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Detailed evaluation of natural circulation mass flow rate in the annular gap between the outer reactor vessel wall and insulation under IVR-ERVC

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ABSTRACT

IVR (In-Vessel corium Retention) through ERVC (External Reactor Vessel Cooling) is known to be an effective means for maintaining the reactor vessel integrity during a severe accident in a nuclear power plant. Detailed simulations of a two phase natural circulation flow in the reactor cavity of an APR (Advanced Power Reactor) 1400 and advanced OPR (Optimized Power Reactor) 1000 under the IVR-ERVC have been conducted to determine the coolant circulation mass flow rate at the annular gap between the outer reactor vessel wall and the insulation of the reactor vessel using the RELAP5/MOD3 computer code. This coolant mass flow rate is very effective on the CHF (Critical Heat Flux) on the outer reactor vessel wall, which is a key factor to the success of the IVR-ERVC. The RELAP5 results have shown that the coolant circulation mass flow rate of a high power reactor of the APR1400 is higher than that of a low power reactor of the advanced OPR1000. Increases in the coolant injection temperature and the water level in the reactor cavity lead to an increase in the coolant circulation mass flow rate, which leads to an increase in the CHF on the outer reactor vessel wall.

1. Introduction

The IVR (In-Vessel corium Retention) through the ERVC (External Reactor Vessel Cooling) is known to be an effective means for the maintenance of the reactor vessel integrity during a severe accident in a nuclear power plant (Theofanous et al., 1996, 1997; Rempe et al., 2008). This measure has been adopted in low-power reactors, such as the AP600, the AP1000, the Loviisa nuclear power plant, and the small integral reactor of SMART, as a design feature for severe accident mitigation (Esmaili and Khatib-Rahbar, 2004; Dinh et al., 2003, 2004; Scobel et al., 2002; Kymalainean et al., 1997; Park et al., 2013), and in the high-power reactors of the APR (Advanced Power Reactor) 1400 and OPR (Optimized Power reactor) 1000 as an accident management strategy (KEPCO, 1998; Park et al., 2001). Many studies have been performed to evaluate the IVR-ERVC, but more efforts on the plant specific geometry are necessary to verify this severe accident management strategy to apply to real power plants. The IVR-ERVC has been evaluated for the APR1400 and the OPR1000.

The OPR1000, a PWR (Pressurized Water Reactor), was developed by incorporating the latest technologies and experiences in the construction and operation gained from previous nuclear power plants, including the EPRI ALWR (Advanced Light Water Reactor) requirements. The design features of the OPR1000 are a two-loop RCS (Reactor Coolant system) design and a 2815 MW core thermal power. The advanced OPR1000 has been developing for prevention and mitigation of severe accident, such as IVR-ERVC. The current OPR1000 has no design of the reactor vessel insulation for the IVR-ERVC. However, the advanced OPR1000 has the reactor vessel insulation design for the success of the IVR-ERVC.

The APR1400, which has a 3983 MW core thermal power, is an evolutionally advanced light water reactor based on the experience and technology of the OPR1000 (KEPCO, 2001). The strategy of the APR1400 for severe accident mitigation aims at retaining the molten core in-vessel first and an ex-vessel cooling of corium second in cases where the reactor vessel fails, reinforcing the principle of a defense-in-depth. When the IVR-ERVC is applied as part of a severe accident management strategy, the cavity will be flooded to the hot leg penetration bottom elevation. Table 1 shows a comparison of the design parameters of the OPR1000 with the APR1400. The total mass of the core materials of the OPR1000 is smaller than that of the APR1400, as the thermal power is small. The reactor vessel

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Table 1
Comparison of the reactor design parameters.

Design parameters	APR1400	OPR1000
Core thermal power (MW)	3983	2815
Fuel(UO_2) mass (ton)	120.0	85.6
Mass for active core zircaloy-4 (ton)	33.6	23.9
Bottom head inner diameter (m)	4.7	4.2
Bottom head thickness (cm)	16.5	15.2
Number of ICI nozzle in the lower head	61	45

size and thickness of the OPR1000 are smaller than those of the APR1000.

Fig. 1 shows a schematic diagram of the IVR-ERVC concept for the APR1400 and the advanced OPR1000. The success criterion of the IVR-ERVC achievement is determined by a comparison of the thermal load from the corium to the outer reactor vessel with a maximum heat removal rate of the CHF (Critical Heat Flux) on the outer reactor vessel wall. The CHF is determined to fix the maximum heat removal rate through the external coolant at the annular gap between the outer reactor vessel wall and the insulation of the reactor vessel. The CHF on the outer vessel wall depends on the water circulation mass flow rate. Some design improvements of the reactor vessel insulation configuration to increase the CHF by a two phase natural circulation flow between the outer reactor vessel wall and insulation material have been proposed to increase the thermal margin for the IVR-ERVC in high-power reactors. The heated lower spherical reactor vessel wall induces a two phase natural circulation flow in the annular gap between the reactor vessel wall and the insulation. In general, an increase in the mass flow rate of the coolant leads to an increase in the CHF at the lower outer reactor vessel wall, which was verified in the SULTAN test (Rouge et al., 1998).

Detailed simulations of two phase natural circulation in the reactor cavity of the APR1400 and the advanced OPR1000 under IVR-ERVC have been conducted to determine the natural circulation mass flow rate in the annular gap between the outer reactor vessel wall and the insulation of the reactor vessel using the RELAP5/MOD3 computer code (The RELAP5 Development Team, 1995). The present study is focused on the determination of the natural circulation mass flow rate for different thermal powers of

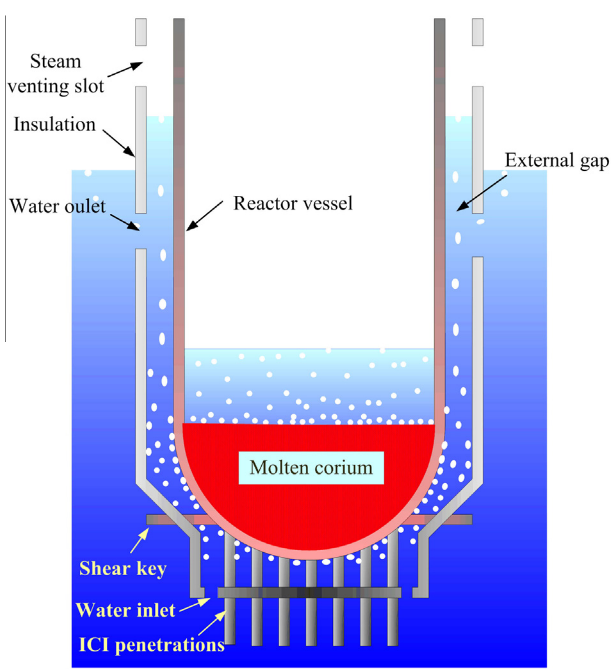

Fig. 1. IVR-ERVC concept of the APR1400 and the advanced OPR1000.

the APR1400 and advanced OPR1000. In the real IVR-ERVC condition, the coolant injection temperature and water level in the reactor cavity are different. For this reason, these effects on the water circulation mass flow rate have been investigated to suggest an optimal water injection into the reactor cavity for the IVR-ERVC.

2. RELAP5 input model

Fig. 2 shows a RELAP5 input model for the two phase natural circulation analysis in the reactor cavity under IVR-ERVC conditions, and Table 2 shows a description of each component of the RELAP5 input model. The RELAP5/MOD3 computer code was used in this simulation. The LWR (Light Water Reactor) transient analysis code, RELAP5, was developed at the INL (Idaho National Laboratory) for the U.S. NRC (Nuclear Regulatory Commission). This code includes the analyses required to support rulemaking, licensing audit calculations, evaluations of accident mitigation strategies, evaluations of operator guidelines, and experiment planning analyses. RELAP5 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for the simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of steam, water, noncondensable gases, and solutes.

The coolant supplied by IRWST (In-containment Refueling Water Storage Tank) in the APR1400 or the RWST (Refueling Water Storage Tank, Time Dependent Volume No. 106) in the advanced OPR1000 circulates from the cavity water pool (Annulus No. 100) through a gap between the outer reactor vessel and insulation (Annulus No. 30, 40, 50, 60, 70, 80, and 90). The water inlet is a Single Junction 11. The cross flow junctions of No. 63 and 93 are the water circulation outlet and steam outlet, respectively. The spherical and cylindrical reactor vessels are simulated using heat structure numbers 100 and 200, respectively. The reactor power is simulated as a boundary condition of the heat flux at the left side of spherical heat structure number 100. The generated steam is vented into the containment atmosphere (Time Dependent Volume No. 104). In all simulations, the initial conditions are assumed to be ambient pressure with no coolant mass flow rate. The coolant level of the reactor cavity maintains a constant value by IRWST or RWST water. This type input model was verified by simulations of the HERMES-HALF (Hydraulic Evaluation of Reactor cooling Mechanism by External Self-induced flow-HALF scale) (Park et al., 2006) and the HERMES-1D test results (Park et al., 2008).

Table 3 shows the RELAP5 input conditions in the base case calculation for the advanced OPR1000 and APR1400, respectively. In the advanced OPR1000, the configuration of the water inlet, water outlet, and steam outlet has not been decided yet. Thus, these values in Table 3 are assumed to be installed. The water inlet and steam outlet areas are same in two reactors. However, the water circulation outlet area of the advanced OPR1000 is smaller than that of the APR1400. The water outlet and steam outlet positions of the advanced OPR1000 are lower than those of the APR1400, because of smaller size of the reactor vessel.

Fig. 3 shows the annular gap area between the outer vessel wall and insulation as a function of height. The annular gap area of the APR1400 is a little higher than that of the OPR1000. Fig. 4 shows the heat flux from the corium pool to the reactor vessel wall, which are MAAP4 results. The heat flux of the APR1400 is a little higher than that of the OPR1000, because of the higher thermal power. The higher value at approximately 80 degrees comes from the focusing effect of the metallic layer of the corium pool in the lower plenum of the reactor vessel. In this thermal load analysis from the corium pool to reactor vessel wall, a two layer formation of the upper low density metallic layer with a lower high density oxidic layer was assumed.