Simulation of the Penetration Tube Failure for APR 1400 using PENTAP plus

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1. Introduction

PWRs (Pressurized Water Reactors) have several ICI (In-Core Instrumentation) penetration tubes that penetrate the reactor vessel through the reactor bottom head. For example, APR1400 has 61 ICI penetrations to monitor the in-core status [1]. They are attached to the inside of the reactor bottom head by a partial penetration weld. When a severe accident like the Fukushima accident occurs, the melted core material (corium) relocated to the lower head of the reactor vessel, the weld is exposed to higher temperatures that range up to melting temperature simultaneously. The penetrations is the one of most vulnerable parts with respect to the reactor vessel failure. Therefore, the determination of the failure modes at the lower head is an important task under a given sever accident condition.

KAERI is developing the PENetration Tube Analysis Program plus (PENTAP plus) to determine the failure modes such as the tube rupture and the tube ejection. Here, the validation works for PENTAP plus and the sensitivity studies were performed using the KEARI's experimental results from Verification of Ex-vessel corium STAbilization (VESTA) facility [2]. Also, the PENTAP plus was linked to the SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) module [3] to examine the penetration tube ejection under the external reactor vessel cooling (ERVC) condition. The numerical simulation was performed to examine the penetration tube ejection of APR1400 nuclear power plant according to severe accident scenarios.

2. Penetration tube mechanism

2.1 Penetration tube mechanism

The penetration tube failure modes and mechanisms were identified by J. L. Rempe et.al [4]. Penetration tube failure can be divided into the two categories: tube ejection out of the vessel lower head and rupture of the penetration tube outside the vessel. Tube rupture assumes that the debris bed has melted the instrument tube inside the reactor and melt migrates down into the tube to a location outside the vessel wall where a pressure rupture can occur, thus breaching the pressure boundary. Tube ejection begins with degrading the penetration tube weld strength to zero when the weld is exposed to higher temperatures that range up to melting and then overcoming any binding force in a reactor vessel wall-penetration tube interface which results from differential thermal expansion of the tube and the reactor vessel.

So, the inside of reactor vessel pressure, the debris mass, the debris temperature, and the component materials can have an effect on the penetration tube failure modes. Furthermore, these parameters are inter-related. In these reasons, the failure model in the severe accident code requires a large amount of effort to enhance the predictability of failure modes.

2.2 PENTAP *plus program*

We call the penetration tube analysis program plus the PENTAP plus [5]. The PENTAP plus was modified based on the PENTAP, which was developed by Park et al. [6]. The PENTAP plus is able to run in a stand-alone manner and fast-running code to determines the failure modes such as the tube rupture and the tube ejection based on the following steps, as shown in Fig.1. The present program determines the tube rupture first and then check the tube ejection.

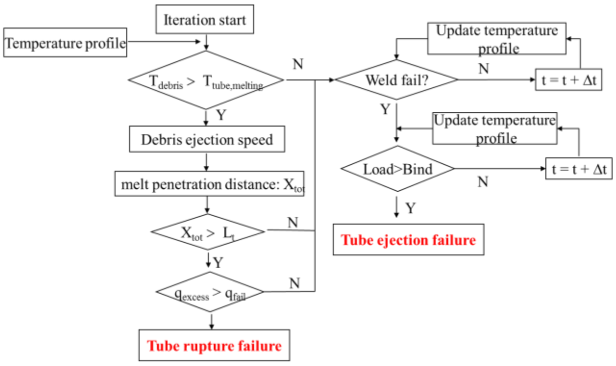

Fig. 1. PENTAP plus calculation flow steps

The procedure of the tube rupture determination is as follows. In the present, the long term tube failure and the creep failure are not considered.

1. Check the minimum debris temperature required for guide tube melt
2. Calculation debris ejection speed and melt penetration distance. There are three difference model which are modified bulk freezing model, conduction layer model, modified conduction layer model (MAAP5). The modified conduction layer model is default model.
3. Plugged tube rupture from excessive heat and Pressure-induced penetration tube rupture.

If the tube rupture doesn't occur, then it determinates whether the tube ejection occurs or not as following procedure.

(1) Calculate the free thermal expansion of the tube and hole at each layer.
(2) Due to the pressure difference between internal reactor vessel and external reactor vessel, the tube diameter expands. Calculate the pressure expansion of the tube at each layer.
(3) Obtain the tube-hole radial gap at the given pressure and temperature. The expansion direction can be changed as the location or the conditions. The default model is Eq.(1)

$$\delta_{\mathrm{i}} = (r_{\mathrm{h}} + \Delta r_{\mathrm{h}}) - (r_{\mathrm{o}} + \Delta r_{\mathrm{o}}) - \delta_{clearance} \qquad (1)$$

where r_{h}, Δr_{h}, Δr_{o} and are the hole diameter, the total hole expansion length, and the total tube expansion length.
(4) For a locked condition, the tube-hole interface pressure that needs to be overcome in order to push out the tube is given by the lesser of the value required to make the tube conform to the final hole radius and the final hole radius and the shear stress, which will cause the tube material to yield. Find the tube-hole interface pressure at each layer.
(5) The total thermal binding shear force is calculated by a summation of all incremental forces.
(6) The ejecting pressure force is calculated.
(7) Compare the ejecting pressure force with the total thermal binding shear force.

The computation domain is shown on the Fig. 2, where L_t, L_w, d_0, d_i, P_o, P_i, and *f* are the total length of the reactor vessel and the length of the weld, the outer diameter and inner diameter of the penetration tube, the pressure outside the reactor vessel and inside the reactor vessel, and the friction factor. The APR 1400 ICI penetrations design values were used. The material of the reactor vessel wall is SA508, Gr.3 Cl.1 and the material of the penetration tube is Inconel 690. The following assumptions were used.

(1) The tube-hole radial gap (δ_{i}) is 50 μm
(2) The pressure difference between the inside reactor vessel and the outside reactor vessel is 10 bar.
(3) If the melt migrates down into the tube to a location outside the vessel wall, the penetration tube temperature is the same as the delivered melt temperature which is not higher than the melting temperature. If not, the penetration tube temperature profile is the same as the reactor vessel temperature profile.
(4) If we don't know the temperature profile of the reactor vessel, the vessel temperature has a linear profile and the internal vessel wall temperature is debris temperature (default).
(5) Since the material properties are not always available for elevated temperatures, the linearly extrapolates from known values.
(6) For the external wall cooling condition, the outer wall temperature was set to be 120$^{\mathrm{o}}$C due to the nucleate boiling condition, the effects of convection, and phase change are assumed negligible at the outer wall for simplicity.

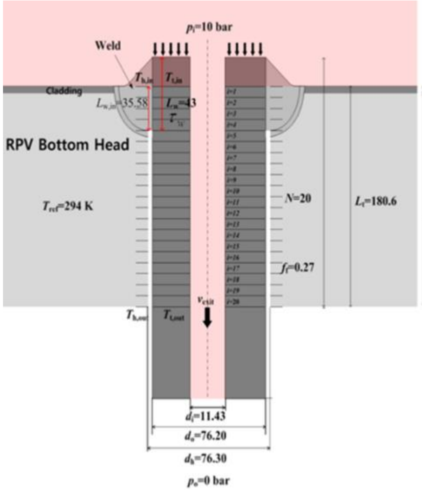

Fig. 2 Conceptual schematic of the failure model

3. Results

3.1 Analysis results using experimental result

KAERI has conducted the penetration tube failure experiments such as tube ejection and rupture for an APR1400 ICI tube under the ERVC. A mixture of UO2 (70 kg) and ZrO2 (33kg) was used. There are 33 K-type thermocouples (-200-1370℃, ±1% error) embedded inside the specimen for measuring the temperature distributions, specially, 4 thermocouples among 33 thermocouples embedded inside the weld region. The reader is referred to An et al [2] for details regarding experimental conditions. In this test, the maximum removal heat flux by ERVC was evaluated at about 466 kW/m^2. These were observed that the weld part was melted, the melt did not flow inside the ICI tube, and the tube ejection did not occur.

Based on the experimental temperature distributions and expansion directions of the tube and hole, the numerical simulation was undertaken using PENTAP plus. The temperature profiles were obtained by a third order least square fit. A comparison of analysis result with experimental one shows good agreement.

When the melt migrated down into the tube to a location outside the vessel wall, in order to check whether the tube ejection, the sensitivity analysis was performed as the maximum debris temperature increases up to 3500K which is larger than UO$_2$ melting temperature. Following assumptions are used for the analysis: (1) external cooling condition, (2) the tube rupture does not occur, (3) the tube temperature is 1500 K because penetration tube temperature is closely the melt temperature due to the decay heat, and (4) the expected temperature profiles from experimental data for the reactor vessel were used. For these cases, we checked that the tube ejection does not occur.

3.2 Linked module results

Also, the PENTAP plus was linked to the SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) module [3] to examine the penetration tube ejection. The numerical simulation was performed to examine the penetration tube ejection of APR1400 nuclear power plant according to severe accident scenarios. When the molten corium attack to the penetration at each location (Fig. 3), SIMPLE module can provide all the information except the penetration tube temperature. In present model, the tube temperature is set to 1500K.

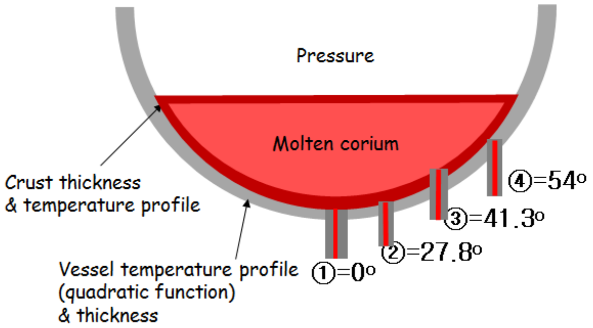

Fig. 3. Configuration of linked PENTAP plus model

Following assumptions are used for the simulation:
- Reference plant: APR1400
- Melt composition

UO_2 = 67% (67 ton)
ZrO_2 = 9% (9 ton)
Zr = 9% (9 ton)
SS = 14% (14 ton)
Inconel = 1% (1 ton)
Total = 100% (100 ton)

- Corium Mass Relocation = 0.2ton/sec
- Time Step: 0.05 second
- Water and steam inlet flow from the down comer to the lower plenum were assumed to be zero.
- Melt Temperature:
- Rate of Constant Core Melt Relocation 100,000kg in 500 sec: 200 kg/sec
- Decay heat: 2% of APR1400 total core power
- Outside temperature : 400 K

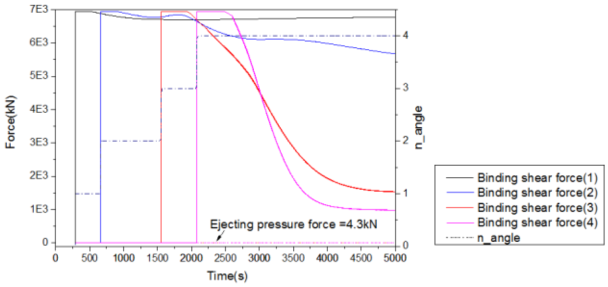

Fig. 4 Tube ejection force & binding shear force

After 283s, the molten corium reaches each annular ring and then it attacks the penetration at location 1 in Fig. 3 as shown in Fig.4. Also, the molten corium reached each annular ring after 665s, 1500s, 2080s. Tube ejection begins with overcoming any binding force in a reactor vessel wall-penetration tube interface which results from differential thermal expansion of the tube and the reactor vessel. In this case, the oxidic and metallic pool do not have enough heat flux to melt the reactor vessel, and the tube ejection was not occurred (Figure 4). The reason is that the temperature of tube is higher than the wall which makes that the penetration tube can adhere to the reactor vessel wall because the tube is more expansion. As shown in Fig.4, the binding shear forces at location 3, 4 are lower than location 1, 2. The reason is that the location 3, 4 is the focusing region. So, the reactor vessel thickness at the location 3, 4 is thinner than the location 1, 2. As a result, the binding shear force is reduced.

In this works, the tube ejection did not occur. In this works for all the cases, although we did consider long term tube rupture, creep failure, and the change of the gap between the hole and the tube. So, we can say that if the melt is in the, it is advantageous to avoid the tube ejection because it makes large temperature difference between the tube and the reactor vessel, although it is possible to lead to long term tube rupture.

4. Conclusions

The code validation was performed based on the VESTA experimental result. The sensitivity analysis were performed to examined the penetration tube failure under certain conditions which are the melt is in the tube and the ERVC condition using PENTAP plus and the expected temperature profiles from experimental data. Also, the numerical simulation was undertaken to examine the penetration tube ejection of APR1400 nuclear power plant using the PENTAP plus linked to the SIMPLE. For all the cases, the tube ejection did not occur. However, we did consider long term tube rupture, creep failure, and the change of the gap size between the hole and the tube in this study. Since the reactor vessel undergoes severe transient with the high temperature, the high internal pressure, the self-weight and the weight of molten corium under severe accident, the creep deformation is expected to occur, which can lead the change of the gaps size between the tube and the hole, and the shape of the hole as the location of the penetration tube. In order to obtain more reliable results, the creep deformation should be taken into account.

Acknowledgments

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