Effect of Cavity Flooding Level on the Integrity of APR1400 RPV Using MAAP5

Sangwoo Shin*, Miro Seo, Taewoo Kim, Sun Heo
Korea Hydro & Nuclear Power Co., Ltd., Yuseong-Gu, Daejeon, Korea
**Corresponding author: sangwoo.shin@khnp.com*

Keywords : Severe Accident, Ex-Vessel Cooling(EVC), Reactor Vessel Failure, MAAP5

1. Introduction

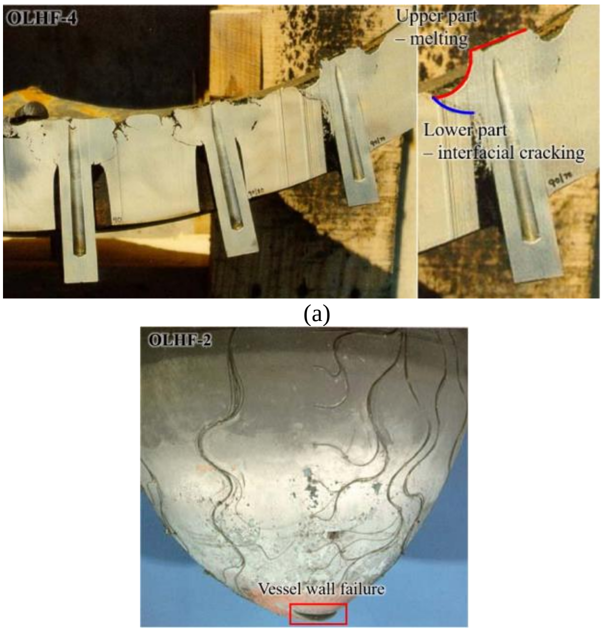
Maintaining the structural integrity of the reactor pressure vessel (RPV) and preventing its failure is a paramount safety objective in severe accident management, as it serves as the barrier against the release of fission products. During a core-melt accident, the relocation of molten corium to the lower head exposes the vessel wall to extreme thermal loading and high internal pressure, which are primary drivers of plastic deformation and creep failure. [1-3]

While previous research has predominantly focused on global rupture of the vessel lower head, large-scale experimental programs, such as the OECD/NEA Lower Head Failure (OLHF) tests [4] as shown in Fig.1, have demonstrated that localized leakage can initiate at bottom-mounted penetrations before the occurrence of global failure. This suggests that thermal imbalances and mechanical vulnerabilities in the penetration regions may govern early failure behavior more significantly than the overall vessel integrity.

One of the key strategies to mitigate such failures is the injection of coolant into the reactor cavity to provide direct external cooling of the vessel wall. Ex-vessel cooling reduces the wall temperature, thereby relaxing thermal stresses and delaying the progression of creep. However, in actual accident scenarios, the water level in the cavity varies depending on the available coolant inventory and injection rates, making the flooding level a critical variable that determines the heat transfer boundary conditions on the vessel's exterior.

In the case of the APR1400, the lower head is equipped with multiple penetrations. The degree of submergence—whether these penetration regions are fully submerged or partially exposed—can lead to significantly different local temperature gradients and deformation patterns. Insufficient cavity flooding levels may cause thermal loads from the uncooled upper sections to concentrate at the penetrations or induce additional strain due to non-uniform cooling, potentially accelerating vessel failure.

The present study utilizes MAAP5 (Modular Accident Analysis Program 5), a comprehensive severe accident analysis code, to numerically analyze the effect of cavity flooding level variations on RPV failure in the APR1400. MAAP5 is well-suited for evaluating the temperature history and structural integrity of the lower head as it allows for an integrated simulation of the complex physical phenomena occurring during a severe accident.



(a)

(b)

Fig. 1 Post-Test examination results showing
(a) Penetration failure in OLHF-4 and
(b) Vessel wall rupture in OLHF-2

By defining the cavity flooding level as a key parameter under various Large-Break Loss-of-Coolant Accident (LBLOCA) scenarios, this paper performs an in-depth analysis of its influence on failure time, failure location, and the underlying failure mechanisms. Through this analysis, the study aims to provide a physical basis for optimizing external cooling strategies.

2. Analysis Methodology and Results

2.1. Nodalization of the Reactor Vessel Lower Head

The MAAP5 code [5] evaluates the thermal-mechanical response of the reactor pressure vessel (RPV) lower head by discretizing its hemispherical geometry into a total of 25 distinct nodes. As illustrated in Fig. 1, the molten corium relocates to the lower head following a core-melt progression, subsequently forming a complex stratified configuration consisting of a crust, oxide pool, metal layer, and particulate bed.

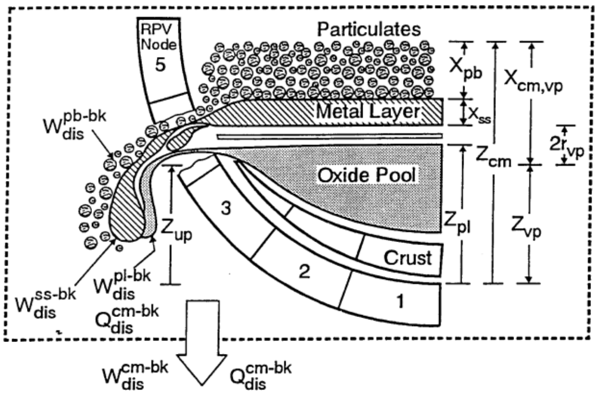


Fig. 2 Schematic of debris layer configuration and RPV wall Nodalization [5]

The code dynamically calculates the heat transfer rates from these diverse corium regions to both the internal vessel wall and the external coolant environment. Fig. 2 provides a detailed schematic representation of this 25-node discretization framework. To investigate the specific impact of the external cooling boundary conditions, a sensitivity analysis was performed by incrementally increasing the cavity flooding level from Node 1 to Node 8, which specifically represents the regions where the In-Core Instrument (ICI) tubes are situated. This approach allows for a granular assessment of how the submergence of penetration areas influences the overall vessel survivability.

2.2. Results

In order to quantify the protective effect of external vessel cooling, the internal wall temperatures of the RPV were analyzed at the precise moment of predicted vessel failure. As shown in Fig. 3, the peak wall temperatures across all flooding scenarios were consistently observed between Node 9 and Node 13, regardless of the initial water level. This phenomenon is attributed to the thermal concentration and the characteristic heat flux distribution of the molten pool within the lower head.

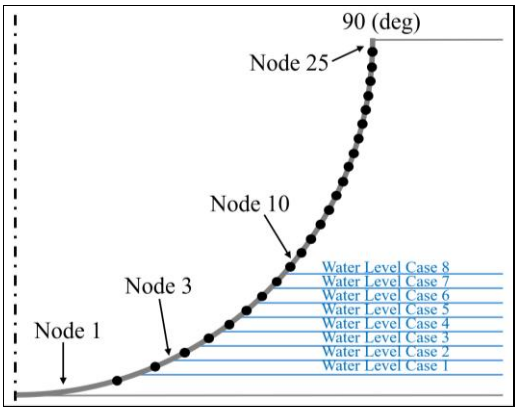


Fig. 3 Conceptual diagram of lower head nodalization and cavity flooding levels in MAAP5

Furthermore, as depicted in Fig. 5, the temperature transients of the weld materials for the ICI tubes located from Node 1 to Node 8 were extracted for comparative analysis. The results clearly demonstrate that Node 8 experienced the most significant thermal loading among the penetration-associated nodes. Consequently, Node 8 was identified as the most vulnerable location for localized thermal failure, suggesting that the integrity of the ICI tube welds is a critical factor in determining the timing of the initial pressure boundary breach.

The comprehensive failure analysis for the eight designated flooding levels revealed a distinct correlation between the water height and the resulting failure modes, as summarized in Table 1. For Cases 1 through 6, where the flooding level was relatively low, the failure was initiated by the localized thermal degradation of the ICI tube weld at Node 8, leading to an early breach of the vessel. However, a significant transition in the failure mechanism was observed in Cases 7 and 8. In these high-flooding scenarios, the ICI tube region was sufficiently cooled by the external water, effectively suppressing localized weld failure. As a result, the failure location shifted to Node 12, where creep rupture occurred due to the sustained thermal load on the upper sections of the lower head.

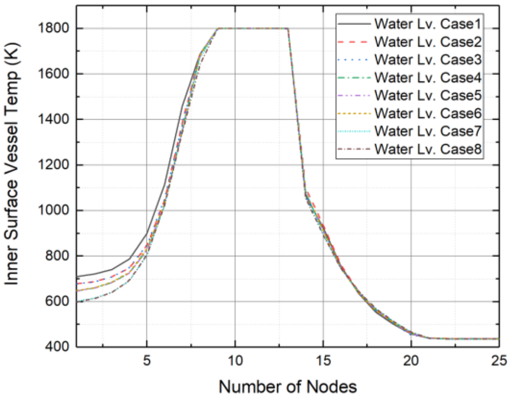


Fig. 4 Inner surface temperatures of the RPV wall for various cavity flooding levels

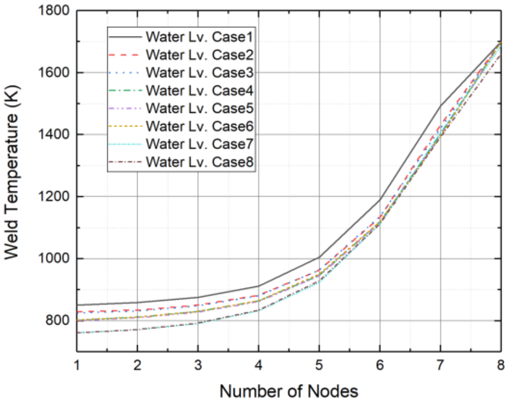


Fig. 5 Weld material temperatures at each ICI tube node

Table 1. Summary of RPV Failure Characteristics

Water Level	Failure Time (s)	Failure Mode	Failure Location
Case1	14,188	TRPTN[1)]	Node 8
Case2	14,301	TRPTN	Node 8
Case3	14,302	TRPTN	Node 8
Case4	14,442	TRPTN	Node 8
Case5	14,443	TRPTN	Node 8
Case6	14,425	TRPTN	Node 8
Case7	14,676	CRLH[2)]	Node 12
Case8	14,684	CRLH	Node 12

[1)] TRPTN : debris plug melt-through of instrument tubes vessel weld
[2)] CRLH : damage fraction due to creep of the lower head wall

Regarding the failure timeline, Case 1, characterized by the lowest flooding level, resulted in the most rapid vessel failure. As the flooding level was increased, a consistent delay in the failure time was observed, underscoring the effectiveness of cavity flooding in extending the grace period for severe accident management

3. Conclusions

This study investigated the influence of reactor cavity flooding levels on the failure characteristics of the APR1400 reactor pressure vessel using the MAAP5 code. A key finding of this research is the identification of a critical threshold flooding height that triggers a distinct shift in the failure mechanism. At lower water levels (Cases 1–6), the vessel is prone to early localized leakage at the ICI tube welds due to concentrated thermal loading. However, ensuring the complete submergence of these penetration nodes provides sufficient heat removal to suppress localized weld failure, thereby shifting the failure mode to a more delayed global creep rupture at higher elevations (Nodes 12).

Furthermore, the results demonstrated that increasing the cavity flooding level progressively delays the onset of vessel failure, effectively extending the grace period for implementing emergency mitigation strategies. To enhance the fidelity of these predictions, future research should involve a high-fidelity structural integrity assessment by coupling specialized structural analysis codes (e.g., ANSYS, ABAQUS) with severe accident analysis tools. This integrated multi-physics approach will serve to verify and refine the failure locations and modes predicted by the MAAP5 analysis, providing a more robust technical basis for optimizing Severe Accident Management Guidelines (SAMG) for the APR1400.

REFERENCES

[1] Rempe, J. L., Chavez, S. a, and Thinnes, G. L., 1993, “Light Water Reactor Lower Head Failure Analysis,” (NUREG/CR-5642; EGG-2618).
[2] Stickler, L. A., Rempe, J. L., Chavez, S. A., Thinnes, G. L., Snow, S. D., Witt, R. J., and Kos, J. A., 1994, “Calculations to Estimate the Margin to Failure in the TMI-2 Vessel,” (NUREG/CR-6196; EGG-2733).
[3] Chu, T. Y., Pilch, M. M., Bentz, J. H., Ludwigsens, J. S., Lu, W. Y., & Humphries, L. L., 1999, “Lower Head Failure Experiments and Analyses,” NUREG/CR-5582, SAND98-2047, Sandia National Laboratories, Albuquerque, NM.
[4] Humphries, L. L., Chu, T. Y., Bentz, J., Simpson, R., Hanks, C., Lu, W., Antoun, B., Robino, C., Puskar, J., and Mongabure, P., 2002, “OECD Lower Head Failure Project Final Report,” CSNI-R2002-27, Sandia National Laboratories, Albuquerque, NM.
[5] EPRI, Computer Code Manual for MAAP5 – Modular Accident Analysis Program for LWR Power Plants, 2021