

## Effect of In-Vessel Coolant Injection Timing on APR1400 Vessel Penetration Failure Using Coupled MAAP–ABAQUS Analysis

Jun-Won Park<sup>a</sup>, Hwang-Young Choi<sup>a</sup>, Yun-Jae Kim<sup>a\*</sup>, Miro Seo<sup>b</sup>, Sangwoo Shin<sup>b</sup>, Soo-Hyun Kim<sup>c</sup>, Ji-Ho Kim<sup>c</sup>

<sup>a</sup>Mechanical Engineering, Korea University, Seoul, 02841, Korea

<sup>b</sup>Korea Hydro & Nuclear Power Co., Ltd., Daejeon, 34101, Korea

<sup>c</sup>Nuclear Engineering, Seoul National University, Seoul 08826, Korea

\*Corresponding author: kimy0308@korea.ac.kr

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### 1. Introduction

During a severe accident, relocation of molten core materials can impose severe thermal loading on the reactor pressure vessel (RPV) lower head, causing plastic deformation, creep, and local failure. Bottom-mounted penetrations are particularly important because geometric discontinuities and differences in the high-temperature properties of the vessel, nozzle, and weld materials can promote localized damage before global vessel-wall rupture.

In-vessel coolant injection can mitigate lower head thermal loading, but its effectiveness depends strongly on the injection timing. Early injection may limit the temperature increase and damage accumulation, whereas delayed injection may allow substantial core degradation and relocation before cooling becomes effective. Therefore, the available timing margin for coolant injection should be evaluated not only from the system response but also from the structural integrity of the vessel penetrations.

MAAP5 can efficiently predict core degradation, molten-core relocation, and the thermal-hydraulic response of the reactor system. However, local deformation and fracture of penetration welds are represented in a simplified manner. A previous coupled MAAP5–ABAQUS study evaluated the lower head integrity of a Korean high-power reactor under an LLOCA scenario, but the penetrations were not explicitly considered [1].

In this study, the coupled analysis framework is extended to an APR1400 lower head model including vessel penetrations. MAAP5 analyses are performed with different in-vessel coolant injection timings, and the resulting temperature and pressure histories are transferred to a three-dimensional ABAQUS model. Material-specific plasticity, creep, and fracture behavior are considered to investigate the effect of injection timing on penetration damage and leakage.

### 2. MAAP5 Analysis under LLOCA

An LLOCA severe accident scenario was analyzed for the APR1400 using MAAP5. The lower head was divided into 25 nodes along the hemispherical vessel to evaluate the spatial and temporal variation of the inner- and outer-wall temperatures.

The reference coolant injection was initiated at 2.5 hr after the severe accident entry time, and the injection timing was subsequently delayed in increments of 10 min. For each case, the progression of core degradation, molten-core relocation, lower head temperature, and vessel failure was examined.

When injection was initiated sufficiently early, the thermal loading of the lower head was reduced and vessel failure was not predicted. As the injection was delayed, the penetration region experienced greater thermal exposure, and vessel failure was first predicted at an injection delay of 70 min. The case immediately before failure and the first failure case were selected for detailed structural analysis. The inner- and outer-wall temperatures and vessel pressure calculated by MAAP5 were extracted as transient boundary conditions for the subsequent ABAQUS analyses.

Table 1. MAAP5 results according to in-vessel coolant injection timing.

| In-vessel injection time  | Vessel failure |
|---------------------------|----------------|
| SA*+2.5 hr<br>+<br>60 min | X              |
| SA+2.5 hr<br>+<br>70 min  | O (4.75 hr)    |

\*SA : Severe Accident Entry time

### 3. Structural Analysis Model

Fig. 1 shows a three-dimensional symmetry model of the lower head constructed in ABAQUS. The model represents a one-eighth symmetric portion of the RPV lower head and includes the central and outermost penetrations. The model explicitly represented the RPV wall, penetration nozzle, and penetration weld, with a refined mesh around the weld region to capture local stress, strain, and damage gradients.

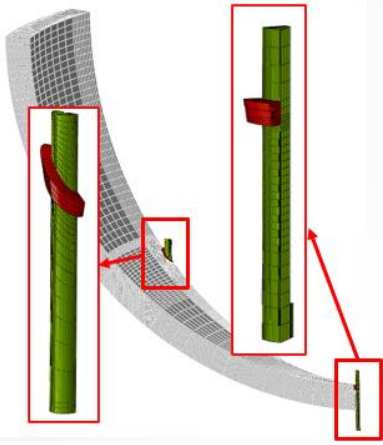


Fig. 1. Three-dimensional FE model of the RPV lower head including the central and outermost penetrations

The MAAP5 temperatures were mapped onto the corresponding lower head locations. Temperatures between the inner and outer surfaces were interpolated through the vessel thickness, and the transient vessel pressure was applied to the internal surface.

Temperature-dependent plastic and creep properties were assigned to the constituent materials. Material-specific deformation and fracture models developed for the vessel, nozzle, and weld materials were used [2,3,4].

Local fracture was evaluated using a strain-based damage model. The multiaxial fracture strain was defined as

$$\varepsilon_f^*(T) = \varepsilon_f(T) \cdot MDF \quad (1)$$

$$MDF = \exp(0.5 - 1.5(\sigma_m / \sigma_e))$$

where  $\varepsilon_f$  is the temperature-dependent uniaxial fracture strain and accounts for the effect of stress triaxiality. The cumulative damage was calculated from the inelastic strain increment as

$$D = \int \Delta \varepsilon_{in} / \varepsilon_f^*(T) \quad (2)$$

where  $\Delta \varepsilon_{in}$  includes both plastic and creep strain increments. Local fracture was assumed to occur when reached unity.

#### 4. Effect of Injection Timing on Penetration Failure

The temperature histories at the penetration region differed significantly depending on the injection timing. In the early-injection case, cooling began before substantial high-temperature deformation developed. Consequently, the inelastic strain remained below the critical level and eventually saturated without penetration leakage.

In the delayed-injection case, the penetration remained at elevated temperatures for a longer period. The prolonged thermal exposure increased creep and plastic deformation in the weld region. Damage was concentrated at outermost penetration weld where the combination of elevated temperature and local stress produced the most severe condition.

Local fracture initiated at approximately 3.22 hr when the cumulative damage reached unity. The damaged region subsequently propagated along the weld-base metal interface and formed a continuous leakage path at 4.65 hr. MAAP5 predicted vessel failure at 4.75 hr, whereas ABAQUS predicted penetration leakage approximately 0.1 hr earlier.

Figure 2 compares the penetration temperature and inelastic strain histories for the selected injection cases. These results can show whether the transition from non-failure to failure is governed mainly by an increase in the peak temperature.

The coupled analyses provide complementary information. MAAP5 identifies the system-level transition between vessel survival and failure, whereas ABAQUS resolves the local deformation, damage concentration, crack initiation, and leakage-path formation within the penetration weld.

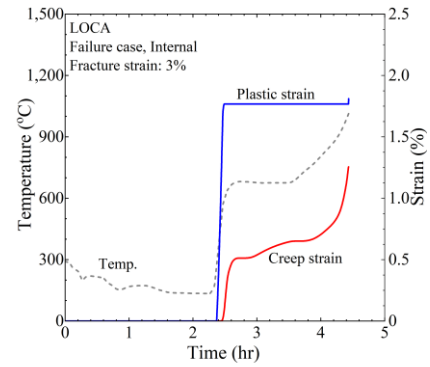


Fig. 2. Variation of temperature and inelastic strain with time at the failed element causing leakage.

#### 5. Conclusion

The effect of in-vessel coolant injection timing on APR1400 lower head penetration integrity under an LLOCA severe accident was investigated using coupled MAAP5-ABAQUS analyses. MAAP5 calculations were performed with different injection timings to identify the transition between vessel retention and failure, and the resulting temperature and pressure histories were applied to a detailed three-dimensional structural model. Earlier injection limited the thermal exposure of the lower head and suppressed inelastic damage in the penetration region. In contrast, delayed injection increased creep deformation and concentrated damage at outermost penetration weld, eventually producing a continuous leakage path. ABAQUS predicted penetration failure at 4.65 hr, compared with the MAAP5 prediction of 4.75 hr, while additionally providing detailed information on the local damage evolution and leakage process. These results demonstrate that the timing of in-vessel coolant injection can affect the margin against vessel penetration failure and that the coupled methodology

can connect system-level accident progression with detailed structural failure behavior.

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