EX155

Spent Fuel Heat-up

FLUENT is used in this example to study the flow and heat transfer inside a containment building used to store spent nuclear fuel rods. Ordinarily, the rods are immersed in a pool of coolant, but in this accident scenario, the coolant is assumed to have completely leaked from the pool and storage region. Results illustrate the three-dimensional nature of the natural convection that cools the rods, and suggest that simplified one-dimensional codes cannot account for the thermal variations that give rise to the complex circulation patterns that develop.

Courtesy of the US Nuclear Regulatory Commission

In support of the Nuclear Regulatory Commission (NRC) rulemaking activity related to decommissioning, the Office of Nuclear Reactor Regulation (NRR) recently completed a study on spent fuel pool accident risks. In support of this effort, the Office of Nuclear Regulatory Research (RES) provided technical assistance in several areas. For one phase of their work, engineers used FLUENT to predict the fuel temperatures and local flow patterns after a complete loss of spent fuel pool coolant.

For the study performed by the NRC, a spent fuel pool in a large containment building with an operable ventilation path was modeled. The pool is filled to capacity with fuel in high density racking, which occupies the lower third of the pool. A total of 4200 fuel bundles of various ages are contained in the pool. A complete reactor core consists of roughly 800 fuel bundles. It is assumed that the rack is filled from right to left over several years of reactor operation. The 800 bundles on the left of the pool are the freshest bundles, assumed to have come from the final core offload. These release the highest amount of energy. The energy released from the fuel decreases over time.

The fuel rack region is modeled as a porous medium with a variable heat source. Steady-state simulations are performed that represent the pool 2, 3, 4, and 6 years after the reactor is shut down. For the project, sensitivity studies were done on the ventilation rate, the outer wall heat transfer coefficient, the location of the hottest fuel, fuel burnup, the flow resistance within the racks, and heat conduction within the racks. Only the decay time and outer wall thermal boundary condition studies are reported here. The simulations do not include terms for radiation or exothermic cladding reactions. These terms are significant at temperatures greater than those focused on in the study.

The main building (Figure 1) is sized to represent a boiling water reactor (BWR) containment. No internal structures are modeled.

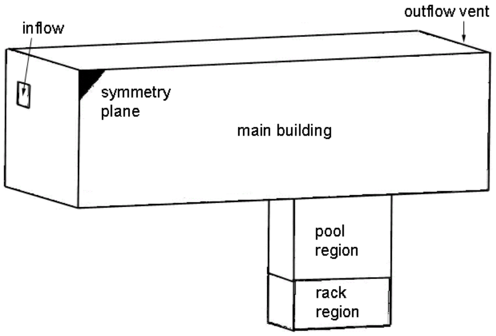

Figure 1: The containment building with the pool region above and throughout the rack region, where the spent fuel rods are stored

The size and location of the containment (rack) region relative to the fuel pool is shown. This figure represents the CFD model domain, which is one half of the symmetric physical structure.

The steady-state base case simulation represents a 4 year decay time (since the reactor shutdown). All external walls are assumed adiabatic. The ventilation rate is based on two building volumes per hour. The

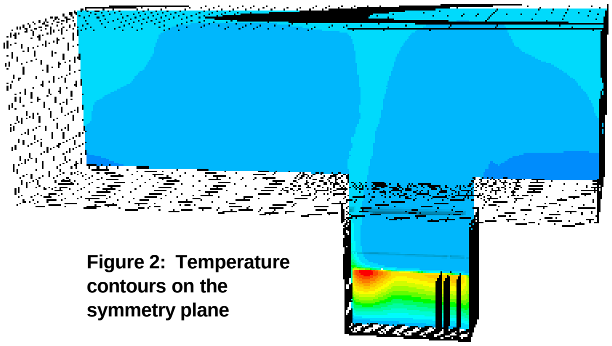

Figure 2: Temperature contours on the symmetry plane

maximum temperature predicted during this scenario varies with the time the fuel rods have spent in the pool. In Figure 2, peak temperature is observed near the top of the hottest fuel (that most recently loaded into the racks) and is on the symmetry plane. A warm plume can be seen rising from the side of the pool containing the hottest fuel. Part of the walls between the fuel types are included in the illustration as a visual aid.

An isosurface of temperature (400 C) in Figure 3 shows the inlet air entering the containment building on the left and falling to the floor and into the rack region. This relatively cool air spreads around the rising hot plume exiting the pool. The air on the floor of the containment building is relatively well mixed. The average temperature difference between the floor and the ceiling in the building is approximately 30 C.

The primary sensitivity study focuses on the decay time, set as the time since the reactor shutdown. As the decay time increases, the heat load from the fuel decreases. Decay times of 2, 3, 4, and 6 years are studied by performing steady-state simulations at each of these times and making adjustments to the heat released by the rods. All other conditions are identical. Predicted temperatures are plotted in Figure 4. At each of these decay times, the peak temperatures in the hottest fuel were of interest. The maximum temperature decreases significantly between 2 and 4 years, and less from 4 to 6 years.

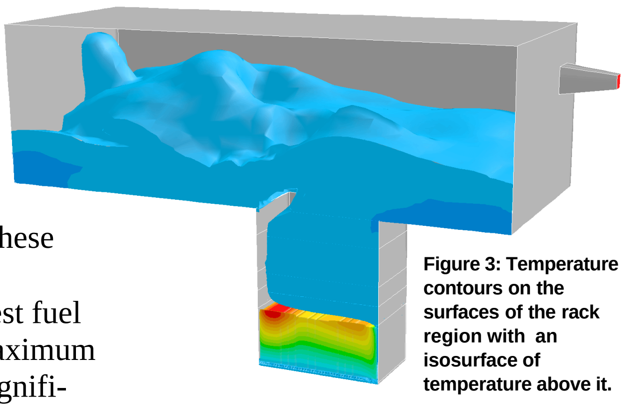

Figure 3: Temperature contours on the surfaces of the rack region with an isosurface of temperature above it.

In another phase of the work, a sensitivity study was done to study the overall heat transfer coefficient between the containment building and the exterior environment. Containment wall and ceiling heat transfer coefficients of 2 and 4 W/m^2-K were applied to the 4 year decay time base case. Predicted temperature results from these simulations are plotted in Figure 5 along with those for the 0 W/m^2-K (adiabatic wall) case. The temperatures drop predictably as the heat transfer coefficient is increased.

A number of simplified codes, such as SHARP, SFUEL, and COBRA-SFS are typically used for pool heat-up predictions. Some have sophisticated physical models tailored specifically to fuel bundle analysis. These codes use idealized conditions above, below, and inside the rack region, however, to represent flow conditions. They do not account for the full variations in velocity, pressure and temperature in the rack region that govern the three-dimensional nature of the flow. By contrast, the CFD results provide additional insight into an accident scenario of this type by focusing on global three-dimensional flow fields in the racks, pool, and surrounding buildings. This is significant since the natural circulation is the most important factor in removing heat from the fuel under these conditions. This knowledge has helped reduce the uncertainty associated with this important aspect of spent fuel pool cooling. The results of the analysis showed that for spent fuel with a decay time of more than about four years, the air alone can keep the fuel temperature below 600 C.

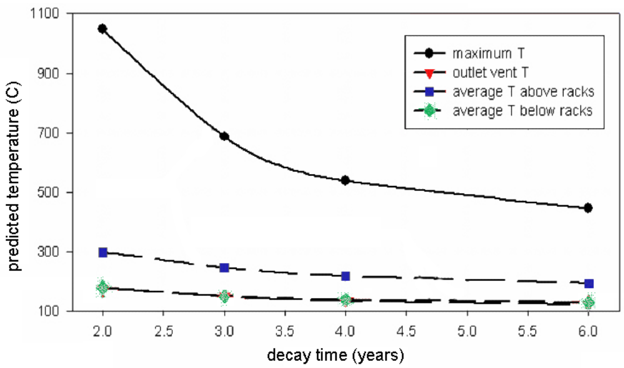

Figure 4: Predicted temperatures as a function of decay time

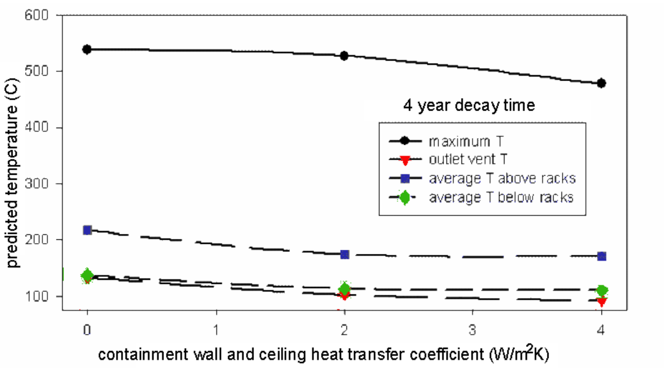

Figure 5: Sensitivity of temperature to external heat transfer coefficient