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Evaluation of ERVC performance and containment integrity in SMART100 under SBO using MELCOR1.8.6

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1. Introduction

SMART100 is a system integrated modular reactor which contains the nuclear steam supply system in reactor pressurized vessel (RPV) with thermal power of 365 MW. Also, passive safety features are installed in the SMART100 such as passive residual heat removal system (PRHRS), passive safety injection system (PSIS) and containment pressure and radioactivity suppression system (CPRSS). By these passive safety features, integrity of the reactor core and the containment can be maintained even under station black out (SBO) accident condition. But if the PRHRS and the PSIS are both unavailable, the reactor core can be damaged. Although probability of this condition is very low, capability to mitigate the severe accident of the SMART100 should be evaluated. Under the severe accident condition, objective of the plant changes to maintenance of the RPV and the containment integrity. This objective can be accomplished by ex-reactor vessel cooling (ERVC) which is a strategy to submerge outside of the RPV and the CPRSS. In this study, performance of the ERVC and the containment integrity under the SBO accident condition without the PRHRS and the PSIS was evaluated based on the MELCOR1.8.6 analysis results.

2. Method

2.1 CPRSS and ERVC in SMART100

The containment of the SMART100 consists of two parts, the lower containment area (LCA) and the upper containment area (UCA). The RPV is located in the LCA, and it is connected to the UCA through the CPRSS. The CPRSS is a passive system to control the pressure and radioactivity in the containment, it consists of in-containment water storage tank (IRWST), radioactive removal tanks (RRTs), and flow paths for water and gas.

Safety relief valves and automatic depressurization system (ADS) are installed on a upper head of the pressurizer. The SRV is a passive safety valve which prevents high pressure failure of the RPV by releasing steam to the cavity located at the bottom of the LCA when the pressure in the pressurizer exceeds a specific pressure. The ADS is an active system to depressurize the RPV by releasing gas including steam and hydrogen to the RRT. This system is activated at 30 minutes after the time when the severe accident management guideline (SAMG) entry condition is satisfied. Pressure relief lines and radioactive transport lines connect the LCA to the IRWST, and the IRWST to the RRT each without valves. The steam in the LCA condense by this system, so the UCA pressure can be maintained below the LCA pressure. An excessive steam can condense through CPRSS steam lines when the pressure in safety injection tank (SIT) room located at top of the LCA exceeds a specific pressure. The CPRSS steam line transports the steam to the IRWST through a heat exchanger in emergency cool-down tank. The valve on the CPRSS steam line closes at 30 minutes after the time when the SAMG entry condition is satisfied. But at the same time, the valve on the flow path between the SIT room and the RRT opens to control the LCA pressure.

To maintain the integrity of the RPV, residual heat from the corium in the lower vessel head (LVH) should be removed. The coolant for the ERVC can be supplied by the cavity flooding system (CFS). The CFS is a passive system which fills the LCA with coolant from the IRWST by the gravity. Because a steam generated in the LCA condenses during transportation to the UCA through the CPRSS, a high pressure failure of the containment can be prevented. However the hydrogen cannot be removed by the CPRSS, passive autocatalytic recombiner (PAR) is installed to prevent the hydrogen burn. Figure 1 shows a schematic of SMART100.

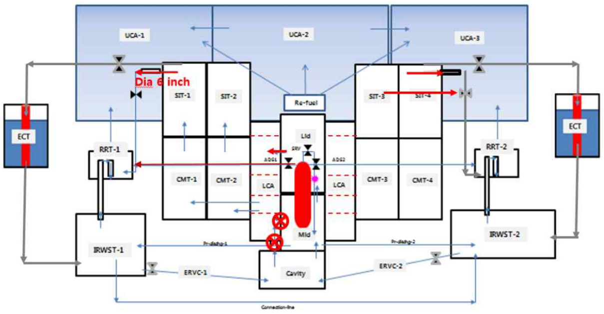

Fig. 1. Schematic of SMART100.

2.2 MELCOR analysis

MELCOR is an integrity system code which models the progression of severe accidents. To simulate the ERVC using MELCOR, the flow path between an insulation with a hemi-spherical shape and the RPV was assumed like in the ERVC of the APR1400. Two cases were analyzed for 300,000 seconds when the reactor core, main feed-water pump, and reactor coolant pump are shut down at 0 second. The case 1 is an accident scenario that the ERVC fails to be performed when the PRHRS and the PSIS are unavailable under the SBO accident condition, and the case 2 is an accident scenario that the ERVC succeeds to be performed with the same condition of the case 1. It was assumed that the SAMG entry condition is satisfied when the core exit temperature exceeds 923.15 K. The hydrogen removal from the PAR was not considered, and the source term analysis was not covered in this study.

3. Result

3.1 Accident scenario

The reactor core, the main feed water pump and the reactor coolant pump are shut down at the initiation of SBO accident. Because the PRHRS is assumed to fail, the steam in the RPV is released periodically to the cavity located at the bottom of the LCA through the safety relief valve on the upper head of the pressurizer by high pressure. The steam moves to the IRWST and the RRT through the pressure relief line and the radioactive transport line. The partial steam condenses during this transportation. Rest of the steam moves the UCA as a final destination. Because the LCA pressure exceeds 1.6 bar, the steam in the SIT room moves to the IRWST through emergency cool-down tank heat exchanger. The flow path from the SIT room to the IRWST is closed at 30 minutes after the time when the SAMG entry condition is satisfied. At the same time, valves on the ADS and the flow path between SIT room and RRT are opened. Through the ADS, gas in the RPV which includes the hydrogen and the oxygen created by fuel-coolant interaction moves to RRT. Non-condensable gas including the hydrogen moves to UCA as the final destination through RRT, so the pressure in the UCA constantly increases. Pressure in the RPV decreases after the initiation of the ADS, however, the coolant is not refilled because the PSIS is assumed to fail. If the CFS cannot operate, there is no way to remove the residual heat, so the corium drops into the cavity after the RPV failure by creep rupture. But if the CFS can operate, the LCA from the bottom to the middle height of the RPV submerges in the coolant from the IRWST at 30 minutes after the satisfaction of the SAMG entry condition. In this case, in-vessel retention can be successfully done by the ERVC.

3.1 Case 1: fail to perform the ERVC

To evaluate the performance of the ERVC, mass of the corium in the LVH was analyzed as shown in figure 1. Mass of the corium in the LVH rapidly increases at about 60,000 seconds. Because support plate on the bottom of the core fails by the residual heat from the corium. At about 90,000 seconds, the RPV fails so that the mass rapidly decreases.

To evaluate the containment integrity, the pressure and the mole fraction of the hydrogen in the LCA and the UCA were analyzed. As shown in figure 3, it was analyzed that pressure in the LCA and the UCA are controlled by the CPRSS below the design pressure with enough safety margin. The highest mole fraction of the hydrogen was analyzed to be seen in the RRT among all volumes in the LCA and the UCA. Although the final destination of the hydrogen is the UCA, but it was analyzed that the mole fraction of the hydrogen in the UCA is lower than that in the RRT because the volume of the UCA is much larger. The fraction increases after the RPV failure as shown in figure 4. It seems like the additional analysis for the mole fraction of the hydrogen in the RRT will be required, but it is expected that the possibility of the hydrogen burn is negligible because the mole fraction of the steam is high enough. Also, the mole fraction of the hydrogen can decrease if the performance of the PAR is considered.

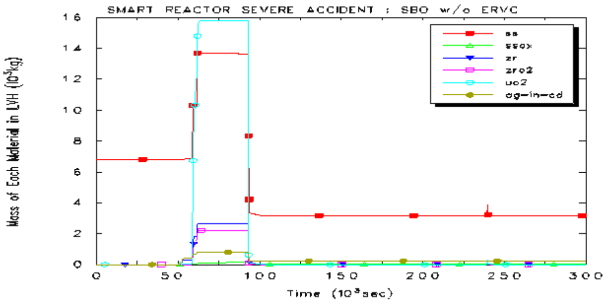

Fig. 2. Mass of relocated corium in the LVH of case 1.

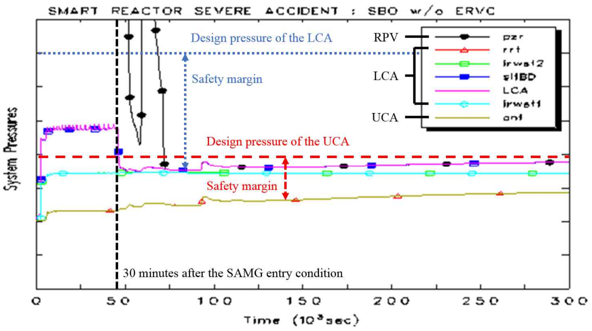

Fig. 3. Pressure in the containment of case 1.

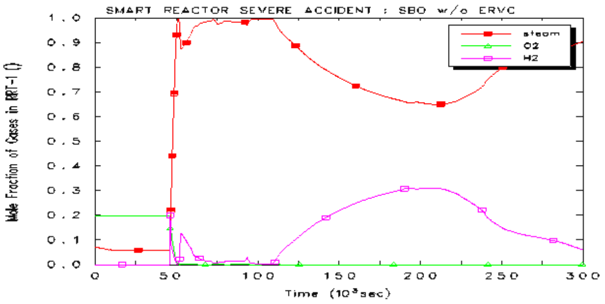

Fig. 4. Gas mole fraction in the RRT of case 1.

3.2 Case 2: succeed to perform the ERVC

Mass of the corium in the LVH rapidly increases at the same time in the case 1. But because the ERVC is successfully performed, the mass is maintained during the accident.

Like in the case 1, it was analyzed that the CPRSS controls the pressure in the LCA and the UCA below the design pressure with enough safety margin. Because the coolant in the LCA supplied by the CFS condenses the steam, it was analyzed that the safety margin is larger in the case 2. The highest mole fraction of the hydrogen was shown in the RRT, same as the result of the case 1. However, it was analyzed that the mole fraction of the hydrogen is lower in the case 2. The fraction is stably maintained after the peak when the valve on the ADS opens as shown in figure 7.

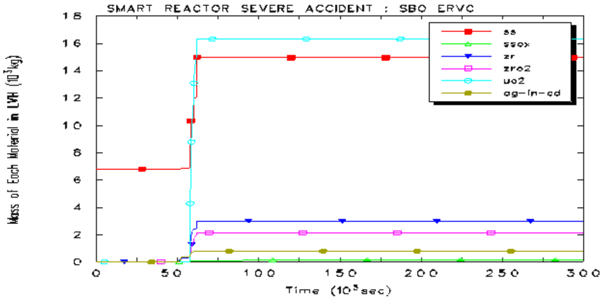

Fig. 5. Mass of relocated corium in the LVH of case 2.

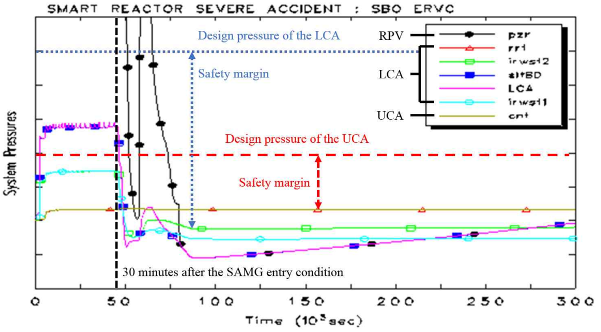

Fig. 6. Pressure in the containment of case 2.

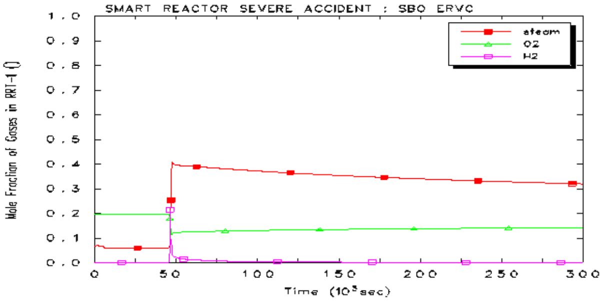

Fig. 7. Gas mole fraction in the RRT of case 2.

3. Conclusion

In this study, an evaluation of the ERVC and the containment integrity under the SBO accident condition without the PRHRS and the PSIS in the SMART100 using MELCOR1.8.6 was performed. It was analyzed that the RPV fails when the ERVC is unavailable, but in-vessel retention can be performed successfully when the ERVC is available. Also, it was analyzed that the containment integrity can be maintained by the CPRSS whether the ERVC succeeds to perform or not. Although it is expected that the possibility of the hydrogen burn is negligible, the safety can be enhanced if additional methods to decrease the mole fraction of the hydrogen in the RRT are considered such as expanding the venting area between the RRT and the UCA.

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