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Thermal and fluid analysis of dry cask storage containers over multiple years of service

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ABSTRACT

A detailed three-dimensional thermal and fluid analysis of a vertical dry storage cask with a canister containing 32 high-burnup pressurized water reactor (PWR) spent fuel assemblies for a storage of 50 years was carried out using a CFD simulation. The input decay heat value was calculated based on a Westinghouse 17 × 17 PWR fuel assembly using the well validated package ORIGAMI imbedded in SCALE, with a total heat load of 38.44 kW for year 5 and 10.67 kW for year 55. The temperature-dependent and anisotropic thermal properties of the fuel assemblies, filling gas within the canister, and air covering the canister were considered in order to preserve accuracy. A peak temperature of 621.4 K occurred in the upper part of the fuel assemblies for at year 5, deceasing to 423.0 K after 50-year service. The simulation results shed light on the temperature and flow environment within the canister for an operational time of 50 years.

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1. Introduction

In the nuclear industry, nuclear fuel rods are first stored in pools of water (wet storage) to remove heat from the assemblies and shield from gamma and neutron radiation left over from the production of radioactive nuclides in power generation. After 5 years or so, this fuel is then separated and stored in dry storage canisters for 30–60 years. After that, the fuel with low decay heat will be transported to a final disposal site for long term storage (Ewing, 2015). In the U.S. alone, there were 1500 loaded dry casks in 2010, and the number has been increasing by 200 each year. Since 2011, the close of the permanent nuclear waste disposal site in the Yucca Mountains, Nevada has brought dry storage and nuclear waste to the forefront of consciousness in the USA. Dry cask storage in the future may extend for up to one hundred years, which will bring large changes to the design of existing canisters.

Because of their lengthy use, monitoring of conditions within dry casks is of critical importance, as the temperature of the fuel and humidity within the cask can play a key role in the health of the system, and overall longevity of the storage containers. In fact, thermal analysis of spent nuclear fuel has been identified as high priority by the DOE Nuclear Energy Division (Adkins, 2012) since potential failure mechanisms to the fuel and canisters are dependent on temperature. This offers a unique problem however, as monitoring the cask internals can be very difficult, or indeed impossible due to a real potential for harm from radiation leakage, (Bruno and Ewing, 2006; Hedin, 1997), and for containment rupture. To address this issue, energy harvesting for wireless communication of conditions within canisters has been studied (Carstens, 2013; Carstens et al., 2013). Wireless communication of data from inside the cask would remove the need for human inspection, and energy harvesting could potentially allow for sensors to run indefinitely. Such a system would be able to report, in a self-powered way, information on the fuel and environment within the canister, without the need for operators. To address this, a detailed thermal environment analysis in the canister is necessary in order to guide the placement of a thermoelectric energy harvester. This paper is primarily concerned with a simulation of the thermal performance of a vertical HI-STORM-100 dry storage cask with a MPC-32 canister containing 32 high-burnup (45 GWd/MTU) Pressurized Water Reactor (PWR) spent fuel assemblies (Westinghouse PWR 17 × 17) for a storage of 50 years. This cask is further outlined in Section 2.

Much of the past work studying the thermal environment in canisters has been based on simulation, due to the dangerous nature of conducting in-situ experiments. The gamma radiation flux in the canister is very high, extremely dangerous for human beings, even after long periods of storage (Hedin, 1997). One of the reliable reported in-situ experiments done is in a DOE report from 1992 (McKinnon et al., 1992) where a performance test was done on a Pacific Sierra nuclear VSC-17 ventilated concrete storage dry cask

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configured for PWR fuel assemblies. The comprehensive report described the details of the fuel assembly type and position, geometry configuration of the cask system, material properties of individual components, and filling gas within the canister. The temperature profiles on the cask surface, concrete, air channel surfaces, and fuel canister guide tubes were described in detail, which provided precious data for validation of simulation results. Other experimental work has been done on both full scale and scaled down cask systems with the fuel simulated by electrical heating (Takeda et al., 2008; Wataru et al., 2008). This type of experiment can accurately represent the real cask system, however due to the complexity, simulation may be preferred.

Most thermal analyses of canisters have been done primarily for the purpose of certification, many of which that can be found from the NRC's library (Creer et al., 1987; Holtec International, 2012). Most of this work, since it was used in certification, was conservative because it was used to ensuring a large enough temperature safety margin in the nuclear fuel. In the 80 s, a lot of thermal simulation work for the low burnup fuel can be found for various canisters using COBRA-SFS (Creer et al., 1987; McKinnon et al., 1992; Rector et al., 1986), a CFD code based on the finite volume method. However, the accuracy of the simulation results was undercut by many uncertainties, such as oversimplified energy and momentum equations, and grid systems which were very sparse.

Due to an increase in computational power, from the beginning of this century, more studies have been performed using CFD to ensure spent fuel is maintained below its critical temperature in various cask systems. This trend is driven by the need to design better performing casks which can host more fuel assemblies and high burnout fuels. Early work includes Xie et al. (2002) who simulated a horizontal 2D dry storage system using the PHOENICS package and Greiner et al. (2007) who conducted 2D numerical studies of multipurpose canisters with 21 PWR assemblies and analyzed how nitrogen and helium cover gas, and different fuel cladding emissivity effected the thermal performance for different fuel decay heat generation rates. Wataru et al. (2008) conducted a 3D thermal analysis for the concrete cask using the FIT-3D thermal hydraulics code and the commercial PHOENICS package. Their computed temperature values and air flow velocities were validated by comparing with experimental data presented by Takeda et al. (2008). Results showed that the CFD approach can provide reasonable temperature estimates for the canisters. Lee et al. (2009) presented a thermal-fluid flow analysis of a vertical dry cask storage system under normal and off-normal conditions using the commercial CFD code, FLUENT. An effective thermal conductivity approach and a porous media approximation was used to model the fuel rods. The temperature and flow velocity profiles in the canister were compared and verified by the thermal test results collected from a half scaled-down model. A lot of CFD work (Das et al., 2010; Li and Liu, 2016; Walavalkar and Schowalter, 2004; Zigh and Solis., 2012) was done to analyze the VSC–17 cask system because the experimental result for this canister was well documented in the 1992 DOE report (McKinnon et al., 1992) mentioned earlier. Walavalkar and Schowalter (Walavalkar and Schowalter, 2004) performed a 3D CFD analysis for a 90-degree section of VSC–17 spent fuel dry storage system using the FLUENT software. They found the CFD simulation result can accurately predict the thermal environment in the VSC–17 spent fuel dry storage system. Work done by Zigh and Solis. (2012) and Das et al. (2010) further demonstrated that the excellent performance of CFD in calculating the temperature and flow velocity in the dry cask. In all of these studies, however, approximations were often used for the conditions inside and outside of the cask, largely due to missing, and difficult to acquire experimental data. Estimations were generally made on: the decay heat generated by the fuel, the distribution of the heat in the fuel assemblies, the thermal properties of both the backfilled helium and steel basket in the MPC, and the thermal properties of the fuel assembly itself.

These unnecessary assumptions and estimations undercut the accuracy of the CFD work. It is evident upon study of these previous works that the heat load applied to the inside of the dry cask in order to simulate the decay heat generated by the spent fuel was somewhat arbitrary and are generally only given as one set value, typically estimated from other work or experimental analysis from many years ago. Recently, Li and Liu (2016) established a 3D model of a vertical dry cask to simulate a vertical storage cask containing a welded canister with 32 Pressurized Water Reactor (PWR) used-fuel assemblies, with a total decay heat load of 34 kW by using the ANSYS/FLUENT code. Their work was performed in order to study the effects in changes of the thermal conductivity of the basket, and of the pressure and makeup of the gas backfilling the MPC canister. Herranz et al. (2015) took data from the Holtec International manual (Holtec International, 2004, 2010) for design of MPC-32, and placed a total heat power of 30 kW in the fuel assemblies, in order to study the sensitivity of maximum fuel temperature to heat load distribution within the canister, cask design (inlet/outlet orientation) and local environmental temperatures.

Much work, however, has been done previously characterizing the distribution of heat along the fuel assemblies (McKinnon et al., 1992; Turner, 1989; Zigh and Solis., 2012), as well as the effective conductivity of the fuel assemblies as a function of temperature within the cask (Bahney and Lotz, 1996; Mittal et al., 2014). Yoo et al. (2010) simulated thermal behaviors of the TN24P cask without a concrete wall. With a geometrical model resolution down to each individual fuel pin level, the simulation did not need to introduce effective thermal conductivity for the fuel assemblies. The heat load applied to their work was the same as estimated by the experiment (Creer et al., 1987), at 20.6 kW in the total cask. Their work was found to agree very well with the reported experimental results. Brewster et al. (2012) demonstrated a simulation on a TN-24P cask with geometry resolution down to each individual fuel and its cladding level. The calculation was carried out on a half-cask scaled model with a grid number up to 42.9 million using a STAR-CCM+ CFD code. This model was found to be more accurate in predicting the peak cladding temperatures (PCTs) when compared with the traditional porous media/effective thermal conductivity approach.

Though the CFD models listed above used for canister simulation have progressed a lot in the past decade, there are still some gaps that need to be filled before this technology can be used to accurately predict the temperature and guide the design of new canisters. While these studies take into consideration many aspects of the dry storage canister, they do not consider precise calculations of the state of the spent fuel upon entering the dry cask canister, nor do they take into account the varying heat load of the spent fuel during its lifetime. Considering the fact that decay heat of the fuel will change throughout the lifetime of the cask due to decreasing activity (or decay) of isotopes present, thermal analysis of the dry cask storage system should reflect this. Precise calculation of both the decay heat present, and its variability with time is generally left out of the literature, and thus it is evident that more work is needed in the area of thermal simulation for dry cask storage. In this work, ORIGAMI (Williams et al., 2015) is used in order to model the decay heat present in the canister at the time of storage, and throughout 50 years of life within the canister. This was done to provide a very accurate approximation of the actual heat load in the canister for a common Westinghouse 17 $\times$ 17 fuel assembly with an initial enrichment of 4.5% and a burnup of 45 GWd/MTU.

To better improve the accuracy of the simulation result and guide the future canister design, the present paper introduces an improved model for thermal-fluid dynamic simulations of an

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