A Behavior of Lower Head by Ex-Vessel Steam Explosion in External Reactor Vessel Cooling

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1. Introduction

In condition of a severe accident, the lower part of nuclear reactor vessel and inner side of ICI nozzles start melting. When the core melt flows out by failure of the lower head or ICI nozzles, the melt comes into contact with the external cooling water to cause a steam explosion (Fig.1). In this case, the steam explosion in external reactor vessel may cause complete failure of the lower head and another large steam explosion.

The purpose of this study is to evaluate the behavior of reactor vessel lower head against ex-vessel steam explosion through the major accident scenarios and analysis.

2. Methods

The analysis has proceeded with two following steps. First, thermal analysis was performed with time lapse process in condition of severe accident. Next, the structure analysis was carried out considering the melting of lower head under the steam explosion pressure. The transient pressure due to steam explosion was calculated using TRACER-II Code [1]. ANSYS[2], structural analysis code, was used for thermal and structural analysis.

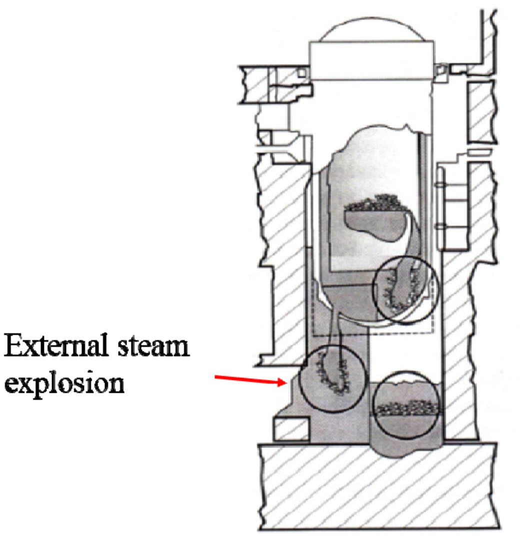

Fig.1 A severe accident scenario [3]

2.1 Failure criteria of lower head

Criterion based on failure at equivalent plastic strain, which is defined in terms of the principal plastic strain.

$$\overline{\varepsilon_p} = \frac{\sqrt{2}}{3}\left[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2\right]^{0.5} \quad (1)$$

For this purpose, the mechanistic ideas of ductile failure based on void nucleation and growth were adopted using the work of Shockey et al.[4] as a specific reference. In applying those ideas to the present situation with a highly non-uniform distribution of plastic equivalent strains across the wall thickness, it was considered that the likelihood of global wall failure could be related to the fraction of wall thickness that supported nucleation and experienced strains, i.e. exceeding the 11% threshold.

2.2 Analysis of lower reactor vessel

In thermal analysis [5], the heat flux on the inside of the head was applied as shown in Fig.2 and the convection boundary condition at the outside of the head was applied as shown in Fig.3. In structural analysis [6], the thermal load and steam explosion were used as shown in Fig.4. The axial symmetry and vertical constraint were applied.

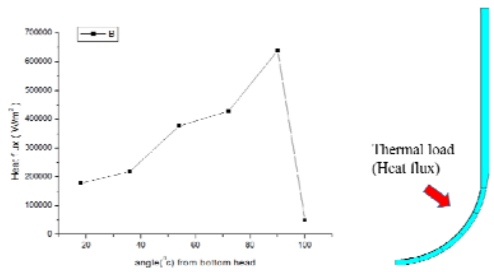

Fig.2 Inner heat flux of lower head

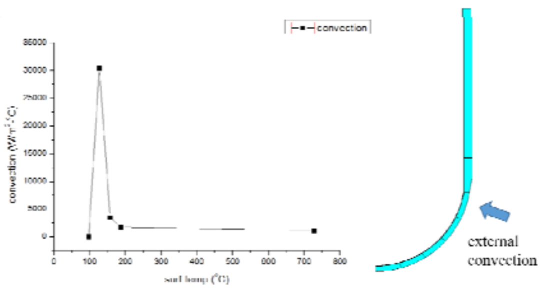

Fig.3 Heat transfer coefficient of external convection

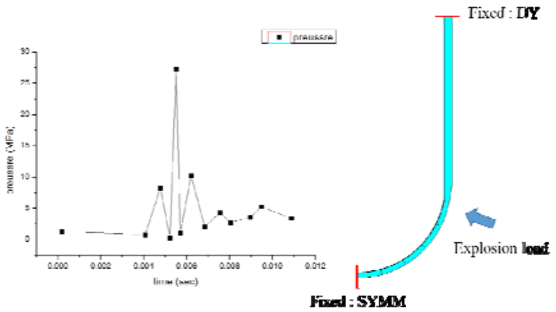

Fig.4 External steam explosion pressure and structural boundary condition

3. Analysis results

3.1 Results of thermal analysis

Melting of the head occurred from 5100 up to 25200 seconds. Thereafter, no further melting occurs and the lower head thickness is maintained. This is because the heat is discharged by the external cooling water. At 30,000 seconds after melting, the thickness of the head becomes almost 1/2 of the initial thickness in shown Fig.5.

3.2 Results structure analysis

Considering the thermal and steam explosion load of a serious accident, the strain is 10% (Figure 6). This result is close to breakage criterion (11%), which may cause vessel failure. The large deformation and complete failure were expected at the thinnest region of the lower head after melting as shown in Fig.6 and Fig.7.

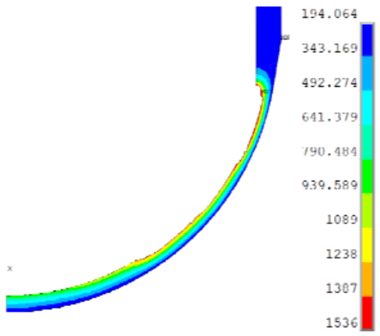

Fig.5 Temperature distribution at 30000 s

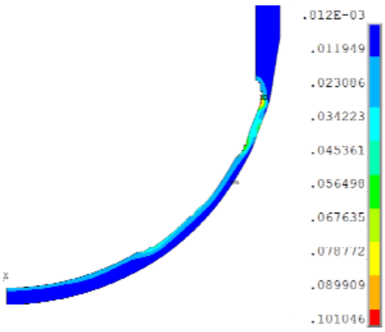

Fig.6 Strain distribution under steam explosion

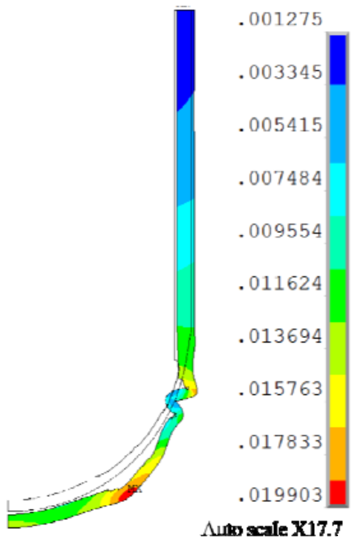

Fig.7 Deformation under steam explosion

4. Conclusions

In condition of a severe accident, the core melt may flow out from the melted lower head or ICI nozzle during in-vessel retention. The melt comes into contact with the external cooling water to cause a steam explosion. In this study, the behavior of the lower head due to ex-vessel steam explosion pressure was investigated. The total failure at the top side of head which was melted by a large heat flux might be expected to occur under the scenario.

REFERENCE

[1] Bang, K. H., Kumar, R., and Kim, H. T., “Modeling corium jet breakup in water pool and application to ex-vessel fuel–coolant interaction analyses” Nuclear Engineering and Design 276 (153–161), 2014.

[2] ANSYS, Inc., “ANSYS Mechanical Parametric Design Language (APDL) Version 12.1,” 2012.

[3] Bal Raj Sehgal, SARNET., “Nuclear Safety in Light Water Reactors: Severe Accident Phenomenology”, 1st Edition. pp. 256

[4] Shockey, D. A., Seaman, L., Dao, K. C., and Curran, D. R., “Kinetics of Void Development in Fracturing A533B Tensile Bars”, J. Press. Vessel. Technol., Vol. 102, No. 1, pp. 14–21, 1980.

[5] Bae, J. H., Cho, J. R., Bang, G. H., and Park, J. W., “A Basic Study on the Ejection of ICI Nozzle under Severe Accidents”, Proc. Korea Nuclear Society, 2016.

[6] Jeon, J.W., Cho, J. R., Bae, J.H., and Bang, G. H., “An Integrity of Reactor Vessel Head and ICI Nozzle under In-vessel Vapor Explosion Loads”, Int. J. Precis. Eng. Man., Vol. 16, No. 7, pp. 1617–1622, June, 2015.