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Analysis program for evaluating the failure mode of penetration tube : PENTAP

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1. Abstract

This paper includes the descriptions for the important models and the calculation steps of the PENTAP program, which was developed by KAERI. PENTAP can evaluate the possible penetration tube failure modes such as a weld failure, a tube ejection, a creep by tube heat-up and a long term tube failure under the given accident conditions. In addition, this paper shows the sensitivity results for each failure mode depending on its influencing parameters.

2. Introduction

2.1 Model review on the penetration tube failure

The penetration tube failure modes and their mechanisms were well identified by J.L.Rempe et.al [1]. Many parameters can have an effect on the penetration tube failure modes.

These parameters are the reactor vessel pressure, debris mass, debris temperature and material type for the related components. These penetration failure modes are in competition with each other and are inter-related. These make the determination of the primary failure mode of the penetration tube under varying severe accident conditions difficult.

Therefore, even MELCOR, which is the representative severe accident code, has actually no model for simulating a penetration tube failure [2]. The current remedy for considering a penetration tube failure is simply imposing its failure temperature such as 1273 k.

On the contrary, the MAAP code considers all penetration failure modes. It is considered that the MAAP has the most advanced model for a penetration tube failure model [3]. However the validation works against the experimental data are very limited.

3. Important input and output

Table 3.1 shows the important input and output data for the PENTAP program.

Table 3.1 Input and output data for PENTAP

Input	*output*
Debris mass/height/temperature	Melt penetration distance -conduction - bulk freezing
Decay heat generation rate	Weld failure -shear/yield stress - or melting
Penetration/thimble/weld geometrical dimensions Clearance size	Tube ejection - Binding for each layer Transient behaviors of tube - creep failure (time)
Thickness of each layer in lower vessel head wall Penetration tube fail height Primary/cavity pressure Cavity air(water) temperature Heat transfer coefficient from tube to fluid in cavity Temperature vs. time for each layer in wall	Long term un-proper heat removal tube failure

4. Models for each failure mode

4.1 Melt penetration distance

The initial melt falling velocity inside of a failed penetration tube was derived below using the Bernoulli equation considering the form losses only.

$$V_{d2} = \sqrt{\frac{2\Delta P/\rho_d + 2g\Delta Z}{K+1}}$$

Where ΔP= pressure difference between reactor vessel and tube inside space
ΔZ= axial distance between debris top and failed tube location
ρ_d = debris density
G = gravity constant
K = form loss coefficient

Using this initial melt falling velocity, the melt penetration distance can be calculated. There are two models. One is a conduction model and the other is a modified bulk freezing model [4].

In the modified bulk freezing model, the first assumption is that the flow regime of the melt is turbulent. Thus, it prevents a stable crust from forming. The second assumption is that the heat transfer coefficient between the tube and the melt always has the value for the melted steel in the turbulent regime. In this model, the melt flow can be stopped when all the melt freezes. With these assumptions and the falling velocity, one can derive the melt penetration distance.

In the conduction model, the melt penetrates the tube in the super-heated state and the saturated state sequentially. Therefore, the total penetration distance consists of adding two distances being calculated from a state in which the melt is superheated and saturated, respectively.

The saturated debris state is defined as 10 K above its melting temperature. The crust starts to be formed from the saturated state. It is assumed that the melt will stop when the crust front reaches the center of the tube.

Figure 4.1 shows a comparison of the melt penetration distance from two models according to whether a thimble tube is considered .

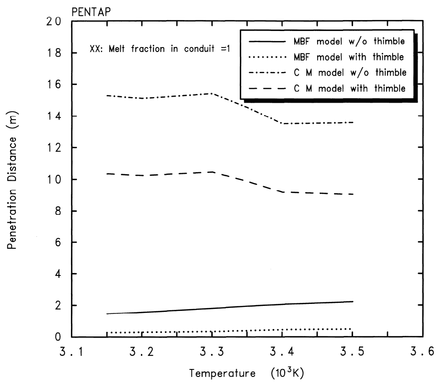

Figure 4.1 Comparison of melt penetration distance between MBF and conduction model

4.2 Tube heat-up and creep failure

The melt relocates downward over the inside of the penetration tube. During this relocation, the tube can be heated-up by the heat flux from the melt to the wall. The tube heat-up was categorized into three steps.

At the end of the first step(=t1), it was assumed that the average temperature of the tube is the arithmetic average of the initial tube wall temperature and the interface temperature [5]. In addition, the average crust temperature is the arithmetic average of the crust melting temperature and the interface temperature.

At the end of the second step(=t2), it was assumed that the average temperature of the tube wall and the crust become the interface temperature.

At the final step, the wall temperature can be escalated owing to the rapid heat transfer from the crust.

During this final step, heat removal from the outer surface of the wall by radiation or convection can be considered. Whether a tube creep can occur was checked at every time step. If a creep rupture occurs, its time is saved and exit to the main program.

Figure 4.2 shows the change in average temperature for the tube after a penetration tube failure occurs. Once the melt is completely frozen, the heat flux is set to zero and a long term tube heat up and creep failure will be checked.

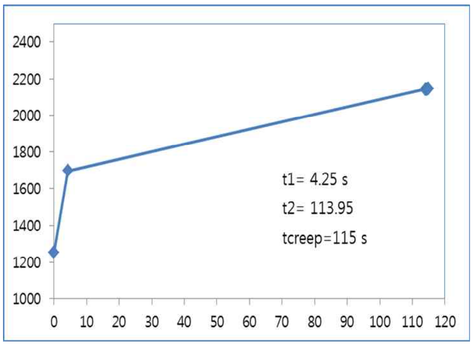

Figure 4.2 Penetration tube heat-up & creep

4.3 Weld failure and tube ejection

The yield stress of the weld material can be determined by inputting the temperature of the weld material. It was assumed that the weld material's temperature is the same as that of the inner-most layer of the lower vessel head.

The determination of the weld material failure is determined by comparing the shear stress and yield stress. The shear stress of the weld is predicted with the reactor pressure, the weld depth size and the penetration tube diameter.

The shear stress (=τ) and yield stress (=σ_{yp}) of the weld material can be correlated as below.

$$\sigma_{yp} = \sqrt{3}\tau$$

If the right side term is greater than the yield stress value, then it is determined that the weld part is failed. Figure 4.3 shows the yield stress value versus weld material temperature. The weld material can be weakened at more than ~1200 K.

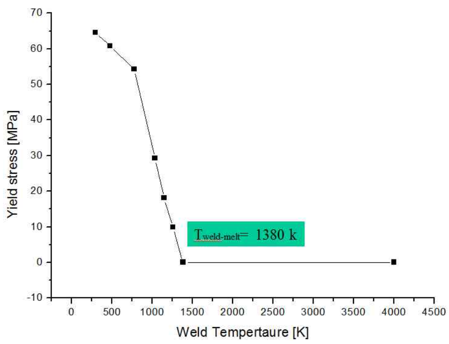

Figure 4.3 weld material yield stress vs. temperature

If the weld part is intact, the tube ejection can be neglected. But if it fails, then the tube ejection will be checked. In the case of heating-up the tube and lower vessel wall, a binding phenomenon between the tube and wall hole can occur owing to the difference in the thermal expansion coefficient between the tube and wall materials.

In addition to the thermal expansion, the tube can be expanded by the increase in pressure. The tube expansion by the pressure increase was modeled using the tangential and radial stress [6]. Then, tube total expansion is the sum of the thermal and pressure expansion terms.

$$\Delta r_{exp,t}^{TOT} = \Delta r_{exp,t}^{T} + \Delta r_{exp,t}^{p} \quad \text{(thermal / pressure)}$$

$$\text{where} \quad \Delta r_{exp,t}^{T} = r_{t,o}\alpha_{exp,t}(T_t - T_{ref})$$

$$\Delta r_{exp,t}^{p} = \frac{r_{t,o}(P_{vs} - P_{cav})r_{t,i}^2(2 - \nu_t)}{E(r_{t,o}^2 - r_{t,i}^2)}$$

For the hole for the penetration tube in the lower vessel head, the hole size can be expanded by the thermal expansion.

$$\Delta r_{exp,h}^{T} = r_h\alpha_{vs}(T_{vs} - T_{ref})$$

where
r_h=hole radius, $r_{t,o}$ =tube outer radius
ν_t = Poisson's ratio of tube
E= elastic modulus of tube
P_{vs}, T_{vs}, P_{cav}= reactor pressure, wall temperature, cavity pressure
α_{vs}=wall thermal expansion coefficient
T_{ref} = reference temperature: 294K

Consequently the condition for binding can be derived by comparing the size of the expansions from between the tube and the hole. The binding can occur in the case of having a positive value of the following correlation.

$$0.0 < \Delta r_{exp,t}^{TOT} - \Delta r_{exp,h}^{T} - \delta_{clearance}$$

4.4 Long-term tube heat-up and failure

The long-term tube heat-up can start after all the melt is plugged and frozen inside of the tube. A tube creep failure by the long term heat-up is estimated by comparing the heat balance between the heat generation rate in the plugged debris and the heat removal rate from the outer surface of the tube.

The creep failure time is predicted using the Larson Miller parameter.

The following correlation is for predicting the average wall temperature change with considering the ex-vessel cooling conditions.

$$\overline{T}_w^{t+\Delta t} = \left[1 - \frac{2 * r_{t,o} * h_{conv}}{(r_{t,o}^2 - r_{t,i}^2)\rho C_p}\Delta t\right] * \overline{T}_w^{t} + \frac{1}{(\pi(r_{t,o}^2 - r_{t,i}^2))\rho C_p}\left[q''' + 2\pi r_{t,o} h_{conv} T_f\right] * \Delta t$$

where $\overline{T}_w^{t+\Delta t}$ = wall temperature at new time [k]
ρ, C_p = tube density, specific heat [kg/m^3], [J/kg]
h_{conv}= heat transfer coefficient between tube and coolant [W/m^2-K]
T_f = coolant temperature [k]
q'''= decay heat generation rate [W/m^3]

Figure 4.4 shows the effect of ex-vessel cooling on the penetration tube wall temperature.

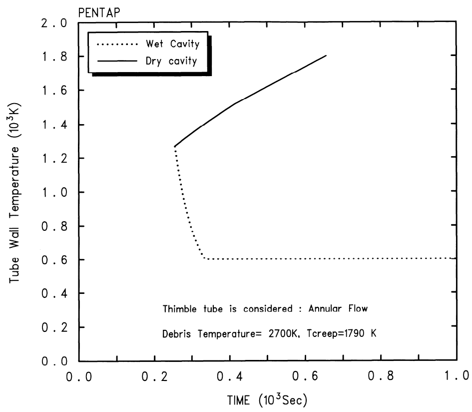

Figure 4.4 Tube temperatures with/without EVC (external vessel cooling)

4.5 Calculation flow steps

The following Figure 4.5 shows the calculation flow of the PENTAP program. The three important penetration tube failure modes are creep, tube ejection and tube creep by improper heat removal.

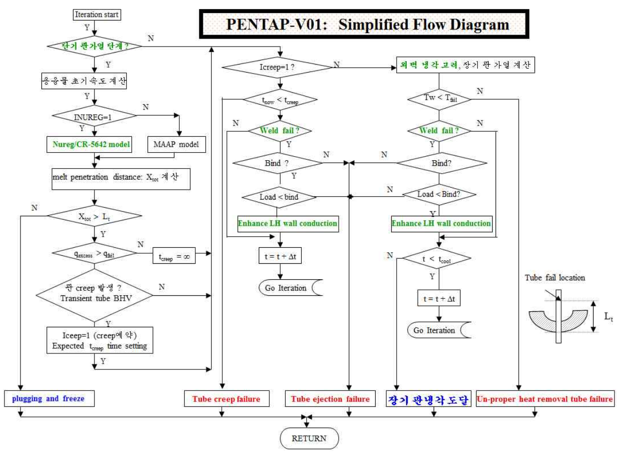

Figure 4.5 PENTAP calculation flow steps

5. Conclusion

The penetration models from the current available severe accident codes such as MAAP and MELCOR and the NUREG/CR-5642 report have been examined. Based on the review results, the PENTAP program for estimating the penetration tube failure modes was developed by KAERI.

If the temperature distributions for each layers in the lower vessel wall according to time are given by the user input, then the current PENTAP program can provide the following information; the penetration distance of the molten debris along the inside of the tube, the plugging within the lower vessel wall, the tube ejection by weld failure and the creep failure of the tube from the outside space of the lower vessel.

However, the prediction capability of PENTAP should be verified using the data from a penetration tube experiment by KAERI.

ACKNOWLEDGEMENTS

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