**THERMAL MODELING OF
A VERTICAL DRY STORAGE CASK FOR USED NUCLEAR FUEL**

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ABSTRACT

Thermal modeling of temperature profiles of dry casks has been identified as a high-priority item in a U.S. Department of Energy gap analysis. In this work, a three-dimensional model of a vertical dry cask has been constructed for computer simulation by using the ANSYS/FLUENT code. The vertical storage cask contains a welded canister for 32 Pressurized Water Reactor (PWR) used-fuel assemblies with a total decay heat load of 34 kW. To simplify thermal calculations, an effective thermal conductivity model for a 17x17 PWR used (or spent)-fuel assembly was developed and used in the simulation of thermal performance. The effects of canister fill gas (helium or nitrogen), internal pressure (1–6 atm), and basket material (stainless steel or aluminum alloy) were studied to determine the peak cladding temperature (PCT) and the canister surface temperatures (CSTs).

The results showed that high thermal conductivity of the basket material greatly enhances heat transfer and reduces the PCT. The results also showed that natural convection affects both PCT and the CST profile, while the latter depends strongly on the type of fill gas and canister internal pressure. Of particular interest to condition and performance monitoring is the identification of canister locations where significant temperature change occurs after a canister is breached and the fill gas changes from high-pressure helium to ambient air. This study provided insight on the thermal performance of a vertical storage cask containing high-burnup fuel, and helped advance the concept of monitoring CSTs as a means to detect helium leakage from a welded canister. The effects of blockage of air inlet vents on the cask's thermal performance were studied. The simulation were validated by comparing the results against data obtained from the temperature measurements of a commercial cask.

Nomenclature

abbreviations	
AMP	aging management program
CFD	computational fluid dynamics
CISCC	chloride-induced stress corrosion cracking
CST	canister surface temperatures
DCSS	dry cask storage system
DOE	Department of Energy
GWd/MTU	gigawatts day/metric ton uranium
ISFSI	independent spent fuel storage installations
MPC	multiple purpose canister
SIMPLE	semi-implicit method for pressure linked equations
PCT	peak cladding temperature
PWR	pressurized water reactor
SSC	structures, systems, and components
SST k- ω	shear stress transport k- ω turbulence model
UDF	user defined function

1. INTRODUCTION

In the U.S. Department of Energy (DOE) gap analysis to support extended storage of used (or spent) nuclear fuel [1], temperature profiles of dry casks were identified as one of the high-priority, cross-cutting areas that need R&D, because most degradation mechanisms are temperature-dependent, with rates generally increasing with temperature. Current safety analyses are appropriately based on bounding temperature profiles, but recent data showed that high-burnup cladding alloys can become brittle at lower temperatures owing to phenomena such as radial hydride reorientation [2]. For these reasons, DOE recognizes the need to obtain realistic, “best estimate” temperature profiles for all dry storage components as a function of extended storage. As part of the DOE’s Used Fuel Disposition Campaign Research and Development Program, Argonne National Laboratory (Argonne) has prepared a report titled “Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel” [3]. This report examines issues related to managing aging effects on the structures, systems, and components (SSCs) in dry cask storage systems (DCSSs) and independent spent fuel storage installations (ISFSIs) for extended long-term storage and subsequent transportation of used fuel. The report contains chapters on generic time-limited aging analyses and aging management programs (AMPs), and their applications to manage aging effects on the SSCs that are important to safety in the DCSS designs that have been and continue to be used by utilities for the dry storage of used fuel. Table 1 summarizes the DCSSs presently in common use in the U.S. The DCSS designs are of two general types, namely, (1) self-contained shielded metallic casks without an overpack and (2) metallic canisters with a separate overpack to provide radiation shielding and physical protection.

All of the self-contained DCSS designs listed in Table 1 incorporate bolted top enclosures with O-ring seals, whereas the canister plus overpack configurations utilize a welded top closure. Figure 1 shows cutaway views of vertically oriented dry storage casks with a bolted closure lid or a welded canister, each containing an internal fuel basket for multiple spent fuel assemblies. After fuel loading into a canister or cask and vacuum drying, the cavity of the cask/canister is filled with helium to provide an inerting environment during long-term storage. This paper is primarily concerned with the simulation of thermal performance of a vertical dry storage cask with a welded canister containing 32 high-burnup (>45 GWd/MTU) Pressurized Water Reactor (PWR) spent fuel assemblies. HI-STORM-100 was chosen as an example of the vertical dry storage cask for the study; the three-dimensional (3D) simulation results on thermal performance of a TN-32 metal cask with a bolted closure can be found in the paper by Mittal et al [4] and will not be repeated here. The main purpose of this study is to investigate the effects of basket materials (stainless steel or aluminium alloy), canister fill gas (helium or nitrogen) and internal pressure (1–6 atm) on the peak fuel assembly cladding temperature and the canister surface temperatures (CSTs).

Previous Work on Thermal Analyses of Used Fuel Storage Casks

Most thermal analyses have been done primarily for the certification purpose. It includes detailed SSC geometries, meshing, analytical method, results and in compliance with the corresponding regulation as specified in US 10 CFR 72. The thermal analytical results are typically documented in Chapter 4 of safety analyses reports, which can be typically found from the NRC's library [5] except those parts that have proprietary materials, such as information of a new generation of advanced basket materials, Metamic-HT. However, it is due to such a certification purpose that thermal performance has typically been analyzed in a rather conservative way to make sure existence of enough temperature margin for thermal safety. Particularly, for a specific cask design, there is no need, or any other motivation, to conduct either a parametric or a comparative study to optimize heat transfer as if the regulation requirement is satisfied.

With the increase of decay heat load induced by the high burn-up fuel, there is a trend and also an urgent need recently to significantly increase the heat load capability for each storage cask such that it can host more fuel assemblies, and thereby to save space, effort and cost. One easy way to achieve the goal is to increase the number of loaded fuel assemblies in each canister. As such, the original canister is designed to host 24 PWR fuel assemblies. Now, it is increased to host 32, and further 37 in the typically newly-designed canisters, such as MPC-37 canister for the Holtec HI-STORM FW cask [6].

With increasing number of fuel assemblies loaded, the mechanism(s) of heat transfer in the canister changes! The original design (e.g. 24 fuel assemblies) can provide larger free space, void and especially flow paths among fuel assemblies in a sealed canister to effectively transfer heat out of fuel assemblies through natural convection. However, with a densely-packed new design, fluid convection will be suppressed. Thermal conduction, together with limited radiation, via the basket wall is the only mechanism by which heat can be dissipated. As a result, a basket has to be made of highly-conductive materials such that peak temperature of fuel assemblies can, still, be maintained under the allowable limit.

Some studies on a natural convection of heat transfer in a closed canister have been reported. The earlier work in this area has been reviewed by Xie et al. (2002) [7]. Herewith, we will briefly review recent studies on heat transfer in a full fuel storage cask that are publically accessible. Nishimura (1996) [8] experimentally and numerically (using ZEPHYRUS code) investigated natural convection heat transfer in a horizontal storage cask containing 24 electrically heated dummy fuel assemblies that used air or water as the cooling media. This experimental cask is a 1/5 scale model of the actual dry shielded canister in which Rayleigh number (Ra , based on inner radius of the canister) varies from 3×10^7 to 2×10^8 . It is concluded that the overall heat transfer coefficients are proportional to the one fourth power ($1/4$) of the Rayleigh number. The sleeve surface temperatures calculated using a 2D model agreed well with experimental data within 8%. These data have also been employed later on by Xie et al. (2002) [7], and

recently by Lee et al. (2013) [9] to validate their 2-D computer simulations of horizontal storage casks using other commercial code of PHOENICS-3.2 and FLUENT 13.5 respectively. This work contributes to characterization of flow and heat transfer in the laminar flow regime primarily.

Xie et al. [7] simulated the same topic as Nishimura did, but using both laminar and turbulent (standard k-epsilon) model with Ra number up to 10^9 . The high Ra results from a higher basket temperature used which was up to 310°C (vs. 80°C). It is concluded that the computational results corresponding to laminar model agree well with Nishimura's experimental data, but the results of turbulent model over predicts the experimental data. Three (3) regional convection heat transfer correlations, i.e. $\text{Nu}_m \propto \text{Ra}^{0.75}$, $\text{Ra}^{0.25}$, and a constant C, respectively for both laminar and turbulent model, were provided. The heat transfer mode was found to change, with increasing Ra number, from heat conduction to natural convection dominant. When $\text{Ra} = 1.3 \times 10^9$, convection dominates.

A similar 2-D simulation has recently been conducted by Lee et al. (2013) [9] using the FLUENT code to analyze flow and heat transfer behaviors of a full-sized horizontal canister that contains 21 fuel assemblies and is filled with helium as a working fluid. It is found that peak temperature is located in the second basket from the top along the vertical center line. The increase of Ra can enhance heat transfer which results in systematically reduced temperatures for all components in the canister. Moreover, a more uniform temperature field can be obtained as well (i.e. the averaged temperature difference between that of the basket surfaces and that of the inner surfaces of the canister decreases with the increase of Ra). Two correlations, i.e. $\text{Nu}_m \propto \text{Ra}^{0.5}$ ($1.5 \times 10^6 \sim 1.0 \times 10^7$); $\propto \text{Ra}^{0.27}$ ($1.8 \times 10^7 \sim 8.0 \times 10^7$), have been provided to quantify heat transfer in that dry shielded canister. More simulation details have been provided in the paper.

With the advent of modern computer technology, it is feasible in the recent years to conduct a 3-D simulation for a full scale cask to obtain a more realistic flow and/or temperature field that has actually three (3) dimensional features, like openings. There are a few of CFD simulations on thermal behaviors of used nuclear fuel storage casks. Lee (2009) [10] conducted 3D numerical (CFD k-epsilon model) and experimental studies on a *vertical concrete storage cask* (half model) using the FLENT code. Boussinesq model was used to calculate fluid density; effective thermal conductivities for both fuel assembly and the composite basket were developed to simplify calculations. In addition, a porous media model was employed to calculate flow field in fuel assemblies. The simulation was firstly validated by comparing data with those from a testing cask containing a dummy fuel assembly (4.56 kW). Then, the cask containing fuel with 25.2 kW heat load has been simulated. It is concluded that peak temperatures of the fuel rods are around 300°C , and nearly 80% of decay heat is transferred out of the cask system through natural convection of air. The off-normal condition of air inlet blockage will not impact remarkably on the temperature profile till 6 out of 8 holes are blocked.

A similar work has been done by Tseng et al. (2011) [11] using FLUENT for a full-size vertical concrete storage cask (1/8 scale model) containing a stainless steel canister with 61 BWR fuel assemblies (with a total heat load of 18.3 kW). A homogenous solid thermal model is assumed for a fuel assembly and its effective thermal conductivity has been calculated in advanced. Natural convection of helium in the canister is neglected and that of air in the concrete gap is modeled using Boussinesq method. The simulation is validated and verified by comparing simulated results with analytic resolution (of simple geometries), correlation (thermal conductivity), and experimental data (VSC-17 test). It is concluded that 1) peak temperature is located in the middle of the central assembly ($\sim 333^{\circ}\text{C}$ in the accident), which deviates from Lee's findings that peak temperature is located at upper part of the central assembly. This may largely be induced by not considering of natural convection; 2) change of the environment temperature (off-normal) does not significantly affect peak cladding temperature (only 13%), and temperature difference between the central and boundary fuel assembly.

Moreover, Simonis et al. (2013) [12] also numerically investigated effect of three abnormal conditions, including helium leakage, erroneous more heat load, and closed ventilation, on thermal performance of a vertical CONSTOR RBMK-1500/M2 (Germany) cask by using ALGOR code for a 2-D model. It is concluded that cladding peak temperatures in the inner canister will rise approximately 160, 80, and $6\text{--}10^{\circ}\text{C}$ respectively as compared to those for normal conditions. Among them, the He-leakage case results in scenarios with the hottest peak temperatures that exceed the 400°C limit, but within the maximum allowable short-term temperature of 570°C .

In contrast with the ventilated concrete cask as discussed above, the other type of vertical but non-ventilated steel cask has also been frequently used commercially, as typically represented by the TN-24P cask developed by Transnuclear Inc. This cask uses a resin-filled exterior shell and lid to isolated itself from the environment. Such a cask was tested and analyzed in the late 80's [13, EPRI, NP-5128, 1987]. Recently, there are resurging interests to analyze thermal behaviors of such a cask, largely due to the fact that thermal experimental data are readily available to validate the simulation. Yoo et al. (2010) [14] simulated thermal behaviors of this cask with the geometrical model resolution down to the each individual fuel pin level, to circumvent the use of effective thermal conductivity and porous media approximation for fuel assemblies, but for a small 1/8 scaled model by using FLUENT code (with the maximum cells of nearly 1.4 millions) Brewster et al. (2013) [15] demonstrated that with present computational capacity it is feasible to simulate the TN-24p cask with geometry resolution down to each individual fuel and its cladding level (for one fuel assembly only in this simulation) for half-cask scaled model by using a STAR-CCM+ CFD code. The total cell number is up to 42.9 million, which is much more than 18.4 million for all homogeneous fuel assembly model. Nevertheless, both the simplified and the high-resolution model provide very impressive predictions that are in good agreement with those from

experiments. Moreover, Professor Greiner's group has been conducting the detailed studies on thermal analyses of casks on the multiple scales, from the rods to the cask, to understand the thermal-physics behind, as well as effects of various simulation approaches on the simulation results, e.g. effect of the assumption of homogeneous model [16]. The insights obtained are useful to guide both the simulations and cask designs.

The results of this study also aims to provide insights on the viability of using canister surface-temperature monitoring as a means to detect helium leakage from a welded canister containing high-burnup fuel. Additional studied were the effects of blockage of air inlet vents on the cask's thermal performance, as well as a validation of the simulation results against data obtained from the temperature measurements of a dry storage cask.

Table 1. Summary of Dry Cask Storage Systems in common use in the U.S. [3]

Vendor	System	Cask/Canister	Type*	Closure
EnergySolutions	FuelSolutions	VSC-24, W150	C/O	Welded
General Nuclear Systems, Inc.	CASTOR	V/21, X/33	Cask	Bolted
Holtec International	HI-STAR-100	MPC-68, MPC-80	C/O	Welded
	HI-STORM-100	MPC-24, MPC-32, MPC-68	C/O	Welded
NAC International, Inc.	S/T	NAC-I28	Cask	Bolted
	MPC	MPC-26, MPC-36	C/O	Welded
	UMS	UMS-24	C/O	Welded
	MAGNASTOR	MAGNASTOR	C/O	Welded
Transnuclear, Inc.	NUHOMS	52B, 61BT, 61BTH, 7P, 24P, 24PHB, 24PT, 24PTH, 24PT1, 32P, 32PT, 32PTH, 12T, HD	C/O	Welded
	TN Metal Casks	TN-24, TN-32, TN-40, TN-68	Cask	Bolted
Westinghouse	MC-10	MC-10	Cask	Bolted

* C/O = metallic canister with overpack; Cask = self-contained metallic cask without overpack.

Figure 1. Cutaway views of vertical dry storage casks with bolted closure lid (a) and welded canister (b), each containing an internal basket for multiple spent fuel assemblies

2. THERMAL MODELING

Figure 2 shows a quarter-section of a 3D model of the vertical storage cask shown in Fig. 1(b). The major components modeled include a concrete overpack enclosed in carbon steel shells; a welded stainless steel multi-purpose canister (MPC); a cask lid and a baseplate with radiation shielding provisions; and air inlet and exit vents that provide passive cooling of the MPC by natural convection. The inner and outer diameters of the overpack are 1.765 m and 3.366 m, respectively, and the height of the overpack cavity is 4.864 m. Near the top and bottom of the overpack are four openings to allow air ventilation and canister cooling. The outer diameter of the MPC is 1.74 m, and the height is 4.82 m. The overall height of the cask is 6.083 m. At the bottom and on the top of each fuel assembly are a header and a footer/spacer combination, respectively. Figure 2(b) shows the mesh representation of the quarter-section of the basket and cask (spent fuel assemblies omitted for clarity). The total number of mesh cells is ~5.05 million. The grid was generated by using a meshing module in the ANSYS Workbench, which is a platform that facilitates meshing, solving (with FLUENT), and data transfer in the 3D simulation. A high-fidelity mesh representation of the physical model can be obtained automatically by tuning the mesh control parameters in the Workbench. Fluid channels, e.g., radial and axial gaps through which natural convection occurs, are represented by no less than 5 cells across for the smallest channel. In a recent paper [17], Herranz et al. reported a grid (mesh) sensitivity study using 1.7 and 13.7 million cells for HI-STORM 100S, which showed **actually no difference** in the calculated temperature profiles.

Figure 2. Cross-sectional view of a quarter-section of a 3D model of fuel basket and cask showing major components (a), and the corresponding mesh representation (b). Spent fuel assemblies omitted for clarity.

It should be pointed out that the fuel assemblies were not modeled as rods with porous spacer plates, but as solid blocks for simplicity. The size of the gap between the fuel block and the basket is 0.1825 and 0.2575 inch along the x and y direction respectively. This simplified approach may affect the predicted temperatures. According to Kamichetty, et al. [16], it under-predicts the PCT slightly as compared to the model that considers the fuel rods and gas separately.

2.1.1. Material Properties

The physical properties of the materials used in the 3D simulation of thermal performance of the vertical storage cask are described below.

17x17 PWR Spent Fuel Assembly:

A detailed two-dimensional (2D) model of a quarter-section of a Westinghouse 17×17 Standard PWR spent fuel assembly was constructed in ANSYS to determine the transverse (i.e., planar) effective thermal conductivity (k_{eff}) of the spent fuel assembly by Mittal et al.[4], following the well-established methodology developed by Bahney and Lotz, which has been described in detail in reference [18]. A 2D homogenized quarter model for the 17x17 spent fuel assembly was also constructed, and a comparison of the peak temperatures calculated by the homogenized and detailed models showed a difference of only 0.2°C for helium backfill and an isothermal boundary condition of 260°C [4]. The homogenized model, therefore, should be suitable for the calculation of peak temperatures and temperature distributions of the spent fuel assembly. Figure 3 shows the transverse (planar) and axial effective thermal conductivities

derived for helium (He) and nitrogen (N₂) fill gas, for which the labeled solid points were taken from references [4], [18], and [19], along with the polynomial line fits of solid points from Mittal et al. [4]. The axial effective conductivities for He and N₂ in Fig. 3(b) were derived by using parallel paths of heat transfer through the cladding and fill gas as the area-weighted mean.

Figure 3: (a) Transverse (planar) effective thermal conductivities derived by using 2D ANSYS model and (b) axial effective thermal conductivities derived from area-weighted mean of cladding and fill gas, for a 17x17 PWR spent fuel assembly. Solid points are taken from references [4], [18], and [19].

Canister/Cask Components and Gases

The physical properties of canister/cask components and gases were obtained from the literature [19, 20]. These properties include density, thermal conductivity, heat capacity, viscosity, and surface emissivity, which are temperature dependent. The density of gas is an important parameter in simulating heat transfer by natural convection, because it is the temperature-induced density difference that drives buoyancy flow, which is calculated using either the Boussinesq approximation or the incompressible ideal-gas law. The Boussinesq approximation is valid for $\beta (T - T_0) \ll 1$, where T and T_0 are the fluid local and bulk temperatures and β is the coefficient of thermal expansion of the fluid. Chenoweth and Paolucci demonstrated that the Boussinesq approximation can lead to significant errors when $(T - T_0)/T_0 > 0.2$ [21]. Given the relatively large temperature gradient in a vertical storage cask, the Boussinesq approximation is not suited for its simulation, and the incompressible ideal-gas law was used instead. The approach is applicable to density calculation when the pressure variation is small enough that the overall canister internal flow conditions are essentially incompressible, but density variation with temperature is used to calculate the driving force for the fluid flow. The variation of fluid density (ρ) is based on the system

pressure (P) and the computed fluid temperature (T) in accordance with the ideal-gas law ($\rho = PM/RT$), where M is the molecular weight of the gas and R is the universal gas constant.

2.2. Heat Loads and Boundary Conditions

The total decay heat load of the cask, 34 kW, was assumed to be uniformly distributed among 32 PWR spent fuel assemblies, with 1.0625 kW for each assembly. The peaking factor for the heat generation rate along the axial length of the fuel assembly is taken from reference [22], see Figure 4, and the decay heat load was applied to the model as volumetric heat sources in each fuel assembly. Numerical implementation of the distributed loading was achieved by using the User Defined Functions (UDFs) provided in FLUENT.

Figure 4 Peaking factor for the heat generation rate along the axial length of the fuel assembly

Natural convection and radiation occur at the cask exterior surface, as well as interior surfaces bordering the air inlet and exit vents. Natural convection and radiation also occur inside the canister. Thermal radiation between surfaces inside the cask was modeled with the surface-to-surface (S2S) model in the code. Table 2 summarizes the boundary conditions and parameter values used in the simulation. A symmetry boundary was applied to the mid-plane of the model. Solar insolation was not considered in the simulation.

Table 2: Boundary conditions and parameter values

Parameter		Value
Temperature	Ambient	25°C
	Soil	15°C*
Pressure	Inlet/exit vents	1 atm
	Canister cavity	1, 4, 6 atm
Convection heat transfer coefficient (cask exterior surface)	Top, side	5 W/m ² -K*
	Bottom	0.17 W/m ² -K*

*Parameter values from reference [23]

2.3. Numerical Methods

The semi-implicit method for pressure-linked equations, the so-called “SIMPLE” algorithm in FLUENT, was used in coupling pressure and velocity to solve the Navier-Stokes equation. The SST k- ω model was selected for turbulence flow. For spatial discretization of pressure, a body-force-weighted scheme was used, since natural convection is buoyancy-driven. [The surface to surface \(S2S\) model was used in our simulations to calculate heat radiation by following the procedure as described in Chapter 7: Modeling Radiation and Natural Convection in the ANSYS FLUENT Tutorial Guide \(rev 14\). In calculations of view factors, ray tracing method has been used.](#) The convergence criteria used were as follows: The first criterion checked the values of the scaled residuals of the equations that are below certain thresholds (e.g., 10^{-3} for the mass, momentum, and turbulence equations, and 10^{-6} for the energy equation). To achieve a reasonable computational time, the second criterion checked the values of the calculated temperatures (e.g., peak cladding temperatures [PCTs] and CSTs) to ensure that a converged steady state has been reached (i.e., a variation of $< 1^\circ\text{C}$ in 1000 iterations).

3. SIMULATION RESULTS

Figure 5 shows the contours of temperatures for the cask (a) and the hottest spent fuel assembly near the center of the canister (b), and profiles of velocity (c) and density (d) of air in the flow channel between canister and overpack, obtained from the 3D simulation of the vertical storage cask with a helium-filled (6 atm) MPC and a stainless steel basket containing 32 spent fuel assemblies with a total decay heat load of 34 kW. The color renditions of the contours indicate that (1) the PCT of 387°C occurred, as expected, in the spent fuel assembly located near the center of the canister/cask, at an axial location of $z/L = 0.85$ where L is the fuel length, and (2) the velocity of air flow was higher at the air exit vent near the top of the vertical storage cask, whereas the density of air is higher at the air inlet vent near the bottom. [The](#)

temperature contour indicate that the peak temperature is located on the upper part of the fuel assembly, rather in the middle, along the vertical direction, which is largely induced by natural convection of the filled gas (it flows upward in the center region) and the poor thermal conductance of the top gas layer. The following subsections will compare different cases for which the effects of basket materials (stainless steel and aluminum alloys), types of fill gas (He and N₂) and canister internal pressure (1–6 atm) were systematically simulated and evaluated.

Figure 5. Contours of temperature (°C) for the cask (a) and hottest spent fuel assembly (b), and profiles of (c) air flow velocity (m/s) and (d) air density (kg /m³), obtained from 3D simulation of the vertical storage cask, with helium-filled (at 6 atm) MPC and a stainless steel basket containing 32 spent fuel assemblies with a total decay heat load of 34 kW.

3.1. Effects of Basket Materials and Fill Gas

Heat removal and passive cooling of the vertical storage cask relies on conduction through spent fuel assemblies and solid components (e.g., basket, canister, and overpack) and natural convection inside and outside the canister and overpack. Heat transfer by conduction through a solid would typically be more effective than that by natural convection through gas, either helium or air in a fuel-storage cask because of low flowrate of the circulating gas. The HI-STORM 100 dry storage cask design uses a stainless steel basket which has a thermal conductivity of 16 W/m-K at 25°C. An aluminum alloy such as Al-1100 has a thermal conductivity of 218 W/m-K at 25°C, which is ~15 times higher than that of stainless steel. The thermal conductivity of helium (0.142 W/m-K) is ~5 times higher than that of N₂ (or air) (0.024 W/m-K), both at 25°C and ambient pressure. For gas phase in the cask, heat transfer is conducted primarily via natural convection due to existence of temperature difference. Natural convection depends on the density of gas, thus the internal pressure. With the increase of the system pressure, it can be enhanced, playing an increasing role in dissipation of decay heat.

Figure 6 shows the 3D simulation results for the axial temperature profiles for the spent fuel assembly located near the center of the canister/cask under three scenarios: a reference scenario with 6-atm He inside the canister and a stainless steel basket [the temperature contour of this case was shown in Fig. 5(a)]; a scenario with 6-atm N₂ inside the canister and a stainless steel basket; and a scenario with 6-atm N₂ and an Al-1100 basket. Notice that the calculated PCT decreases from 387°C (6 atm He) to 315°C (6 atm N₂) with a stainless steel basket, and to 190°C with a N₂-filled (6 atm) canister and an Al-1100 basket. While the axial locations of the calculated PCTs showed little difference between the helium and N₂-filled canisters with a stainless steel basket, the axial temperature profile flattened over a considerable length of the spent fuel assembly in the N₂-filled canister with an Al-1100 basket.

Figure 6. 3D simulation of axial temperature profiles for the spent fuel assembly located near the center of the canister/cask under three scenarios.

Figure 7 shows the 3D simulation results for the radial temperature profiles for the spent fuel assemblies, basket, and other components of the vertical dry storage cask under the three scenarios depicted in Fig. 6,

Figure 7. 3D simulation of radial temperature profiles (4 m above the fuel bottom) for the spent fuel assemblies, basket, and other cask components under three scenarios.

where the corresponding axial height is 4 m above the fuel bottom. For the scenarios with the stainless steel basket, the PCT decreased by $\sim 70^\circ\text{C}$ and the peak basket temperature decreased by $\sim 100^\circ\text{C}$ at this axial location when the canister fill gas of He was replaced by N_2 , both at 6 atm. The changes in the calculated PCTs and peak basket temperatures in the canister with 6-atm N_2 and an Al-1100 basket are even more dramatic: the PCTs of 190°C remained nearly the same for the spent fuel assemblies located near the center, middle and peripheral regions of the canister, and the basket temperatures remained flat and near 60°C from the center to the peripheral region of the canister. However, the difference between the peak cladding and basket temperatures increased to $\sim 130^\circ\text{C}$.

3.2. Effects of Gas Pressure and Density

The parameters that affect natural convection include gas type (molecular weight M), system pressure (P), temperature gradient, and gas expansion. To explain the effects of these parameters, the simple empirical equations below [for a vertical plate with the characteristic length of height \$l\$ \[24\]](#) are useful and selected to [understand the physics](#):

$$Nu = \begin{cases} 0.59Ra^{1/4} & 10^4 < Ra < 10^9 \\ 0.10Ra^{1/3} & 10^9 < Ra < 10^{13} \end{cases}$$

$$\rho = \frac{P \cdot M}{R \cdot T} \quad Ra = Gr \cdot Pr = \frac{g\beta(T-T_\infty)\rho^2 l^3}{\mu^2},$$

where Nu is Nusselt number, Ra is Rayleigh number, Gr is Grashof number, and Pr is Prandtl number, all dimensionless; μ is the viscosity, l is the characteristic length, g is gravity, and all other parameters have been defined before. These equations show that natural convection can be manipulated by tuning the fluid properties (μ , ρ , and M), as well as the system pressure, P (or canister internal pressure). For comparison, the densities of He and N_2 are 0.1786 and 1.251 kg/m^3 , respectively, at 0°C and 101.325 kPa . At room temperature, the kinematic viscosity of N_2 , $\nu = \mu/\rho = 2.06 \times 10^{-5} \text{ m}^2/\text{s}$, is $\sim 18\%$ of the value ($11.7 \times 10^{-5} \text{ m}^2/\text{s}$) for He. Therefore, a N_2 -filled canister should have higher Ra and Nu values, and a higher pressure would further increase these parameters. A Ra less than 10^8 indicates a buoyancy-induced laminar flow, with transition to turbulence occurring over the range of $10^8 \sim 10^{10}$. However, since the thermal conductivity of He is ~ 5 times higher than that of N_2 (0.142 W/m-K vs. 0.026 W/m-K), enhanced heat transfer by gas-phase conduction and convection of N_2 can only occur at a higher Ra number with a high enough system pressure. Table 2 illustrates the pressure effects of N_2 in the 3D simulation of the changes in the PCT in the canister with a stainless steel basket [the 6-atm N_2 results were shown in Figs. 6 and 7]. The PCT increased from 315 to 349°C when the MPC N_2 fill-gas pressure decreased from 6 to 4

atm; the PCT increased further, to 500°C, when the MPC fill gas was replaced by air at ambient pressure of 1 atm. Ambient air was used to simulate helium leakage after canister breach; the PCT for N₂ at ambient pressure is expected to be very close to that of ambient air, since ~78% of air is N₂.

Table 2: Pressure effects of N₂ on peak cladding temperature (PCT)

Fill Gas	MPC Pressure (atm)	PCT (°C)
N ₂	6	315
N ₂	4	349
Air*	1	500

*Physical properties of air are very close to those of N₂.

3.3. Effect of Canister Leakage

Table 3 shows the 3D simulation results for the PCTs and CSTs following a small canister leakage, during which the pressure of the He fill gas drops from 6 to 1 atm, with the He eventually replaced by air at ambient pressure. The calculated PCT increases from 387°C to 462°C when the pressure in the He-filled canister drops from 6 to 1 atm, whereas the axial location of the PCT decreases from $z/L = 0.85$ to 0.54, which is only slightly above the mid-plane of the canister. The PCT increases further, from 462°C to 500°C, when the He fill gas at 1 atm is replaced by ambient air, and the axial location of the PCT increases from $z/L = 0.54$ to 0.71. These changes are generally consistent with what would be expected from the first-principles physics of natural convection, geometry, and fluid properties, particularly gas densities and pressure.

The calculated CSTs at the center top of the canister are also peak values that first decrease from 178°C to 96°C and then increase to 126°C when the canister fill gas changes from 6 atm He to 1 atm He, and then to ambient air. If the canister leakage and the He depressurization and replacement by air follow the prescribed scenario with the intermediate stage of 1-atm He, the changes in CST of 82 and 52 °C should be readily detectable with continuous monitoring using temperature probes properly placed on the canister surface.

Table 3: 3D simulation of peak cladding temperatures (PCTs) and canister surface temperatures (CSTs)

Fill Gas	Pressure (atm)	PCT (°C) / (z/L)	CST (°C)*
He	6	387 / (0.85)	178
He	1	462 / (0.54)	96
Air	1	500 / (0.71)	126

*The locations of CSTs are at the center top of the MPC [shown in circles in Fig. 8 (a), (b) and (c)].

Figure 8 shows the contours of CSTs for the three cases shown in Table 3. Notice that when the canister leaks, heat transfer by natural convection inside the canister becomes less effective because of depressurization, and the gas layer above the spent fuel assemblies hinders heat transfer to the top lid. As a result, the decay heat in the fuel assemblies accumulates towards the center and mid-plane of the canister, showing increased PCTs but with the peak value shifting downward, as shown in Table 3. The locations of the peak CSTs also change from the center at the top of the canister in Figure 8(a), with 6-atm He, to the side of the canister in Fig. 8 (b) and 8 (c), with 1-atm He and ambient air, respectively.

Figure 8. 3D simulation of contours of canister surface temperatures (CSTs): (a) He (6 atm), (b) He (1 atm), and (c) air (1 atm).

3.4. Effect of Blockage of Air Inlet Vents

The vertical dry storage cask depends on passive cooling by air that enters the inlet vents near the bottom of the cask, flows upward in the annulus gap between the canister and overpack, and exits near the top of

the cask via the air exit vents [(see Fig. 1(b)]. The Ventilation System Surveillance Program, III.M2 in the aging management report [3], is recommended for managing the loss of cooling capabilities of the passive ventilation systems of the DCSS designs due to obstructions. The AMP III.M2 is based on temperature monitoring of the system inlet and outlet air and/or system inspections and daily walkdowns. In this section, the effect of blockage of the air inlet vents in the HI-STORM 100 cask is studied by computer simulation, assuming complete blockages of one and two air inlet vents shown in Fig. 2(a). These assumptions amount to 50% and 100% blockages of the air inlet vents of the dry cask, since only a quarter-section of the 3D model was constructed for numerical simulation. The other simulation conditions are the same as those used for the standard storage case as reported in the beginning of Section 3.

Figure 9 shows the temperature contours of the storage cask with (a) no blockage, (b) 50% blockage, and (c) 100% blockage [Note: Fig. 9(a) is the same as Fig. 5(a)]. The PCT increased only slightly, from 387°C to 390°C, when 50%, i.e., two of the four air inlet vents, were blocked. With 100% blockage of all four air inlet vents, however, the PCT increased more substantially, to 413°C. The temperature increases due to blockages of air inlet vents may be explained by noting the corresponding air flow behavior; i.e., air can still enter from the neighboring air inlet vents when only 50% of the inlet vents are blocked, whereas 100% blockage of all air inlet vents would result in a negative-pressure region near the bottom of the cask, which intensifies internal circulation in the annulus gap between the MPC and overpack, thus inhibiting heat flow out of the air exit vents near the top of the cask. This effect is shown in Fig. 9(c) by a down-shifting, almost symmetrical temperature contour compared to that shown in Fig. 9(b) or Fig. 9(a).

Figure 9. 3D simulation of temperature contours of the storage cask with (a) no blockage, (b) 50% blockage, and (c) 100% blockage [Note: Fig. 9(a) is the same as Fig. 5(a)].

Figure 10 shows the effect of blockage of the air inlet vents on the air flow fields (m/s) in the annulus gap between the MPC and overpack. As shown in Fig. 10(a), the flow field is symmetrical with no blockage of the air inlet vents, and the highest velocities occur at the air exit vents. When one air inlet vent is blocked (in the x-direction), Fig. 10(b) shows that the air flow with the highest velocity moves from the air exit vents near the top to the bottom air inlet vent that remains open. As mentioned before, the phenomenon is largely due to the negative pressure generated via natural convection. It is this air redistribution that still maintains effective cooling, resulting in only a small increase in PCT. In contrast, a complete blockage of all air inlet vents would result in little or no air flow or circulation in the annulus gap near the bottom region of the cask, as shown in Fig. 10(c), but rather significant air circulation in the annulus towards the middle and upper regions of the cask. This flow distribution pattern keeps the air circulation in the annulus gap beneath the air exit vents of the cask, resulting in a significant increase in PCT.

Figure 10. Effect of blockage of air inlet vents on the flow field (m/s) in the annulus gap between the MPC and overpack: (a) no blockage, (b) 50% blockage, and (c) 100% blockage.

The effects of blockages of the air inlet vents on the axial and radial temperature distributions are shown in Figures 11 and 12, respectively. Figure 11 shows that with 100% blockage of the air inlet vents, the location of the PCT shifted slightly downward, from $z/L = 0.85$ to 0.82 , whereas the PCT increased from 387 to 413°C .

Figure 11. Effect of 100% blockage of air inlet vents on axial temperature distribution along the central fuel assembly in the storage cask

Figure 12 shows substantially higher temperatures not only for the central fuel assembly, but also near the MPC surface and through the bulk thickness of the overpack until a crossover occurred near the outer region of the overpack, where the temperature dropped below that of the case with no blockage.

Figure 12. Effect of 100% blockage of air inlet vents on radial temperature distributions in the storage cask [obtained at 4 m above the bottom of the fuel]

4. VALIDATION OF THERMAL ANALYSIS

Validation of thermal analyses is important to lend credence to the computer simulations. The focus in this section is on validating the thermal analysis of a vertical dry storage cask against the temperature measurement data and the results obtained by others in thermal modeling of a HI-STORM 100 storage cask at Diablo Canyon's ISFSI. The cask chosen for thermal analysis contains a welded canister for 32 PWR used-fuel assemblies in a stainless steel basket similar to that used in the previous analysis. An effective thermal conductivity model was used to represent the used-fuel assemblies with non-uniform assembly heat loads; the other parameters used in the analysis are briefly described below.

4.1. Heat Loads and Boundary Conditions

As of December 2013, the total decay heat load of the HI-STORM 100 storage cask at the Diablo Canyon ISFSI was 17.05 kW, which was distributed among the 32 PWR spent fuel assemblies as shown in Figure 13 [25, 26]. A heat load of 4.26 kW was used to represent the quarter region in x(4,6)-y(3,1) in Figure 13, which is approximately a quarter of the total decay heat of 17.05 kW. Non-uniform heat generation along the axial direction of each fuel assembly was modeled using a peaking factor found in reference [22]. The decay heat load was applied to the thermal model as a volumetric heat source in each fuel assembly. Numerical implementation of the distributed loading was achieved by using a UDF in the FLUENT code.

Figure 13: Assembly decay heat loads in the Diablo Canyon HI-STORM 100 storage cask as of December 2013 [25]

After drying, the MPC was backfilled with helium to a nominal pressure of 31.3 psig (maximum 33.3 psig) at a reference temperature of 21°C (70°F) [27]. The helium pressure inside the MPC during normal storage was assumed to be 5 atm for the thermal analysis [where thermal induced pressure increase is considered due to volume expansion of the filled gas](#). Natural convection and radiation occur at the cask exterior surface and at interior surfaces bordering the air inlet and exit vents. Natural convection and radiation also occur inside the canister. The thermal radiation between surfaces inside the cask was determined with the S2S model in the FLUENT code. Solar insolation was also applied to cask exterior surfaces on the basis of values provided in 10 CFR 71.71(c)(1). A symmetry boundary was applied to the mid-plane of the one-quarter model. The boundary conditions and other parameter values used in the analyses are the same as those shown in Table 2; the only exception is the ambient temperature, 10°C for the validation, as opposed to 25°C in Table 2.

4.2. Numerical Methods

The numerical methods used are the same as those described in Section 2.3, [therefore, they will not be repeated here](#). To obtain a reasonable computing time, the following convergence criteria were used: The first criterion checked the values of the scaled residuals of the equations that are below certain thresholds (e.g., 10^{-3} for the mass, momentum, and turbulence equations and 10^{-6} for the energy equation). The other three criteria checked the values of the calculated temperatures (e.g., PCTs and CSTs) to ensure that a converged steady state has been reached, i.e., a variation of <0.55, <0.7 or <1°C in 1000 iterations, respectively. [Note: A variation of <1°C in 1000 iterations was used in previous simulations.]

4.3. Validation of the Canister Surface Temperature Results

Figure 14(a) shows the temperature contours of the HI-STORM 100 cask: the peak fuel assembly temperature of 280°C occurred near the center of the cask at $z/L = 0.78$, where L is the axial length of the fuel assembly. Figures 14(b) and 14(c) show the air flow velocity and air density, respectively, in the annulus gap between the air inlet and exit vents of the cask shown in Figure 2(a). The highest airflow velocity, 1.44 m/s, occurred at the exit vent, whereas the highest air density, 1.25 kg/m³, occurred at the inlet vent; this is qualitatively consistent with what is expected from first-principles physics.

Similarly to the 3D simulation results reported in Section 3, the peak CST occurred at the lid top, near the center of the canister; this is to be expected in heat transfer by natural convection inside the canister, with helium circulating upward toward the center as a result of the so-called “thermal siphoning” phenomenon.

Figure 14: (a) Temperature contours ($^{\circ}\text{C}$) of the cask (hottest fuel assembly near center); (b) airflow velocity (m/s) and (c) air density (kg/m^3) in the annulus gap between the inlet and exit vents

The calculated temperatures along the side wall of the MPC at 0 degrees (reference datum), shown in Figure 15(a), were plotted in Figure 15(b) along with the data measured at Diablo Canyon [26] and the simulation results obtained by Cuta et al. [25] “The same conditions but with a slightly different cask configuration were used in Cuta’s simulations where the code of COBRA-SFS has been employed. The interested readers can find the details of Cuta’s simulations from the report [25].” Temperature measurements were performed at Diablo Canyon with instruments inserted from one of the air exit vents near the top of the cask; therefore, they should be close to the 0-degrees location shown in Figure 15(a). The results showed that the convergence criterion in the ANSYS/FLUENT simulation was important in this case; a better agreement with data was achieved with a tighter convergence criterion of $<0.55^{\circ}\text{C}$ in 1000 iterations. There are discrepancies between the ANSYS/FLUENT temperatures and those reported by Cuta et al. near the bottom of the MPC. These may be caused by differences in modeling the details of the cask’s geometry. Another important parameter is the ambient temperature, 10°C , assumed in the simulations. A change in ambient temperature would affect the MPC surface temperatures, as illustrated in reference [25].

The results in Figure 15(b) show that a significant portion of the canister surface is below 85°C, the temperature below which chloride-induced stress corrosion cracking (CISCC) of the welds may need to be considered, as well as the weld residual stress and marine salt deposits [28]. However, for condition monitoring of helium integrity in welded canisters during storage, the key parameter of interest is the difference between the surface temperatures at the top and bottom of the canister (i.e., ΔT_{BT}) as defined and used by Takeda et al. [29] when they developed and tested their method for detecting helium gas leaks from a canister. The change in the fill-gas condition inside a canister (e.g., due to helium leakage) can be detected by monitoring ΔT_{BT} , which has been shown to increase after canister helium depressurization (i.e., leakage) to a plateau of about 22–24°C in a mockup cask electrically heated to 22.6 kW.

5. DISCUSSION

Figure 15: (a) The MPC canister side wall with temperature values collected along 0 degrees for (b) comparison with measurement data [26] and those obtained in simulations by Cuta et al. [25].

The ANSYS/Fluent software can simulate the thermal behaviors and capture the important features of a vertical storage cask. Based on the validation results, it is indicated that a reasonable tighter convergence criteria is needed to obtain a more accurate temperature profiles and thus peak temperatures, yet in an

acceptable simulation time cost. Accordingly, some precaution should be taken when the specific temperature data are used since some of the calculations may slightly under predict the peak temperature when a relatively loose convergence criteria is employed.

As mentioned earlier, the aging management report [3] contains generic AMPs for managing aging effects on the SSCs in the DCSSs and ISFSIs for extended long-term storage and subsequent transportation of used fuel. Two AMPs, Welded Canister Seal and Leakage Monitoring Program (AMP IV.M3) and Canister/Cask Internals Structural and Functional Integrity Monitoring Program (AMP IV.M5), depend on monitoring and inspection to detect aging effects on welded canisters and canister internals to ensure their structural and functional integrity during extended long-term storage and subsequent transportation. Both AMPs also recommend following the guidance in selected NRC Interim Staff Guidance (ISG) documents as preventive actions to ensure proper confinement evaluation, vacuum drying, material evaluation, design and testing of lid welds, and pressure and helium leakage testing of confinement boundaries of spent fuel dry storage systems. AMP IV.M5 consists of three main parts: (1) assessment of records of canister fabrication, testing and fuel loading operations pertaining to the relevant ISG documents, (2) thermal modeling, and (3) monitoring and inspection [30].

Best-estimate thermal modeling of spent fuel assemblies, canister internals and canisters enables assessment of PCTs and CSTs against certain temperature thresholds, such as 400°C for potential hydride re-orientation in high-burnup PWR cladding alloys [31], or 85°C, below which CISCC can potentially degrade a stainless steel canister weld in a marine environment owing to salt deliquescence and the residual stress in the weld [28]. As shown in the preceding sections of this paper, the temperature profiles obtained in the 3D simulation depend on many factors; they are not static and will change during prolonged dry storage as the fission-product decay heat load in the canister decreases with time. However, once the model for the dry storage cask is constructed, conducting 3D simulations for the change in the cask heat load is straightforward. For a vertical storage cask with a welded canister and a total decay heat load of 34 kW, several significant findings may be gleaned from the 3D simulation in this study:

(1) A stainless steel canister with a basket of high-thermal-conductivity material such as Al-1100 aluminum alloy dramatically reduces the PCT and CST. In 2009, Holtec introduced a HI-STORM design using a basket material called “Metamic-HT,” which is a dispersoid of nanoparticles of alumina (Al_2O_3) and boron carbide (B_4N) powder in an aluminum matrix. The thermal conductivity of this material, ~184 W/m-K (based on U.S. Patent 8,323,373B2), is lower than that (218 W/m-K) of the Al-1100, which does not incorporate neutron poison for criticality control. For the HI-STORM design with Metamic-HT,

Holtec claimed that the decay heat load can be raised from 34 to 47.05 kW, which enables loading of spent fuel assemblies after a shorter cooling time (e.g., 3 years) in the spent fuel pool [32].

(2) The effects of N₂ fill gas on PCT and CST are also dramatic, as shown in Figs. 6 and 7. One significant implication here is that switching the canister fill gas from He to N₂ should be relatively easy for any vertical storage cask designs, and N₂, while not an inert gas like He, can provide a non-oxidizing environment inside the canister during extended long-term storage and subsequent transportation of high-burnup fuel. A flattened PCT for high-burnup spent fuel assemblies in the vertical storage cask, with a combination of N₂ and a basket with high thermal conductivity, is also desirable; however, the lowering of CST below 85°C means that CISC of canister welds may occur sooner during long-term storage, if other conditions for CISC are met.

The challenges in the monitoring and inspection of welded canisters in vertical dry storage casks are inaccessibility, as well as the locations and frequency of inspection and monitoring (i.e., periodic versus continuous). Advanced surveillance technologies for the long-term storage of used fuel in DCSSs/ISFSIs have been under development by Argonne in recent years [33–35]. The latest development, the “Remote Area Modular Monitoring (RAMM)” system [35], appears promising for DCSS designs in general and vertical dry storage casks in particular, on the basis of the 3D simulation results of the changes in CSTs shown in Table 3 and Fig. 9, which were obtained assuming uniform decay heat load in each of the 32 PWR spent fuel assemblies. Herranz et al. [17] studied regional loading of PWR spent fuel assemblies in an MPC-32 canister for which the ratio of the assembly heat loads between the inner and outer regions varied between 0.5 and 3.0. A key observation by Herranz et al. is that while the distribution of the assembly heat loads affected assembly temperatures at the periphery of the MPC, there was no major effect at the central locations near the top of the canister. Thus, a weather-protected RAMM unit may be mounted near the top of each vertical dry storage cask with thermocouples routed through the air exit vent and be placed near the center top and side of the canister, where large changes in CSTs are predicted to occur after a canister breach.

In the above conceptual deployment, each RAMM unit would have its own power supply from the grid and battery (backup), a suite of sensors (e.g., temperature, humidity, shock, radiation [gamma and neutron], seal), and data and alarm communication capabilities, forming a wireless sensor network that is self-forming, or self-healing, even after certain units are damaged and no longer fit for service. It is also envisioned that once the RAMM unit is properly placed on a dry cask, it can stay dormant except during the brief period of scheduled measurements. Because they are outside of the vertical storage cask and

away from the spent fuel assemblies, the sensors and electronic boards in RAMM are away from the sources of radiation and heat, and, therefore, should operate reliably during extended period of service. What remains to be demonstrated is the benchmarking of 3D simulation of thermal performance of the vertical dry storage cask against temperature measurements obtained by conventional instrumentation, or by deployment of a RAMM unit with external thermocouples. Contract-manufactured prototype units of RAMM are expected to be ready for testing by December 2015. A preliminary plan has been developed [36] for field-testing and evaluation of multiple (e.g., 5 to 10) RAMM units, each fitted to a dry storage cask on an ISFSI site. The main reasons that multiple RAMM units are recommended for field testing are to form a wireless sensor network for performance evaluation, as described previously in the development of ARG-US RAMM [35], as well as for trending – allowing comparison of canister surface temperatures measured for each installed dry storage cask against its known heat load under nearly identical environmental exposure conditions. Whereas leakage of individual canister may be difficult to decipher particularly if the leak rate is low, trending may be possible in making any perturbations more visible with a populated database of 10 or more canisters. Daily and seasonal variations in ambient temperature and blockage of vents on the dry casks are factors that would affect canister surface temperatures; however, the changes in patterns should be readily identifiable from the histograms of the recorded data.

6. SUMMARY AND CONCLUSION

The thermal performance of a vertical dry storage cask with a welded canister containing high-burnup fuel has been studied, using the ANSYS/FLUENT code simulating heat transfer and gas flow, in a 3D model of a vertical storage cask containing 32 PWR spent fuel assemblies with a total decay heat load of 34 kW. A 2D finite element model was used to derive planar effective thermal conductivities for a 17x17 spent fuel assembly, whereas its axial effective thermal conductivities were derived as area-weighted means of the cladding and the fill gas. Key factors examined for their effects on thermal performance include canister basket materials (stainless steel versus aluminum alloy Al-1100) and canister fill gas (helium versus nitrogen or air) under different pressure conditions from ambient to 6 atm.

The calculated PCT and CSTs are of primary interest in this study. The 3D simulation results showed that a high-conductivity basket with N₂ fill gas dramatically lowered the PCT and produced flat temperature profiles in the spent fuel assemblies in the radial and axial directions. The effect of N₂ fill gas and pressure on natural convection and thermal siphoning in the vertical dry storage cask appears even more pronounced than that of helium. On the basis of 3D simulation results of changes in CST at the center top and side of the canister after the 6-atm He is replaced by ambient air, continual monitoring of CST

appears promising as a means to detect helium leakage from a breach of a welded canister, e.g., due to aging degradation caused by CISCC or other causes.

The validation results showed reasonably good agreement between the calculated and measured canister axial surface temperatures. For the ANSYS/FLUENT simulations, the results showed that a tighter convergence criterion yielded slightly better agreement with the data, but that improvement could also be obtained by adjusting the ambient temperature value assumed in the simulation. The validation of the results of the ANSYS/FLUENT simulation against the data, coupled with the experience and additional insights gained from the validation exercise and blockage simulation, are important to future simulation and analysis of the thermal performance of vertical dry storage casks—particularly for monitoring cask conditions and performance as part of aging management during extended long-term storage at the ISFSIs. A preliminary plan for field-testing and evaluation of multiple RAMM units for monitoring canister surface temperatures has been developed.

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