Analysis of Sacrificial Material Characteristics for APR1000 Core Catcher

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1. Introduction

The APR1000 (Advanced Power Reactor), which is under development for export to Europe, takes into account ex-vessel corium cooling system to mitigate a severe accident according to European Utility Requirements (EUR), and the core catcher development is underway accordingly. The sacrificial material (SM), one of the main components of the core catcher, absorbs the impact that may occur during the release of core melt and prevents deformation of the core catcher. In addition, it reacts with the core melt until the coolant from the IRWST is supplied into the core catcher, lowering the temperature and reducing the viscosity of the corium-SM mixture to increase its spreadability. In the process of developing the core catcher of EU-APR1400, the reference plant of APR1000, the core melt-sacrificial material erosion tests were conducted on the sacrificial material using the special concrete material developed by NITI[1]. In the sacrificial material erosion experiment using the VESTA-S test equipment, it was anticipated that the sacrificial material would erode much sooner than initially expected [1]. In addition, the VESTA test equipment showed high erosion rate caused by the collision of the core melt jet, which would significantly influence the overall sacrificial material erosion time [2]. This rapid erosion phenomenon can have a very large impact on the management of severe accidents in APR1000, which adopts a post-flooding strategy, because there is a possibility of liquid burning [3]. In this paper, we used the MAAP5 severe accident analysis code to analyze the behavior of the core catcher depending on different types of sacrificial materials to select the optimal sacrificial material for the APR1000 core catcher.

2. Methods and Results

As described above, it was found that the existing special concrete sacrificial material could cause rapid erosion due to liquid burning. Consequently, this study considered changing the sacrificial material to a different substance. The materials examined were three different types: Limestone, Limestone Common Sand (LCS), and Basaltic concrete. The MAAP5.05 version was used for the analysis, with the physical properties of each sacrificial material input as shown in Table I below, to confirm the depth of erosion, an amount of CO_2 production, and temperature changes of the molten corium. In order to lower the temperature and viscosity of corium mixture and protect the core catcher body, the sacrificial material should maintain an appropriate erosion rate and sufficient thickness until the coolant from the IRWST is supplied. In addition, the CO and CO_2 gases produced by the reaction between the core melt and the sacrificial material replace the existing oxygen in metal oxidation and have the effect of limiting the possibility of hydrogen explosion. The CO_2 gas generated in the melt-sacrificial material mixture can create porosity and a large surface area, facilitating subsequent heat transfer (Fig. 1) [4].

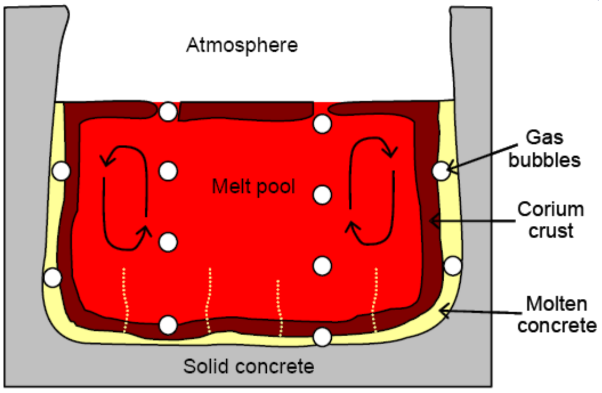

Fig. 1. The schematic diagram of MCCI [4]

2.1 Accident Scenario for Analysis

The selected sequence for this study is a Large Break Loss of Coolant Accident (LBLOCA). The initial break size is assumed to be a 0.24 m (9.5 inch) in diameter in the cold leg. Engineered safety features for core cooling such as the safety injection system and the shutdown cooling system are assumed unavailable except four (4) passive safety injection tanks (accumulators). Table I lists the history of key events predicted by MAAP5 calculation. At 300 seconds after the reactor pressure vessel failure, coolant was injected from the IRWST (In-containment Refueling Water Storage Tank).

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[1] NITI: A.P. Aleksandrov Scientific Research Technological Institute

Table I: Accident progression of LBLOCA sequence

Event	Time (sec)
Large break LOCA	0
Core uncover	131
Core damage	3,592
Corium relocation to lower head	7,570
Vessel failure	11,932

2.2 Input Properties of Sacrificial Material

The main input properties of sacrificial material are shown in Table II [5]. It lists compositions and physical properties of each type of concrete.

Table II: Input properties of SM [5]

Properties	**Limestone**	**LCS**	**Basaltic**
SiO_2	0.036	0.358	0.5484
CaO	0.454	0.313	0.0882
Al_2O_3	0.016	0.036	0.0832
CO_2	0.35698	0.21154	0.015
Density	2300 kg/m^3	2300 kg/m^3	2300 kg/m^3
Absorbed Energy	1.77E6 J/kg	1.14E6 J/kg	2.7E5 J/kg
Specific Heat	663 J/kg-C	1088 J/kg-C	1413 J/kg-C
Thermal Conductivity	1.3 W/m-C	1.3 W/m-C	1.3 W/m-C
Melting Temperature	1813 K	1586 K	1550 K
Latent Heat of Melting	7.6E5 J/kg	5.6E5 J/kg	5.5E5 J/kg

2.3 Erosion Depth of Sacrificial Material

Fig. 2 shows the erosion depth of sacrificial materials for each type of concrete. Limestone concrete showed the lowest erosion rate, while the other two materials did not immediately stop eroding even after the injection of coolant. It appears that there is a possibility of complete erosion of the sacrificial material if the coolant injection is delayed.

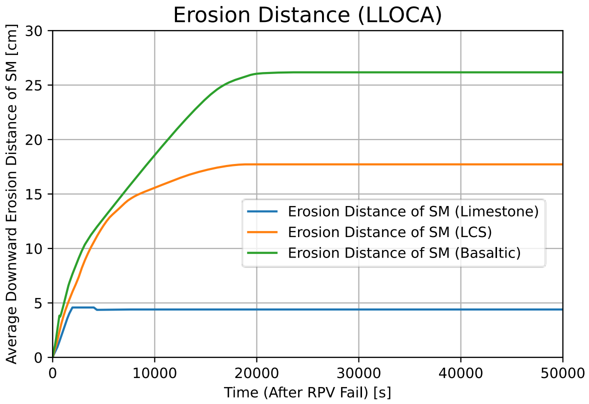

Fig. 2. Erosion depth of sacrificial material.

2.4 The Amount of CO_2 Production

The CO_2 mass produced by the reaction between the core melt and sacrificial materials was examined for each type of concrete as shown in Fig. 3. The result showed that basaltic concrete had the least amount of CO_2 production, while LCS concrete had the most CO_2 production.

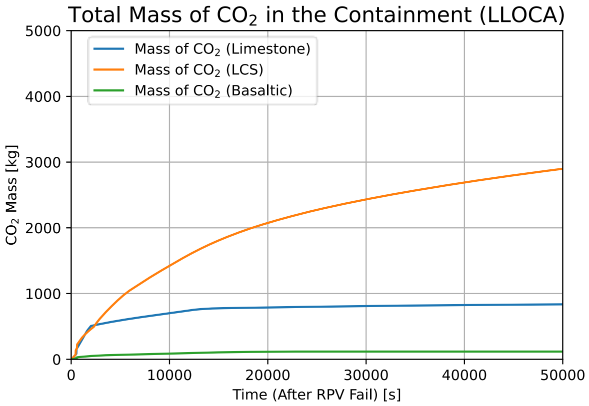

Fig. 3. Amount of CO_2 production by melt reactions.

2.5 The Average Temperature of Corium Mixture

Fig. 4 shows the average temperature changes of core melt according to the sacrificial material. After the supply of coolant, it was confirmed that the limestone concrete was the first to quench the corium within about 8,000 seconds, followed by LCS, and then basaltic concrete. This result is due to several factors. First, the absorbed energy from the chemical reactions in limestone concrete is greater than in other materials. This helps to reduce the temperature of the corium more quickly. Also, the large amount of off-gas generated during concrete erosion agitates the corium mixture, which improves cooling efficiency, resulting in faster quenching.

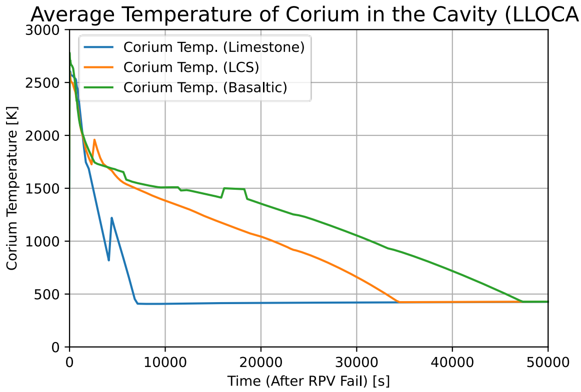

Fig. 4. The average temperature of corium mixture.

3. Conclusions

As described above, the behavior of the core catcher in the APR1000 was examined in terms of erosion rate, gas production, and core melt cooling performance to optimize the sacrificial material. The sacrificial material needs to remain in place until the coolant injection time, even if the coolant injection is delayed under conservative assumptions, in order to maintain the core catcher's integrity. Furthermore, the gases generated from the reaction with the corium can contribute to improving the cooling performance of the mixture. Therefore, after taking into account all the analysis results, limestone concrete is considered to be the most suitable sacrificial material for the APR1000 core catcher. Moreover, limestone concrete has already been proven as used in the existing APR1400 reactor cavity.

ACKNOWLEDGEMENTS

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REFERENCES

[1] NITI, Joint study for development of sacrificial material in KHNP core catcher system, on the work performed for the Task #2, Modeling of melt pool formation in EU-APR1400 core catcher, Final Report, 2011.
[2] KAERI, EU-APR1400 Severe Accident Management Equipment Technical Meeting Materials, 2013.06.13.
[3] Sulatsky, A. A., et al. "Molten corium interaction with oxidic sacrificial material of WER core catcher." International Congress on Advances in Nuclear Power Plants 2005, ICAPP'05. Seoul. 15 May 2005-19. Vol. 2. 2005.
[4] H. Zhong, A Study on the Coolability of Ex-vessel Corium by Late Top Water Flooding, School of Engineering Sciences Department of Physics Stockholm, 2011.
[5] R. K. Cole, Jr., et al., CORCON-MOD2: A Computer Program for Analysis of Molten-Core Concrete Interactions, Sandia National Laboratories, NUREG/CR-3920, SAND84-1246, October 1984.
[6] MAAP5 User’s Manual, EPRI, 2008.