Coolability analysis of initial ex-vessel molten corium for pre-flooding strategy

Jaehoon Jung[a]*, Hwan-Yeol Kim[a], and Sang Mo An[a]
[a]Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong-gu, Daejeon, Korea
*Corresponding author: jhjung@kaeri.re.kr

Introduction

Backgrounds & Objective

- During the late phase of severe accidents in PWRs, the molten corium may be discharged into the reactor cavity if the lower head of the reactor vessel is breached. **The cooling and stabilization of the discharged molten corium in the reactor cavity is crucial to suppress further accident progression** such as molten core-concrete interaction (MCCI) which can cause the containment failure and significant release of radioactive material outside the containment.
- KAERI is developing the module for the ex-vessel debris coolability [1, 2]. In this study, the module was validated on the initial cooling model by comparing the analysis results with FARO experiment [3].

Coolability module

Simplified ex-vessel debris bed coolability module

- The cooling process of the ex-vessel corium debris can be divided like melt jet breakup, particle dynamics, debris bed formation, and the its cooling.
- **Melt jet breakup:** The jet break-up length is obtained by Epstein's correlation: $\frac{1}{2E_o}\left(\frac{\rho_m}{\rho_l}\right)^{1/2}$
- **Particle dynamics**
  - The particle movement is tracked by the kinetic equation considering the fluid dynamic resistance.

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

  - The heat release from a particle during a sedimentation. To evaluate the particle temperature, it is assumed that the particle are lumped. The particle temperature during a sedimentation is evaluated by the energy conservation law.

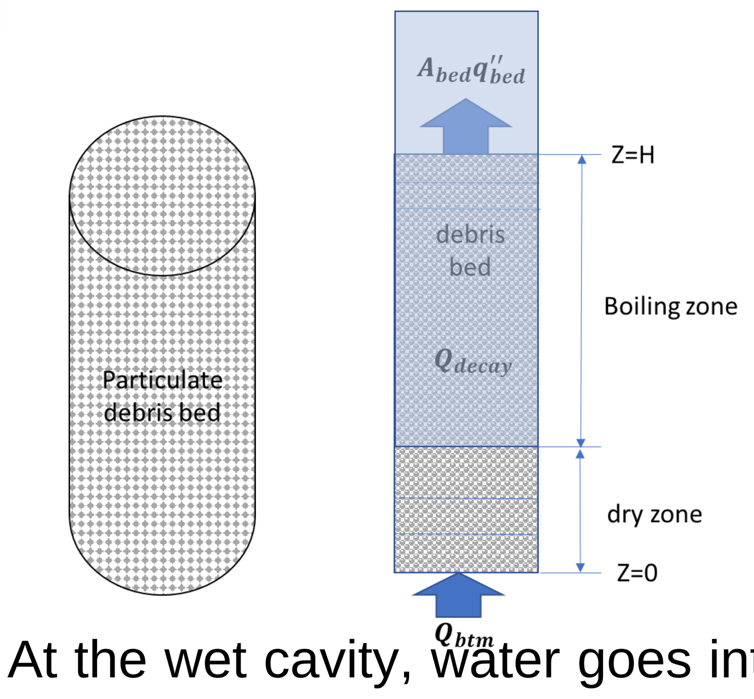
$$T_m^{new} = T_m - \left(\int A_p h_{eff} (T_m - T_w) dt - \int m_p Q dt - m_p h_{sf}\right) / m_p c_m$$

  - 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 debris bed shape is assumed as a cylindrical shape. The heat transfer in the and cake is calculated with Eqs:
  - $Q_{cake} = Q_{MCCI} + Q_{btm} - Q_{decay}$

where Q_{bed} is the heat transfer in the debris bed; Abed is the top surface area of the bed; Q_{decay} is the decay heat; Q_{btm} is the heat input at the debris bed bottom from the cake; Q_{MCCI} is the heat released by a MCCI, and h is the heat transfer coefficient, which is determined by comparing the effective heat transfer coefficient and DHF to a smaller value. The Lipinski model was used to obtain the DHF value

Modified heat transfer model

- To obtain the temperature distribution of the particulate debris bed, we seek to solve the unsteady one-dimensional heat conduction equation.



Unsteady one-dimensional heat conduction equation

$$\rho_{eff} c_{eff} \frac{\partial T_{bed}}{\partial t} = \frac{\partial}{\partial z}\left(k_{eff} \frac{\partial T_{bed}}{\partial z}\right) + S$$

$q''(z) = \frac{Q_{btm}}{A_{bed}}$, at z=0

$q''(z) = -q''_{bed}$, at z=H, $q''_{bed} = \min(q''_{film}, q''_{DHF})$

$$\rho_{eff} = (1-\varepsilon)\rho_{bed} + \varepsilon_l \rho_{liquid} + \varepsilon_v \rho_{vapor}$$
$$c_{eff} = (1-\varepsilon)c_{bed} + \varepsilon_l c_{liquid} + \varepsilon_v c_{vapor}$$
$$k_{eff} = (1-\varepsilon)k_{bed} + \varepsilon_l k_{liquid} + \varepsilon_v k_{vapor}$$
$$\varepsilon_l = \frac{V_l}{V} \qquad \varepsilon_v = \frac{V_v}{V}$$

- At the wet cavity, water goes into the particular debris bed, so we can divided by two parts, which are boiling zone and dry zone. The length of boiling zone can be obtained from solving the equation for energy conservation, mass conservation and momentum conservation.
- Main parameters for solving the heat conduction equation can be written by follows

Boiling zone :

$$\rho_{eff} = (1-\varepsilon)\rho_{bed}$$
$$c_{eff} = (1-\varepsilon)c_{bed}$$
$$k_{eff} = (1-\varepsilon)k_{bed}$$

S = decay*debris bed mass in control volume * (1-f)

dry zone :

$$\rho_{eff} = (1-\varepsilon)\rho_{bed} + \varepsilon \rho_{vapor}$$
$$c_{eff} = (1-\varepsilon)c_{bed} + \varepsilon c_{vapor}$$
$$k_{eff} = (1-\varepsilon)k_{bed} + \varepsilon k_{vapor}$$

S = decay*debris bed mass in control volume

[1] J. Jung, S.M. An, and S.H. Kim, ANS2019, MN, USA, Jun. 2019.
[2] J. Jung, D. Son, and S.M. An, transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, July 9-10, 2020.
[3] D. Magallon, Nuclear Engineering and Design 236 (2006), 1998-2009.

FARO experiments

- FARO tests were selected as a benchmark problem
- The FARO tests were designed to study the integral corium melt jet/water mixing and quenching behavior using UO2 based melt under prototypical conditions.
- 12 tests were performed that involved quenching of 18-177 kg corium melts in saturated and subcooled water [3].
- we were first selected L-28 test as a benchmark problem

Table I. FARO test conditions and results [3]

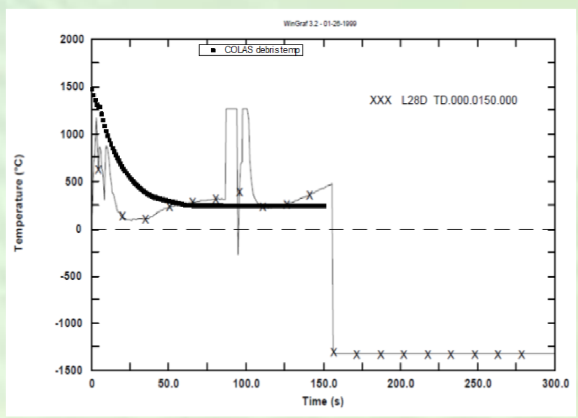
Test	L-06	L-08	L-11	L-14	L-19	L-20	L-24	L-27	L-28	L-29	L-31	L-33
Experimental conditions												
Corium composition[a]	A	A	B	A	A	A	A	A	A	A	A	A
Melt mass[b] (kg)	18	44	151	125	157	96	177	117	175	39	92	100[c]
Melt temperature (K)	2923	3023	2823	3123	3073	3173	3023	3023	3052	3070	2990	3070
Melt release diameter[d] (mm)	100	100	100	100	100	100	100	100	50	50	50	50
Melt fall height in gas (m)	1.83	1.53	1.09	1.04	1.99	1.12	1.07	0.73	0.89	0.74	0.77	0.77
System pressure (MPa)	5	5.8	5	5	5	2	0.5	0.5	0.5	0.2	0.2	0.4
Gas phase	Steam/Ar	Steam/Ar	Steam/Ar	Steam/Ar	Steam[e]	Steam[e]	Steam[e]	Steam[e]	Steam[e]	Argon	Argon	Argon
Water depth (m)	0.87	1.00	2.00	2.05	1.10	1.97	2.02	1.47	1.44	1.48	1.45	1.60
Water temperature (K)	539	536	535	537	536	486	425	424	424	297	291	293
Water subcooling (K)	0	12	2	0	1	0	0	1	1	97	104	124
Water Mass (kg)	120	255	608	623	330	660	719	536	517	492	481	625
Debris bed data[f]												
Hard debris, cake (kg, %)	6, 33	14, 32	0, 0	20, 16	77, 49	21, 22	27, 16	26, 23	77, 48	39, 100	0, 0	8, 8
Loose debris (kg, %)	12, 67	30, 68	146, 100	105, 84	80, 51	73, 78	141, 84	70, 77	84, 52	0, 0	83, 100	89, 92
Mean loose debris size (mm)	4.5	3.8	3.5	4.8	3.7	4.4	2.6	Na[g]	3.0	–	3.4	2.6[h]

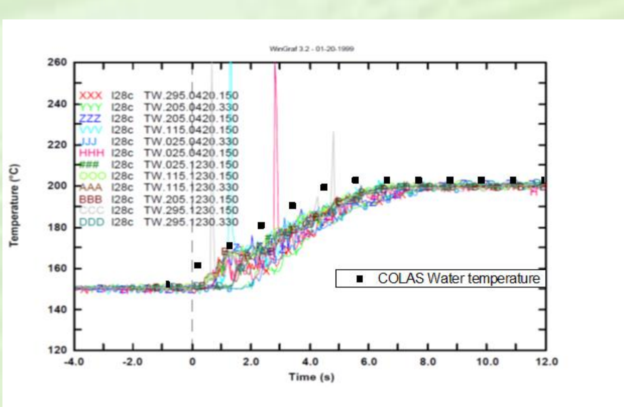
[a] A: 80 wt.% UO_2–20 wt.% ZrO_2; B: 77 wt.% UO_2–19 wt.% ZrO_2–4 wt.% Zr.
[b] Total mass which interacted with water.
[c] Approximately 25 kg in water at time of trigger.
[d] Diameter of the orifice. In general a crust ~3 mm thick forms during melt release.
[e] >95 wt.% steam; <5 wt.% argon.
[f] Refers to debris found in the debris catcher.
[g] Not available.
[h] Steam explosion after ~25 kg of melt had penetrated in water.

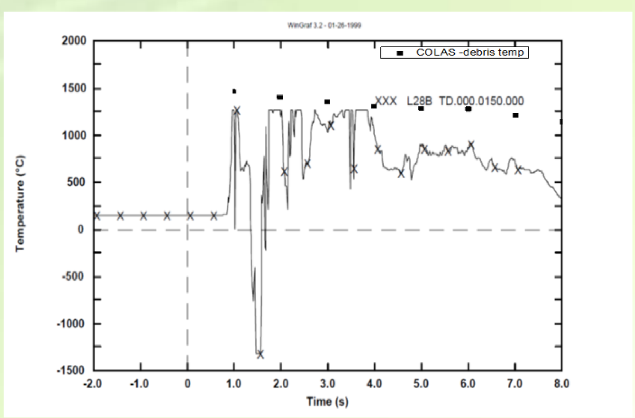
Results & conclusion

- When comparing the Satio and Epstein's jet break-up model with the experimental results, it can be seen that the analysis results of the Satio's model have a smaller difference with the experimental results.
- The debris bed temperature was higher than FARO results at the beginning of the debris bed cooling. The reason is that the minimum heat flux model was used at the debris bed temperature is between CHF temperature and leindenfrost temperature. The heat transfer model is currently being improved.
- Also, It can be seen that the temperature of the cooling water is well predicted.
- It is still underway to develop the debris bed heat transfer model. After developing 1-D analysis model, it will be expanded to analyze the local temperature of various shaped debris bed.

	FARO L-28 [3]	COLAS-Saito	COLAS-Epstein
Hard debris, cake (kg)	77.48	69.41	52.5
Loose debris (kg)	84.52	105.59	109.9







This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT; Grant No. 2017 M2A8A4015274) and the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry, and Energy) (No. 20193110100090).