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Safety evaluation of an extended refilling mode operation after the permanent shutdown of a BWR/4 reactor

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ABSTRACT

As limited by the capacity of the spent fuel pool (SFP), the last discharged full core will remain in the core for storage for an undetermined period. As a result, an extended refilling mode operation will be expected after the permanent shutdown of a BWR/4. During the extended refilling operation, the SFP, refilling cavity and reactor vessel are all connected. In the early transition phase, the residual heat removal (RHR) system will provide cooling to the reactor core, while the enhanced SFP cooling system will provide cooling to the SFP. While after the transition phase, the enhanced SFP cooling system will provide cooling to both the SFP and reactor core. An evaluation was performed to determine the duration of the transition phase containing both RHR and SFP cooling systems. Furthermore, systematic safety analysis was also performed to ensure the safety of the extended refilling mode operation. In this paper, advanced modeling techniques for RELAP5 and MELCOR were successfully developed to analyze the thermal hydraulic response of the extended storage pool. A postulated loss of cooling accident of the extended storage pool without any emergency mitigation was analyzed by RELAP5 and MELCOR, and good agreement between these two codes was observed.

According to the steady state analysis of the extended storage pool, the early transition phase with RHR system cooling to the core will be three days, to assure the maximum water temperature in the core below the technical specification limits. Moreover, an assessment of a LBLOCA with rupture at recirculation line was performed by RELAP5 model. It was indicated that the existing makeup system cannot provide effective makeup coolant to the reactor core, unless the makeup coolant could be directed into the core shroud. It was also demonstrated by RELAP5 simulation that only the core spray can provide effective cooling to the reactor core, even under the worst recirculation line break scenario.

1. Introduction

In the nuclear industry, spent fuels are offloaded periodically from operating reactors and stored in onsite spent fuel pool (SFP) as an interim storage measure to remove residual decay heat, as well as providing radiological shielding (USNAS, 2005). Ordinarily, to provide adequate remaining storage capacity in SFP for operating reactor unloading, spent fuels in SFP should be shipped offsite periodically for reprocessing or final disposal after a term of pool residence. Generally, under normal operating conditions, SFPs are regulated to have capability to accommodate the fuels discharged from a complete core to enable operational flexibility or an unpredictable accident. Unfortunately, a nuclear power plant waiting decommissioning may possibly suffer a shortage in storage capacity of the SFP, due to the limited capability of reprocessing and the ultimate disposal in question due to environmental consideration. In the case of a fully occupied SFP, when dealing with the last spent fuels in the reactor core after permanently shutdown, an alternative for the expansion of fuel storage is to store the last spent fuels in the reactor vessel. Considering a BWR/4 reactor, the SFP can be intercommunicated with the reactor vessel via the reactor cavity by means of opening the SFP movable gate and removal of the upper head of reactor vessel. The reactor core will be operating as a special fuel interim storage with the purpose of removing the high decay heat produced by the last spent reactor fuels. In the early transition period, the residual heat removal (RHR) system will be required to remove high decay heat from the core, and then an enhanced SFP cooling system will provide cooling to both the core and connected SFP alone.

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Several previous investigations have been carried out to assess the risk of the SFPs, especially after the SFP accident in Fukushima NPP (Benjamin et al., 1979; Sailor et al., 1987; Boyd, 2000; USNRC, 2013). In particular, the NUREG-1738 (Collins and Hubbard, 2001) provided a risk assessment of potential severe accident scenarios associated with SFPs and evaluation to estimate the likelihood and consequences of accident scenarios for the decommissioning facilities. However, perceptions regarding the operation of an extended storage pool containing SFP, refilling cavity and reactor vessel, were insufficient. Moreover, the likelihood of potential accident challenging to the cooling and integrity of the extended storage pool is more complicated than that of an isolated SFP. As a result, the assessment of the capability of the cooling system and emergency mitigation to ensure the cladding integrity of spent fuels stored in the reactor and SFP, is essential.

To perform thermal hydraulic analysis of an extended storage pool for spent fuel cooling of a BWR/4, both RELAP5 (INL, 2001) and MELCOR (Gauntt et al., 2005a,b) code were adopted to develop the modeling techniques for the extended storage pool. MELCOR is a fully integrated, engineering-level code and possesses a broad capability to model thermal-hydraulic response and severe accident progression. Although MELCOR is less rigorous than RELAP5 in those fundamental thermal hydraulics calculations, it is currently the most advanced tool for severe accident calculation and it still can perform reasonable fundamental local thermal hydraulic calculation before entering into severe accident phenomena. Focusing on the thermal hydraulic response, both RELAP5 and MELCOR has the capability to analyze the entire spectrum of transient occurring in extended regular SFP under normal and postulated accident condition (INL, 2001; Gauntt et al., 2005a,b). The objective of the counterpart calculation between the two codes is principally to afford a mutual verification of the integral effect evaluation for the thermal hydraulic response in the extended storage pool, so that appropriate thermal dynamic behaviors of the extended storage pool can be correctly simulated.

In this paper, the modeling techniques for the extended storage pool applied by both RELAP5 and MELCOR are presented. A counterpart calculation of a postulated loss of cooling accident of the extended storage pool without any emergency mitigation was performed. The predictions of the important timing including the pool reaching boiling temperature, the water level descending to the minimum shielding depth, the bottom of SFP gate and the top guide of the core, and the clad temperature escalation after core uncovery, will be compared.

With the verified RELAP5 model, a steady state performance evaluation of the extended SFP cooling system will be evaluated, and the required RHR core cooling period right after shutdown will be quantified. Regarding the steady state performance analysis, water temperature distribution, natural circulation flow, temperature rise and mass flow in core will all be evaluated. Finally, an evaluation for the mitigation capability of the existing SFP makeup system under loss of coolant accident induced by a postulated pipe rupture at the recirculation system will be performed to ensure effective cooling to the reactor core, even under the worst recirculation loop line break scenario. Furthermore, provided the makeup system cannot provide sufficient cooling to the core, the mitigation function of RHR core spray under the worst loss of coolant scenario also will be evaluated.

2. Description of the extended storage pool

2.1. Configuration of the extended storage pool

Typically, a BWR/4 reactor pressurized vessel is housed in a drywell that located adjacent to the SFP structure for a BWR reactor plant. Exception for the duration of refueling operations, the SFP movable gates separate the SFP from the adjacent refueling cavity above the reactor vessel. Fig. 1 shows the configuration of the reactor vessel, adjacent refueling cavity and the SFP. In order to interconnect the SFP with the reactor vessel, the SFP gate would be opened to interconnect the SFP and adjacent refueling cavity above the reactor vessel. The upper head of the reactor vessel would also be removed, as well as all of the upper internals including steam dryer assembly and separator assembly in the reactor vessel. In so doing, the upper space above the upper plenum of the core would be vacated. The refueling cavity above the reactor vessel would be filled with water to equal the water level of SFP. Hence, the extended storage pool would be a combination of the SFP and the pool of refueling cavity and reactor vessel.

The SFP is rectangular in cross section and the pool contains several fuel storage racks and a cask loading region in the northeast corner. In a BWR containment design, the bottom of the SFP movable gate is above the top of racks in the SFP to separate the SFP from the adjacent reactor cavity for remaining water level always above the spent fuels in case of a loss coolant inventory in reactor vessel or refueling cavity during refueling operation.

2.2. The cooling system for the extended storage pool

Generally, the removal of decay heat from spent fuel assemblies in the SFP is provided by the spent fuel pool cooling and cleanup system (SFPCCS), which takes suction from the overflow from the SFP and pumps the coolant into SFP through heat exchangers (USNRC, 2007a). Since the heat load of the extended storage pool is primarily dominated by the reactor core, a new dedicated spent fuel cooling system (enhanced SFPCCS) was proposed as a substitute for the existing SFPCCS to provide the adequate cooling for the reactor core. The enhanced SFPCCS takes suction from the SFP at a certain elevation above storage racks, pumps the coolant through heat exchangers for removing the decay heat, and returns to the pool near the bottom of the refueling cavity. Circulation flow with the maximum capacity of 332.42 kg/s (2400 GPM) is designed for full heat removal capability. Besides, the heat exchanging efficiency of SFPCCS was considered to vary with the temperature of coolant returned from the pool. Therefore, the temperature of coolant discharged by SFPCCS also can vary with the pool returning water temperature. However, in order not to exceed the design heat load for the new cooling system, it will be necessary to remove the decay heat in the reactor core employing by the RHR system in the early transition phase. After this early transition period, the enhanced SFPCCS will be responsible for removing all the total decay from both the core and the SFP.

2.3. Decay power calculation of spent fuels in the extended storage pool

The last spent fuels stored in the reactor core will continue to generate substantial decay heat after permanently shutdown. The residual heat produced by the last spent fuels in the core is far more than the total amount of decay heat generated from the SFP during the first several weeks after shutdown. The SFP is fully loaded with more than three thousand spent assemblies including fuel discharge batches spanning over more than three decades. The calculation for the residual decay heat of spent fuels is made in accordance with the Branch Technical Position ASB 9–2 (USNRC, 1981). The heat load decayed with the time after shutdown is shown in Fig. 2. The total heat load from the SFP is about 0.68 MW, while the decay heat from the core 7 days after permanent shutdown is about 5.20 MW.