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Thermal modeling of a vertical dry storage cask for used nuclear fuel

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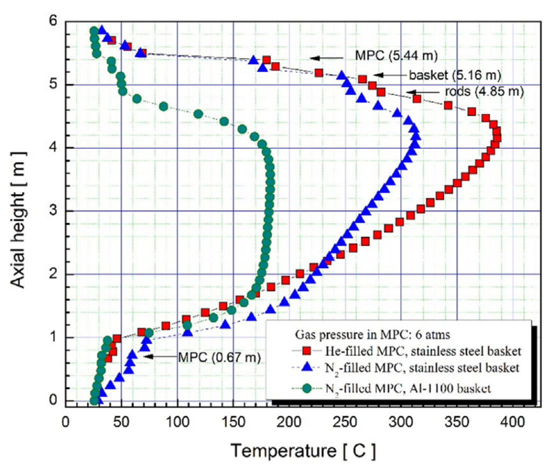
HIGHLIGHTS

- Thermal performance of a 3-D vertical dry cask under various conditions has been numerically studied by using ANSYS/FLUENT code.
- The simulation was validated by comparing the results against data obtained from the temperature measurements of a commercial cask.
- The results indicated that the basket with higher thermal conductivity dissipates decay heat out of the cask more efficiently than that with a lower thermal conductivity (aluminum composite vs. stainless steel). A heavier cooling gas is also helpful to enhance heat transfer via enhanced natural convection (N_2 vs. He).
- Coolant release from the fuel canister results in temperature change of the canister external surfaces. The simulation shows that such a change is large enough and detectable, which can provide a mechanism for leak detection by continuously monitoring this temperature change at the top center of the canister surface.
- Partial blockage of the cask air inlets affects the temperature profiles marginally for both the fuel canister and those components inside. In contrast, fully blocked air inlets will lead to remarkable increases of the component temperatures.

GRAPHICAL ABSTRACT



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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

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total decay heat load of 34 kW. To simplify thermal calculations, an effective thermal conductivity model for a 17 × 17 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.

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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 (Hansen et al., 2012), 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 (Billone et al., 2013). 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" (Chopra, 2014). 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. Fig. 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. (2014) 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).

1.1. 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 (US NRC, in press) 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

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