Analysis of suppression pool effect during DCH in SMART100 using MELCOR

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1. Introduction

If reactor pressure vessel (RPV) rupture occurs due to core damage in case of high pressure accident such as loss of offsite power or transient, the molten corium in the lower plenum can be ejected to the containment atmosphere under the high pressure condition. The heat transfer between the fragmented molten corium and atmosphere rapidly increases the pressure and temperature of the containment. Such phenomenon is called direct containment heating (DCH), and the initial stage of DCH caused by RPV rupture is called high-pressure melt ejection (HPME).

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 which is connected to the UCA through the containment pressure and radioactivity suppression system (CPRSS). When HPME occurs, the containment pressure can be controlled by the CPRSS passively.

In this research, the analysis of suppression pool effect when DCH occur was performed, using MELCOR code (ver. 2.2).

2. Methods and Results

2.1 DCH analysis model

The MELCOR code is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants [1,2]. This code is being developed at SNL for the U.S. NRC as a second-generation plant risk assessment tool. The FDI package in MELCOR calculates the behavior of debris in containment unless or until it is deposited in a cavity modeled by CAV package. Two types of phenomena are treated in the FDI package; one is low-pressure molten fuel ejection from the RPV, and the other is DCH by the HPME from the RPV.

If the velocity of the molten debris ejected from the RPV exceeds a critical value, then the FDI will be treated by the HPME model. The critical value was assumed as 10 m/s in this analysis.

The parametric HPME model requires user input to control both the distribution of debris throughout the containment and the interaction of the hot debris with the containment atmosphere. The processes modeled include oxidation of the metallic components of the debris (Zr, Al, and steel) in both steam and oxygen, surface deposition of the airborne debris by trapping or settling and heat transfer to the atmosphere and deposition surfaces.

Surface deposition of debris can occur in two distinct ways. Ejected debris which impacts structures prior to any significant interaction with the atmosphere is sourced directly to the destination surface via the user-specified transport fraction for that surface. Alternatively, debris which interacts significantly with the atmosphere should be sourced to the appropriate control volume, in which a user-specified settling time constant will determine the rate of deposition to the specified settling destination (either a heat structure surface or a cavity).

If the advanced time total airborne mass is insignificant compared to the total mass of material sourced into the control volume atmosphere over the duration of the DCH event, then all of the remaining airborne mass in the control volume is immediately deposited on the appropriate settling surface. The ratio used to determine when the airborne mass has become insignificant was assumed as 0.1 % in this analysis.

First-order rate equations with user-specified time constants for oxidation, heat transfer and settling are used to determine the rate of each process. Settling time constant is approximated as settling height divided into settling velocity. Typical values of settling height and velocity would be on the order of 1 to 10 m and 1 to 10 m/s, respectively. Consequently, settling time constant is expected to be on the order of 1 s. Heat transfer time constant is approximated as density of debris multiplies specific heat capacity of debris, equivalent spherical diameter of debris particles, and debris-togas heat transfer coefficient. Typically, density is on the order of 10,000 kg/m^3, specific heat capacity is on the order of 500 J/kg-K, equivalent spherical diameter is on the order of 0.001 m and heat transfer coefficient is on the order of 1000 W/m^2-K. Hence, heat transfer time constant is expected to be on the order of 0.5 s. Assuming the oxidation rate is limited primarily by mass transfer in the gas phase and applying the analogy between heat and mass transfer rates in turbulent flow, it is expected that the oxidation time constant is approximately equal to heat transfer time constant.

Oxidation of airborne and deposited debris is only calculated if the debris temperature exceeds a minimum value. The minimum value was assumed as 600 K in this analysis. The HPME model contains two options for oxidation modeling. These may be selected independently for each control volume. The first is the sequential oxidation option, in which the order of oxidation is Zr, Al, and steel (typical metallic elements associated with reactor cores and/or simulation experiments). This is invoked by specifying a positive value for the oxidation time constant. The second option is simultaneous oxidation of the metals, which is invoked by specifying a negative value of oxidation time constant, in which case the time constant will be equal to the absolute value of oxidation time constant. Under normal conditions where the metallic constituents exist in a more or less well-mixed state, the sequential oxidation option is recommended because it is more realistic. Elements with higher oxidation potentials will tend to be preferentially oxidized unless some kinetic limitation exists.

2.2 SMART100 input model

There is a pathway between cavity and the upper part of LCA including the SIT and the CMT rooms through the annular space around the RPV, but there is no direct path from the cavity to UCA except the venting through CPRSS. Therefore, most of the debris and steam from HPME can be confined in the LCA and only hot atmospheric air in LCA passes through CPRSS to UCA. 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, and flow paths.

Fig. 1 shows a MELCOR nodalization of the SMART100. MELCOR allows the user specifies a set of debris destinations with a corresponding set of transport fractions that prescribe where the ejected debris is assumed to go. The debris destinations may include the atmosphere of any control volume, the surface of any heat structure and cavity. Transport of the ejected debris to its assumed destinations occurs instantaneously, with no interactions occurring between the point of ejection and the destination sites. It is assumed that 30% of total melt mass is transported into the atmosphere of CPRSS lid, 30% into the atmosphere of annulus of LCA, and 40% into the atmosphere of cavity [3].

To examine the suppression pool effect during DCH, it was assumed that a virtual flow path is set up from the RPV annulus to UCA directly and the flow paths from the annulus to CPRSS are closed. By setting a virtual path, it is possible to transport the steam of high temperature and pressure directly to UCA without suppression effect (case 1: CPRSS exclusion). Since the virtual flow path is directly connected between UCA and LCA, we can compare it with the actual case (case 2: CPRSS inclusion) and could verify the effect of suppression pool.

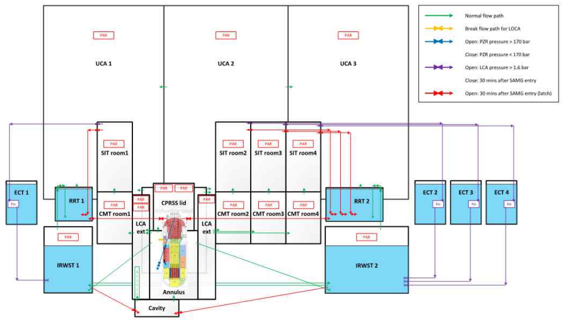

Fig. 1. Nodalization of SMART100 for MELCOR

2.3 Analysis results

Table I shows the major event timing during SBO sequence in case 1. When RPV fails at 145,545 s by creep rupture, RCS pressure decreases rapidly as shown in Fig. 2. During the depressurization, DCH occurs for a short time by a small amount of ejected corium under the HPME condition because core support plate does not fail yet. Most of corium are released after the RCS pressure equalizes to the LCA pressure. Fig. 3 and 4 show the containment pressure and gas temperature respectively. The LCA and the UCA pressure are same during the whole simulation because virtual flow path between these volumes are always open. The peak pressure in the containment reaches about 1.6 bar which is below the design pressure when the RPV fails at about 150,000 seconds. So the containment integrity can be maintained under the DCH condition. It is because the DCH occurs for a short time before the core support plate failure. At the same time, the peak gas temperature in the LCA reaches about 1000 K. However, the peak gas temperature in the UCA reaches about 400 K because the volume of the UCA is much higher than that of the LCA.

Table I: Times of Major Events during SBO in case 1

Major Events	Time (sec)
Reactor trip	0
Main feed water isolation	0
RCP trip	0
Initial pressurizer SRV opening	2,295
Core uncover starts	33,214
Fuel rod dry-out	41,160
Entry of Severe Accident (Core exit temp. reaches 923.15 K)	44,605
Lower plenum dry-out	83,156
RPV rupture	145,545
First relocation of molten corium	148,006
DCH initiation	148,352
DCH termination	148,359
Core support plate failure	152,970

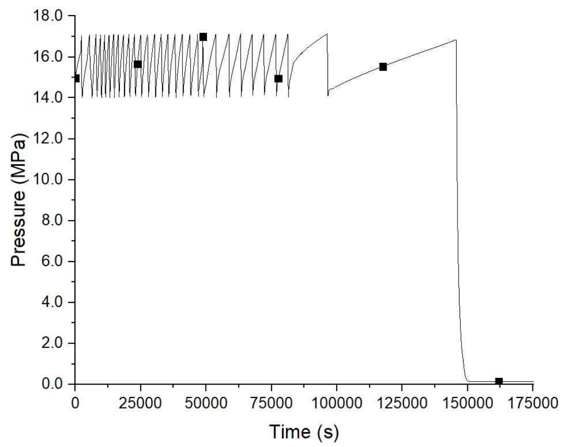

Fig. 2. RCS pressure in case 1

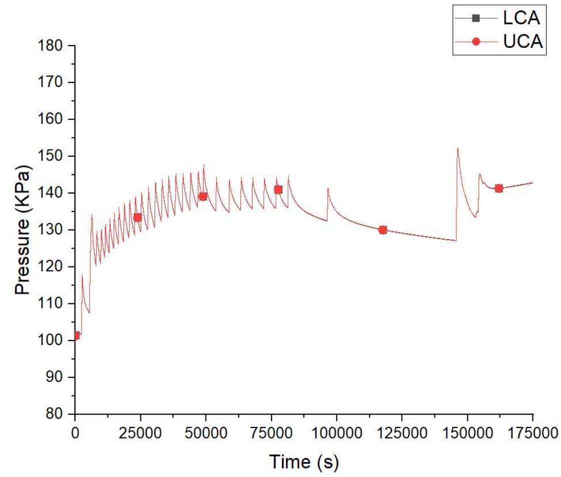

Fig. 3. Containment pressure in case 1

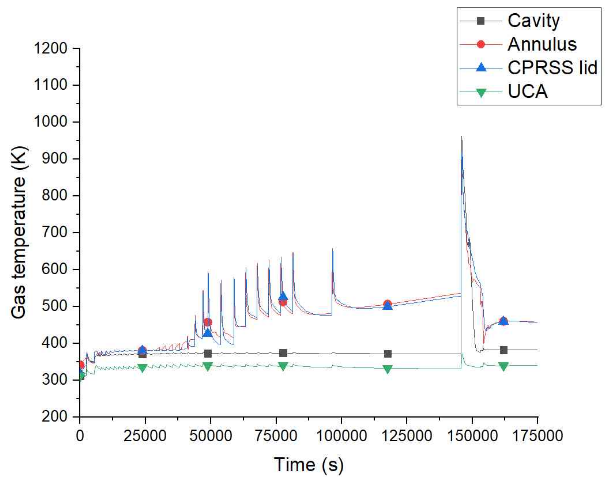

Fig. 4. Containment gas temperature in case 1

Table II shows the major event timing, and Fig. 5 shows the RCS pressure during SBO sequence in case of SMART100. The accident sequence are similar to the case 2. Fig. 6 and 7 show the containment pressure and gas temperature. In this case, the UCA pressure is maintained below the LCA pressure because almost steam condenses in the CPRSS. For this reason, the IRWST pressure is higher than the UCA pressure constantly during the simulation. When the RPV fails at about 150,000 seconds, the LCA peak pressure reaches about 2.0 bar. Until the RPV breach, the LCA pressure decreases to 1.2 bar because of steam condensation, thus there is about 1.5 bar margin between the peak pressure and the design pressure. The UCA pressure does not rapidly increase like the LCA pressure when the DCH occurs. The design pressure of the UCA is 1.9 bar, so the UCA integrity also can be maintained under the DCH condition. The peak gas temperature in the LCA reaches about 1000 K, but the gas temperature is maintained as almost constant during the whole simulation because the IRWST absorbs the heat from the LCA.

Table II: Times of Major Events during SBO in case 2

Major Events	Time (sec)
Reactor trip	0
Main feed water isolation	0
RCP trip	0
Initial pressurizer SRV opening	2,285
Core uncover starts	32,593
Fuel rod dry-out	40,398
Entry of Severe Accident (Core exit temp. reaches 923.15 K)	43,896
Lower plenum dry-out	81,936
RPV rupture	144,033
First relocation of molten corium	147,727
DCH initiation	147,939
DCH termination	147,946
Core support plate failure	152,691

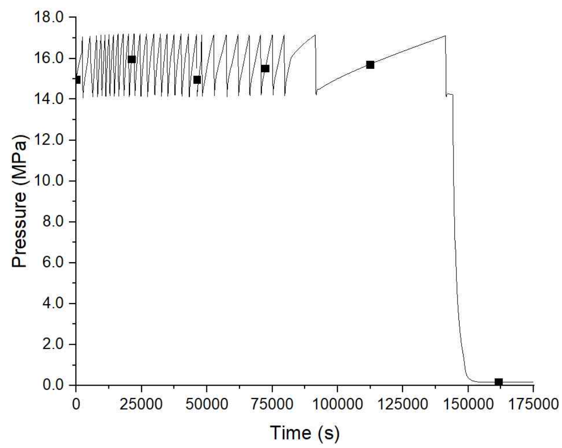

Fig. 5. RCS pressure in case 2

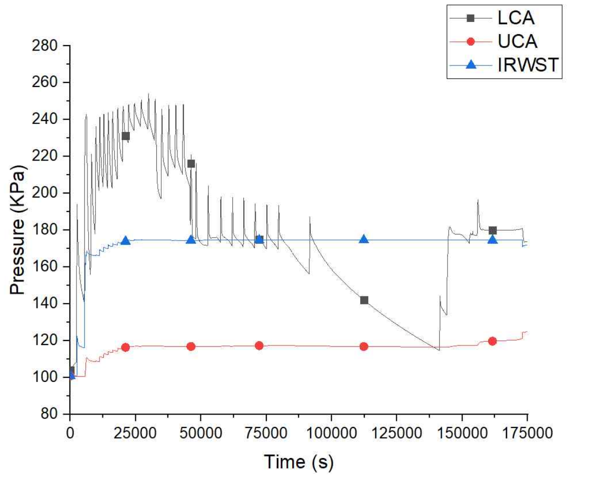

Fig. 6. Containment pressure in case 2

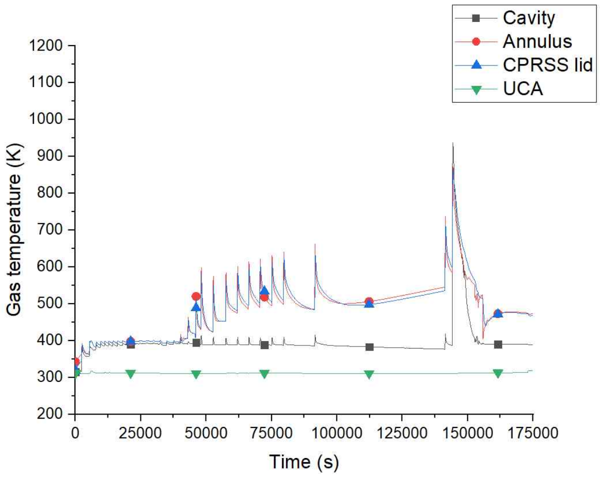

Fig. 7. Containment gas temperature in case 2

3. Conclusions

Through this analysis, the effect of suppression pool under DCH condition was verified. When the CPRSS is considered, there is barely no change in the UCA pressure. For the further study, sensitivity analysis of user-specified time constants and coefficients related to the creep rupture may be required. The source term analysis including the molten corium-concrete interaction phase after DCH condition may need to be performed for the SMART100 safety analysis.

Acknowledgement

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