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Thermal Evaluations for Hypothetically Drain-Down Spent Fuel Storage Facility at SRS

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INTRODUCTION

The L-Area Spent Nuclear Fuel (SNF) underwater storage facility at Savannah River Site (SRS), referred to as L-Basin SNF facility, has an array of Vertical Tube Storage (VTS) racks and a group of High Flux Irradiation Reactor (HFIR) fuel cores. The underwater facility is integrally designed as a wet SNF storage system with a chemically-controlled water pool. The SNF storage racks are seismically qualified. The L-Basin pool holds about 3.4 million gallons of water with concrete wall thickness of about 5ft and water depths of 17 ft to 30 ft. The facility has mainly two different elevation levels of 30 ft and 17 ft below the ground level. At the level 30ft below the ground, a maximum of 110 racks of VTS and 5 racks of Dry Cave can be stored. At the level of 17 ft below the ground, 120 HFIR cores can be stored, considering that each rack contains two HFIR cores. In case of a hypothetical accident, all cooling water in the storage pool may be drained away, resulting in dry SNF storage condition.

The primary objective of the work is to estimate the maximum fuel temperature in a conservative manner when the L-Basin facility is completely dry due to the hypothetical drain-down of the pool water. A three-dimensional Computational Fluid Dynamics (CFD) modeling approach was taken for the thermal evaluations of the water-drained SNF storage facility. The modeling calculations were performed, assuming that all of the storage racks in L-Basin are fully loaded with SNF assemblies containing decay heat sources. In the case of full loading, the L-Basin facility stores 14,600 SNF assemblies in VTS racks and 120 cores in HFIR racks.

The thermal analysis results of the L-Basin model yielded maximum temperatures of VTS and HFIR fuel assemblies for different fuel loading scenarios and boundary conditions of the SNF storage racks.

DESCRIPTION OF THE ACTUAL WORK

The basic solution method was based on a two-step scaling approach of the macro and micro modeling approaches under steady state conditions for computational efficiency as shown in Figure 3. The two-step model consists of macro model as a macroscopic integral model and micro model as a detailed component model to minimize computational time because the computational domain contains a very large scale of storage space and a large number of fuel racks. The macro model was based on the rack homogenization to provide thermal ranking information regarding the peak location of the fuel bundle rack to be used for conservative differential loading patterns and to provide boundary conditions for the detailed micro model. The micro model was based on a detailed prototypic configuration for estimation of maximum fuel temperatures for a given loading scenario.

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Main approach and assumptions used for the present work are as follows:

- All modeling calculations were based on steady state conditions.
- All VTS racks consisted of Missouri University Research Reactor (MURR) SNF assemblies for a conservative thermal estimate.
- Prototypic geometry for the L-Basin storage facility was created by using the boundary-fitted coordinate system under a three-dimensional CFD domain.
- Major obstructions such as the concrete curbs between the racks were included, neglecting ground-level platforms above the disassembly basin.
- No ventilation system was available for the conservative assessment.
- Solar heat was considered by using 10 CFR 71.71 (800 watts/m^2 for top flat surface, 200 watts/m^2 for vertical flat side wall based on 12-hour period [3].).

- Soil region surrounding the storage facility was included with 150-ft soil depth, and the boundary of the soil region could be kept constant, 68°F.
- Ambient temperature was kept at 100°F for a conservative estimate.
- When maintenance and operation rooms adjacent to the storage facility are present, the room temperatures are kept at 150°F.
- Air was assumed to follow the ideal gas behavior, considering temperature-induced natural convection.
- All internal airflows driven by local temperature gradients were assumed to be laminar for a conservative estimate of natural convection.

The steady-state three-dimensional equations governing the heat transfer problem of the SNF storage facility in SRS L-Basin under the Cartesian coordinate system are shown below.

For the mass continuity,

$$\sum_{i=1}^{3} \left\{ \frac{\partial \left(\rho u_i \right)}{\partial x_i} \right\} = 0 \tag{1}$$

where the variables with the subscript, i = 1, 2, or 3, correspond to those of the x-, y-, or z-direction, respectively.

For the momentum equation in tensor notation,

$$\rho u_j \frac{\partial u_i}{\partial x_j} - \frac{\partial \sigma_{ij}}{\partial x_j} - X_i = 0 \tag{2}$$

where

$$\sigma_{ij} = -\left(P + \frac{2}{3}\mu \frac{\partial u_k}{\partial x_k} \right)\delta_{ij} + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \; \delta_{ij} = \begin{pmatrix} 1 \, for \, i = j \\ 0 \, for \, i \neq j \end{pmatrix}$$

The first term is rate of momentum increase per unit volume, and the second term in Equation (2) represents stress force per unit volume. A parameter σ_{ij} in the equation is stress tensor. All other parameters of the momentum equation are defined in the Nomenclature section. For the present modeling domain as shown in Figure 6, the gravity forces per unit volume along the horizontal x and y coordinates are zeros, $X_1 = X_2 = 0$, and the gravitational term of the momentum equation along the vertical z coordinate, X_3, is used to include the buoyancy-induced natural convection. The work neglects all variable property effects due to temperature change in the governing equations except for air. The thermal conductivity of air is considered to be dependent on temperature, and air density is approximated as an ideal gas under 1 atm ambient pressure, that is, the gravity term in the z direction in Eq (2), $X_3 = -\rho g$.

When the conduction, convection, and radiation heat transfer mechanisms are applied for the evaluation of the thermal performance for the L-Basin SNF storage facility, the steady-state energy balance equation under the Cartesian coordinate system is shown below.

$$\rho C_p u_j \frac{\partial T}{\partial x_j} - \sum_{i=1}^{3} \left\{ \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} - q_{r,i} \right) \right\} - q''' = 0 \tag{3}$$

The first term in Equation (3) is a natural convective term derived by local air velocity u_j induced by the air temperature gradient inside the fuel storage facility, assuming indoor air to follow the ideal gas behavior, and the radiation heat flux term $q_{r,i}$ in the equation was calculated by the discrete ordinate method [4]. The viscous dissipation term was not considered in the present model because the storage facility with the ventilation system turned off is assumed to be naturally convective. The decay heat source term q''' is provided to the energy equation as a model input.

Complete setup of the modeling calculations requires the input parameters such as thermal and material properties of the storage components, heat source term, boundary conditions, and domain discretization, along with the established modeling domain and assumptions. They will be discussed subsequently.

As discussed previously, the modeling domain includes the disassembly basin consisting of 30 feet level of VTS racks and dry cave VTS, 17 feet level of HFIR racks, transfer bay building, and ventilated cooling fan room at south side wall, including two doors open at north wall side and one breathing hole of 4 feet wide and 4 feet long at the roof of the transfer bay. The computational domain for the macro model was discretized for the numerical calculations in a three-dimensional domain. Optimum number of discretized meshes was established to be 6 x 10^6 from the mesh sensitivity analysis.

For a detailed calculation of the assembly level, the micro model was developed to calculate maximum temperature of SNF assembly region for the domain boundary conditions as provided by the macro model for a given bundle power. The model consisted of four fuel bundles. Each bundle had four fuel assemblies in series. The modeling domain for prototypic 4x1 fuel bundle geometry containing four 24-inch fuel assemblies was discretized for the calculations. The total number of meshes for the modeling domain was established as 3x10^6 mesh nodes for the detailed calculations. Typical computational time for each of the two modeling domains required about two weeks when eight cpu's were used in a parallel way under SRNL high performance computing platform.

For the calculations, a commercial CFD software, ANSYS-FLUENT [2], was applied to the modeling domain. The benchmarking tests related to the current CFD model were made as the typical cases representing the physical cooling mechanisms of convection, conduction, and radiation.

Thermal heat dissipation through the wall boundaries of the L-Basin storage building is not symmetric about the central axis of the building. This requires full domain of three-dimensional modeling calculations. The above-grade building walls and roof are exposed to direct solar radiation. Cooling mechanisms for the modeling domain are conduction and radiation coupled with natural convection to the indoor ambient air within the storage facility.

For the analysis, all racks of the storage facility were assumed to be cooled by natural convection, neglecting forced convective ventilation system. The heat transfer coefficient at the outside wall of the facility (h_w) was obtained by using an empirical correlation available in the literature. In this situation, the natural convection flow regime for the air-cooled design should be estimated based on the non-dimensional Grashof number (Gr_L), which is the parameter describing the ratio of buoyancy to viscous forces for a vertically-oriented cylinder with height L. The Grashof number performs much the same function for natural convection flow as the Reynolds (Re) number does for forced convection. Under normal conditions one may expect that the laminar-to-turbulent transition will take place between $Gr_L \approx 10^9$ and 10^{10} [5].

A typical natural convective heat transfer coefficient (h_w) of 1.5 W/m^{2}K was used as an external wall boundary condition from the previous work [1,3]. The value of the heat transfer coefficient can be justified on the following basis.

For a conservative calculation, a low temperature gradient at the wall boundary layer was used to estimate the natural convection capability for the present geometrical configurations. The heat transfer coefficient (h_w) for natural convective cooling under a turbulent flow regime ($\mathrm{Ra}_f = Gr_L Pr_f > 10^9$) is given in terms of non-dimensional numbers empirically.

$$Nu_L = \frac{h_w L}{k_w} = C\left(Gr_L \Pr_f\right)^m \quad \text{for } Gr_L \Pr_f < 10^{12} \tag{4}$$

where C and m are the coefficients determined from literature data and L is the characteristic length of the facility.

For the present geometrical configuration, C=0.10 and m=0.33 are given by Warner and Arpaci using the experimental data [6]. In this case, Prandtl number, Pr, for the cooling media is close to unity because the L-Basin storage facility is filled with air. From Equation (4), the external wall heat transfer coefficient of about 1.5 W/m^{2}K, corresponding to $Nu_L \approx 190$ under the present conditions, was used for a conservative estimate of component temperatures inside the dry storage facility.

For the modeling calculations, the boundary temperature of the soil domain surrounding the L-Basin storage facility was kept at 68°F, assuming the soil medium to be an infinite heat sink. The sensitivity calculations of the thermal penetration depth for various sizes of soil domain were performed for a typical SNF decay heat. The results indicate that when size of soil domain is larger than about 115 feet, the thermal gradient becomes insensitive to the soil depth. The results are consistent with the literature results [7]. Based on the sensitivity results, 150 ft soil region was chosen in the present calculations as a domain size of soil region for a computational boundary.

One door is 9.6 ft wide and 12.5 ft high at the corner of the North-Western (NW) side, and the other is 4 ft wide and 25 ft high in the middle of the north side. For the thermal sensitivity evaluations of the L-Basin SNF facility for different modeling cases, physical conditions at the domain boundary and decay heat source terms for the SNF regions were applied to the computational domain.

For the sensitivity calculations, three different opening sizes of the door at the corner wall boundary of the NW side were considered for the sensitivity assessment of the thermal rankings and performance with respect to the nominal facility operation case during the hypothetical water drain-down accident of the L-Basin SNF storage facility. This paper will focus on presenting the results for the nominal operating conditions due to page limit. For computational efficiency, each of the SNF fuel racks was assumed as a single homogeneous material zone instead of multiple material zones by considering effective thermal conductivity.

Table 1. Material and thermal properties used for the analysis

Material	Thermal conductivity (W/mK)	Density (kg/m3)	Specific heat (J/kgK)
Concrete	1.5	2400	750
Aluminum	202	2700	900
Fuel	39.5	2093	300
soil	1.25	2000	1450
Air	0.03	Ideal gas	1000

RESULTS AND SUMMARY

Three-dimensional steady-state CFD models were developed for thermal performance evaluations of the SNF temperatures when all water in L-Basin storage pool was completely drained away in the case of a hypothetical accident. The modeling calculations were performed, assuming that the storage racks are fully loaded with SNF assemblies containing a series of different decay heat sources. The model was benchmarked against the theoretical results and literature data. Based on the verified model, several sensitivity calculations with respect to nominal operating case were performed.

The calculation results show that when SNF fuels are fully loaded with uniform decay heats of 250W VTS bundle and 400W HFIR core, maximum SNF temperature reaches 282^{o}C (540^{o}F) in the case of a hypothetical drain-down accident. The temperature distributions for the VTS and HFIR racks are presented in Figures 1 and 2. The conservative results demonstrate that the maximum SNF temperature does not exceed a temperature limit 400^{o}C (752^{o}F) in the case of hypothetically dry storage conditions.

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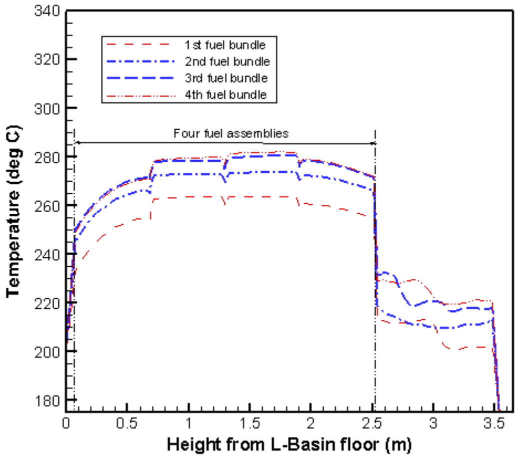

Figure 1. Temperature distributions for each of the four bundles along the vertical height from the L-Basin floor (250-watt per bundle VTS rack)

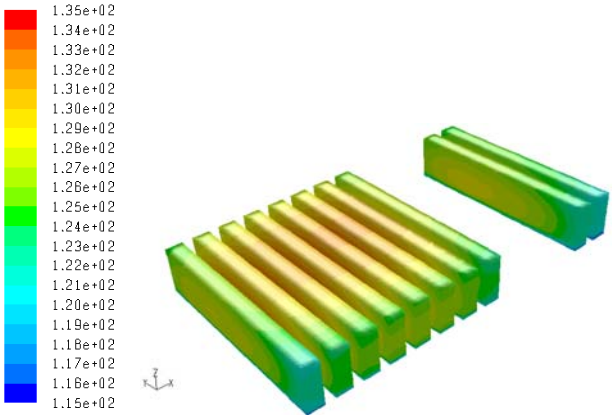

Figure 2. Surface temperature distributions and maximum HFIR temperature 142^{o}C for 400-watt HFIR core (Numbers in the figure are in ^{o}C.).