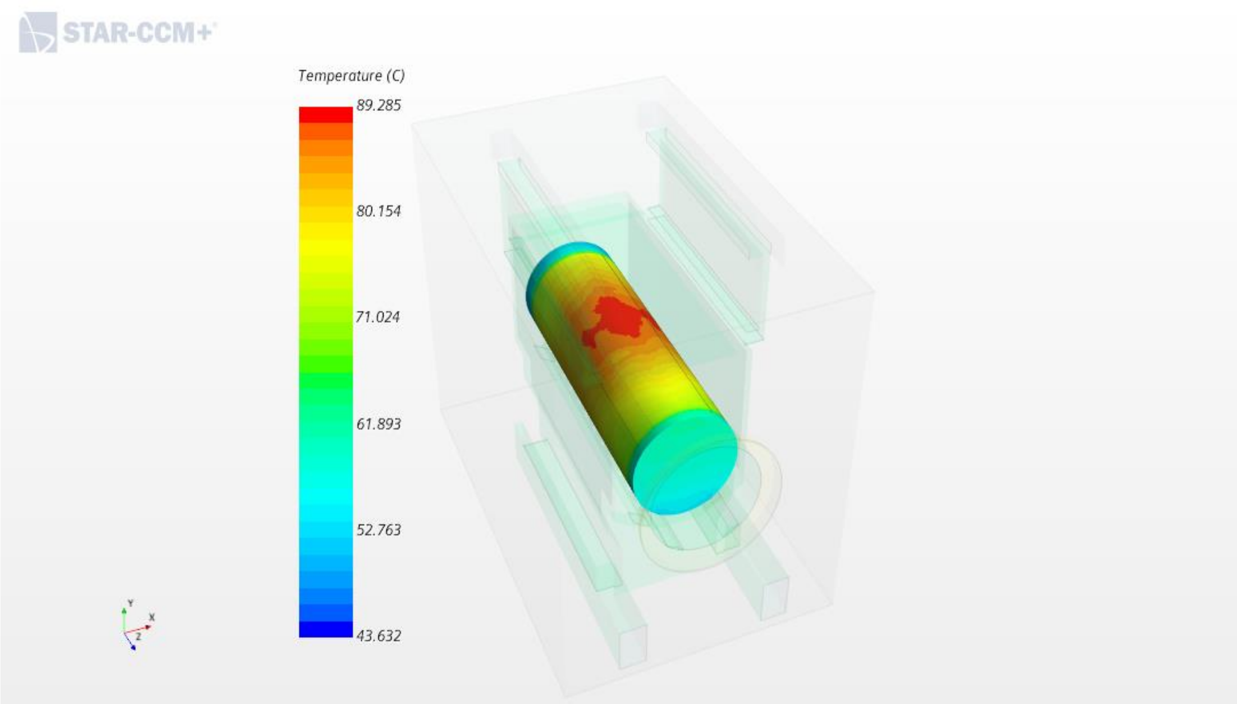

Figure 2.6 Surface temperature distribution of a 32PTH2 canister uniformly loaded with 10 kW of spent fuel.

Table 2.1 Calculated 32PTH2 spent fuel canister surface temperatures.

Model	32PTH2 Porous Media	32PTH2 Porous Media
Canister Fluid	Helium	Helium
Heat Load [kW]	10	40
Avg. Shell Canister Temp. [°C]	75	181
Max. Shell Canister Temp. [°C]	89	218
Min. Shell Canister Temp. [°C]	44	94
Standard Deviation Shell Canister Temp. [°C]	13	40
Avg. Top Lid Temp. [°C]	50	114
Max. Top Lid Temp. [°C]	53	124
Min. Top Lid Temp. [°C]	44	95
Standard Deviation Top Lid Temp. [°C]	2	6
Avg Bottom Canister Temp. [°C]	59	127
Max Bottom Canister Temp. [°C]	65	144
Min Bottom Canister Temp. [°C]	51	110
Standard Deviation Bottom Canister Temp. [°C]	7	25

2.2.1 Heater Design

The heater design is currently under design and development. Two candidate heater designs are presently under consideration. Each has advantages and drawbacks. The goalpost radiative style heater shown in Figure 2.7 will cost less to manufacture and have much more symmetric heat transfer into the fuel compartment but will operate at significantly higher temperatures, which could be a concern for reliability over long test periods. The more conductive open platen style heater shown in Figure 2.8 should offer overall lower heater temperatures but will cost more to manufacture and will bias heat into each fuel compartment onto the face in which it is in contact.

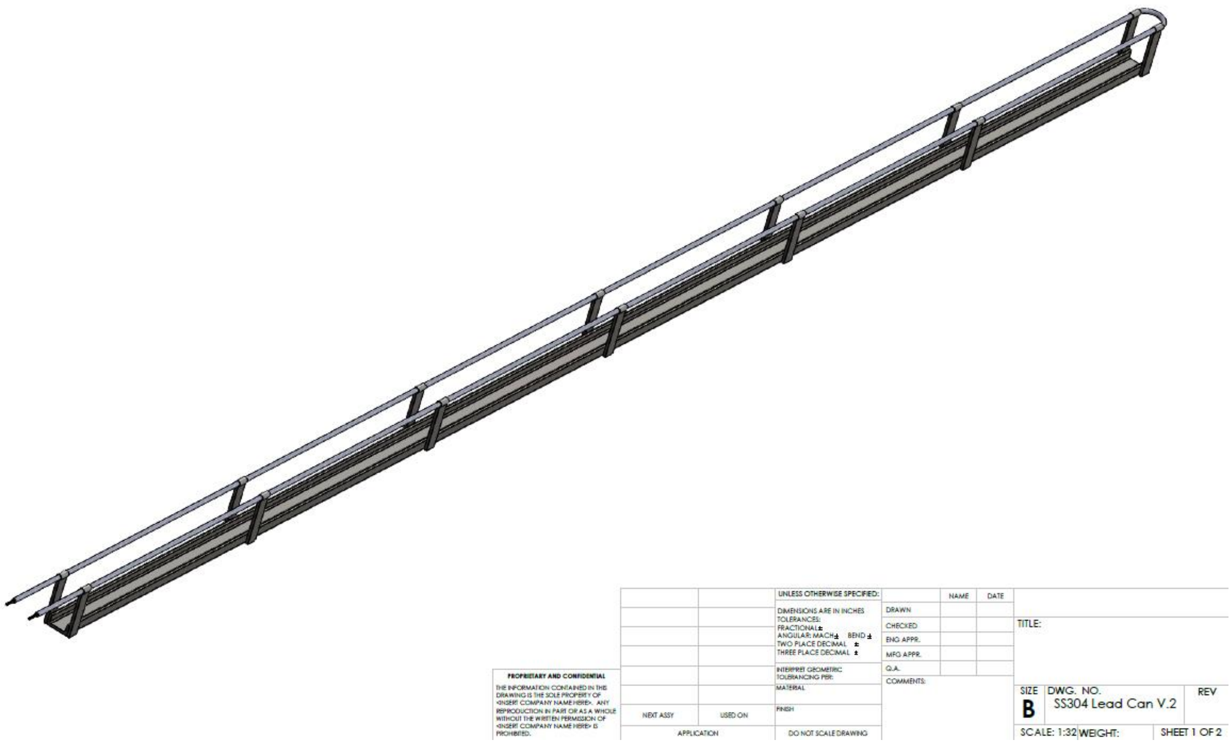

Figure 2.7 Goalpost radiative heater design.

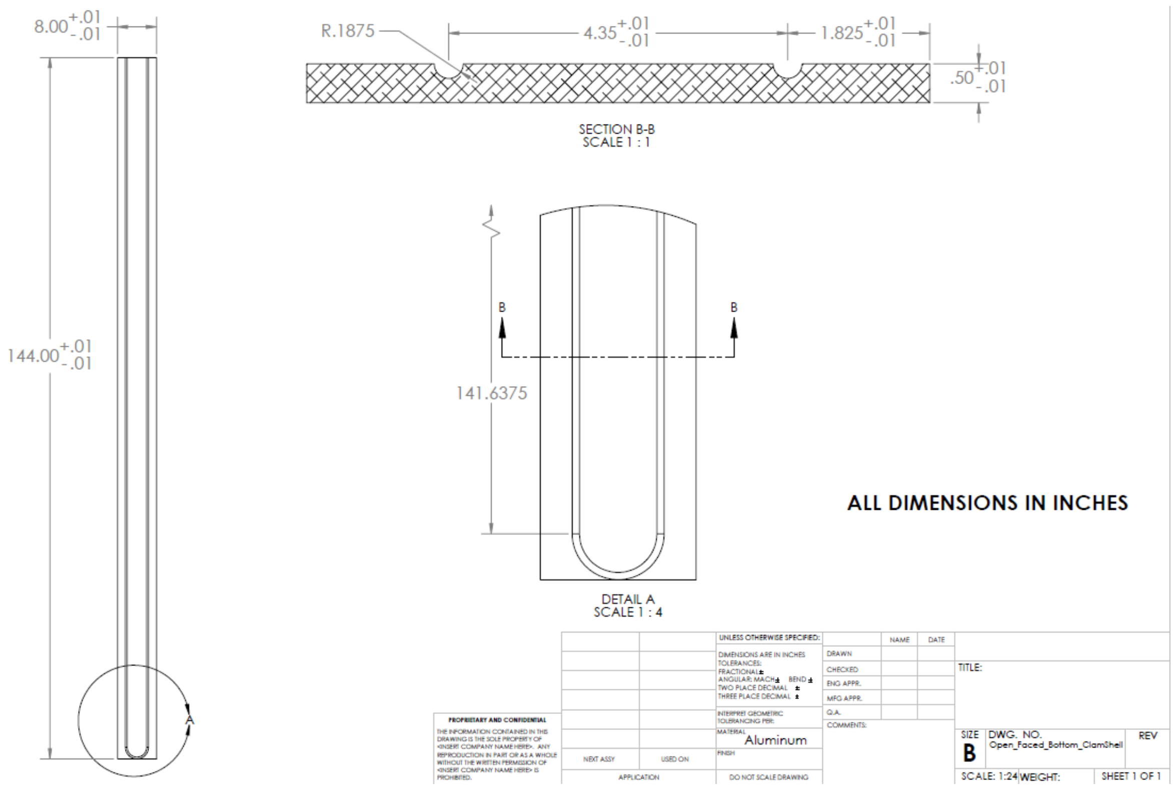

Figure 2.8 Open platen heater design.

2.3 Instrumentation Plan

2.3.1 Internal Measurements

The interior of the basket will be instrumented with 1.0 mm (0.040 in.) type-K TCs. Because the internal surface of the basket is largely inaccessible, the internal TCs will be installed on the heater assembly that is positioned in each of the 32 basket storage cells. The exact number and location of these TCs will not be finalized until the heater assembly design is finalized. At a minimum, two to three TCs will be installed along the length of each heater assembly (with a practical maximum of 96) and exit through penetrations in the inner top cover plate.

2.3.2 External Measurements

The exterior surface of the canister will be instrumented with type-K TCs to provide a minimum of one temperature measurement for each surface sample location as shown in Figure 2.9. An equally important consideration is to make these temperature measurements in a manner that minimizes any flow disturbance of the naturally induced air flow over the canister surface carrying the particulates of interest. In order to minimize air flow disturbance on the surface of the canister, smaller diameter 0.81 mm (0.032 in.) type-K TCs will be used, and the sheaths will be routed just above the canister support rails as shown in Figure 2.10. The TCs will run straight longitudinally along the canister shell and then route perpendicularly along an arc to the location of interest. The TC sheaths will be passed out of the heated zone through the rear hatch in the AHSM. If any TCs and sample locations are located below the canister support rails, the traverse to the junction box at the back of the vault will be just below the support rail. Because the canister support rails already introduce a significant flow obstruction, the addition of a TC chase in the wake of the rails should not add any significant disturbances.

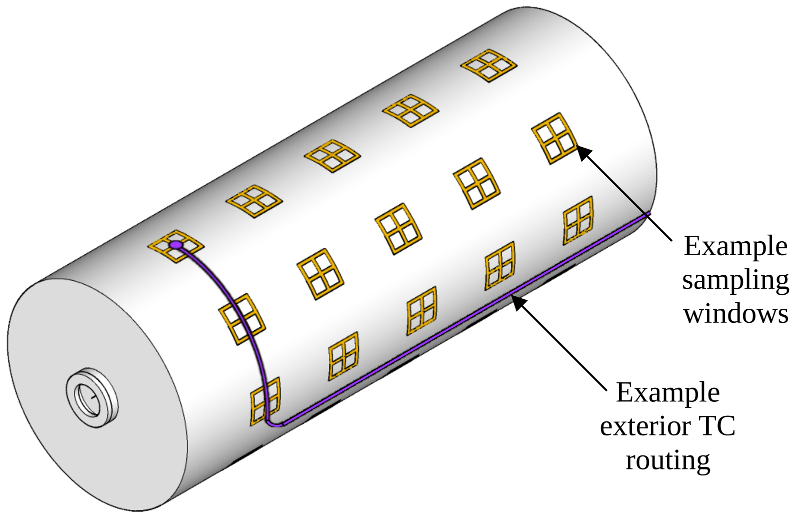

Figure 2.9 Canister exterior TC and sample collection locations.

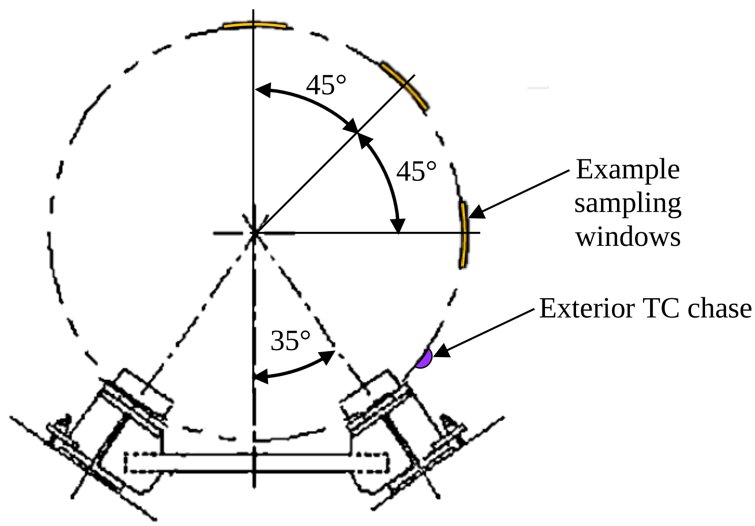

Figure 2.10 End view of the canister and support rails showing example sampling locations. Adapted from Figure B.3.1-7 [Transnuclear, 2016].

The area around each TC location on the exterior of the canister will be sampled on a periodic basis (perhaps yearly) for surface deposits in a regular pattern as envisioned in Figure 2.11. Each of the four colored squares represents a sampling location approximately 10 × 10 cm. The central TC location is indicated by the purple circle in the center. Baseline thermal modeling indicates that a maximum temperature difference of 10 °C can exist between the extremes (corners) of the sample windows. The sampling locations may be utilized in sequential order of sampling events. The sample square labeled “A” could be utilized in the first sampling event. The sample square labeled “B” could then be utilized in the second sampling event, and so on. The four sibling locations around the TC should provide comparable results due to close proximity. The other squares previously sampled may be resampled to provide differential deposition measurements.

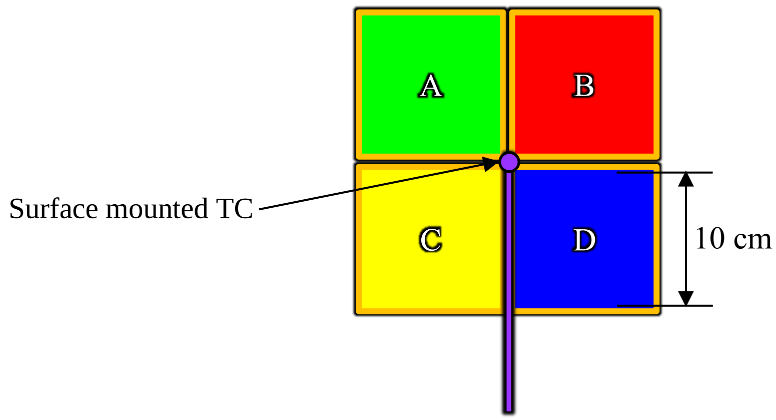

Figure 2.11 Surface deposition sampling pattern.

2.4 Atmospheric Monitoring

Ambient monitoring will be conducted on or near the storage vaults. Continuous monitoring will include typical weather station parameters such as air temperature, absolute ambient pressure, wind speed and direction, humidity, and precipitation. Additionally, particulate matter (PM) sensors will be used to continuously monitor various size ranges of aerosols in the air. Deposition models require the particle composition and density (mass per m^3 air), as well as size distribution, for inputs. Periodically, on-site aerosol sampling will be conducted to characterize these parameters.

3 SUMMARY

This report provides a high-level test plan for evaluating three commercial Orano 32PTH2 spent fuel canisters housed in NUHOMS AHSMs. The goal of the testing is to collect highly defensible and detailed surface deposition measurements of dry storage system in a marine coastal environment to guide CISCC research. To facilitate surface sampling, the otherwise highly prototypic DCSS will not contain SNF but rather will be electrically heated to mimic the prototypic thermal environment.

Three testing attributes are required to meet project objectives.

1. Marine coastal environment to provide limiting conditions for CISCC research.
    a. Hosted at or near an actual nuclear power plant or ISFSI.
    b. Simulation of marine conditions at site of convenience is backup plan.
2. Modified prototypic components to facilitate testing yet maintain full-scale physics.
    a. Electrical heating of 32PTH2 canisters at 0, 10, and 40 kW (0, 27, and 108% of design, respectively).
    b. Insulated AHSMs with rear entry hatch.
        i. Insulated side and rear walls to minimize thermal-hydraulic influence on neighboring systems and improve modeling boundary conditions.
        ii. Cut through rear wall of AHSM to facilitate cable management.
3. Meticulous and periodic surface sampling.
    a. Unhampered access to canister outside of AHSM provides ideal platform for sample collection that may serve as validation standard for remote collection methods.
    b. Cross correlation with visual and alternative inspection methods possible.

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