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Structural Integrity Assessment through Reactor Lower Head Failure Analysis under LBLOCA Scenario

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1. Introduction

During a core meltdown accident, the lower part of a nuclear power plant reactor pressure vessel (RPV) is exposed to intense thermal and pressure stress. One effective accident management strategy, known as IVR-ERVC (In-Vessel Retention of molten corium through External Reactor Vessel Cooling), works to prevent reactor containment failure by stopping the progression of a severe accident within the reactor. The mechanical behavior of the RPV lower head is critical for evaluating both the severe accidents and the effectiveness of accident mitigation strategies.

In this study, the structural integrity was evaluated under large break loss of coolant (LBLOCA) accidents using the IVR-ERVC strategy. For the most realistic simulation, deformation and failure models previously proposed by the authors were used. The model is plastic and creep constitutive model that captures the material strain hardening and softening, along with its time-dependent inelastic behavior. In addition, thermal boundary conditions generated using MAAP5 were used.

2. Structural Analysis Model

2.1 Plastic and creep constitutive model

Under severe accident conditions using the IVR-ERVC strategy, the inner vessel wall was subject to very high temperatures from the molten core, while the outer wall is kept at a much lower temperature by external cooling. This steep temperature gradient can cause the vessel to deform rapidly and significantly. To study this phenomenon, Park et al. [1] developed a combined constitutive model that integrates both plasticity and creep behaviors for A533B1 pressure vessel steel, allowing for the quantification of deformation across a wide range of temperatures and strain rates. The plastic model was derived from tensile test data at a strain rate of 1%/s conditions under which creep effects are minimal. By extending Takahashi's [2] solutions to capture the full stress–strain behavior up to failure, closed-form equations were established, as detailed in Ref. [1]. The power law creep is given by

$$\dot{\varepsilon} = K(T)\sigma^{n(T)} \tag{1}$$

where, K and n are temperature dependent parameters.

NUREG/CR-5642 [3] reported the creep tensile test performed on constant stress and temperatures from 600ºC to 900ºC respectively. The parameters were determined by comparing FE simulation using ABAQUS with the test results.

2.2 Failure model

Park et al. [4] introduced a strain-based failure model to predict the failure behavior of a pressure vessel under severe accident conditions. In this model, the fracture strain is calculated by multiplying the temperature-dependent uniaxial fracture strain by a multiaxial ductility factor to account for multiaxial stress effects, expressed as:

$$\varepsilon_f^*\left(T\right) = \varepsilon_f\left(T\right)\cdot MDF \tag{2}$$

where, $\varepsilon_f^*(T)$ is the fracture strain under multiaxial loading, while $\varepsilon_f(T)$ is the uniaxial fracture strain derived from existing tensile test data (total elongation and true fracture strain data) for A533B1 across various temperatures and strain rates.

$$MDF = \exp\left(\frac{1}{2} - \frac{3}{2}\frac{\sigma_m}{\sigma_e}\right) \tag{3}$$

MDF represents the multiaxial ductility factor. Given the complex nature of failure mechanisms, the authors proposed a simplified formulation using constant and linear functions. Depending on the physical failure mode, the critical fracture strain is determined either by taking the lower bound of the true fracture strain or by using the average total elongation, based on temperature.

3. Thermal Analysis Model

Thermal boundary conditions from MAAP5 results were used to assess the structural integrity of the reactor vessel under severe accident conditions using the IVR-ERVC strategy.

The inner and outer surface temperatures calculated by MAAP5 were assigned to each node in ABAQUS FE model, and the linear interpolation temperature was also assigned to all FE nodal points. In addition, in order to match the ablation results of MAAP5 with the results of FE analysis, the temperature assigned to the corresponding FE node when ablation occurred was increased to the melting point.

4. Failure simulation under LBLOCA scenarios

Figure 1 shows the temporal variations of equivalent stress, inelastic strain, and temperature at the point on the inner-wall surface where the maximum strain occurs. Initially, the stress increased gradually due to thermal expansion, reaching approximately 420 MPa by 9000 s. After the inner wall melted, the stress rapidly decreased as thermal stress relaxed, dropping to about 60 MPa. Simultaneously, the temperature at the newly exposed inner-wall surface surged sharply, reaching 920°C. As the temperature rose and the material strength diminished, both the plastic and creep strains increased, reaching 1.4% and 12.6%, respectively. However, the plastic strain increase eventually plateaued due to stress relaxation resulting from creep, with the stress further reducing to around 6 MPa at 11,000 s. Consequently, the creep strain also leveled off at this time, indicating that the structural integrity of the inner-wall surface could be maintained under the LBLOCA conditions with IVR-ERVC as described in the study.

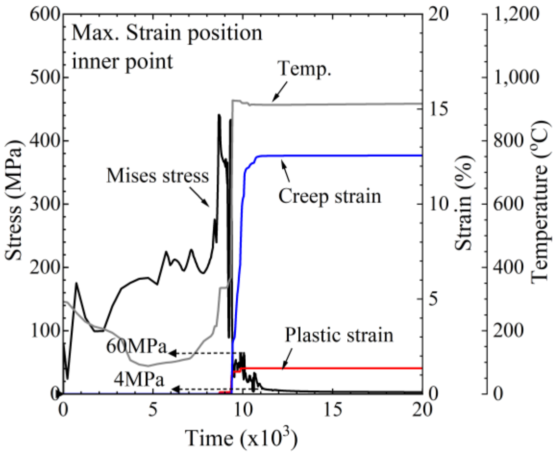

Fig. 1. Time-dependent changes in equivalent stress, inelastic strain, and temperature at the inner wall surface point at the maximum strain position.

5. Conclusion

This study aims to perform a finite element deformation and failure simulation of nuclear reactor vessels under LBLOCA severe accident conditions with IVR-ERVC to evaluate their structural integrity. For a realistic analysis of severe accident conditions, thermal analysis results from MAAP5 are used while considering the core degradation process and the main thermal hydraulic phenomena in the reactor vessel during LBLOCA using the IVR ERVC strategy for a typical Korean high-power reactor. Temperature distributions calculated by MAAP5 are used as the thermal boundary conditions in an initial ABAQUS thermal analysis. The simulated thickness variation of the vessel wall due to ablation showed good agreement with the MAAP5 results, confirming that the temperature distributions from MAAP5 were accurately transferred to ABAQUS. Later, ABAQUS structural analysis was performed using the proposed deformation and failure model. Through FE analysis, it was confirmed that strain was saturated due to stress relaxation by creep and that structural integrity was maintained under the LBLOCA accident.

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