ANALYSIS OF MOLTEN-CORIUM CONCRETE INTERACTION FOR SMALL MODULAR REACTOR

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ABSTRACT

Molten-corium concrete interaction (MCCI) is one of the important phenomena in a severe accident analysis of a nuclear power plant. When a reactor vessel is broken, molten corium spreads out into the cavity. Various chemical reactions occur as the molten corium ablates the cavity concrete. Ex-vessel phenomena also have to be analysed for recently developed small modular reactors (SMRs). In the analysis of the MCCI, the main variables characterised in SMRs are drawn in comparison with those of large power pressurised water reactors. The designs of the core, reactor coolant system, and containment are included. The variables are controlled to analyse the effects on the MCCI. The results of the analysis showed that the ablation of concrete proceeded slowly owing to the relatively large cavity area and small amount of corium. The large metal content in corium caused an increase in hydrogen generation.

1. Introduction

Nuclear fuels become melted when the core is not sufficiently cooled during an uncontrolled nuclear accident. If core melting continuously progresses, it threatens the integrity of the reactor vessel. During the damage to the reactor vessel, the molten-corium drops into the cavity. In the case of a dry cavity, it widely spreads out into the cavity. The release of radioactive materials into the environment has to be prevented for all severe accidents of a nuclear power plant. Analysing the behaviour of the corium is important to predict the overall state of the nuclear power plant for retaining corium inside the final barrier. A molten-corium concrete interaction (MCCI) is one of the important issues in an ex-vessel analysis inside the containment.

Diverse SMRs are being developed in many parts of the world for the expected demand of small power capacity and modularization. In a pressurised water reactor, the main components such as the steam generators, reactor coolant pumps, and pressuriser are designed to be integrated in a reactor pressurised vessel. NuScale, mPower, and IRIS are PWR-type SMRs developed in the US. Russia is developing a series of KLT reactors for each objective. In addition, China is developing diverse SMRs including ACP120, CAP150, ACPRs, and NHR200. CAREM is also an integral PWR developed by Argentina [1].

SMART (System-integrated Modular Advanced Reactor), which is a 330 MWth PWR, received standard design approval in 2012. Korea launched a project for the exportation of SMRs to Saudi Arabia after its standard design authorization. SMART was designed with a passive residual heat removal system operated by natural phenomena. In addition, the use of a passive containment cooling system has been newly considered.

SMART has a bigger reactor vessel than that of a loop-type PWR because the reactor coolant pumps and steam generators are installed inside the integrated reactor vessel. Accordingly, it has a bigger safety margin in the strategy of corium in-vessel retention through external reactor vessel cooling (IVR-ERVC) than that of a loop-type conventional PWR. In spite of the merit of an in-vessel strategy, all ex-vessel phenomena have to be identified closely to maintain the integrity of the containment.

The purpose of this study is to analyse the MCCI phenomenon with varying main design parameters characterised in a SMR. SMART was used as a reference reactor for the simulations.

2. Analysis of MCCI

2.1 Analysis code

A MCCI is a complex phenomenon simulated by a computer code. A number of physical processes have to be included in the modeling of a MCCI. These include internal generation, heat transfer between the melt and concrete, heat transfer between the melt and coolant, chemical reactions, and the basic transfer of mass and energy. In addition, there are significant phenomena that can affect the coolability of the melt during the MCCI process. It includes bulk cooling, melt eruptions, water ingression, and a crust breach.

Various analysis codes were developed and used for the simulation of a MCCI. The main features of the MCCI analysis codes are displayed on Tab. 1. In addition, there are COCO, CORIUM2D, COSACO, MEDICIS, SOCRAT, TOLBIAC-ICB, and WECHSL [2].

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactors [3]. MELCOR-version 1.8.6 developed by Sandia National Laboratories is used in this study. For the MCCI, the effects of heat transfer, concrete ablation, cavity shape change, and gas generation are included in MELCOR, using models taken from the CORCON-Mod3 code [4].

The MCCI phenomenon was simulated using MELCOR-version 1.8.6 in this paper.

Item \ Codes	MELCOR (CORCON)	CORQUENCH	MAAP5
Corium pool	mixed *or* stratified	homogeneously mixed	
Ablation configuration	ray method with dots	averaged axial & radial ablation depth	front model for rectangular or cylindrical +sump
Interface of molten-corium and concrete	‘slag film *or* stable gas film’ + ‘crust’		only crust
Heat transfer to upper coolant pool	*Modified Kutateladze with Farmer`s model*	*Kutateladze*	*User-provided heat transfer coefficient or Mayinger*
Melt eruption	-	*User-specified entrainment coeff. or model`s*	*Ricou`s with coeff.*
Water ingression	-	*Darcy`s or Lomperski-Farmer`s*	*Lister-Epstein`s or parametric*

Tab. 1: Code features for MCCI analysis

2.2 Code input

The input model of SMART was developed for a stand-alone analysis of a MCCI. A specific plant of SMART-PPE (Pre-Project Engineering for the exportation), whose core thermal-power was increased to 365 MW, was adopted for the analyses. The containment of SMART was modeled with a free volume of about 50,000 m^3. The height of the cavity was designed to be relatively lower than that of a large power PWR.

The composition and mass of corium were set from the sequence analysis of the extended loss of AC power by the MELCOR code. In addition, the operation of four passive residual heat removal systems was assumed for simulating a core melt accident.

Moreover, it was assumed that there was a small amount of water in the cavity when the reactor vessel was broken. Accordingly, the strategy of IVR-ERVC (in-vessel retention

through external reactor vessel cooling), which is the key severe accident mitigation strategy in SMART, was set to be not actuated.
The MCCI simulations started under the condition in which the inputted corium was located on the dry cavity. A case had a water supply into the cavity. In addition, passive containment cooling systems and emergency containment spray systems are not simulated in the analyses. Discussions are conducted on the characteristics of general SMRs based on the results of SMART.

3. Analysis results from SMR-characterised variables

3.1 Small core thermal power

SMRs have small core electrical power, which is normally smaller than 300 MWe. As the number of fuel rods is small compared with the size of the cavity, the corium layer is formed thinly in the cavity.
Fig. 1 shows the initial formation and elimination of layers. HOX is a layer of heavy oxide. HMX is a heterogeneous mixture layer of heavy oxides and metals. MET is a metal layer. LMX is a heterogeneous mixture layer of light oxides and metals. LOX is a layer of light oxide. The ablation of concrete was delayed owing to the small depth of corium and the inversion of metal and oxide layers during the initial state. At the start of the simulation, the LOX containing zirconium oxide was separated from the HOX of uranium oxide and the MET. After that, the concrete ablation at the interface of HOX and concrete caused its density to decrease. Finally, as the MET was mixed with HOX, HOX was recognized to be converted into HMX. As the concrete was continuously ablated, the mass of HMX increased with the decrease in density. After three hours, the mixed layer was recognized to be converted into the LMX in the code owing to its density.

3.2 High metal content in a reactor vessel

More structural materials caused by the integrated design of the main components of a reactor coolant system increased the amounts of the metals in the integrated reactor vessel. It delayed the fuel melting in the vessel; however, it increased the portion of metal in the corium layer in the cavity. It also caused a greater generation of hydrogen and carbon-monoxide, as shown in Fig. 2. In actual cases of SMRs, the portions of zircalloy and iron in the corium will also increase.

3.3 Composition of containment cavity

Containment is made of concrete, which is a mixture of cement, water, aggregates, and chemical additives [2]. The containment is set to be a type of siliceous concrete (SIL) in the simulations. The degree of ablation of the lateral wall was mainly dependent on the composition of the cavity concrete.
When the concrete composition was changed into limestone aggregate/common sand (LCS) concrete, the shape of the concrete ablation was changed, as shown in Fig. 3. The ablated degree of axial to radial concrete for the cases of SIL and LCS was similar with the results of previous MCCI experiments [5]. Furthermore, more CO2 was generated in the LCS case than in the SIL case owing to the high content of calcium carbonate in the LCS concrete.

3.4 Coolability of corium in cavity

The decay heat generated in the corium is transferred to the concrete, and the part above to the corium layer. When the cavity is filled with water and the heat is sufficiently transferred to the upper water in the coolable geometry, corium can be cooled by the top flooding. The process of concrete ablation can be delayed or stopped by top flooding with the crust growth. Fig. 4 shows the difference in the maximum ablation thickness with and without the supply of coolant into the cavity. The possibility of cavity flooding in the SMRs is high owing to the presence of a high pool or a strategy for in-vessel cooling.

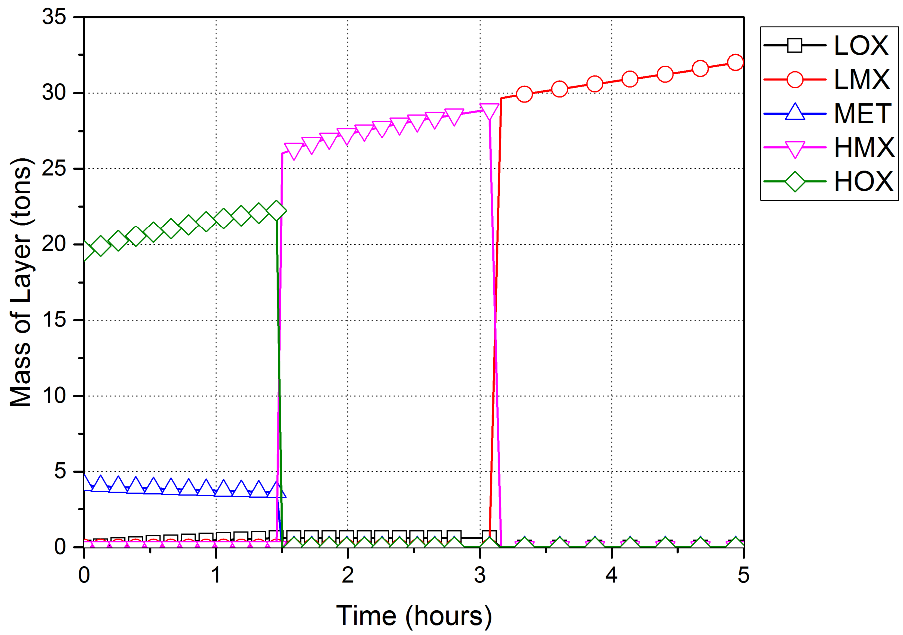

Fig. 1. Initial Layer Inversion of Metal and Oxide

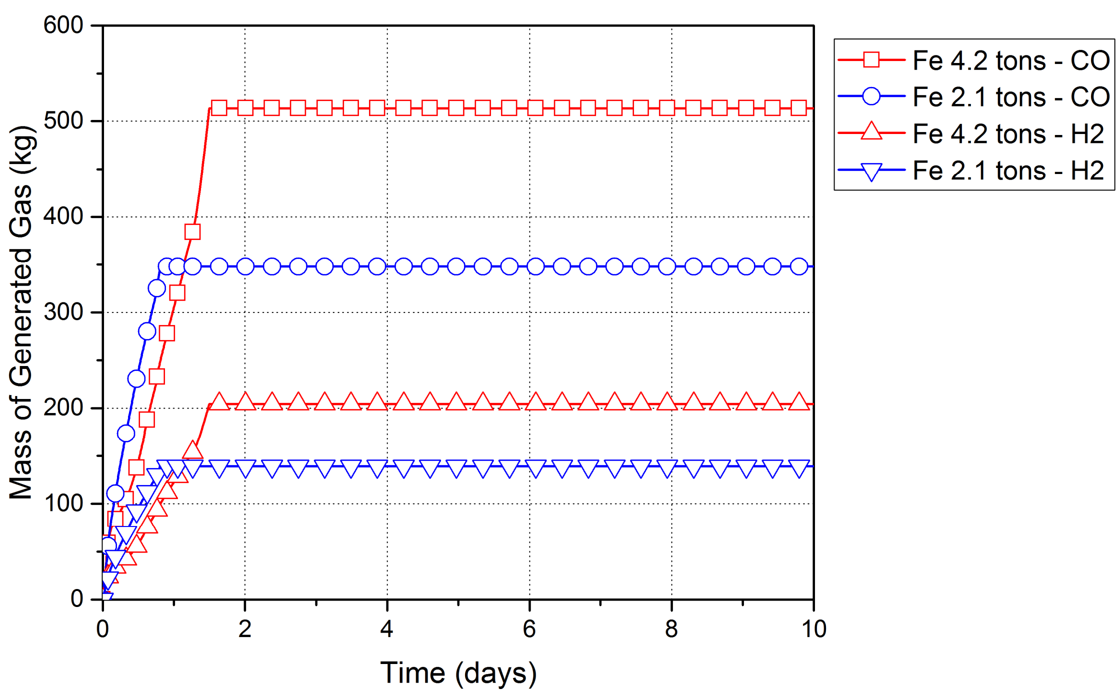

Fig. 2. Masses of Generated Gases

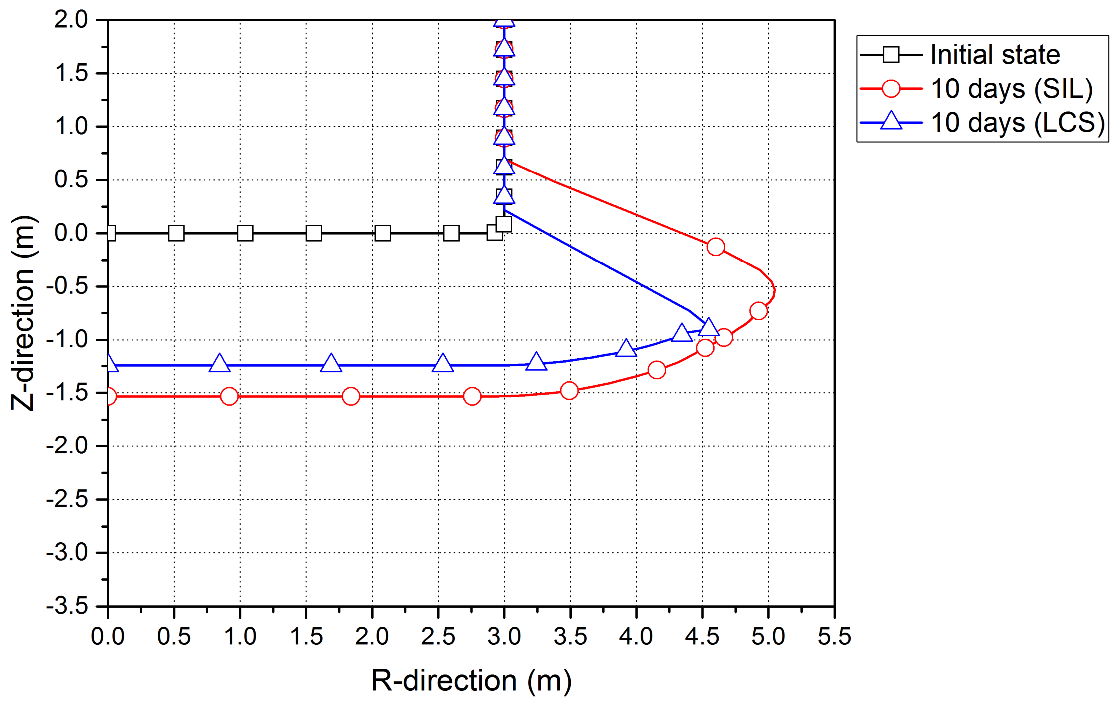

Fig. 3. Shape of Ablated Cavity for each Concrete Composition

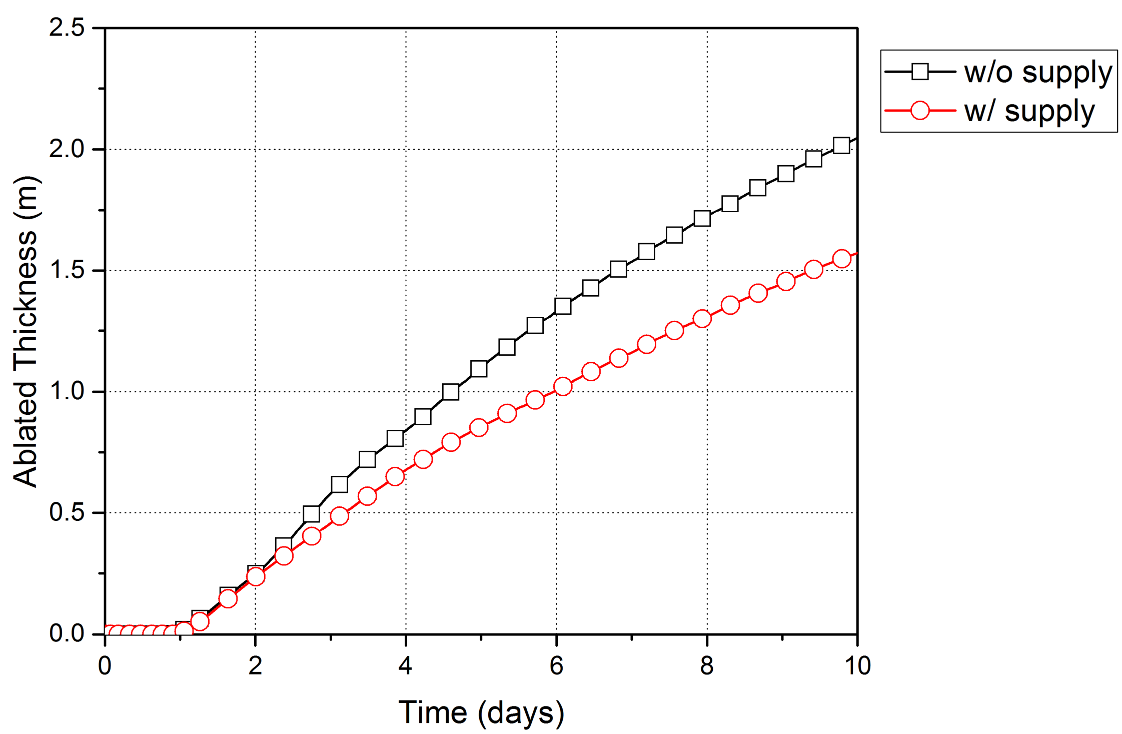

Fig. 4. Maximum Ablation Thickness under Conditions of Water Supply

4. Conclusion

First, an SMR has about one-tenth core mass of large power PWRs; however, the cavity areas for both types are similar. Accordingly, the low height of the heavy oxide layer results in an early layer inversion with the metal layer.
Second, a siliceous type of concrete is recommended for a small free volume of containment and wet-type containment. It can achieve a smaller generation of non-condensable gases.
Third, the risk of hydrogen in MCCI with regard to the internal components and structures in an integrated vessel has to be deeply considered in the design of the containment and the severe accident management strategy.
Fourth, an underestimation of heat transfer from the melt pool to the coolant has to be revised by applying the coolability mechanisms investigated during previous experiments.

5. Acknowledgement

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