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Development of Double Containment Pressure and Temperature Methodology Using CONTEMPT-LT/028

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1. Introduction

Nuclear power plants (NPPs) are required to maintain structural integrity under extreme conditions, such as during a loss-of-coolant accident (LOCA). The containment structure plays a crucial role in ensuring the safety of the plant by containing the release of radioactive materials. In advanced reactor designs like the APR1000, the introduction of a double containment structure is being considered to enhance safety. This design includes an annular compartment, which introduces additional complexities in the thermal and pressure dynamics within the reactor building. One of the APR1000's key features is its double containment structure, designed to minimize the risk of radioactive material release. The gap between the two containment walls is maintained under vacuum pressure to further reduce the potential for leakage.

Recently, Korea was selected as the preferred bidder by the Czech government for the construction of two APR1000 at the Dukovany site, a project valued at approximately 24 trillion won (about 17.7 billion USD). This selection underscores the global confidence in Korea's nuclear technology and the importance of ensuring that the double containment operates as intended.

This study investigates the impact of double containment structures on the temperature and pressure within the reactor building, specifically in the context of the APR1000 nuclear power plant, which is considering the adoption of such a structure. Unlike the APR1400, the APR1000's design involves an annular compartment between the containment wall and the shield building wall. Using the CONTEMPT-LT/028 model, this study explores the thermal-hydraulic behavior under a hypothesized scenario where the HVAC system within the annular compartment is non-operational, and initial conditions are set to the upper bound of normal operation states. The analysis utilizes the APR1400 as a proxy due to the lack of detailed APR1000 design data.

2. Methodologies

The primary objective of this study is to analyze the effects of a double containment structure on the temperature and pressure within the containment using the CONTEMPT-LT/028 model. Figure 1 shows double containment of APR1000. Specifically, this study focuses on:

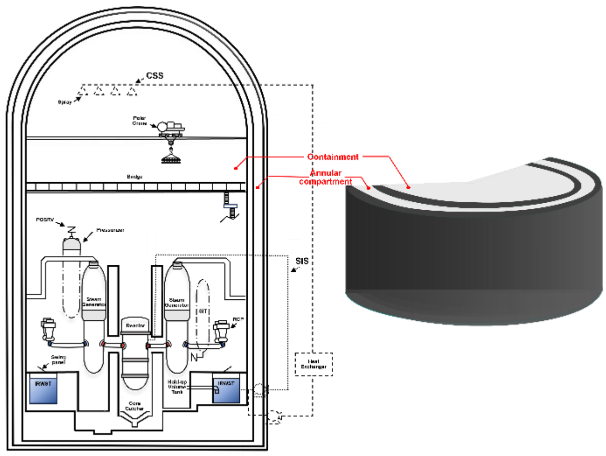

Figure 1. Schematic of Korea NPPs' APR1000 double containment.

1)Evaluating the maximum temperature and pressure within the containment under the assumption that the HVAC system in the annular compartment is non-operational.

2)Comparing the thermal response of the containment structure in different material configurations, particularly between carbon steel and concrete walls.

3)Applying various heat transfer models to assess the thermal behavior of the annular compartment and surrounding structures.

A critical reason for analyzing the maximum pressure and temperature within the reactor building is to ensure the structural integrity and operational reliability of the containment structures and systems under postulated accident conditions [1]. By understanding these extreme conditions, it is possible to design and implement safety features that mitigate the consequences of hypothetical accidents, thereby ensuring the robustness of the containment system.

2.1 Objectives

Given the absence of detailed APR1000 design data, the analysis is conducted using the APR1400 design from Shin-Kori Units 3 and 4 as a reference. The scenarios considered include a LOCA involving a cold leg break and a discharge pipe break. The volume of the annular compartment is derived from the volume ratio between the annular space and the reactor building in Kori Unit 2, which has a carbon steel containment wall.

DEDLB Max SI (Double-Ended Discharge leg guillotine Break with Maximum SI flowrate). causes a 2nd peak (The 2nd peak occurs due to the residual heat in the steam generator affecting the primary side coolant) and was selected as the representative case for this analysis. DEDLB is limiting for LBLOCA according to SKN34 FSAR.

2.2 Scope of Study

For the assumptions, we used those typically employed in the analysis of maximum pressure and temperature in the reactor building. Specifically, the walls inside the reactor building were modeled using the Tagami HTC correlation. Additionally, the walls in contact with the outside were modeled using Uchida's lowest limit [2]. The heat transfer models available in CONTEMPT-LT/028 include 1) Uchida's lowest table, 2) Natural convection, 3) Radiation, and 4) Natural convection + Radiation. The double containment feature in CONTEMPT-LT/028 was used for modeling. As shown in Figure 2, the HTC of the walls in contact with the annular compartment was analyzed using models 1) through 4). Additionally, an analysis was performed by applying carbon steel to the inner shield building, similar to Kori Unit 2.

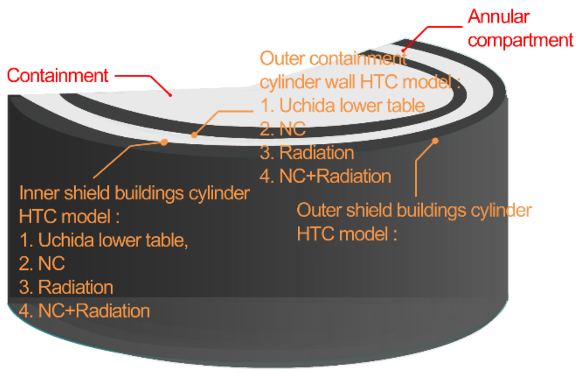

Figure 2. Scope of HTC model double containment using CONTEMPT-LT/028

2.2.1 Natural convection

A natural convection is applicable when the product of Grashof and Prandtl numbers is within the range:

$$\sim 10^7 \leq (Gr \cdot Pr) \leq 10^{12}$$

This correlation is given by

$$q_c = h_c \mathrm{A}(T - T_B)$$

$$h_c = 0.13\left[\rho_f{}^2 \cdot g \cdot \beta_f \cdot \Delta T \cdot C_{pf} \cdot \frac{k_f^2}{\mu_f}\right]^{1/3}$$

h_c = natural convection heat transfer coefficient
A = area
T = surface temperature of the structure
T_B = temperature of the medium to the boundary
ρ_f = density-of gas region, including air and water vapor
g = acceleration due to gravity
$\beta_f = 1/T_f$ where T_f is absolute temperature of film
ΔT = temperature difference between wall and bulk gas region
C_{pf} = specific heat of gas at constant pressure
k_f = thermal conductivity of gas region
μ_f = viscosity of gas region

2.2.2 Radiation

The fundamental equation for direct radiative heat transfer between Surface 1 and Surface 2 is as follows.

$$q_{r12} = \sigma\, A\, F_{12}(T_1^4 - T_2^4)$$

q_{r12} = energy absorption rate at Surface
σ= the Stefan-Boltzmann constant
F_{12} = view factor
T_1= absolute temperature of Surface 1
T_2 = absolute temperature of Surface 2

In CONTEMPT-LT/028, the view factor can be input, and in this case, it is assumed that all the radiative energy emitted from Surface 1 is transferred entirely to Surface 2 without any loss[3].

3.Analysis Results

The results in Figures 3 and 4 show the pressure and temperature graphs of the reactor building when all walls are composed of concrete. The application of any heat transfer model to the walls in contact with the annular compartment did not significantly affect the pressure and temperature of the reactor building. However, the pressure and temperature in the annular compartment varied depending on the heat transfer model after 10^5 seconds. In CONTEMPT-LT/028, the radiation model assumes that the heat transfer direction is constant from the wall to the annular compartment, leading to similar pressure and temperature results as when the Uchida lower limit of 2 BTU/ft^2-hr-°F is applied. Although the combination of natural convection (NC) and radiation results in a larger heat transfer coefficient (HTC) than radiation alone, there was no change in the pressure and temperature of the annular compartment. This is because the direction of heat transfer was predefined when applying radiation and Uchida's lower limit.

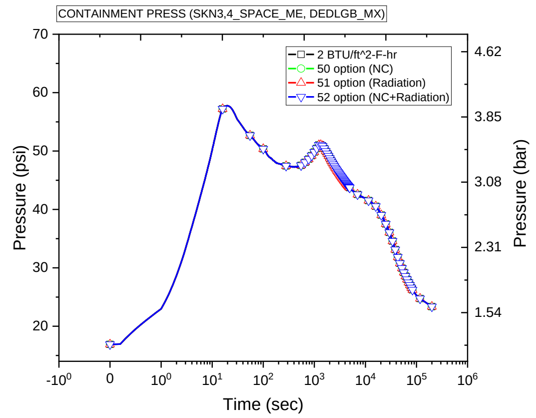

Figure 3. Pressure of containment by HTC model using CONTEMPT-LT/028

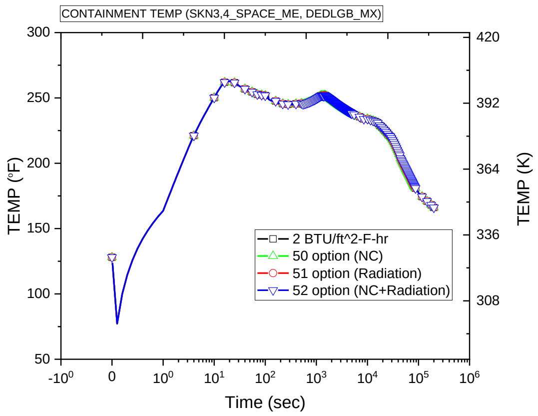

Figure 4. Temperature of containment by HTC model using CONTEMPT-LT/028

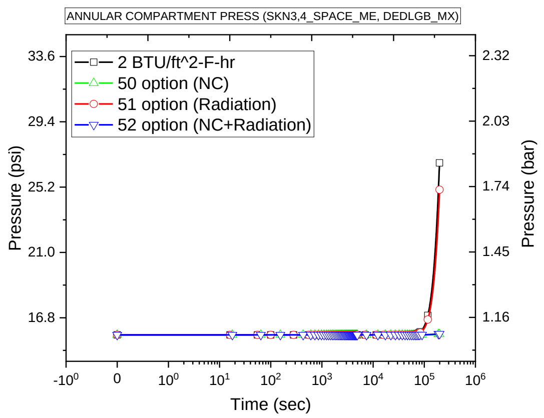

Figure 5. The annular compartment pressure by HTC model using CONTEMPT-LT/028

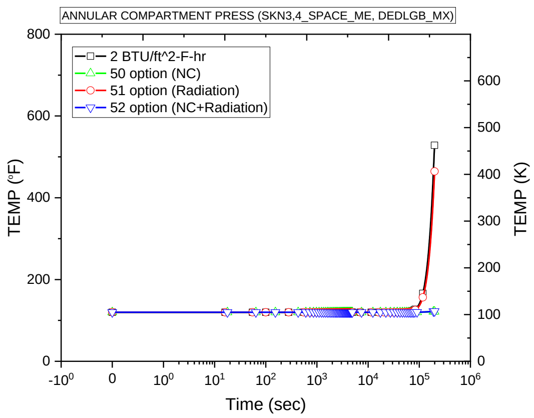

Figure 6. The annular compartment temperature by HTC model using CONTEMPT-LT/028

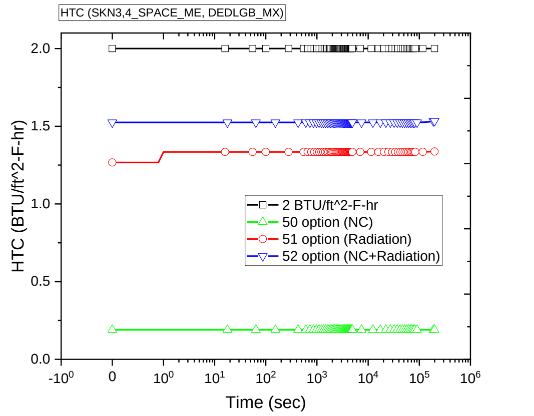

Figure 7. Outer containment cylinder wall HTC using CONTEMPT-LT/028

Figures 6 and 7 show the surface temperatures of the structure, which is a variable other than HTC. In a heat transfer model where the direction of heat transfer is set from the structure to the medium, the surface temperature does not increase because the energy continually flows from the structure to the medium. As a result, the temperature of the annular compartment increases, and as ΔT increases, the heat transfer escalates exponentially over time. Changing the reactor building material from concrete to carbon steel had almost no impact on the pressure and temperature of the reactor building. However, in the radiation model, the temperature of the annular compartment increased too much, causing the model to fail around 10 seconds.

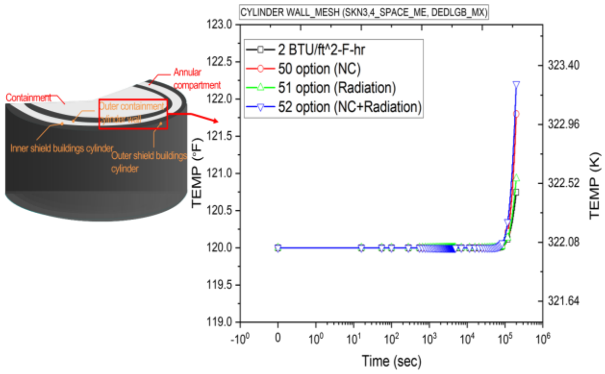

Figure 8. Outer containment cylinder wall surface temperature

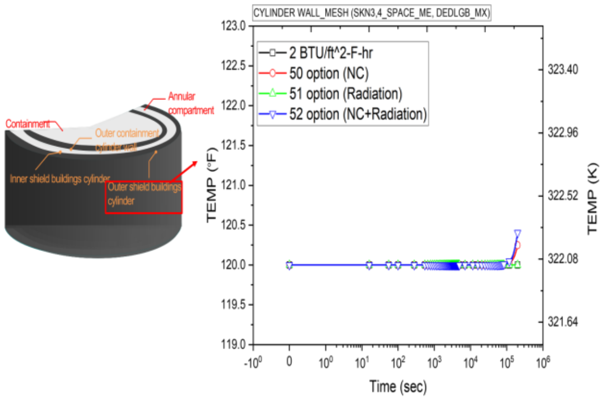

Figure 9. Outer shield buildings cylinder surface temperature

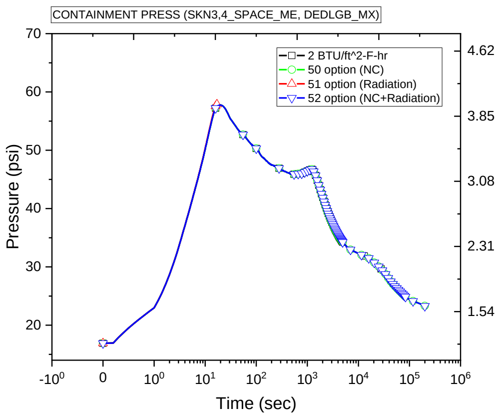

Figure 10. Containment pressure when the containment wall was changed from concrete to carbon steel

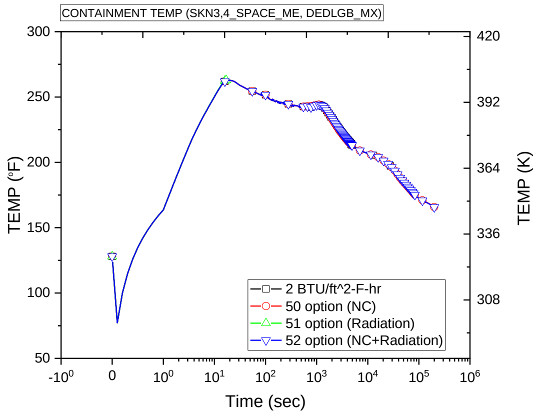

Figure 11. Containment temperature when the containment wall was changed from concrete to carbon steel

4.Conclusion

This study investigates the impact of double containment structures on the temperature and pressure within the reactor building, specifically in the context of the APR1000 nuclear power plant, which is considering the adoption of such a structure. Unlike the APR1400, the APR1000 design involves an annular compartment between the containment wall and the shield building wall. Using the CONTEMPT-LT/028 model, this study explores the thermal-hydraulic behavior under a hypothesized scenario where the HVAC system within the annular compartment is non-operational, and initial conditions are set to the upper bound of normal operation states. The analysis utilizes the APR1400 as a proxy due to the lack of detailed APR1000 design data. Applying any heat transfer model to the annular compartment had little effect on the pressure and temperature of the containment.

REFERENCES

[1] ANSI/ANS-56.4, Pressure and Temperature Transient Analysis for Light Water Reactor Containments, 1988.
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[3] Don W.Hargrove, CONTEMP-LT/028 NUREG CR-0255 TREE-1279, 1979.