

Analysis of Corium Cooling Behavior in the APR1400 reactor cavity using the CORQUENCH Code

Ji-Hyeon Lee*, Hee-Hong Chae
KEPCO Engineering & Construction
*Corresponding author : jh57@kepco-enc.com

***Keywords :** Severe Accident, MCCI, CORQUENCH

1. Introduction

Nuclear power plants are subject to strict technical standards throughout all stages, including design, construction, and operation. Although the likelihood of a severe accident—exceeding design basis events—that could result in core damage and significant release of radioactivity into the environment is very low, such an accident could have serious social and economic consequences if it were to occur. Therefore, it is essential to establish severe accident management strategies to minimize both the probability of such accidents and the potential risks to the public. To support these strategies, one important aspect of severe accident phenomenological analysis is the evaluation of Molten Core-Concrete Interaction (MCCI), for which understanding the cooling characteristics, particularly the cooling performance of ex-vessel core melt material is crucial.

MCCI is a severe accident phenomenon that occurs when core melt materials fall from the RPV into the cavity. MCCI involves concrete melting and decomposition, chemical reactions between the corium and concrete, and heat transfer between the corium and surrounding structures. It poses potential risks such as : i) the release of large amounts of non-condensable and combustible gases during concrete decomposition; ii) significant heat generation due to chemical reactions between the corium and released materials/gases; iii) the release of fission products from the core melt into the reactor building atmosphere; and iv) substantial concrete erosion.

The CORQUENCH code plays a crucial role in analyzing the behavior of corium following RPV failure. In this paper, the CORQUENCH code version 3.03[1] employed to evaluate the cooling performance of core melt materials in the APR1400 reactor design.

2. Methods

2.1. Scenario

The Large break Loss of Coolant Accident (LLOCA) sequence was selected in this analysis. According to the MAAP analysis results for APR1400, the reactor vessel failure occurs only during the LLOCA accident sequence. The time of RPV failure during the LLOCA accident sequence, as predicted by MAAP5, was used in this analysis[2].

2.2. Model

CORQUENCH provides some options for melt eruption model—such as Ricou Spalding correlation and ANL mechanistic model. In this analysis, Ricou-Spalding correlation, which is known to accurately predict entrainment rates across a wide variety of fluid systems and different flow geometries was selected for the melt eruption model [1].

2.3. Concrete

CORQUENCH includes built-in initial data for limestone/common sand concrete, siliceous concrete, and limestone/limestone concrete, and allows users to define a user specified concrete composition.

Therefore, in this analysis, the reactor cavity floor concrete material used is a SW1 type, limestone-type concrete developed in Korea, which is identical to the material used for the reactor cavity floor of Saeul Units 3&4. The concrete properties such as solidus/liquidus temperature, latent heat, and decomposition energy were referenced from the properties of SW1-type concrete. And the composition of SW1-type concrete is shown in Table 1 [3]. The floor area and design of the reactor cavity was also considered based on the APR1400 reactor design.

2.4. Corium

Also, CORQUENCH code needs some information of corium, such as temperature and compositions. After RPV failure, the core melt composition ratios and the temperature of the core melt material in the reactor cavity were calculated using the MAAP5 code. The temperature of the corium falling into the reactor cavity after reactor vessel failure was applied with consideration of conservatism.

Table 1: SW1 type Composition

No.	Content	No.	Content
1	SiO ₂	7	K ₂ O
2	TiO ₂	8	Fe ₂ O ₃
3	MnO	9	Al ₂ O ₃
4	MgO	10	Cr ₂ O ₃
5	CaO	11	CO ₂
6	Na ₂ O	12	H ₂ O

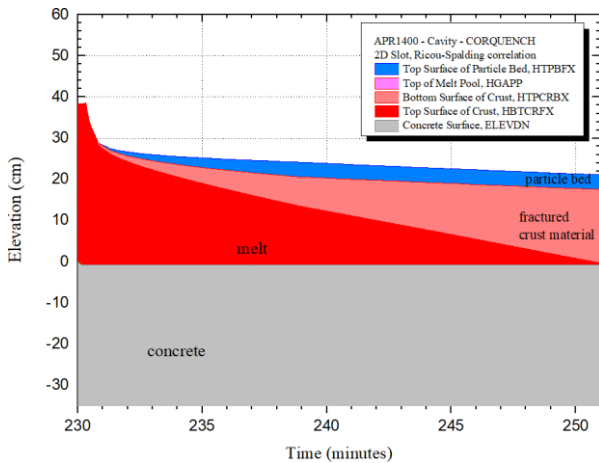


Fig. 1. Elevation of Corium

3. Results

This section presents the CORQUENCH analysis results for the APR1400 nuclear reactor design, incorporating SW1-type concrete developed in Korea, under a Large Break Loss of Coolant Accident (LLOCA) scenario.

The analysis results indicate that the molten material, relocated from the core into the reactor cavity, is effectively cooled and stabilized within a relatively short period of approximately 30 minutes. This is attributed to the favorable thermal characteristics of SW1 concrete and its interaction mechanism with the molten material, which promotes more efficient heat removal. As shown in Figure 1, initially, the melt spreads across the concrete base with a thickness of over 30 cm and begins rapid cooling. During this process, the outer surface quickly solidifies, forming a firm crust layer. Simultaneously, a particle bed composed of relatively small particles develops above the crust.

It was assumed that cooling by cooling water begins immediately after RPV failure at approximately 230 minutes in the LLOCA sequence. Under this assumption, the melt, initially about 38.4cm, is observed to cool rapidly, forming a crust and a particle bed. During this process, the ablation depth of the SW1 type concrete is predicted to be very low.

4. Conclusion

CORQUENCH code was used to analyze the cooling behavior of corium that relocates into the reactor cavity following RPV failure in the APR1400.

In this analysis, the initial corium conditions derived from MAAP5 were used as input parameters for CORQUENCH, enabling a more accurate prediction of Molten Core-Concrete Interaction (MCCI) behavior during the LLOCA accident sequence. The CORQUENCH code utilized the specific corium conditions at the time of RPV failure to predict the

cooling behavior and the resulting concrete ablation depth for the analyzed scenario.

The analysis results show that the initial molten corium layer, approximately 30 cm thick, gradually solidifies during the cooling process, forming a top crust and particle bed. As a result, the thickness of the remaining melt decreases, while the solidified regions increase in thickness over time.

This indicates effective cooling of the corium and suggests that long-term risks associated with Molten Core-Concrete Interaction (MCCI) - such as concrete ablation and generation of non-condensable and combustible gases - can be significantly mitigated.

The analysis employed SW1-type limestone concrete, a material actually used in Korean NPPs, providing realistic and reliable initial conditions. The corium composition and temperature, calculated using the MAAP5 code, further enhanced the accuracy of the CORQUENCH simulations.

In conclusion, this study demonstrates that the corium cooling performance in the APR1400 design is effective, supporting the stabilization of corium within the reactor cavity. Future work should include sensitivity analyses under various cooling conditions and with different concrete types to further improve understanding of MCCI behavior.

Also, the CORQUENCH code is continuously being improved through the ROSAU project. In this study, version 3.03 was used, and as the ROSAU project progresses, further updates to the CORQUENCH code are expected. Therefore, it is expected that the corium cooling behavior for various reactor designs can be analyzed using the improved CORQUENCH code.

REFERENCES

- [1] M.T. Farmer, OECD MCCI Project The CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability under Top Flooding Conditions Code Manual – Version 3.03, ANL, 2011
- [2] MAAP5 – Modular Accident Analysis Program for LWR Power Plants computer code manual, EPRI, 2021
- [3] Final Report on Suitability Assessment for Limestone Concrete MCCI (Molten Core-Concrete Interaction) of Shin-Kori Unit 3&4, KICT, 2014.