Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

How to Win the Uncertainty of Ex-vessel Corium Coolability in Pre-Flooded cavity. Part 2: MELCOR-COOLAP Coupled Analysis

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1. Introduction

During severe accidents in nuclear power plants, corium melt can be released into a reactor cavity due to the reactor vessel failure. In countries including South Korea, the cavity pre-flooding strategy has been included in the nuclear power plant design concept [1]. If this severe accident management strategy is employed, the corium melt jet will be broken up and accumulated on the cavity floor. Although this strategy is expected to provide improved cooling performance to mitigate molten corium-concrete interactions (MCCI), the coolant evaporation can lead to containment overpressure.

However, the current MELCOR code has a limitation to simulate the key fuel-coolant interactions (FCI) phenomena including melt jet breakup, particle debris bed formation and debris bed cooling. Especially, the code cannot estimate the formation of debris bed unlike continuous lump (melt pool) [2]. For this reason, we developed COOLAP code to simulate these key phenomena with mechanistic modeling approach in pre-flooded cavities. The COOLAP code employed improved FCI models; Jet breakup model, particle size distribution model and debris bed figuration model [3]. Recently the code has been improved with additional models of FCIs, debris bed formation and DHF [4].

The MELCOR-COOLAP coupled analysis can predict ex-vessel corium behavior by dividing it into early and late phases. The early phase of FCI is simulated using the COOLAP-3 code, then the late phase of FCI/MCCI is subsequently simulated by the MELCOR code. The CORCON-Mod3 models in MELCOR code can predict the ablation depth and gas generation during MCCI. However, single scenario based computation cannot consider inevitable uncertainties in these phases. Uncertainty parameters can be classified into three categories; accident scenario, COOLAP-FCI models and MELCOR-MCCI models.

The objective of this study is to perform a MELCOR-COOLAP analysis to evaluate the ex-vessel corium coolability considering those three types of uncertainty. The Linux shell script is developed for one-way coupling of both codes. The uncertainty analysis was also performed by the Linux shell script with Latin hypercube sampling (LHS) method. To suggest the effectiveness of this analysis, a prototypic APR1400-type PWR reactor (pre-flooded cavity condition) was selected. *Section 2* introduces the MELCOR-COOLAP analysis methodology. *Section 3* describes the simulation results of the prototype reactor to investigate the effectiveness of this analysis. *Section 4* summarizes and concludes this paper.

2. MELCOR-COOLAP coupled analysis

2.1 MELCOR

MELCOR is a severe accident simulation code to simulate the progression of the severe accidents in LWRs such as PWR and boiling water reactor (BWR) [2]. Sandia National Laboratories developed several versions of the MELCOR code for plant risk assessment and source term analysis since 1982. The MELCOR code is mostly used by regulatory body and academic studies to evaluate strategies for severe accident mitigation and to simulate detailed features of severe accident sequences. Current knowledge indicates that the verification of the mitigation strategy by using MELCOR code is meaningful in improving the nuclear reactor safety. In the study, MELCOR code version 2.2 was utilized to simulate ex-vessel phase during station blackout (SBO) scenarios. As shown **Fig. 1**, the MELCOR-CAV package can simulate the effects of heat transfer, concrete ablation, cavity shape change and gas generation using models taken from the CORCON-Mod3 code [2].

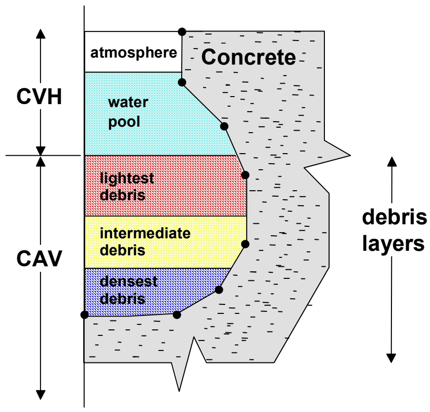


Fig. 1. Overview of MELCOR-CAV package

2.2 COOLAP-3

Fig. 2 shows the modeling concept of the COOLAP-3 code for simulate FCIs using simplified assumptions and models. The modeling phase can be divided into the melt jet breakup, sedimentation and cooling. In melt jet breakup phase, the unified empirical correlations for jet breakup are used as shown **Eq. (1)**. If an incomplete breakup occurs, the excess corium forms a melt pool. Unlike debris bed, melt pool can erode the cavity concrete by MCCI. In recent version of COOLAP-3, the truncated Rosin-Rammler distribution model was used to exclude non-physical particle size range (Eq. (2)).

$$\frac{L_{br}}{D_j'} = 3.3\left(\frac{\rho_m}{\rho_w}\right)^{0.5}\left(\frac{{v_j'}^2}{gD_j'}\right)^{0.5(1-\frac{1}{21354Q+1})} \quad (1)$$

$$F = 1 - \exp\left(-\left(\frac{D_p^n - D_{min}^n}{D_e^n}\right)\right) \quad (2)$$

Particle motion in water and the film boiling heat transfer for the particles is analytically solved with parametric approaches. When the particles are accumulated in the cavity bottom, the debris bed shape can significantly affect the coolability of the melt pool and debris bed. The shape was primarily characterized on a cylindrical two-dimensional coordinate with radially distributed heights. If the slope at the particle arrival location exceeds the repose angle, the location is shifted to the adjacent ring either inside or outside until the repose angle limit is no longer exceeded.

In the previous COOLAP versions, the repose angle determining the arrival location of a new particle element, was given by the user input. This fully parameter-dependent approach is difficult to estimate debris formation. For this reason, the debris bed formation model validated by the experimental results was added to the COOLAP-3 code. This model was developed considering the kinetic interactions between debris particle and the bubble-induced coolant flow. A conical bed with a constant side slope angle was assumed. As shown in **Eq. (3, 4)**, the characteristic length and the side slope angle of the developing debris bed were expressed using parameters reflecting the volumetric decay heat rate q_d''', the melt-release rate $\dot{m}$, the melt-jet size, and the cavity flooding level [4]. The more detailed description about the COOLAP-3 modeling can be found in [3].

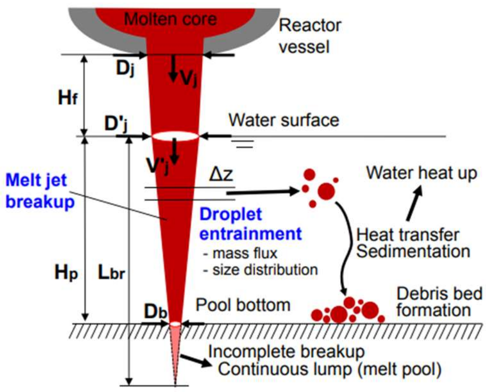


Fig. 2. Summary of COOLAP-3 modeling approach.

$$R_{75\%} = 0.414\left\{\frac{(\rho_l-\rho_g)^2}{\rho_p\rho_g h_{fg}}\frac{q_d'''H_s^2\tau}{\dot{m}}\frac{\alpha v_b D_{pc}^4}{(1-\varepsilon)v_p^4}\right\}^{1/3} \quad (3)$$

$$\tan\theta = 4.127\left\{\frac{\rho_g h_{fg}}{(\rho_l-\rho_g)^2}\frac{\dot{m}^2}{q_d'''H_s^2}\frac{v_p^4}{\alpha v_b D_{pc}^4}\right\} \quad (4)$$

2.3 MELCOR-COOLAP coupled analysis

Fig. 3 shows the difference between the current MELCOR code and the MELCOR-COOLAP coupled analysis. In MELCOR code, the melt pool spreads uniformly in the cavity bottom as soon as the melt jet released. Although the code can divide pool layers according to their composition, the particle debris bed cannot be modeled. It means that the cross-section area and mass of the debris bed cannot be estimated. The accumulated melt pool is cooled through the top water, while MCCI proceed in the bottom.

On the other hand, the MELCOR-COOLAP analysis can simulate the formation of debris bed following melt jet breakup with the COOLAP-3 code. The initial condition just before the melt ejection is determined using the reference MELCOR results. The COOLAP-3 code predict the cooling behavior for 1 hour after the debris bed and the melt pool are separated. Then the thermal-hydraulics results of the reactor cavity are transferred to the initial condition of the MELCOR code. Since the MELCOR code can calculate the MCCI, the accident progress is calculated over the next 72 hours.

It is important to determine the variables transferred from COOLAP to MELCOR. In order to simulate the decay heat, the time after shutdown is required. The cavity water level after 1 hour is also transferred. One of the most important variables is the area of the melt pool which MELCOR cannot predict. The cavity bottom area in the MELCOR input is overwritten by the COOLAP calculation results.

Additionally, uncertainty parameters are included in each step of the framework as indicated by the orange box. MELCOR code also provides an uncertainty evaluation program called DAKOTA, but a Linux shell script based program was developed for coupling COOLAP uncertainty parameters. Using this program, it is also possible to select various uncertainty parameters such as reactor vessel failure area. The more detailed description about the framework can be found in [5].

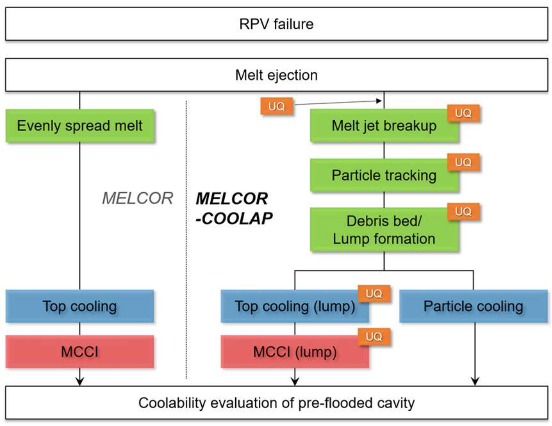


Fig. 3. MELCOR-COOLAP framework to advance corium coolability evaluation methodology.

3. Evaluation of ex-vessel corium coolability

3.1 Prototype APR1400 input

In this study, APR1400-type PWR reactor was selected as a reference power plant to verify the need for the developed framework. Because the design of APR1400-type reactor includes the cavity flooding system, the practicality of the MELCOR-COOLAP framework can be effectively explored. A prototype MELCOR input was developed based on the published literature on APR1400 reactor design [6]. As the COOLAP-3 results is used as an initial condition, the main packages of this input are CAV, CVH/FL, HS and DCH. **Table 1** shows the main parameters of the input.

Table 1. Main parameters in MELCOR input

Parameter	Value
Number of CVs	6
Total volume of CVs	95,490 m^3
Containment HS thickness	1.074-1.304 m
Concrete type	Basaltic
Cavity height	7.7185 m
Cavity area	(COOLAP results)
Decay heat function	$P = 0.125P_0 t^{-0.2752}$

3.2 Uncertainty parameters

Although the MELCOR-COOLAP coupled computation can improve the accuracy of the ex-vessel corium coolability evaluation, single scenario based computation cannot consider inevitable uncertainties in severe accidents. **Table 2** shows the selected uncertainty parameters for the prototype APR1400 coolability evaluation. #1 to #5 are scenario parameters, #6-13 are COOLAP parameters and #14-17 are MELCOR parameters. The particle mixing column factor is a parameter used for debris bed formation model. The range of this parameter was determined through benchmarking studies between experimental results and COOLAP-3 code. In this study, 17 parameters of 500 cases were determined using the LHS method. The meaning and range of each parameter are described in more detail in [5].

Table 2. Uncertainty parameters in this study

#	Parameter
1	T0SD: Time after shutdown
2	HPI: Initial water pool depth
3	DJIN: Melt jet diameter
4	VJIN: Melt jet velocity
5	TJIN: Melt jet T (liq.2670+ΔT)
6	CBR: Jet breakup length factor
7	CDMM: Particle size factor
8	CHTP: Heat transfer factor
9	CDPC: Particle mixing column factor
10	FDHF: DHF factor
11	EPOR: Debris bed porosity
12	FTCR: Merge criterion const.
13	FQBDHF: Lump heat transfer limitation factor
14	UEMS: Melt emissivity
15	UBOI: Top boiling HT factor
16	UCND: Melt conductivity factor
17	UHTSD: Melt HT factor (side)

3.3 Evaluation results

As described in **Fig. 3**, the developed framework starts with COOLAP-3 computation. The initial condition was determined using the reference MELCOR results (APR1400-SBO with decompression strategy before reactor vessel failure) [6]. It should be noted that, because the scenario uncertainty parameters were included in this framework, the cavity coolability results is not limited to the reference scenario. **Fig. 4** shows the COOLAP results distribution for the main variables at 1 hour. First, in more than 200 cases, the mass of melt pool present in the reactor cavity was less than 20 tons. On the other hand, MELCOR code assumes that all corium in the reactor cavity is in the melt pool state. Second, in more than 300 cases, the cross-section area of the melt pool was calculated to be smaller than the cavity bottom area. The debris formation model predicted that the melt pool would not spread to the end of the cavity. It means that the MELCOR-COOLAP framework can improve the accuracy of MCCI calculation.

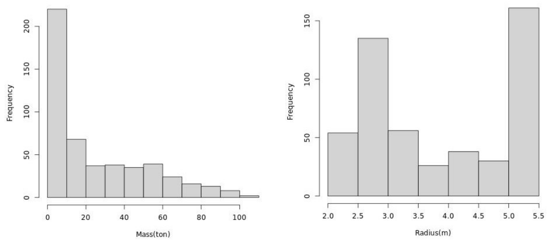
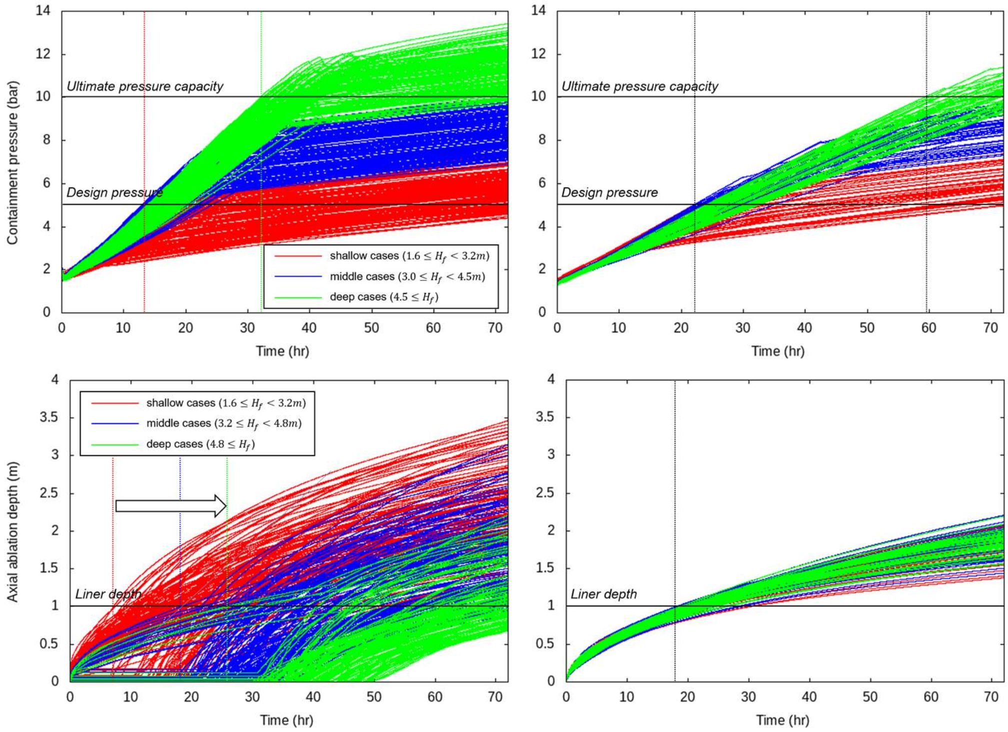


Fig. 4. COOLAP-3 results: distribution of melt pool mass (left) and melt pool radius (right) among 500 cases.

Consequently, **Fig. 5** shows the MELCOR-COOLAP computation results which evaluated the ex-vessel corium coolability for 72 hours. Since it was assumed that no mitigation strategy is implemented in all MELCOR/COOLAP computation, we can investigate the operator's available time of mitigation measures in terms of corium coolability. The pressure increase rate is higher in the MELCOR-COOLAP results because the decay heat of the debris bed is more easily transferred to the coolant than the melt pool. However, considering the ultimate pressure capacity, the available time by cavity ablation was shorter than the time by overpressure. The MELCOR-COOLAP framework can predict the ablation delay due to cavity flooding, but the MELCOR code predicted almost similar ablation trends between all cases. In conclusion, only the developed framework can reasonably evaluate the ex-vessel coolability in pre-flooded reactor cavity.

4. Conclusions

In this study, we performed a MELCOR-COOLAP coupled analysis to evaluate the ex-vessel corium coolability considering three types of uncertainty; accident scenario, COOLAP-FCI models and MELCOR-MCCI models. APR1400-type PWR reactor was selected as a reference power plant to verify the need for the analysis. Unlike the current MELCOR code, COOLAP-3 code can estimate debris bed mass and lump area depending on the cavity and corium conditions. For this reason, the MELCOR-COOLAP coupled analysis can predict the ablation delay due to cavity flooding, but the MELCOR code predicted almost similar ablation trends between all cases. Only the present analysis can reasonably evaluate the ex-vessel coolability in pre-flooded reactor cavity. Noteworthy, because the scenario uncertainty parameters were included in this analysis, coupled analysis results is not limited to the specific scenario.



(a) MELCOR-COOLAP (b) MELCOR

Fig. 5. Comparison of ex-vessel corium coolability evaluation results between (a) MELCOR-COOLAP framework and (b) MELCOR code. No mitigation strategy was implemented after the pressure vessel failure. It was noted that only the MELCOR-COOLAP coupled analysis can predict the different trend of ablation depth variation according to the water level group.

Acknowledgement

The authors would like to acknowledge the support from the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (Grant No. 1805001-0522-CG100).

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