Evaluation of Ablation rate by the change of Sacrificial Material for PECS in EU-APR

Do Hyun Hwang*, Yong Soo Kim, Keun Sung Lee
KHNP-CRI, 1312 Gil, 70. Yuseongdaero Yuseong-gu, Daejeon 305-343, Korea
**Corresponding author: crihwang@khnp.co.kr*

1. Introduction

EU-APR, modified and improved from its original design of APR1400, has been developed to comply with European Utility Requirements (EUR) and nuclear design requirements of the European countries [1].

In EU-APR, Severe Accident Mitigation Systems are dedicated to providing an independent defense line from that of Engineered Safety Feature (ESF) and Diverse Safety Feature (DSF). They consist of Emergency Reactor Depressurization System (ERDS), Passive Ex-vessel corium retaining and Cooling System (PECS), Severe Accident Containment Spray System (SACSS), Hydrogen Mitigation System (HMS) and Containment Filtered Vent System (CFVS).

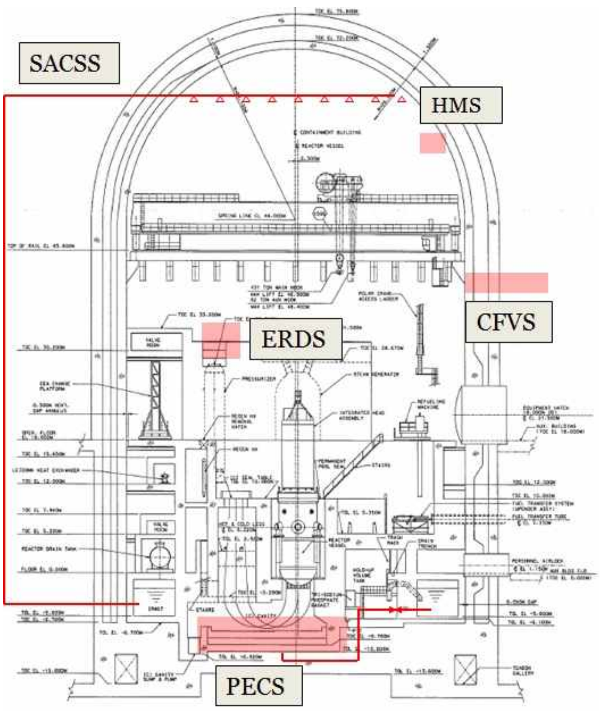

Fig.1 Severe Accident Mitigation Systems in EU-APR

The PECS, so called core catcher, was introduced to prevent the Molten Core Concrete Interaction (MCCI) after Reactor Vessel (RV) failure. It is located inside the reactor cavity under a reactor vessel and equipped with Sacrificial Material (SM) layer on the ex-vessel core catcher body, cooling channel, downcomers, cooling water supply subsystem and monitoring instrumentation as shown in Fig. 2 [2].

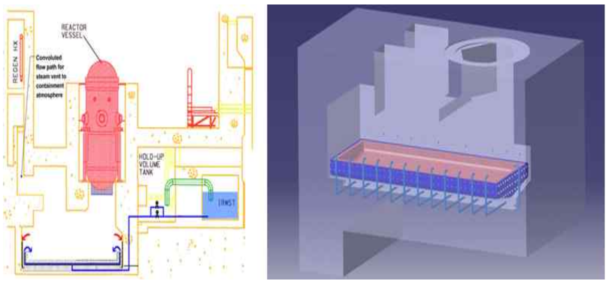

Fig.2 Schematic Diagram for PECS

The PECS has experienced a lot of changes from its original design. Recently, the most significant change was that as a SM, limestone concrete is installed on PECS's body wall instead of previous sacrificial material rich in Fe_2O_3. The main reason of this design change is to overcome the issue that the sacrificial material is ablated rather too fast when reacting with corium that contains a large fraction of Zr metal. Other changes in the geometry of PECS's wall and downcomer design are considered as minor ones.

In this paper, the comparison of ablation rates between previous SM and limestone concrete is carried out using MAAP5 code with respective MCCI model according to the material.

2. Previous model for sacrificial material in MAAP5

The purpose of previous sacrificial material (SM) is to oxidize free Zr in the corium to reduce hydrogen generation via the steam-zirconium reaction. The conversion of Zr metal to oxide occurs via an exothermic chemical reaction between the Fe_2O_3 chemical components of the SM and the free metal Zr in the overlying corium melt. The chemical heat released is divided between heating the overlying corium and melting the underlying SM.

Previous model using SM was developed based on theoretical and experimental work on the corium-SM interaction which had been performed at the Alexandrov Scientific Research Institute of Technology (NITI) and KAERI. In the model of corium-SM interaction, buoyancy force is responsible for vigorous mixing of SM melt and corium in the reaction zone due to the difference in the material densities of the SM and the heavier corium rather than due to the temperature difference between the reaction layer and the melting SM surface. The model also accounts for the thermal resistance of the SM melt layer that undoubtedly covers the solid SM [3].

Several laboratory studies [4~8] have shown that the melting of a solid beneath a hot pool of heavier miscible material is a boundary-layer phenomenon involving the steady generation of narrow columns or streamers of melt material from a stable melt layer that exists between the melting solid and the overlying pool. The streamers originate at discrete sites at the melt layer-pool interface and continuously inject melt material into the overlying pool. The streamers produce vigorous mixing between the melt and pool material so that they lose their identities just above the melt layer. It is reasonable to assume that streamers of molten SM are present near the bottom of the corium pool (beneath the reaction layer) and are chiefly responsible for SM melt removal and mixing with the oxidic corium pool.

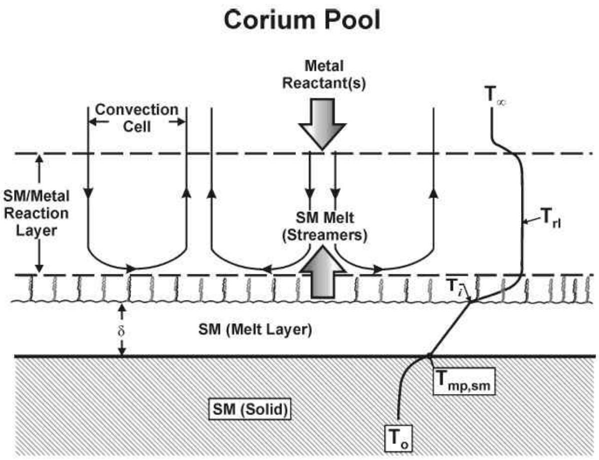

Fig.3 Illustration of SM-metal reaction layer fed by SM melt layer streamers from below and metal reactant from overlying corium pool

2.1 Liquid Phase Burning Model

In the experiments by NITI and KAERI, as the time of the material exceeds the Liquid Phase Burning (LPB) initiating temperature, the interaction starts between the corium and SM at a point of the initial boundary between the corium and SM. It proceeds at a constant rate until all the Zr and U metals are fully oxidized.

The standard MCCI model calculates the ablation rate at about 0.1 mm/s or less. The ablation rate due to LPM can be as high as 1 to 2 mm/s. Evidently, it fails to capture the much quicker ablation rate at the earlier phase of SM and corium interaction due to LPB model.

For applying LPB model to MAAP5, the calculations of ablation rates and the calculations of heat transfer rate from the corium and the SM are de-coupled that the ablation rate is calculated by the distributed heat sink model while the heat transfer rate is calculated by the SM and corium interaction model.

3. New Model for Limestone Concrete in MAAP5

The latest design change in EU-APR has replaced the sacrificial material with limestone concrete in the core catcher wall because the previous sacrificial material was determined to be susceptible to liquid phase burning and could be fully ablated before water is delivered into the core catcher [9]. This posed a threat of core catcher failure and defeated the main purpose of retaining the corium in the core catcher.

According to the newly introduced limestone concrete for the PECS in EU-APR, melt eruption and particulate bed models are added to the core catcher model in the MAAP5 code in order to capture the key phenomena during MCCI with limestone concrete [10].

3.1 Melt Eruption Model

Melt eruption is a phenomenon observed in many "wet cavity" MCCI experiments. In these experiments, off-gases from concrete ablation are vented through many sites on the top surface of the corium periodically. The gases entrain and carry molten corium in the corium pool into the water above it, where the entrained corium is quenched to form solidified particles. Eventually the particles accumulate on top of the corium pool to form a particulate bed. The significance of melt eruption is that it generates particles with large surface areas compared to the contiguous corium pool so that it helps quench the corium in the containment.

Melt eruption model in MAAP5 is based on Ricou-Spalding entrainment correlation [Ricou and Spalding, 1961], where the rates of mass, energy and the number of particles generated by the melt eruption are correlated by

$$\dot{M}_{pb} = K_e \dot{V}_{og} \rho_{cm} = E_0 \left(\frac{\rho_{cm}}{\rho_{og}} \right)^{1/2} W_{og}$$

$$\dot{U}_{pb} = \dot{M}_{pb} h_{cm} = E_0 \left(\frac{\rho_{cm}}{\rho_{og}} \right)^{1/2} W_{og} h_{cm}$$

$$\dot{N}_{pb} = 6\dot{M}_{pb} / \left(\rho_{cm} \pi d_{pb,me}{}^3 \right)$$

where ρ_{cm} and ρ_{og} are the densities of molten corium and off-gas, W_{og} is the mass flow rate of the off-gas, h_{cm} is the enthalpy of the molten corium, and $d_{pb,me}$ is the average diameter of the entrained particles (specified by users through input). The diameter of the entrained particle is typically about a few millimeters [Farmer, 2010].

A key modeling parameter in Equations above is the entrainment coefficient E_0, which determines the efficiency of the melt eruption. The rate of melt entrainment by using the following definition of the empirical melt entrainment efficiency coefficient K_e:

$$K_e = \frac{\dot{V}_{cm}}{\dot{V}_{og}} = \frac{j_{cm}}{j_{og}} = \frac{\dot{M}_{pb}}{W_{og}} \frac{\rho_{og}}{\rho_{cm}}$$

where $\dot{V}_{cm}$ and $\dot{V}_{og}$ are, respectively, the volumetric flow rates of the entrained melt (cm) and the concrete off gas (og); and j_{cm} and j_{og} are the superficial velocities of the entrained melt and the concrete off gas. Combining equations above yields:

$$K_e = E_0 \left(\frac{\rho_{og}}{\rho_{cm}} \right)^{1/2}$$

Fig. 4 displays the K_e values inferred from the tests with reactor materials. The Ricou-Spalding correlation with E_0=0.08 is reasonably close to most of and below the entire measured entrainment coefficient during MCCI.

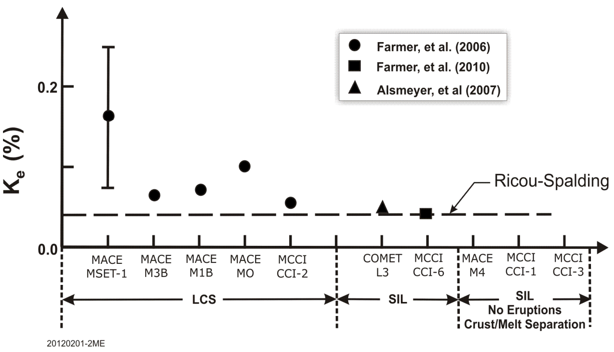

Fig.4 Time-averaged corium melt entrainment coefficients inferred from integral reactor material tests

3.2 Particulate Bed Model

Melt eruption and Fuel Coolant Interaction (FCI) during corium relocation can form a particulate bed. Enormous heat transfer rates can be sustained from the particulate bed to water due to the fact that the particulate bed is highly permeable to water and steam and the heat transfer area is very large. Therefore, the corium in the particulate bed is expected to be fully quenched, such that the temperature is only slightly higher than water saturation temperature. This contrasts with other regions in the corium pool where temperatures can be significantly higher. The large temperature difference between the particulate bed and the rest of the corium pool prompts separate mass and energy tracking in the particulate bed and other region.

Fig. 5 shows the geometry of corium considered in the improved core-catcher model that considers a particulate bed. Heat transfer between the particulate bed and its surroundings is modeled for the wet cavity and dry cavity cases.

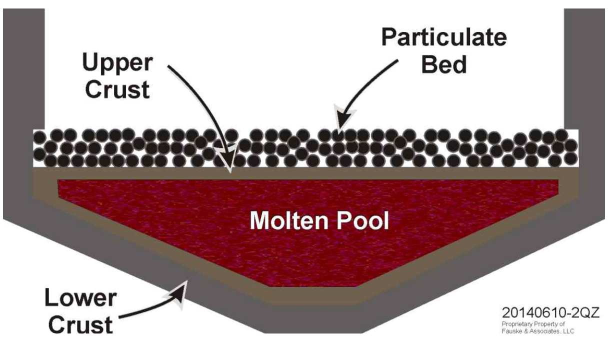

Fig.5 Corium Configuration in the PECS for EU-APR

For wet cavity case, the corium pool to water heat transfer is much larger than that to particulate bed because water is able to reach the top of the underlying continuous corium pool as long as the heat transfer from the particulate bed to water does not result in film boiling. On the other hand if the particulate bed is very high, the heat transfer rate of film boiling could exceed that of CHF. As a result, the heat transfer rate from the particulate bed to the water is expressed as the smaller value of the two different heat transfer areas, either the nucleate boiling rate or the larger of the CHF and the film boiling rate.

For dry cavity case, it is subject to heat and mass exchange with the surroundings including the gas (through convection), heat sink (through radiation) in the cavity, the side concrete wall (through conduction and radiation) and the underlying corium pool (through conduction and radiation) so that the mass and energy rates of change within a dry particulate bed are determined by those evaluated based on energy balances at the interfaces.

4. Comparison of Analysis Results for the previous Sacrificial Material (SM) Model and the new Limestone Concrete (LC) Model for the Ablation

As mentioned in the introduction, properties of sacrificial material installed on PECS's body are changed to limestone concrete from the previous sacrificial material rich in Fe_2O_3. In this chapter, analysis results of ablation depth for two models (SM model and LC model) are compared with a large break LOCA (LBLOCA) sequence. It is assumed that water is provided after 300 seconds of vessel failure

4.1 Analysis Result of Ablation for the SM Model

Fig.6 shows ablation rate results for the SM model in case of the both bottom and top corium cooling with several conditions such as regular sacrificial material (SM), SM with the middle layer of steel, SM with the middle layer of SM and steel rebar.

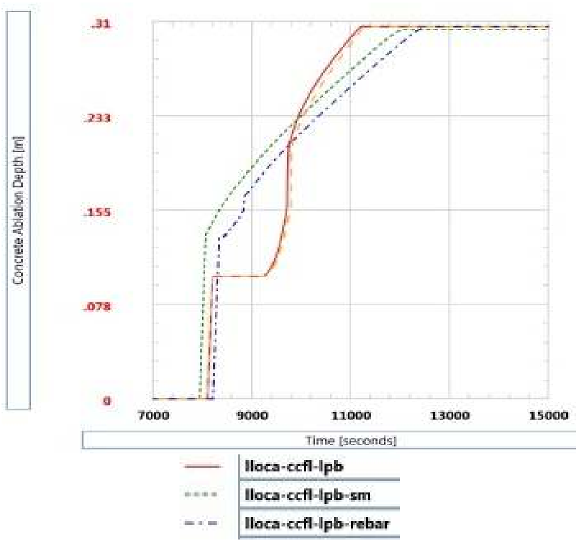

Fig.6 Axial Ablation Depths for the previous SM in case of bottom and top corium cooling

The results show that the SMs with 30 cm thickness are fully ablated at most 5,000 seconds after the vessel failure for all conditions.

4.2 Analysis Result of Ablation for the LC Model

Fig.7 shows ablation rate results for the new Limestone Concrete (LC) model in case of both bottom and top corium cooling.

The result shows that the ablation depth of limestone is less than 11 cm and the ablation process does not seem to proceed further.

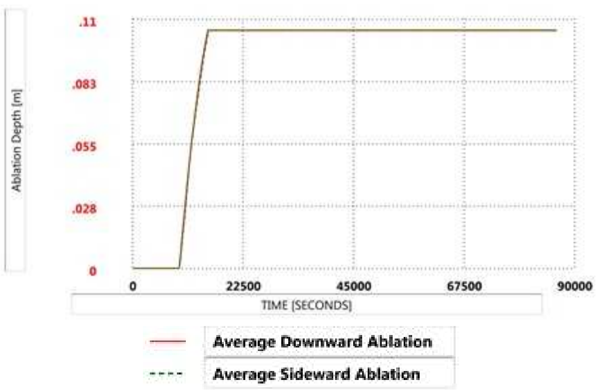

Fig.7 Ablation depths for the new SM in case of both bottom and top corium cooling

5. Conclusions

In this paper, major improvements of MAAP5 model for PECS in EU-APR are presented and the evaluation of ablation rate for the previous SM model and the new LC model is carried out by means of ablation depths with LBLOCA sequence. The results are summarized as shown in Table 1.

Table 1 Comparison of Ablation Depths for the SM model and the LC model in case of both bottom and top corium cooling according to the time sequence of LBLOCA

Time (sec)	Sequence	SM Model (cm)	LC Model (cm)
0	RV failure	0	0
300	Start of cooling water injection	10	0.08
400	Start of Top flooding	13	0.1
600	Water filled with top level of cooling channel	15	0.3
2,400	Water filled with top level of downcomer	23	1.3
4,200	SM fully ablated	30	2.1
20,000		-	10.5

It is found that the LC model using limestone concrete has a very strong ablation-resistant feature in comparison with the SM model using Fe_2O_3 rich sacrificial material.

In addition, two models have respective unique ablation process. The ablation of LC model proceeds at a constant rate regardless of water while the ablation of SM model proceeds at a faster rate before the arrival of cooling water for corium and SM mixture.

The change of sacrificial material also takes advantages of the high gaseous content, high melting temperature and latent heat of ablation of limestone concrete. It means that the corium may be stabilized with limited concrete ablation depth so that the amount of sacrificial material to be installed on PECS can be reduced in case of using limestone concrete.

In the near future, a study will be carried out to derive a 3-dimensional flux distribution based on the result of MAAP5 analysis for PECS in EU-APR.

Acknowledgement

This work was supported by the Major Technologies Development for Export Market Diversification of APR1400 of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Ministry of Trade, Industry and Energy.

REFERENCES

[1] Do Hyun Hwang et al., "Analysis of Ex-Vessel Steam Explosion in PECS of EU-APR1400", WORTH-6, Busan, Korea, April 2013.

[2] KHNP, "Plant Design Description of EU-APR", December 2014.

[3] FAI, "Implementation and Analyses of Sacrificial Material and Corium Interactions in EU-APR1400 Core Catcher," Rev.0, November 2013

[4] Farhadieh, R. and Baker, L., "Heat Transfer Phenomenology of a Hydrodynamically Unstable Melting System," J. Heat Transfer 100, pp. 305-310, 1978.

[5] Catton, I. et al., "Heat Transfer from a Heated Pool to a Melting Miscible Substrate," J. Heat Transfer 105, pp. 447-543, 1983.

[6] Fang, L. J. et al., "An Experimental Study of Natural," J. Heat Transfer 105, pp. 447-543, 1984.

[7] Eck, G. et al., "Experimental Studies of Penetration of a Hot Liquid Pool into a Melting Miscible Substrate," J. Heat Transfer 64, pp. 275-289, 1984.

[8] Epstein, M. et al., "Natural Convection Characteristics of Pool Penetration into a Melting Miscible Substrate," J. Heat Transfer 108, pp. 190-197, 1986.

[9] Sulatsky, A. A. et al., "Molten Corium Interaction with Oxidic Sacrificial Materials of VVER Core Catcher," Proceedings of ICAPP 05, Seoul, Korea, May 15~19 2005.

[10] FAI, "Analyses of EU-APR1400 Passive Ex-Vessel Corium Retaining Cooling System (PECS) with the MAAP5.02.1150 Code", Rev.1, September 2014.