Overview of the Hanford Lead Canister – 22340

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ABSTRACT

The Hanford site is preparing to place cesium and strontium material in a dry storage canister system that is similar in design to spent nuclear fuel dry storage systems. The system includes a welded stainless steel canister inside a vertical concrete overpack. As part of the site's aging management plan, a spare canister system will be deployed with heaters inside to accurately simulate the environmental conditions experienced by units containing radioactive material. The heated unit is intended to act as a leading indicator of canister degradation as the nuclear material sits in dry storage for potentially many decades. The Hanford Lead Canister is intended to offer the site an early warning of canister degradation. Regular inspection of the Hanford Lead Canister and data collection is expected to benefit the site by reducing the need for inspections of the canisters containing radioactive material.

A second use of the Hanford Lead Canister is as an accessible facility for research and development efforts related to canisters. The similarity in design and function between the Hanford canisters and spent nuclear fuel canisters makes it an opportunity to collect data that is relevant to spent nuclear fuel storage (such as temperatures, particle deposition rates, etc.) and to demonstrate technologies (such as non-destructive evaluation tools, repair or mitigation processes, etc.) that could assist the long-term storage of spent nuclear fuel.[1]

This paper provides a technical overview of the Hanford Lead Canister, describes the current state of its development, and discusses the plans for long-term operation and data collection. Thermal analysis of the Hanford cesium and strontium canister systems is presented that compares the system to SNF canister dry storage systems. Heater units were designed to simulate the decay heat from the cesium and strontium capsules. Thermal modeling was conducted to ensure the electrical heater units can produce a similar temperature distribution to what is expected within a cesium and strontium capsule storage system. A detailed computational fluid dynamics model of the Hanford Lead Canister was constructed using the commercial software STAR-CCM+. The detailed computational fluid dynamics model included the stainless steel canister within the concrete overpack, and explicitly modeled the parts that make up the heater assembly, including the carrier tube, heater rod tape, and sleeve tube. Temperature results for the Hanford Lead Canister thermal model compares well with the baseline cesium and strontium canister thermal model, with very similar canister temperature profiles between the two models.

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[1] This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This paper reflects technical work which could support future decision-making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Thermal modeling indicates that the heater units provide prototypic canister temperatures.

INTRODUCTION

The Hanford site is preparing to place cesium and strontium material in a dry storage canister system that is similar in design to spent nuclear fuel dry storage systems. NAC International designed the Management of the Cesium and Strontium Capsules (MCSC) system, which includes a welded stainless steel canister inside a vertical concrete overpack. The system is similar in design to NAC's MAGNASTOR SNF storage system, with changes in overall size and canister internal design to accommodate the cesium and strontium capsules.

As part of the Hanford site's aging management plan, a spare MCSC canister system will be deployed with heaters inside to accurately simulate the environmental conditions experienced by units containing radioactive material. The electrically heated Hanford Lead Canister (HLC) is intended to act as a leading indicator of canister degradation as the nuclear material sits in dry storage for potentially many decades. The HLC is intended to offer the site an early warning of canister degradation, with the ability to detect such signs as pitting or discoloration. Regular inspection of the HLC and data collection is expected to benefit the site by reducing the need for inspections of the canisters containing radioactive material.

A second use of the HLC is as an accessible facility for R&D efforts related to canisters. The similarity in design and function between the Hanford canisters and SNF canisters makes it an opportunity to collect data that is relevant to SNF storage (such as temperatures, particle deposition rates, etc.) and to demonstrate technologies (such as non-destructive evaluation tools, repair or mitigation processes, etc.) that could assist the long-term storage of SNF.

This paper provides a technical overview of the HLC, describes the current state of its heater and control system development, and discusses the plans for long-term operation and data collection.

BACKGROUND

The HLC is a canister storage system that will contain heaters to simulate the decay heat of nuclear material and provide the canister storage system with an environmental condition equivalent to the operating units on the dry storage pad. The HLC will be equipped with long-term data collection and monitoring to provide an early warning of corrosion, pitting, cracking, or other signs of canister degradation that might threaten the integrity of the containment boundary over the potentially long term of dry storage. The concept is illustrated in **Error! Reference source not found.**. PNNL is providing the technical leadership to develop and implement the HLC, in close collaboration with the associated Hanford contractor. The technical collaboration also includes participation from the EPRI and the cask system vendor, NAC. PNNL is the point of contact for coordinating the use of the HLC within the dry storage community for the R&D activities noted above (in the introduction) and mentioned throughout the paper.

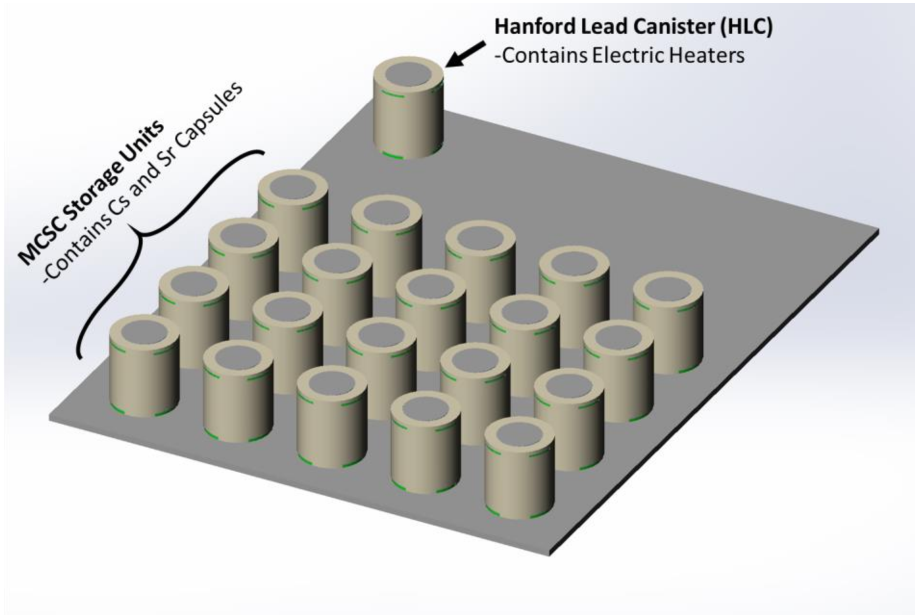

Fig. 1. Hanford Lead Canister Concept Sketch.

Within each MCSC concrete cask system is a welded stainless steel transportable storage canister (TSC) that holds up to 22 cylindrical universal capsule sleeves (UCS) in 11 stacks of 2. Each UCS holds up to 6 capsules containing cesium (Cs) or strontium (Sr) salts. The distribution of nuclear material and the total decay heat of all nuclear material in each capsule and each UCS loadout will be known when the canisters are loaded for dry storage. The HLC heaters will be operated to match the temperature profile of the loaded system with the lowest temperature. The outlet temperatures of all MCSC units will be recorded, so a detailed temperature history will be documented over a long period of time. The heaters have been designed with significantly more heating capability than is anticipated, to help with system longevity. The control system is still being finalized, but it is anticipated that a relatively close match of the actual system temperatures can be achieved with knowledge of the original nuclear material load and the ability to compare to the documented temperature history.

As part of the aging management plan, the HLC will be frequently observed with visual inspections and constant data acquisition. The goal of using the system is to provide a leading indicator function and one of the benefits may be a reduction in the frequency and total number of visual inspections that will be needed over time for the systems containing nuclear material. Another anticipated benefit of the HLC system is an opportunity to advance R&D related to the mitigation and repair of stress corrosion cracks in stainless steel canisters in dry storage applications. As an R&D opportunity, the data coming out of the HLC is expected to be valuable because of its similarity to spent nuclear fuel dry storage systems. Temperature over time, air flow within the system, and the response of the system to natural environmental effects like wind, rain, snow, or other phenomena are all expected to be valuable for informing models and analysis methods. The HLC team is planning to develop a long-term data acquisition plan in the coming year.

Heater Design Summary

The heat generation of the UCS loaded into the TSC will be simulated using electrical heaters. The maximum heat generation for each UCS is 1.13 kW and there are 22 UCSs to be loaded into 11 basket locations within a TSC with two UCSs stacked directly on top of one another per basket location. Therefore, the total maximum heat generation load for the TSC and 22 heater assemblies is 24.8 kW.

The heater system design provides an independently controlled heater assembly to simulate decay heat generation in each 127 cm tall UCS. The outside diameter (OD) of a UCS is 19 cm and the inside diameter (ID) of each basket location is 19.7 cm (dimensions for ambient temperature conditions). Fig. 2 depicts the concept for the system design. Note that the TSC basket locations are circular openings that allow UCSs to be placed within relatively thick and massive aluminum heat sink blocks. This is an important thermal design feature of the MCSC canister storage systems that the HLC heaters are designed to work with.

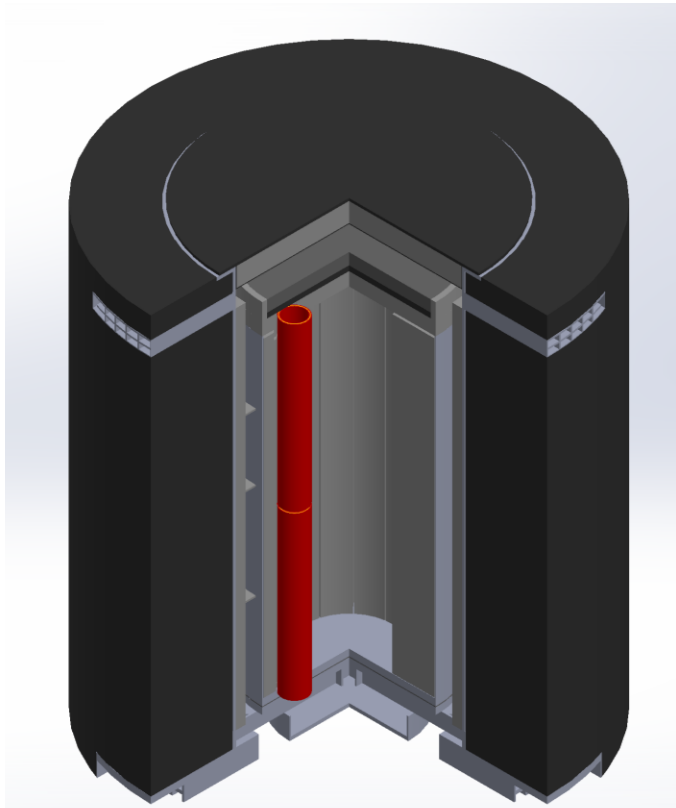

Fig. 2. HLC Heater Concept Sketch. Two Heaters Are Shown In The Canister Where Two UCSs Would Normally Be Located.

Each heater assembly is to provide a uniform heat load over the height of the simulated UCS. For actual payloads, this may not always be the case as the UCS are governed by a maximum thermal load, consisting of up to six capsules loaded into each UCS, and can have capsules loaded with various volumes of salt. Within a UCS, there are three cylindrical ports for loading up to two capsules vertically in each port. Fig. 3A shows the UCS (left) and heater design concept (right). Fig. 3B (left) provides a cross section of two of the capsule ports in a UCS depicting the variation in salt loading (indicated by blue) within each capsule. Fig. 3B (right) shows a section through the heater assembly. Fig. 3C shows the main components of the heater assembly in an exploded view. Heater tape (yellow) is wrapped around an inner carrier tube (red), and those two components slide into an outer sleeve tube (red). The inner carrier tube and outer sleeve tube are both stainless steel. Design details like wiring and lifting hardware are omitted. The heater assembly matches the height and OD of the UCS. Thermal modeling of the UCSs and heater assemblies (discussed in the next section) indicates that the temperatures and spatial differences in the thermal gradients at the outside of a UCS are similar for the slight variations in power density resulting from potential differences in the simulated uniform electrical heat loads and those of variable salt loading in each capsule.

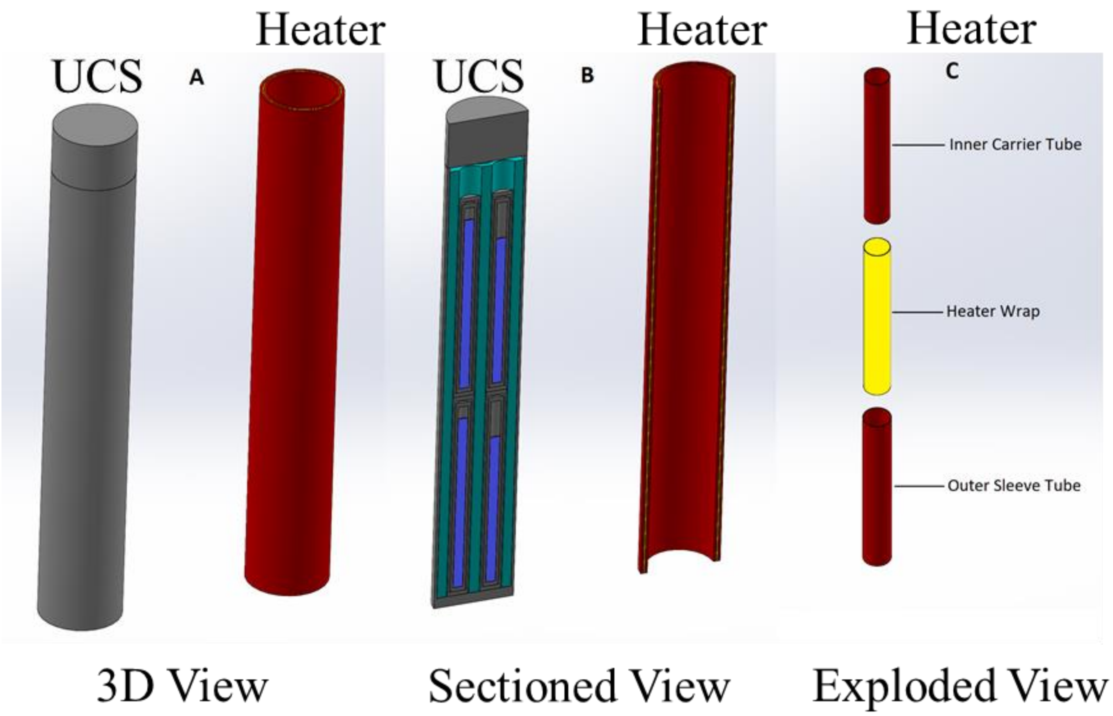

Fig. 3: UCS and Heater Geometry. Exploded View Shows Major Components Of The Heaters As They Are Represented In The Thermal Models. Wires And Other Minor Features Are Omitted.

At the time of this writing, the design of the heater assemblies is being completed and the heaters are expected to be fabricated and delivered in time to start bench scale testing and control system programming in early 2022.

THERMAL ANALYSIS

A detailed computational fluid dynamics (CFD) model of the HLC was constructed using the commercial software STAR-CCM+ [1]. The detailed CFD model explicitly modeled the parts that make up the heater assembly, including the carrier tube, heater rod tape, and sleeve tube.

The geometry for the detailed CFD model was generated using the commercial computer-aided design (CAD) software SolidWorks [2]. The geometry includes a TSC within a ventilated concrete cask. Heater assemblies are contained within the TSC. It is very similar to the MCSC dry storage system, except that the storage capsules have been replaced by heater assemblies. The CAD geometry for the cask and TSC was constructed from drawings and details provided by NAC. The CAD geometry for the heater assemblies was built from information provided by the vendor providing the assemblies, INDEECO.

The CAD geometry of the HLC is shown in Fig. 4. The concrete cask inner cavity and air flow passages are lined with carbon steel plates. The TSC sits on an elevated pedestal above the four air inlets. At the ground level, each of the inlet passages is partially filled with several rows of vertical, cylindrical pins that provide shielding. Radial positioning of the TSC within the concrete cask cavity is maintained by carbon steel standoff supports that extend outward from the concrete cask inner shell. Outlet air passages and vents are included near the top of the concrete cask. Access to the inner cavity for insertion of the TSC is provided by a removable lid.

Within the TSC the heater assemblies are inserted into aluminum structures, referred to as the heat sink blocks, to enhance heat transfer. The TSC of the HLC is assumed to be filled with air.

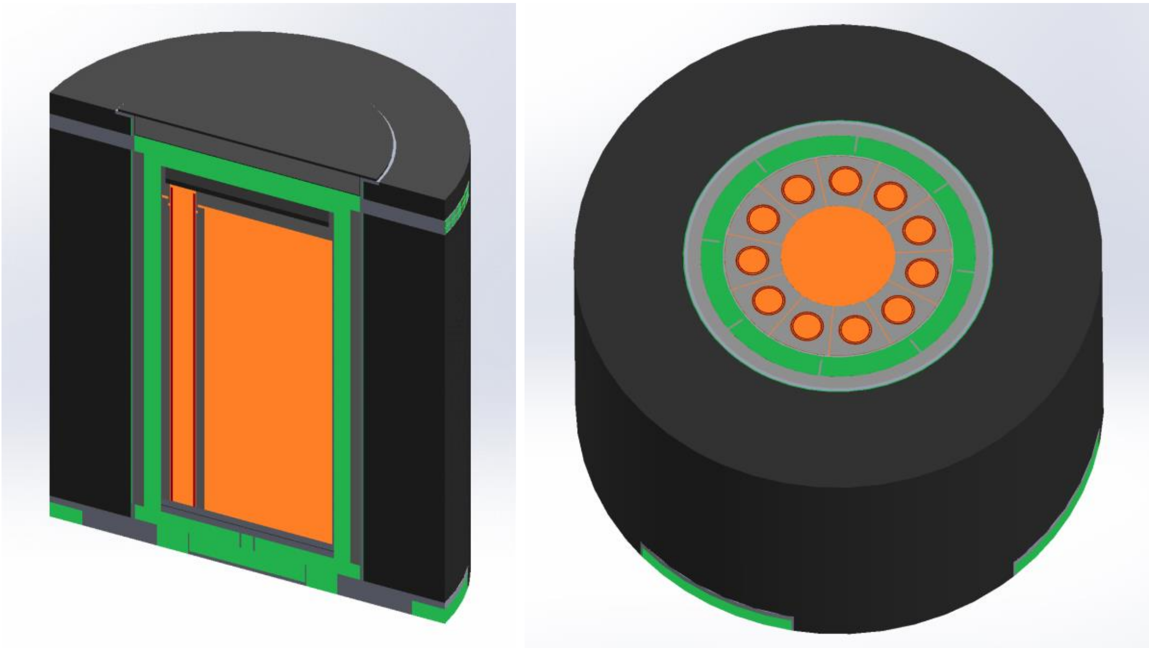

Fig. 4. CAD Geometry For The Hanford Lead Canister Model (a) Axial Cross Section Of Geometry And (b) Radial Cross Section Of Geometry. The External Ventilated Air Is Shown In Green, And The Internal TSC Air Is Shown In Orange.

The heat load was assumed to be uniform across the heater tape. Two different heat loads were considered: a high heat load case of 24.8 kW corresponding to the strontium capsules and a low heat load case of 3.52 kW for the cesium capsule storage. Internal radiation was included in the gas regions and the emissivity values applied along the inner surfaces were taken from similar, previous PNNL cask storage system modeling applications. External convection and radiation were applied along the vertical outer and top horizontal surface of the concrete cask assembly. The external convection coefficients were calculated based on textbook natural convection coefficient correlations [3].

A k-omega shear stress transport (SST) turbulence flow model was applied to the cooling air region where the flow is driven by natural convection. The inlets to the air region were set to stagnation inlets and a pressure outlet was applied to each outlet. Laminar flow was assumed in the internal canister gas region. The Boussinesq model was applied to the laminar flow region that provides a buoyancy source term.

The SolidWorks geometry was imported into STAR-CCM+. The geometry was then meshed into regions connected by interface boundaries, resulting in a single conformal polyhedral volume mesh across all regions. Along each wall/fluid interface, the mesh contains prism cell layers to improve the accuracy of the flow solution near the walls. The prism cell layer consists of orthogonal prismatic cells adjacent to the wall boundaries.

A mesh sensitivity study was performed on the HLC model to ensure that the mesh was sufficiently resolved. The high heat load case (24.8 kW) was used for the sensitivity analysis. Three different resolutions of mesh were generated. The resulting peak TSC outer surface temperature and airflow for the three mesh cases are shown in TABLE I.

The standard deviation of the TSC surface temperature is also shown in TABLE I and this value represents the temperature variation at the surface.

TABLE I. Mesh Sensitivity Results @ 24.8 kW

Model	**Baseline Mesh Size (m)**	**# Cells**	**Max TSC Outer Shell Temperature (C)**	**TSC Outer Shell Temperature Standard Deviation (C)**	**Mass Flow Outlet (kg/s)**
Default	0.7	10831307	237.0	8.5	0.29
Refined	0.6	13580018	235.8	8.6	0.29
Very Refined	0.4	24910986	235.7	9.1	0.30

The results show that all three mesh cases produced similar results, and the maximum TSC surface temperatures were within 2°C of each other. Airflow was within 0.1 kg/s of each other for all three mesh cases. Using these results, an estimate of discretization error can be obtained by determining the Grid Convergence Index (GCI). This parameter is calculated following the approach outlined by Oberkampf and Roy [4]. The GCI is given by

$$GCI = \frac{F_s}{r^p - 1}\left|\frac{f_2 - f_1}{f_1}\right| \quad \text{(Eq. 1)}$$

where

Fs = is the factor of safety, equal to 1.25 for this calculation,
r = the grid refinement factor,
p = the order, which is 2 for these cases,
f = the solution for the cases, with f_1 designating the fine mesh solution and f_2 the solution for the coarse mesh.

The grid refinement ratio can be computed as

$$effective\ r = \left(\frac{N_1}{N_2}\right)^{1/D} \quad \text{(Eq. 2)}$$

where N_1 and N_2 are the total cell count for the fine and course meshes, respectively, and D is the dimensionality of the system. Applying this for the cell counts of the different mesh resolutions and TSC surface temperatures shown in TABLE I yields the two estimates of GCI shown in TABLE II. In the first case, the comparison is between the very refined mesh and the default mesh. The second case compares the very refined mesh and refined mesh solutions. For these two cases, it is prudent to use the larger of the two estimates. So, for a peak TSC surface on the order of 237° C, an estimate of the relative numerical error for the default mesh solution is 0.009338 × 237°C, which is 2.2 °C. Note that the GCI is not a bounding error estimate, rather an indication of the relative error.

TABLE II. Grid Convergence Index

N_1	N_2	f_1	f_2	**GCI**
24910986	10831307	235.7	237.0	0.009338
24910986	13580018	235.7	235.8	0.000909

In summary, the mesh sensitivity test results demonstrate satisfactory predictions for all three mesh cases. The default mesh was used for the model results presented in the rest of this study.

The model was run at both the high heat load, 24.8 kW, and the low heat load, 3.52 kW. An ambient temperature of 26.7°C (80°F) was assumed and solar insulation was applied to external surfaces of the overpack. For the 3.52 kW heat loading only the bottom heater assemblies are active.

Results for the HLC component temperatures and mass flow at the outlets of the ventilated cask are shown in TABLE III.

TABLE III. Hanford Lead Canister Component Temperatures

Heat Load (kW)	Avg TSC Temp (C)	Max TSC Temp (C)	Avg Heater Temp (C)	Max Heater Temp (C)	Mass Flow Outlet (kg/s)
24.8	219	255	367	422	0.29
3.52	76	88	106	142	0.17

The resulting canister temperatures were also compared with those of the MCSC cask at the same heat loads and ambient conditions. Fig. 5 plots canister temperatures for the HLC model compared to the MCSC cask at the same high and low heat loads. The HLC model compares well with the MCSC; canister temperatures between the two models are very similar. This is expected because the two cask systems have the same ventilated cask and TSC geometry. The fill gas within the canister is air for both systems. Fig. 6 shows an axial temperature contour plot for both models at the 3.52 kW heat load.

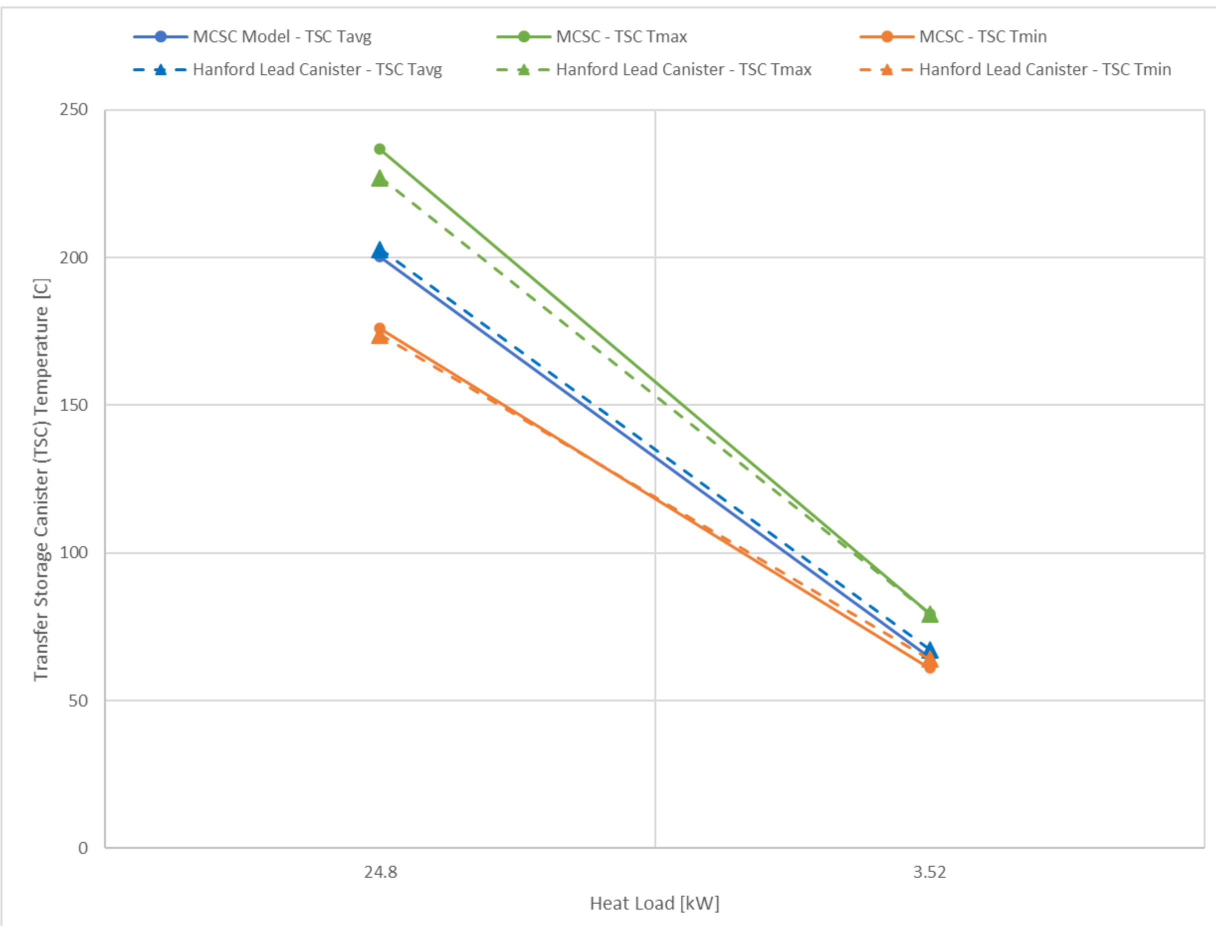

Fig. 5. Comparison Of The MCSC Canister And The Hanford Lead Canister.

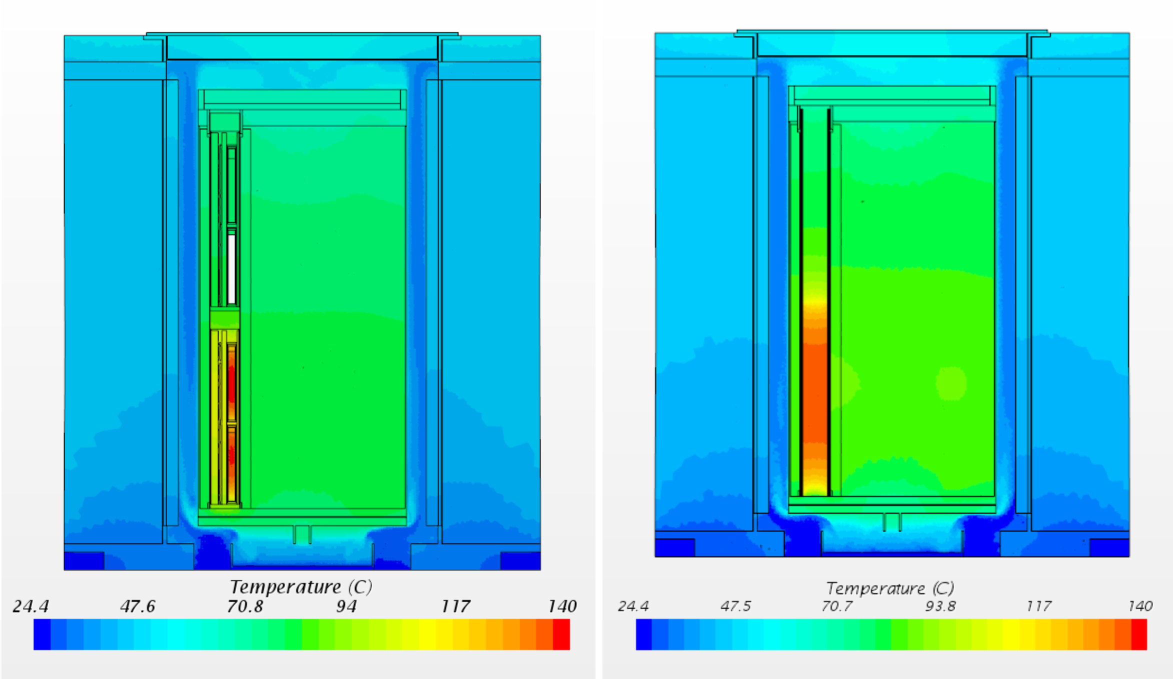

Fig. 6. Axial Temperature Contour Plot Through The Center Of The Cask Assembly Of The (a) MCSC Model And (b) Hanford Lead Canister Model.

The HLC was run at a series of different heat loads to compare canister temperatures with those of a ventilated SNF storage cask, the MAGNASTOR system, over its storage lifetime. The MAGNASTOR model is described by Fort et al. (2016) [5]. Fig. 7 plots the storage canister temperatures over the years in storage. The HLC model has higher canister temperatures but the same temperature trend over its storage lifetime as the SNF model. It is important to note that the ventilated cask geometry is different between the two models. The canister fill gas and pressurization were also different between the two models. These differences account for the higher canister temperatures for the HLC at the same heat load. Because the trend is the same the HLC could be run at a lower heat load to simulate the temperatures of the MAGNASTOR canister.

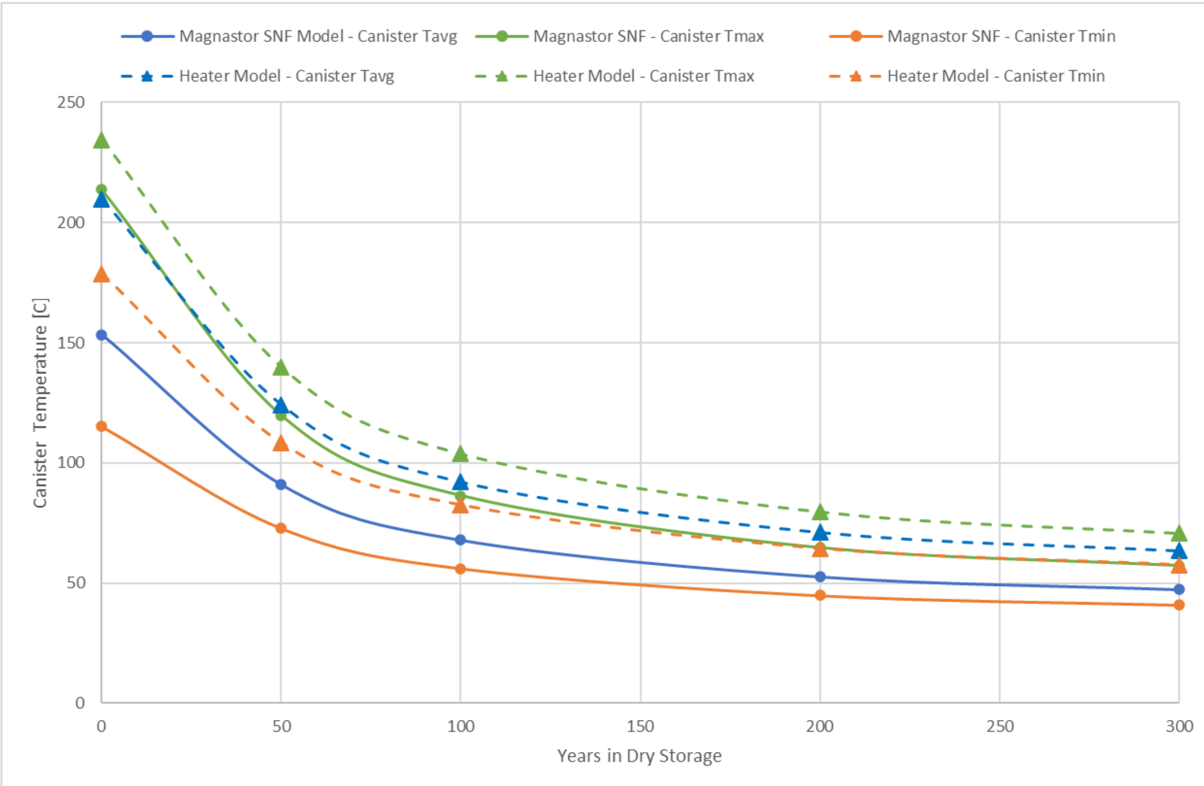

Fig. 7. Comparison Of The MAGNASTOR SNF Canister and Hanford Lead Canister.

NEXT STEPS

The heater assemblies for the HLC are being finalized and fabricated in late 2021. In early 2022 a series of heater bench tests are being planned to confirm the function of the heaters and the control system and to provide thermal model validation data for heater function. This bench testing and model validation is intended to provide information needed to deploy the HLC after all the MCSC systems are filled and placed on the dry storage pad in 2025-2026. Details of this test series are still being finalized, but it is expected that all 22 heaters will be tested together in a configuration that is similar to the inside the canister.

Another important demonstration of heater capability is planned for summer of 2022, where the heaters will be used during canister loading preparations to confirm the tolerances of the MCSC system will permit the loading of UCSs as planned. This is both a check of the dimensional tolerances and of the planned loading procedures. This test series is also expected to provide additional canister level thermal model validation data.

PNNL is also expecting to begin developing the long-term data collection plan in 2022, with the goal of identifying the data, data collection procedures, and any additional data collection systems needed to collect data from the HLC to benefit the nuclear material and SNF dry storage community. The initial time duration being planned for is 20 years, with the understanding that the actual dry storage period could extend much longer.

PNNL will continue coordinating R&D activities proposed by external organizations that want to use the HLC to advance canister mitigation and repair technologies, non-destructive evaluation technologies, or other technologies that can benefit the SNF dry storage industry.

Some organizations are planning pre-deployment R&D in the 2023-2025 timeframe. There is a potential for the HLC to be made available for a broad range of R&D activities, with the key caveat that the leading indicator function of the HLC must not be compromised. Any R&D related to long-term operation has the additional requirement that it must be ready to deploy with the HLC at the end of the MCSC loading campaign, which is currently estimated to be in 2025-2026.

CONCLUSIONS

Progress has been made to develop the HLC for use in the Hanford site's aging management plan for the long-term dry storage of Cs and Sr capsules. Electric heaters have been designed to provide an equivalent decay heat thermal load to achieve an environment that is predicted to match the canister exposure environment of a loaded MCSC system. Bench testing of the heaters will follow in early 2022, followed by heated canister testing in summer 2022. A long-term data acquisition plan will be developed in 2022, with time to prepare sensors and data acquisition systems before the HLC is deployed in 2025-2026.

PNNL is the point of contact for coordinating R&D activities using the HLC. There is an opportunity for pre-deployment R&D in the 2023-2025 timeframe. Any R&D related to long-term operation needs to be ready for deployment in 2025.

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