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Structural integrity assessment of nuclear pressure vessel under LBLOCA accident

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1. Introduction

Ensuring structural integrity of reactor vessels under severe accident conditions is critical for safe and reliable operation of nuclear power plants. Recently, in-vessel retention (IVR) of the molten core via external reactor vessel cooling (ERVC) has been recognized as an effective accident management strategy and been adopted for advanced light water reactors as well as for many operating nuclear reactors [1].

However, under severe accident conditions, the inner wall of reactor vessel can be subjected to very high temperatures due to heat transfer from the molten core, while external wall is cooled by external reactor vessel cooling, resulting in large thermal gradient across the wall. The large thermal loading combined with internal pressure can cause large deformation and failure of reactor vessel [2]. Thus, to keep structural integrity in severe accident, it is important to accurately predict deformation and fracture behavior of reactor vessel in severe accident conditions.

This paper provides simulation results of a APR1400 nuclear pressure vessel of under large break loss of coolant accident (LBLOCA) with IVR-ERVC strategy. The simulation results using MAAP5 [3] are used as thermal boundary conditions for ABAQUS thermal analysis. Then structural analysis is performed using the combined plastic and creep model [4] and fracture model [5] of the nuclear pressure vessel.

2. Thermal analysis for LBLOCA scenarios

2.1 Description of LBLOCA scenario [3]

LBLOCA is an important design basis accident for a pressurized water reactor (PWR). During the LBLOCA, coolant discharges for a double-ended Guillotine Break of 9” pipe at a cold leg. Several important assumptions made for this scenario include:
(1) The safety injection was performed only with safety injection tank (SIT)
(2) From the start of accident, the main feed water system (MFWS), auxiliary feed water system (AFWS) and reactor coolant pump (RCP) are tripped.
(3) From the start of severe accident management strategy, the reactor cavity is filled with water.

2.2 Thermal analysis results using MAAP5 [3]

Figure1 shows the modeling of APR1400 lower head of reactor vessel used in MAAP5. The lower head was equally divided into 25 sections in axial direction.

The heat transfer from corium pool through reactor wall to coolant was modelled by heat conduction and radiation. From the analysis, variations of inner and outer wall surface temperature and reduction of vessel wall thickness with time on each section were obtained and presented in report [3]. The wall thickness at upper section of lower head of reactor vessel is severely reduced due to the highest heat flux near the metallic molten pool by the focusing effect as same with the results of prior IVR-ERVC studies [6-7]

2.3 Thermal analysis using ABAQUS

Thermal analysis using ABAQUS was performed using MAAP5 results as boundary conditions. For the thermal analysis using ABAQUS, four-node linear axi-symmetric heat transfer quadrilateral element (DCAX4 in ABQUS) was used as shown in Fig. 2. The calculated internal and external temperature of reactor vessel by MAAP5 were directly applied as thermal boundary condition to ABAUQS analysis. The internal and external temperature used for thermal boundary conditions are calculated by considering the heat transfer at the internal wall surface from molten core retained in the vessel, and the heat transfer at the external wall surface from the water filled with the cavity.

3. Structural analysis under LBLOCA scenarios

3.1 Structural analysis model

For the structural analysis, the axis-symmetric quadrilateral element (CAX4 in ABAQUS) was used with the large geometry change option. The top nodes of the vessel wall were fixed in vertical directions. True stress strain curves and creep model determined by combined plastic and creep model in [4] were used to predict inelastic deformation. Furthermore, the multi-axial fracture strain model proposed in [5] was used to simulate local fracture. The internal pressure calculated by MAAP5 [3] was used. The pressure decreases just after the initiation of severe accident from 15MPa to 0.3MPa.

3.2 Structural analysis result using ABAQUS

Figure 3 shows the time history of temperature, stress and strain at the inner and outer surface point of the most eroded part. For inner surface, in 8,000s~12,000s, significant variation of stress and strain occur with increasing temperature. The creep strain starts to increase from ~9,000s with increasing temperature. At the same time, the stress generated from thermal loading in the earlier of accident is released by increasing creep strain and the plastic deformation is restrained by reduced stress. Consequently, 13% of creep strain and 1% of plastic strain are occurred, with 20% of cumulative damage. The cumulative damage of pressure vessel was calculated using strain-based fracture model proposed by authors [5]. On the other hand, the outer wall surface point of the most eroded part shows large thermal load. However, by the high material strength resulted from low temperature by external reactor vessel cooling, external wall also maintains the structural integrity, showing similar results with the prior studies [6-7].

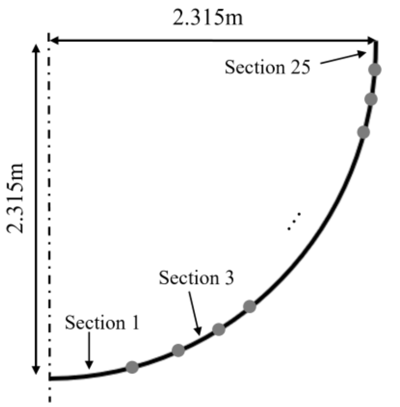

Fig. 1. Modeling of APR1400 lower head of reactor vessel used in MAAP5.

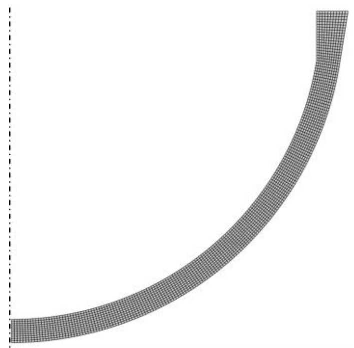

Fig. 2 Axi-symmetric FE model of the vessel for the severe accident analysis using ABAQUS

4. Conclusion

For structural integrity assessment of lower head of reactor vessel in the severe accident condition with IVR-ERVC strategy, FE simulation was performed. For the severe accident condition, large break loss of coolant (LBLOCA) was used with several assumptions for scenario. For the thermal analysis, the results using MAAP5 was used. The structural analysis results at the inner wall surface point of the most eroded part shows that stress generated from thermal loading is released due to creep with restrained plastic deformation. The cumulative damage is also calculated as about 20%, showing good structural integrity. The outer wall surface point of the most eroded part also maintains the structural integrity by external vessel cooling.

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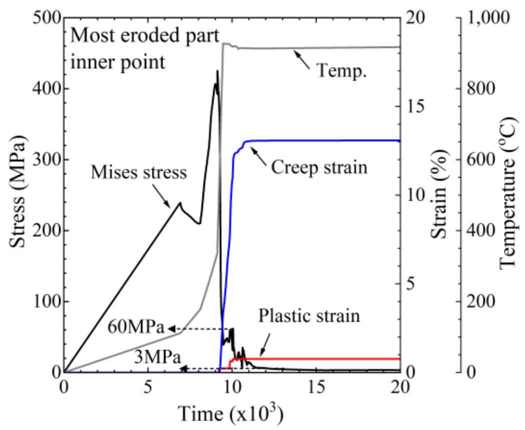
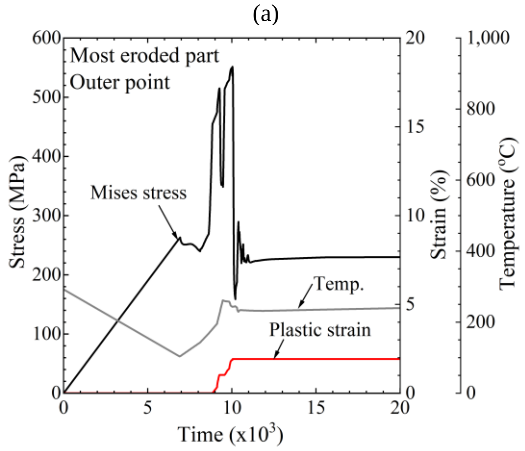


(a)



(b)

Fig. 3 FE results at the most eroded part: (a) inner (b) outer point.

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