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A Study of Nuclear Reactor Pressure Vessel Lower Head Penetration using Numerical Analysis

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1. Introduction

Nuclear reactors have dozens of penetration tubes on the reactor lower head. When the tube is installed in the penetration part of the reactor vessel, the inside of the reactor is welded, and the tube is maintained by the welded part [1].

When a severe accident occurs, a molten core is generated and core rearrangement occurs. Heat flux from the molten core heats up the pressure vessel inside and melts the inside penetrations and the welding zones. When a welding zone is melted, penetration tube ejection or rupture can occur. In this situation, the only mechanism that held the penetration fixed is the friction force between penetration tube and vessel hole.

In that case, the bonding force due to the contact is influenced by the friction force between the tube and the lower vessel. This is due to the differences in thermal expansion experienced in the high temperature environment after the re-location of the molten core [1, 2, 3].

In this study, a numerical analysis using ANSYS 17.1 Release 17.1 [4] was performed to investigate the contact status due to thermal expansion between the penetration tube and the lower vessel. Three major nuclear accidents, i.e., Large Break Loss-of-Coolant Accident (LBLOCA), Station Black Out (SBO), and Total Loss of Feed-Water (TLOFW), were considered as part of the study. Based on the results, the status of the penetration tube ejection was examined.

2. Background knowledge and simulation preparation

2.1 Penetration tube ejection

Figure1 [2] shows the ejection mechanism when the tube is connected to the reactor by welding. Both the reactor and the tube endure the self-weight, the pressure, and the weight of molten core. As the materials of the tube and the bottom of the reactor are different, differences in the properties of materials are expected.

Among the material properties, the coefficient of thermal expansion is related to the degree of expansion of two objects according to the temperature. And due to the difference in thermal expansion coefficient, the two materials expand differently and come into contact with each other.

As shown in Figure1, the internal pressure and the self-weight can be compared with respect to the frictional resistance to check whether the tube is ejected.

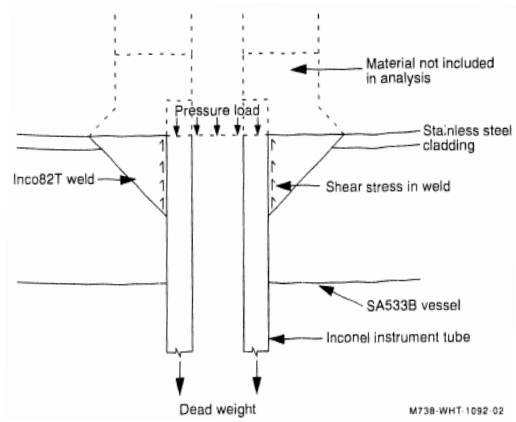

Figure1 Penetration tube ejection mechanism

2.2 Modeling of pressure vessel and penetration tubes

The numerical analysis was performed by modeling the shape of the lower vessel under a real scale. In the case of the tube modeling, four tubes were considered as the objects. The tubes were set at 0 °, 2.8 °, 41.3 °, and 54 ° from the center axis. The tubes were sequentially numbered as No.1 to No.4 in the order of distance from the center. The lower reactor vessel was set to be SA508 as used in the OPR1000, APR1400, etc., and the penetration tube material was set to be INCONEL690 as used in APR1400 [1].

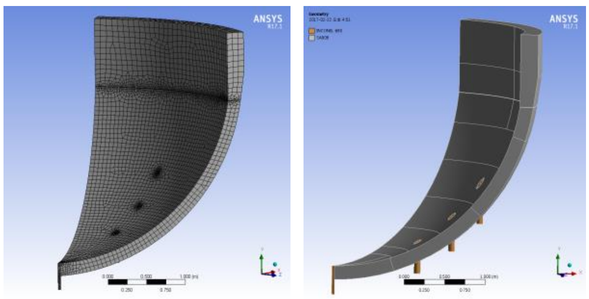

Figure 2 Lower vessel modeling and position of pipe tube according to angle

2.3 Boundary conditions

It was assumed that the outer wall of the reactor vessel was cooled by cooling water and maintained at 120 ° C, and that the inside of the tube was heated by the molten core and held at 1300 ° C.

Among the three nuclear accidents considered in this study, i.e., Large Break Loss-of-Coolant Accident (LBLOCA), Station Black Out (SBO), and Total Loss of Feed-Water (TLOFW), TLOFA was used in this study to set the thermal boundary condition. For each accident condition, the heat flux from the molten core is expected to vary as a function of the angle from the center of the bottom of the reactor [5, 6]. The composition of molten corium and molten pool geometry were based on the result of the Idaho National Engineering and Environmental Laboratory (INEEL) [6]. The depth of Oxide layer and metal layer are 1.67m, 0.59m (TLOFW), 1.67m, 0.58m (SBO) and 1.45m, 0.54m (9.6'' LBLOCA). The larger the angle from the center, the larger the heat flux. Particularly at an angle of about 80 ° or more, rapid changes in the heat flux is expected to occur due to the differences in the materials composition with the re-arrangement of the molten core. The internal pressure acting in the plane vector direction inside the reactor vessel was assumed at 10 bars.

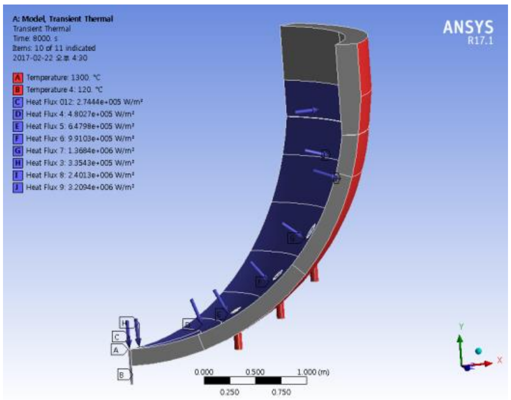

Figure 3. Applied thermal boundary conditions based on the result from Total Loss of Feed-Water (TLOFW) Accident

3. Result and discussion

3.1 Thermal transient analysis

Figure 4 shows the temperature distribution of the vessel over time since the occurrence of the accident. The first picture at 250 seconds showed that high temperature occurs inside of each of the pipes, showing the highest values in the case of tube 4. The temperature was estimated to rapidly increase at the inner wall of about 80 ° or more at which the heat flux is most dominant. Simulation results showed that most of the inner wall reached the melting point in about 7000 ~ 8000 sec. The position considered to be most susceptible to failure was the section where the angle is about 70 ~ 90 ° from the center.

In contrast, the results for the bottom part of the lower vessel showed that the temperature did not exceed 1000 ° C even after 7020 seconds passed. Thus the bottom part of the vessel can be considered to remain in a relatively safe condition. Results for the ducts region showed a tendency that temperature increases from tube No. 4 toward the outer wall, in which the heat velocity is higher. In the tube No. 4 at 720 seconds, the temperature becomes higher at the penetration portion toward the center of the reactor. This is due to the influence of the temperature inside the reactor vessel and the tube, as the gravity tube is connected through the hemispherical lower vessel.

On the other hand, the increase in temperature was not very high in the tubes No. 1 and 2 as shown in Figure 6. Most of the upper part and the welding zone of the tube No. 4 reached the melting point at 5200 s. However, temperature of the tube No. 1 and No. 2 were estimated to be at about 760℃ and 1350 ℃, respectively, falling short of the melting point, 1500 ℃.

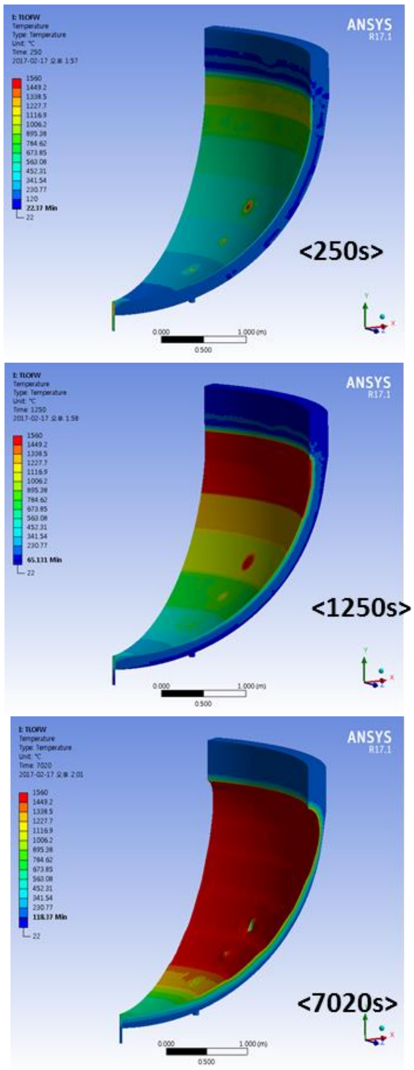

Figure 4. Temperature distribution of the reactor vessel under severe accidents (TLOFW)

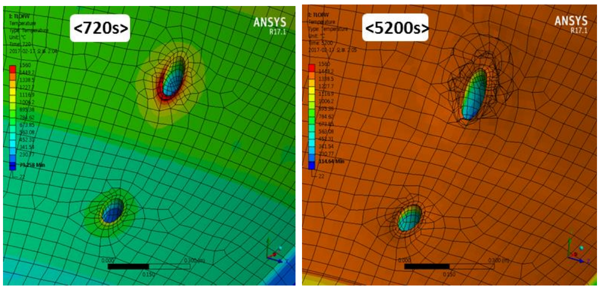

Figure 5. Temperature distribution at proximal section of welding zone of 3rd, 4th penetrations (TLOFW)

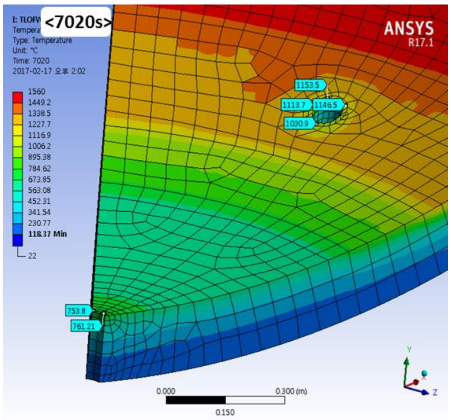

Figure 6. Temperature distribution of the welding zone of the 1st, 2nd penetrations (under TLOFW)

3.2 Structural analysis

Based on the temperature distribution data for the lower reactor vessel acquired by the thermal analysis simulations, structural analysis was performed. The purpose of this structural analysis was to examine the status of the contact region between the tube and the reactor vessel caused by thermal expansion, and to determine the size of the contact area. Calculation of the contact area was made for tube No. 4, which was considered the earliest one to fail, and for tube No. 3, which was considered a region of possible failure.

The result of the structural analysis indicated, as shown in the Figure 7 (at 53 seconds since the accident) that there is a limited area of contact at the beginning, with the occurrence of momentary bending. However, after 400 seconds, the reactor vessel also began to heat up and the contact area decreased. After 4000 seconds, the contact area of the orange color appeared at the upper end of the pipe. It can be deduced that thermal expansion occurred from the upper end of the pipe and the inner wall of the reactor vessel due to the heat flux.

For accurate analysis, the contact area between the tube No. 2, 3, 4 and the reactor vessel over time was checked. As shown in Figure 8, the farther the penetration tubes from the reactor center, the larger the contact area. The rate of contact area increase was the largest at tube No. 4 and the contact area at tube No.2 and tube No. 3 increased relatively slowly.

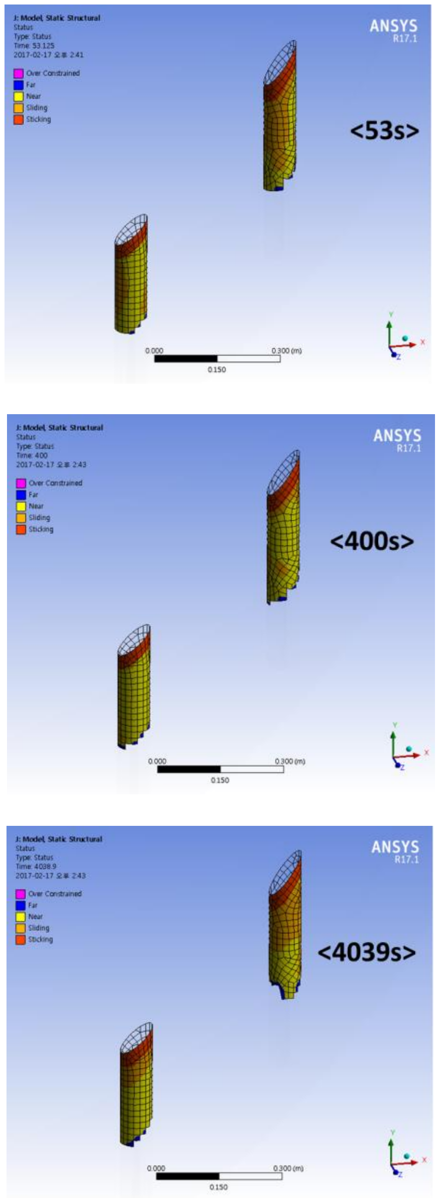

Figure 7. Contacting status of 3rd and 4th penetration tubes (TLOFW)

In addition, all of the three tubes were shown to have a large initial contact area due to the influence of the initial heat load and temperature. They were stabilized initially but then increased with the increase in time.

In all three severe accident cases, the changes of the contact position and area with time showed the same tendency. However, due to the differences in temperature, there was a difference in the rate of increase in contact area.

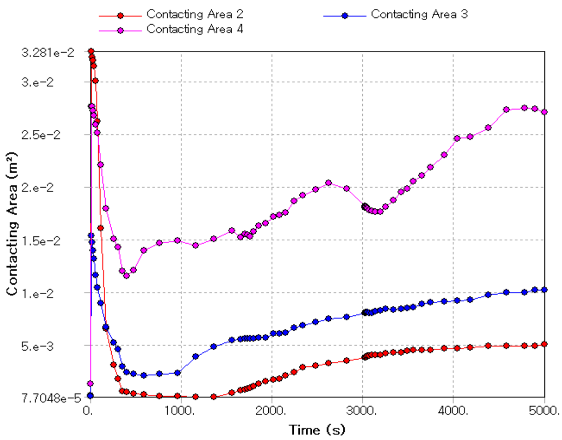

Figure 8. Contact area of 2nd,3rd and 4th penetration tubes (TLOFW)

The parts that are likely to be damaged were found to be tube No. 3 and No. 4. The ratios of the surface area to the contact area for each accident cases for these two tubes are shown in Table1. The contact area of the tube No. 4 initially covered about 40% of the total surface area, but decreased within 300 to 400 sec., and then increased again with time.

TLOFW		SBO		LBLOCA	
Time (s)	tube4 Ratio (%)	Time (s)	tube4 Ratio (%)	Time (s)	tube4 Ratio (%)
53	**40.53**	33	**39.1**	48	**35.0**
116	**34.59**	112	**27.2**	191	**12.6**
350	**18.83**	300	**14.5**	300	**8.0**
756	**23.04**	415	**10.1**	400	**11.4**
956	**23.33**	559	**9.7**	550	**13.3**
1556	**24.84**	842	**11.6**	840	**15.1**
2018	**26.89**	1215	**15.5**	917	**16.9**
2335	**30.02**	1822	**18.2**	1158	**20.8**

Table 1. Ratio of contact area to target surface area of 4th tube

3. Summary and Discussions

Results indicated that when a severe accident occurs, the inside of a penetration is initially heated up. Later, the upper part of inner vessel and the welding zone of tube No.4 are heated up. Because of the heat input and thermal expansion, contacts between the vessel and tubes occur. This contact was found to increase over time. It is probable that the tubes do not eject because of the friction forces.

In order to confirm whether the tubes eject, the reaction forces at the surface where the tubes are to be contacted should be analyzed. It is important to estimate the contact area as well as the contact pressure when the contact is generated due to thermal expansion. For this purpose, it is desirable to perform detailed analysis for the elasto-plastic region based on the information on the yield behavior after the elasticity limit.

In addition, since the nuclear reactor pressure vessel undergoes severe transients with high temperature, high internal pressure, self-weight and the weight of molten core under severe accident, creep deformation is expected to occur, which should be taken into account for obtain more reliable results.

Acknowledgement

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