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Advanced modeling techniques of a spent fuel pool with both RELAP5 and MELCOR and associated accident analysis

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ABSTRACT

A spent fuel pool (SFP) is designed as a temporary storage facility for spent fuels before the spent fuels can be shipped away for intermediate storage or reprocessing. Although the likelihood of an SFP cooling accident is extremely low, the SFP event at the Fukushima Daiichi unit 4 demonstrated how confusion and lack of information during the progression of an SFP accident could adversely contribute to emergency response actions. Advanced SFP modeling schemes for both RELAP5 and MELCOR were successfully developed to analyze accidents of SFP. According to the heat load density, an SFP was divided into one high power region for the latest discharged fuel bundles and several regular power regions for other fuel bundles with proper lumping schemes. Particular to the RELAP5 modeling, a 3×3 hot channel model was also included in the high power region to calculate the interactive responses between adjacent bundles. Detailed thermal hydraulic responses of regions with different power densities, including the hottest bundle, can all be properly simulated. The detailed thermal hydraulic responses observed include temperature rise and inlet mass fluxes driven by bundles with different power, termination of natural circulation flow by descending water level, and sequential heat up of bundles with different powers. A comparison of the counterpart calculation of a loss-of-cooling accident before fuel degradation with both RELAP5 and MELCOR is also demonstrated, and general consistency between the two codes is observed. The SFP RELAP5 model was further applied to evaluate SFP emergency operation procedures involving makeup and spray mitigation in the event of loss-of-cooling or loss-of-coolant. Moreover, the SFP MELCOR model was also applied to calculate severe accident progression after a loss-of-cooling accident in the SFP. The entire progression calculated by MELCOR successfully demonstrates the capability of MELCOR to calculate the SFP responses covering both thermal hydraulics and severe accident progression during an accident involving both loss-of-cooling and loss-of-coolant accidents.

1. Introduction

Spent nuclear fuels are continuously discharged from operating reactors and are stored temporarily in a spent fuel pool (SFP) for further reprocessing and ultimate disposal. As the interim storage to accommodate large quantities of spent fuels, the SFP is designed to preclude the possibility of criticality accidents and to remove the substantial decay heat generated by spent fuel assemblies from the storage pool water, which also provides adequate shielding from radiation (USNAS, 2005). Although the likelihood of an SFP cooling accident is extremely low, the cooling capability or the structural integrity of the pool can be compromised by a beyond design basis seismic event (Sailor et al., 1987). The SFP event at the Fukushima Daiichi unit 4 demonstrated how confusion and lack of information during the progression of an SFP accident could adversely contribute to the emergency response actions without the availability of reliable instrumentation or procedures (USNRC, 2012). This raised concerns that the loss of cooling and/or coolant might result in heating up and boiling off SFP coolant inventory, and possibly leading to fuel damage and radiation release (Gauntt et al., 2012; USNRC, 2013).

Several previous studies have been performed to assess the potential risks of SPFs (Benjamin et al., 1979; Boyd, 2000; Collins et al., 2001; USNRC, 2013). In general, the study of an SFP accident involves either a loss-of-coolant inventory or a-loss-of-cooling capacity (USNRC, 1997). The loss-of-cooling capacity of an SPF can be caused by a loss of SFP cooling flow or due to a failure of the SFP heat sink. A loss-of-cooling accident would result in heat up and boiling off of the SFP coolant inventory. Subsequently the fuel elements would heat up after the active fuel assemblies are uncovered. Once the fuel rod temperatures reach a threshold tem-

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perature of about 1100 K (Urbanic et al., 1978), an enhanced oxidation reaction can occur in a steam or air condition (Duriez et al., 2008). The large quantities of extra heat produced by oxidation may exceed the spent fuel decay heat, resulting in a rapid escalation of the cladding temperature and subsequent fuel degradation, which can even trigger a zirconium cladding fire (Best et al., 1983). As a byproduct of zirconium-steam oxidation, hydrogen gas will be generated. If the conditions are appropriate, a hydrogen explosion may occur, which could possibly cause structural damage to the containment, and increase the release of radioactive fission products from the SFPs into the environment.

To analyze accident responses following a loss-of-cooling or loss-of-coolant event in the SFP, advanced modeling schemes of SFPs for transients analysis have been developed using both RELAP5 (INL, 2001) and MELCOR 1.8.6 (Gauntt et al., 2005). RELAP5 has the capability of non-homogeneous, non-equilibrium two-fluid flow model to simulate a wide variety of hydraulic and thermal transients in an SFP. MELCOR possesses the general capability to treat the full spectrum phenomena (including severe accidents) that could occur during an accidental condition in the SFP. According to the heat load density, an SFP was divided into one high power region for the latest discharged fuel bundles, and several regular power regions for other fuel bundles with proper lumping schemes. Particularly in RELAP5 modeling, a 3×3 hot channel model was also included in the high power region to calculate the interactive responses between adjacent bundles. Before entering the condition of a severe accident, both RELAP5 and MELCOR appear to be suitable tools to analyze SFP thermal hydraulics during the accident progress, including different temperature rise and inlet mass fluxes driven by bundles with different powers, termination of natural circulation flow by descending water level, and sequential heat up of bundles with different powers. Moreover, MELCOR can perform extended evaluation of the accident progress in SFPs involving thermal hydraulic, core uncover, core damage, core relocation, vessel failure, and fission product release and transport.

In this paper, detailed SFP modeling schemes using both RELAP5 and MELCOR are presented, and a counterpart calculation between the two codes is also included, focusing on the thermal hydraulic response of a loss-of-cooling accident. Moreover, the application of the RELAP5 model to evaluate SFP emergency operation procedures is also performed. Finally, a complete progression including thermal behaviors and severe accidents in the SFP is also presented via MELCOR calculation.

2. Design features of typical SFPs

2.1. Configuration of an SFP

In general, most boiling water reactors (BWRs) are designed with SFPs within the reactor building well above ground level; whereas SFPs of pressurized water reactors (PWRs) are located in an auxiliary building or within a fuel handling building adjacent to the containment, almost at ground level (USNRC, 1997). The configuration of spent fuel storage pools is similar for most nuclear plants. A typical SFP of a Fukushima-typed BWR employing a Mark-I containment system is analyzed in the present analysis. Fig. 1 shows the pool layout of fuel storage racks. The pool contains 14 fuel storage racks and a cask loading region in the northeast corner. Each storage rack consists of roughly 16×16 cells.

Fuel assemblies are vertically stored in stainless steel storage racks embedded with neutron-absorbing material. All the racks are submerged with about 7.2 m of water above the top of the fuels for radiation shielding. The storage racks are about 4.5 m in height and are installed near the pool floor. The rack base plate is designed to support fuel assemblies and is made of stainless steel with an inner diameter orifice, which provides the inlet channel for circulating water. The height of the base space, beneath the rack base plate providing the inlet region for circulation of the coolant, is about 20 cm.

2.2. Decay power distribution of spent fuels

The present layout of all the assemblies includes fuel discharge batches going back to more than three decades of operation from the oldest discharge, Cycle 1, to the most recent offload, Cycle 25, in the SFP as shown in Fig. 2. One hundred assemblies from the latest discharged Cycle 25 are located in the racks marked J and F1 near the center of the pool. It can be seen that unloaded empty cells are placed around each of the latest discharged bundles in a checkerboard pattern to reduce the power density of the associated racks and to enhance heat transfer of the high power bundles. The partial cells of rack J also contain discharged fuels from the previous cycle, Cycle 24. Assemblies discharged from Cycle 1 to 23 are distributed in the remaining rack region. Realistic decay heat calculations are performed using the Branch Technical Position ASB 9-2 (USNRC, 1981). According to the ASB 9-2 formula, the total calculated decay power is approximately 1.87 MW, of which about 20.8% is produced by assemblies from Cycle 25 and about 4.8% is produced by assemblies from Cycle 24.

3. Modeling of an SFP using Relap5 and MELCOR

3.1. SFP modeling using RELAP5

Generally, BWR SFPs contain several rack modules divided into a number of rack cells, and each cell contains one fuel bundle in a canister. Three types of flow channel can be distinguished in each rack module. They are the active fuel flow channel within the canister, the bypass flow channel in the interstitial space between the canisters and rack cell walls, and the unloaded flow channel within the empty rack cells if there are any. According to decay power distribution of the targeted SFP, the whole rack storage region was grouped into one high power set for the latest discharged fuel bundles and four regular sets for other fuel bundles in the RELAP5 SFP modeling. Particularly, to calculate the interaction between high power bundles, a 3×3 hot channel model exists in the high power set, as shown in Fig. 3. In each set, heat structures and flow channels are included. Other than the high power set with the latest discharged fuel, a general lumping technique was applied to regular sets. In each regular set, similar flow paths and heat structures were lumped. Since the empty rack cells exist only in the high power regions, therefore, in each regular set after lumping there are only two flow paths, which are one active flow paths and one interstitial bypass flow path. Besides, heat structures are applied to represent fuel rods, the fuel channel canister and the cell wall.

Regarding the high power set, there are 196 rack cells containing the latest 100 discharged fuel bundles with unloaded cells placed between loaded cells. To allocate the densest heat load location for the 3×3 hot channel model, the decay power of each bundle in this high power set was precisely evaluated separately. To investigate the interactive thermal behaviors between the high-power spent fuel assemblies, the nine rack cells of the 3×3 hot channel model were modeled separately without lumping. The 3×3 cells can be either partially or fully loaded with fuel assemblies. Other than the 3×3 hot channel model, the general lumping techniques were still applied to the remaining 187 cells (196-3×3) of the high power set.

According to the current loading pattern, the configuration of the separated 3×3 hot channel includes five hottest spent fuel