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Thermal Performance Sensitivity of SNF Storage Rack depend on Heat Distribution

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1. Introduction

The objective of a thermal evaluation of a spent fuel storage system is to ensure that a decay heat removal system is capable of a reliable operation so that the temperatures of the spent fuel and storage system components remain within the allowable limits under normal, off-normal, and accident conditions. A spent fuel cladding must be protected from a degradation during a storage, which could lead to a gross fuel rupture. Zircalloy fuel cladding temperature limit at the beginning of a dry storage is typically below 380 ◦C for a 5-year cooled fuel assembly for normal operations. The fuel temperature should also be maintained below 570 ◦C for the short-term off-normal and accident conditions. The storage rack shall be designed to allow natural convection coolant flow to remove the maximum decay heat generated by the fuel assemblies. Therefore, the pool water temperature will be maintained in the range of 40˚F(4.4℃) to 150˚F(65.6℃) and maximum temperature will not exceed 230˚F(110℃). Much of the thermal performance assessment is conducted the conservative views of the safety. However, the research for quantitative analysis result of various conservatism factors is rare. In this research, 3-D computational fluid dynamics (CFD) have been used to the analysis for the conservativeness is performed the effect of thermal performance with heat distribution for spent fuel.

2. Methods and Results

2.1 Assumptions

The following assumptions are chosen to render a conservative portrayal of thermal-hydraulic conditions in spent nuclear fuel storage pool (SFP).

a. Minimum center-to-center pitch of two type of region I racks is used in local water temperature analysis. This maximized volumetric heat generation as an input data of CFD analysis.
b. The inertia. Resistance of the fuel assemblies stored in the fuel racks includes expansion and contraction flow losses through the space grids. Assuming extremely thick grid spacer foils conservatively maximizes the flow restriction at the grid spacers.
c. All rack cells are assumed to be 50% blocked at the top of cells.
d. All fuel assemblies are assumed to have the flow resistance of the pedestal cells. These cells have more restrictive flow resistance characteristics compared to non-pedestal cells. These cells have the minimum available flow area for the cooling of the fuel assemblies.
e. No downcomer flow is assumed to exist between the rack modules.
f. 50% of the assemblies in the discharge batch are conservatively assumed to emit heat at the peak fuel assembly heat emission rate. These peaked fuel assemblies are conservatively assumed to be located in a continuous area in the freshly discharges fuels region racks.

2.2 Analytical Method

There are several significant geometric and thermal-hydraulic features of SFP with need to be considered for a rigorous CFD analysis. From a fluid flow modeling standpoint, there are two regions to be considered. One is the bulk pool region where the classical Navier-Stokes equations are solved with turbulence effects included. The other is the heat-generating zone of spent fuel racks loaded with fuel assemblies, located near the SFP bottom. In this region, water flow is directed vertically upwards by the buoyancy forces through relatively small flow channels formed by the fuel assembly rod arrays in each rack cell. This situation is modeled as a porous solid region in which the classical Darcy's Law governs fluid flow.

2.2 CFD Analysis

The CFD analysis is performed using the industry standard ANSYS FLUENT fluid flow and heat transfer modeling program. The FLUENT program enables buoyancy flow and turbulence effects to be included in the CFD analysis. Turbulence effects are modeled by relating time-varying Reynolds Stress term to the mean bulk flow quantities by the k-ε turbulence model. The number of total calculation grids is about 900,000, which is generated in hexagonal mesh form.

The distributed heat sources in the SFP racks are modeled by identifying distinct heat generation zones considering full-core discharge, peaking effects and presence of background decay heat from old discharges. Three heat generating zones were modeled. One is background fuels (Cold region) from previous discharges. Others are freshly discharges fuels that differentiated by one zone with higher (Hot region) than, and the other with less (Warm region) than, the average decay heat generation of full cores. All of these three regions and in/outlet boundaries are depicted in figure 1. Figure 1 shows the SFP geometry developed for CFD analysis. The heat generating fuel racks region, inlet and outlet are shown in this figure. A mass flow rate of inlet and outlet is 3,500 gpm and inlet temperature is 50.3℃. Heat generation rates of spent fuel regions are 401820, 234515 and 5050 W/m^3 in hot, warm and cold regions. Figure 2 shows heat generation rate by height in spent fuel regions that depend on uniform (Case A) and based on peaking factor (Case B).

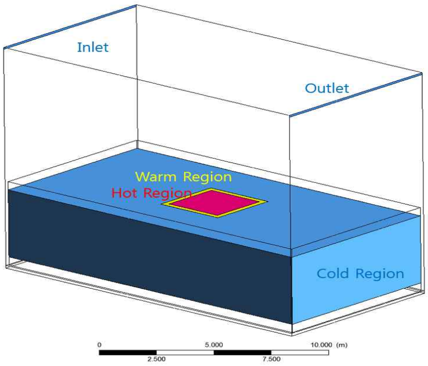

Fig. 1. Analytical model of the spent fuel pool.

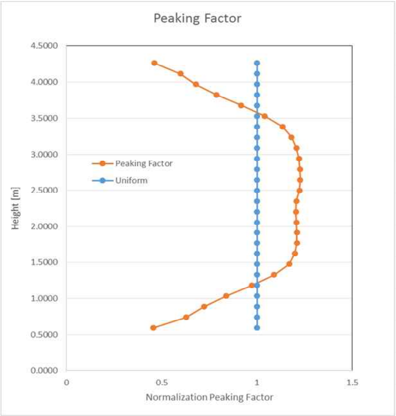

Fig. 2. Peaking factor of decay heat generation regions.

2.4 Analytical Results

A steady-state solution of the assembled CFD model is performed to obtain the SFP flow and temperature field. Temperature contours of Case A and B are shown in fig. 3. The plot confirm that hot fuel is safely and reliably cooled by thermo-siphon action. Local hot spots induced by water natural circulation in the racks are rapidly dissipated in the pool water resulting in a nearly uniform temperature distribution away from the hot racks. A similar trend is confirmed in the Case A and Case B. The peak local temperature near the top of the fuel assemblies is predicted to be 97.4℃ and 98.2℃in Case A and Case B.

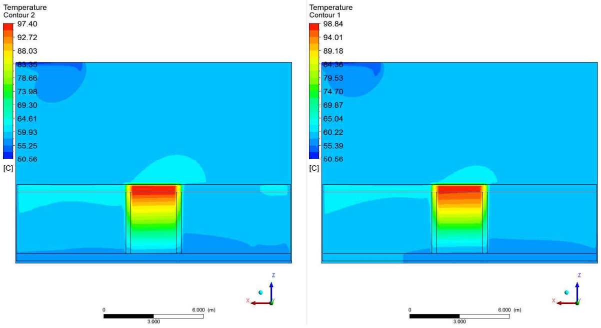

Fig. 3. Comparison of local maximum temperature between Case A and B.

3. Conclusions

The SFP temperature should be maintained under the saturation temperature. At the top of racks, the location is approximately 7.8 m below the water surface. Therefore, acceptance criteria for local maximum temperature of SFP is the local saturation temperature that is 115℃. From the CFD analysis results of Case A and Case B those are concluded that the local water temperature remains below saturation temperature.

The local maximum temperature of Case B is higher than Case A about 1.4℃. Thus, the analytical method using ununiformed heat generation rate based on peaking factor has more conservativeness than uniformed heat generation rate in the conservative views of the safety.

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