Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Investigation of a Particulate Debris Temperature according to Accident Scenarios

Jaehoon Jung[a] *, Sang Ho Kim [a], Sang Mo An [a]
[a]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil,*
Youseong-Gu, Daejeon 305-353, Republic of Korea
[*]*Corresponding author: jhjung@kaeri.re.kr*

1. Introduction

During the late phase of severe accidents in PWRs (Pressurized Water Reactors), the molten corium may be discharged into the reactor cavity if the lower head of the reactor vessel is failed. The cooling and stabilization of the discharged molten corium in the reactor cavity is important to suppress further accident progression such as molten core-concrete interaction which can cause the containment failure and significant release of radioactive material outside the containment.

The strategy of pre-flooding of coolant into a reactor cavity for ex-vessel corium cooling and stabilization was adopted for the most operating Korean NPPs. It is expected that the molten corium breaks up in the water pool, and accumulated on the cavity floor in the form of a particulate debris bed. Also, it can be coolable. However, if the molten corium reaches the cavity floor without the completely break-up, or the debris bed is re-melted, a continuous molten pool is produced on the floor and it leads to MCCI.

The properties of the discharged molten corium and the pressure difference between in- and ex-vessel depend on the accident scenarios. As a results, the status of particulate debris varies. In this work, the accident scenario analysis was carried out using MELCOR1.8.6 code to set the initial failure conditions. Five initiating events which were SBO, TLOFW, SGTR, SLOCA, LLOCA were adopted for the sequence analysis. For each accident scenario, the status of a particulate debris at the cavity floor was calculated to check for the existence of cake.

2. Description of Model

2.1 simplified ex-vessel debris bed coolability module

So far, the cooling process of the ex-vessel corium debris can be divided into four categories which are melt jet breakup, particle dynamics, debris bed formation, and the bed cooling (Fig.1). When the molten corium release from the RPV and goes into the water, the melt jet may break and will fragment simultaneously. The fragmented particles fall into the cavity floor and accumulate on the cavity floor in the form of a debris bed. The heat generated by the debris bed can be removed by natural circulation of coolant through the porous bed.

The coolability of the debris bed may be affected by the ex-vessel melt behaviors which are the PRV failure condition, jet fragmentation, debris solidification, two-phase flow in porous media, spreading of debris in the pool, spreading of particulate debris bed, etc. The simplified ex-vessel debris bed coolability model covering important parts of the ex-vessel melt behavior, such as the melt jet break-up, debris bed sedimentation, debris bed formation, its cooling is under development [1]. Two modules which are DEJET and DECOOL will be developed (Fig. 2). DEJET dealt with both the melt jet break-up and debris bed sedimentation. The results of DEJET module which are the particle size distribution, the particle temperature and mass, and the cake temperature and mass if the breakup length is longer than pool height, provide the initial condition for DECOOL module. Here, to obtain the particle temperature when the particle fall into the cavity floor, we used DEJET only.

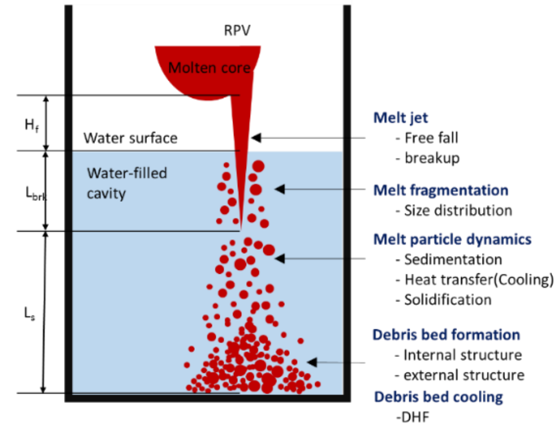

Fig. 1. Scenario of melt outflow from RPV and formation of particulate debris in pre-flooding cavity

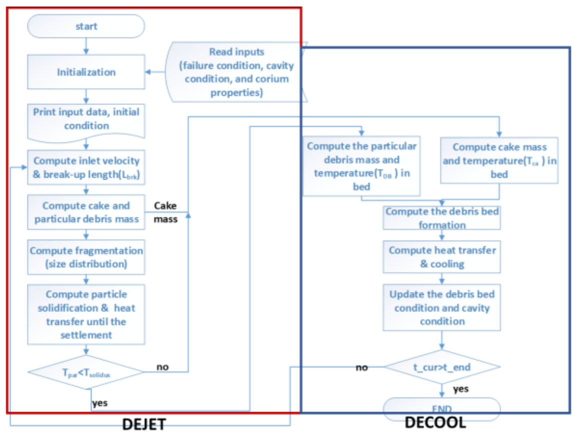

Fig. 2. Debris bed coolability analysis flow chart [1]

2.2 Failure condition

The accident scenario analysis was carried out using MELCOR1.8.6 code to set the initial conditions of this research [2]. The reference reactor was OPR1000 as a representative operating nuclear power plant in Korea. Five initiating events which were SBO, TLOFW, SGTR, SLOCA, LLOCA were adopted for the sequence analysis. Specific accident sequence of each initiating event presenting an earliest failure of a reactor vessel was determined. According to the selection of each scenario, HPSI, LPSI, spray on a pressurizer, motor-driven auxiliary feedwater pump (MDAFP), turbine-driven auxiliary feedwater pump (TDAFP), atmospheric dump valve, condenser dump valve and containment spray system were assumed to be failed all. That is because the earliest failure of a reactor vessel is directly connected to the largest decay heat of a corium on the containment cavity in a conservative view of coolability. In all the scenarios, the open of two safety depressurization valves on a pressurizer was assumed to decrease the pressure in a primary side at the SAMG entry (when a core exit temperature was higher than 923 K).

In addition to the scenarios of the five initiating events, for analyzing the effect of the delay of the reactor vessel failure, one case was added with the operation of two TDAFPs for four hours before the reactor vessel failure in a SBO scenario. It is SBO-T4 as the most likely scenario in a PSA level 2 [3].

Table I summarizes the results of the analysis. The initial break diameter on a reactor vessel was 0.15 m. It increased due to the ablation of the failure opening. Due to the operation of TDAFPs before the core melting, the failure of the reactor vessel was delayed in the SBO-T4 scenario. Therefore, the Zirconium oxidation ratio in the SBO-T4 was higher than in the other scenarios. In a lower vessel head (LVH), there was a wide range of corium temperature due to the presence of particulate debris and a molten pool. The melt discharge velocity decreased due to the decrease of the pressure in a reactor vessel.

Table I: Range of each variable at the reactor vessel failure

Variable Name	Unit	Ranges of Results
Break diameter	m	Increased from 0.15
Corium composition	%	UO2 :Zr :ZrO2 :SS&SSOX = 65~75 :5~15 :5~15 :0~10
Mass in LVH	ton	110 ~ 130
Corium temp.	K	2200 ~ 2800
Corium discharge velocity	m/s	6 → 1 (in LLOCA), 22 → 8 (in the others)

2.3 Melt jet breakup & sedimentation model [1]

The melt jet initial diameter (D_i) and velocity ($V_i = \left(\frac{2\Delta P}{\rho_{melt}}\right)^{0.5}$) is determined by scenarios of accident progression. The jet diameter (D_e) and the velocity (V_e) at the water surface is as follow:

$$D_e = D_i\left(1+\frac{2gH_f}{v_i^2}\right)^{-0.25} \quad (1)$$

$$V_e = \left(V_i^2 + 2gH_f\right)^{0.5} \quad (2)$$

where, H_f is the free fall height form the melt release point to the water surface. The jet break-up length is obtained Epstein's correlation [4].

It is assumed that the jet velocity is constant in the water. So, the initial particle velocity is the same as jet velocity at the water surface. On a conservative assumption, the particle fall to the cavity floor along only vertical direction. The particle movement is tracked by the kinetic equation considering the fluid dynamic resistance.

$$\frac{\partial z^k}{dt} = U_p^k, \quad \frac{\partial U_p^{\ k}}{dt} = -F_{drag}/m_p + \left(\rho_p - \rho_l\right)/\rho_p g, \qquad (3)$$
$$\overline{F}_{drag} = \frac{3}{4}C_d\rho_l\left(\overline{U}_p - \overline{U}_a\right)^2$$

where, U_p, m_p, z, and C_d are the particle velocity, the particle mass, the particle location, drag coefficient. For the drag model, Schiller and Naumann drag model [5] was adopted.

The heat release from a particle during a sedimentation. To evaluate the particle temperature, it is assumed that the particles are lumped. The particle temperature during a sedimentation is evaluated by the energy conservation law. Initial particle temperature is assumed the discharged molten corium temperature. Before particles completely solidify, the heat release from a particle is used for the phase change (Eq.4) after that, the particle temperature is evaluated by Eq. 5.

$$\Delta m_s = \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de} dt\right)/\left(h_{sf} + c_m\left(T_m - T_{s,sf}\right)\right) \quad (4)$$

$$T_m^{\ new} = T_m - \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de} dt\right)/m_p c_m \quad (5)$$

where, h_{eff}, T_w, Q_{de}, and A_p are the effective heat transfer coefficient, the water temperature, the decay heat, and the particle surface area. The effective heat transfer coefficient is evaluated by various correlations which are Ranz-marshall [6], Kutateladze [7], Zuber [8], Lienhard and Dhir [9] depending on the particle surface temperature.

2.4 results and discussion

Properties of ex-vessel corium are summarized in table II. The initial conditions of the pool and the cavity are in table III. We assumed that pool height is 6 or 6.858 m, free fall height is 0.858m or 0 m, and the failure diameter in reactor vessel is 0.3 m. Also the pool temperature assumes the saturation temperature at 1 bar.

Table II: Melt properties [10]

Material property	Unit	value
Material		70% UO_2 and 30%ZrO_2
Density liquid	Kg/m^3	8000
Cp-liquid	J/kg/K	510
Cp-solid	J/kg/K	450
Tsolidus	K	2840
Tliquidus	K	2870
Latent heat	J/kg	320000

Emssivity		0.79
Decay heat	W/kg	80

Table III: Initial pool and cavity condition

Variable	Unit	value
Particle diameter	mm	1-10
Pool height	m	6~6.858
Free fall height	m	0.858-0
Pool temperature	K	373
Cavity pressure	bar	1
Failure diameter	m	0.3

Table IV: Results

Scenario	SBO-T4	SBO	TLOFW	SGTR	SLOCA	LLOCA
RV pressure [MPar]	1.5	1.6	1.7	1.6	1.9	0.2
Temperature[K]	2600	2600	2700	2700	2300	2400
Break-up length [m]	4.19					
Pool height = 6m						
Min ΔT*	848	846	913	914	653	856
Pool height = 6.858m						
Min ΔT*	1064	1066	1140	1140	846	936

*ΔT=initial molten corium temp – particulate debris temp at cavity

During the breakup process, the size of the generated particle varies. The particle temperature also strongly depends on the particle diameter. In the simple calculation using the energy balance, the temperature is proportional to diameter of the third power. When it is assumed that the typical particle diameter is 3 mm, which is commonly used, results show in table IV.

The reactor vessel pressure varies from 0.2 to 1.6 MPa and temperature is about 2300 to 2700K as the scenarios. To find the maximum particulate debris temperature, we tracked the debris particle from the end of melt jet in the pool. So, we find the minimum temperature difference between the discharged molten corium and the particle temperature as the cavity floor. The breakup length is 4.19 m which is shorter than the pool height. It means that the melt jet is completely break-up. The table IV shows that the minimum temperature difference is about 900K and 1000K for pool height are 6 m and 6.858 m respectively. It indicates that the particles are solid, but the temperature is still high as the film boiling region.

For six scenarios, the temperature of the particles was calculated. Although the particle temperature greatly depends on the diameter of the particles, when a typical 3mm particle, which is commonly used, is used, the particle is a solid state but a temperature of the film boiling region. The debris bed formation experiment will be carried out in KAERI. At that time, the test matrix will be made with reference to these conditions.

3. Conclusions

The accident scenario analysis was carried out using MELCOR1.8.6 code to set the initial failure conditions for ex-vessel debris cooling. Five initiating events which were SBO, TLOFW, SGTR, SLOCA, LLOCA were adopted for the sequence analysis. For six scenarios, the temperature of the particles was calculated, when the condition is the pre-flooding of coolant in a reactor cavity using a typical 3mm particle. The results show that although the melt jet is completely break-up and particles are solid, but the temperature is still high as the film boiling region.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4015274).

REFERENCES

[1] J. Jung, H.Y. Kim, and S.M. An, Current Status of Development of Simplified Ex-vessel Debris Bed Coolability Model, Transactions of the Korean Nuclear Society Spring Meeting, 2018

[2] USNRC, MELCOR Computer Code Manuals Vol. 1: Primer and Users' Guide, Sandia National Laboratories, NUREG/CR-6119, Vol. 1, 2005.

[3] Park S. and Ahn K., Development of the Severe Accident DB for the Severe Accident Management Expert System (I), KAERI/TR-4211, 2010.

[4] M. Epstein and H.K. Fauske, Application of the turbulent entrainment assumption to immiscible gas-liquid and liquid-liquid systems. Chemical Engineering Research and Design, 79:453–462, 2001.

[5] Schiller, L., Naumann, A., 1935. A Drag Coefficient Correlation. V.D.I. Zeitung.

[6] W.E. Ranz and W.R. Marshall. Evaporation from drops: part I. Chemical Engineering Progress, 48:141–146, 1952.

[7] S.S. Kutateladze. Heat transfer in condensation and boiling. ACE-tr-3770, US AEC, 1952.

[8] N. Zuber et al. Int. Development in Heat Transfer, Part 14 II, page 230. ASME, 1961. paper 27.

[9] J.H. Lienhard, V.K. Dhir, Hydrodynamic prediction of peak pool-boiling heat fluxes from finite bodies, J. Heat Transfer, C-95 (1973), pp. 152-158

[10] Hong S.W., Min B.T., Hong S.H., An investigation on size distribution and physical characteristics of debris in TROI FCI tests, Nuclear Technology, Vol.191, pp.122-135, 2015.