Study on the in-core-instrumentation tube ejection failure at APR1400 lower reactor vessel

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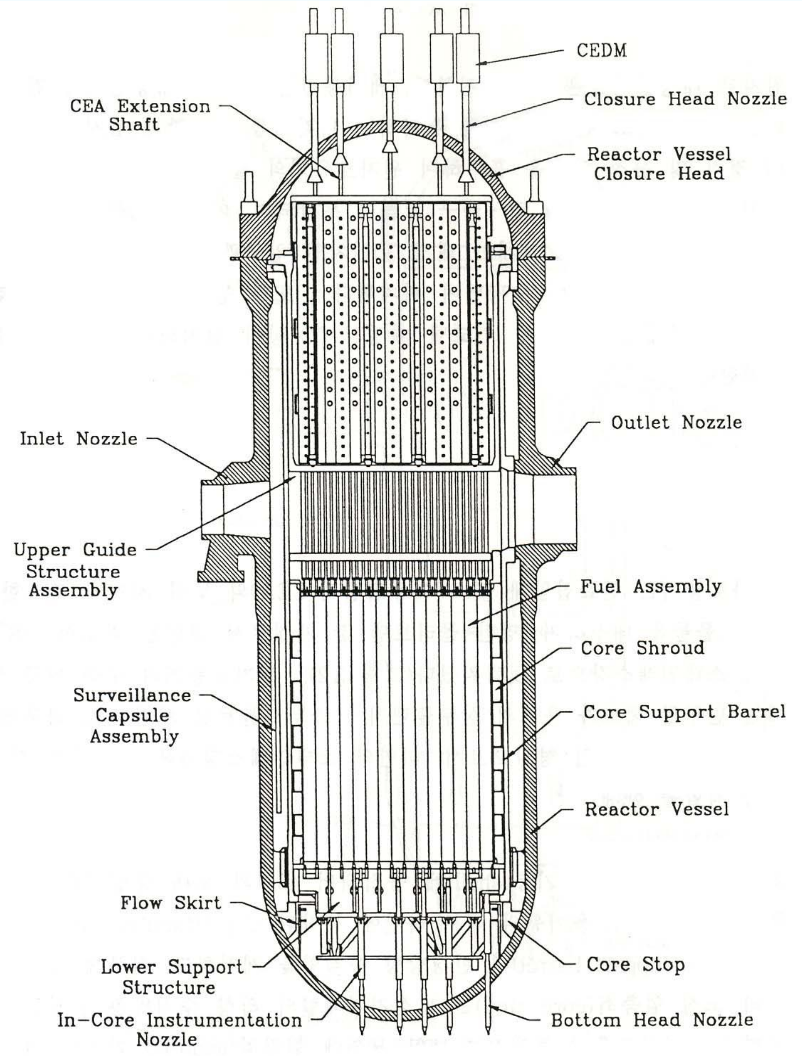
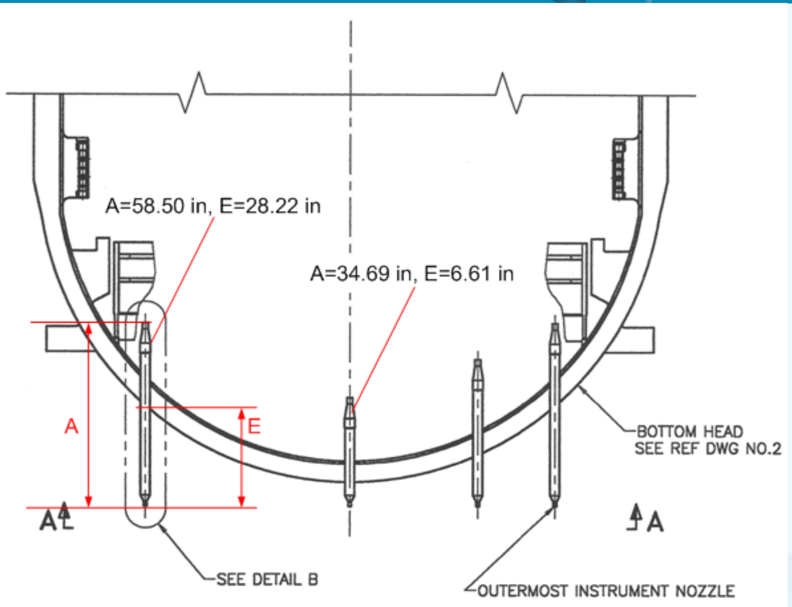
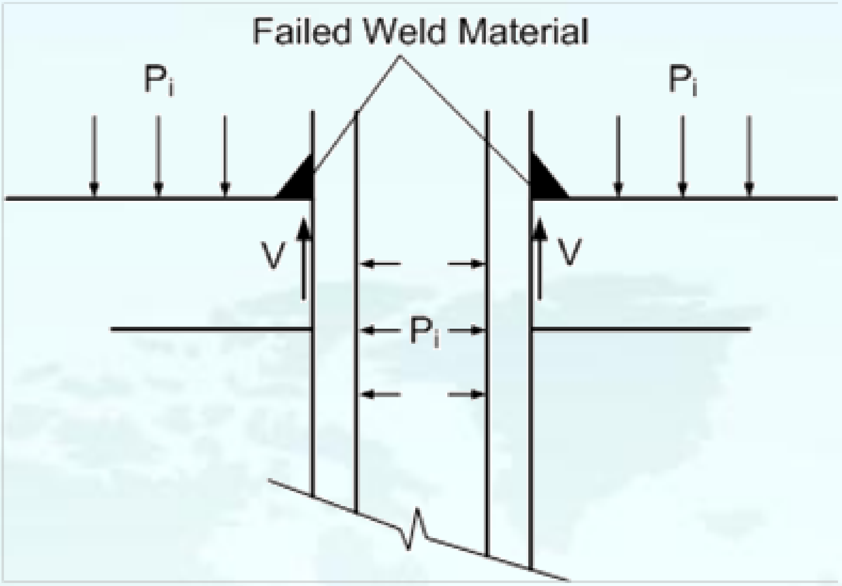
ICI Penetration for APR1400



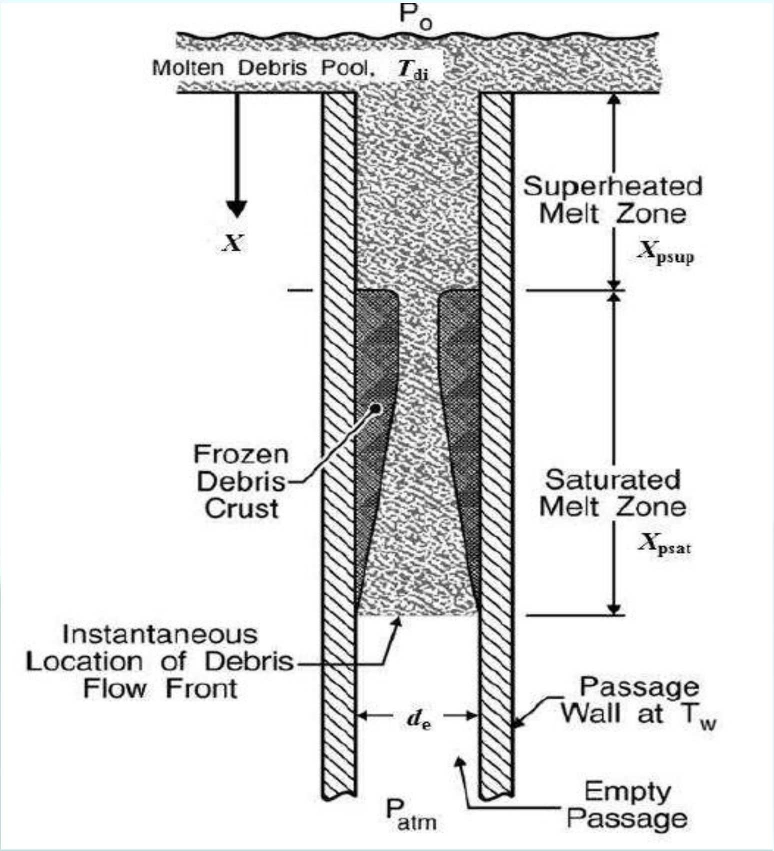


ICI Penetration Failure



Penetration tube ejection & rupture

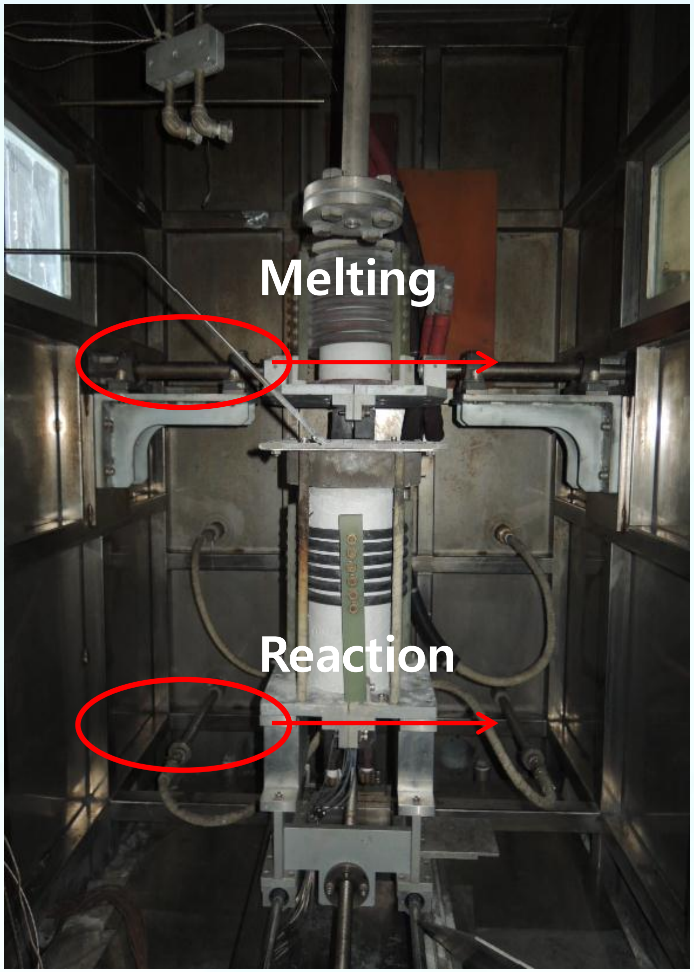
Compare Pi and V

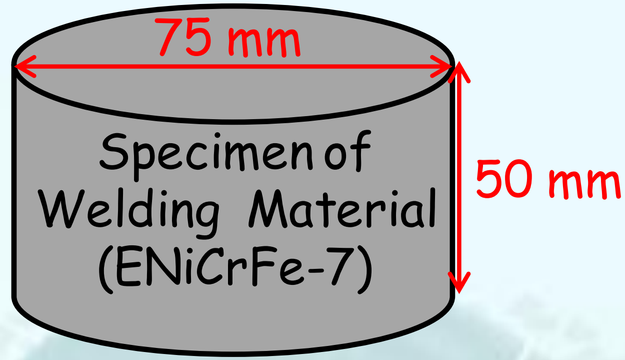


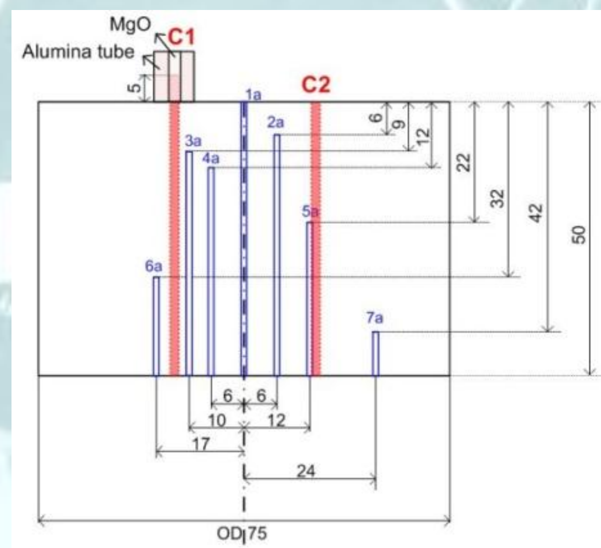
Penetration tube heat-up & rupture

Welding Erosion Test (1)

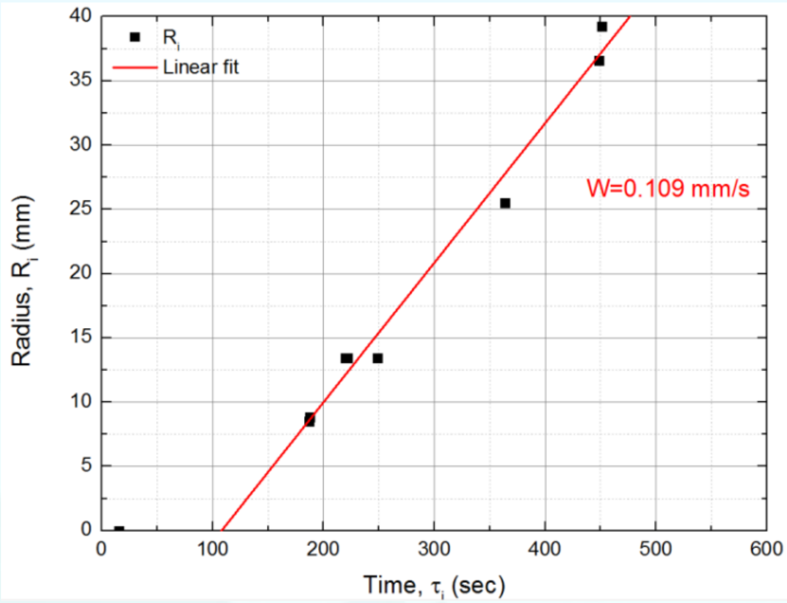
VESTA-S Test Facility



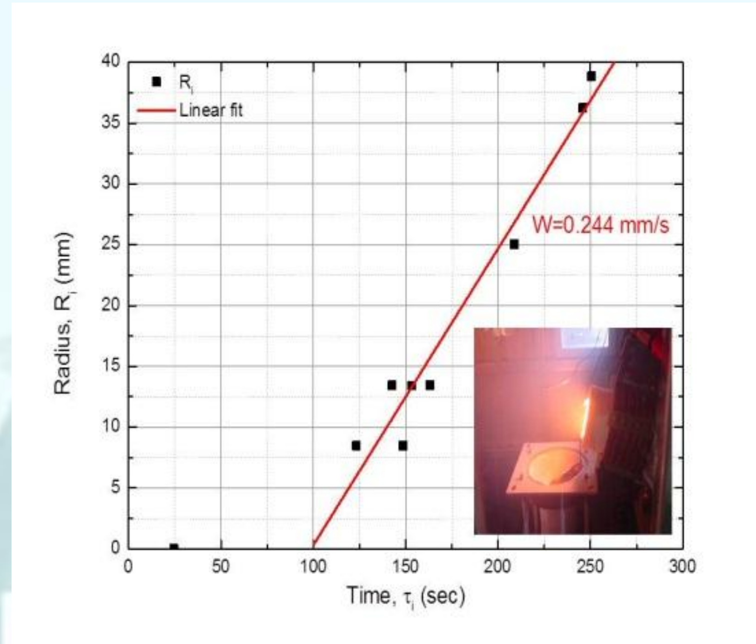




Welding Erosion Test (2)

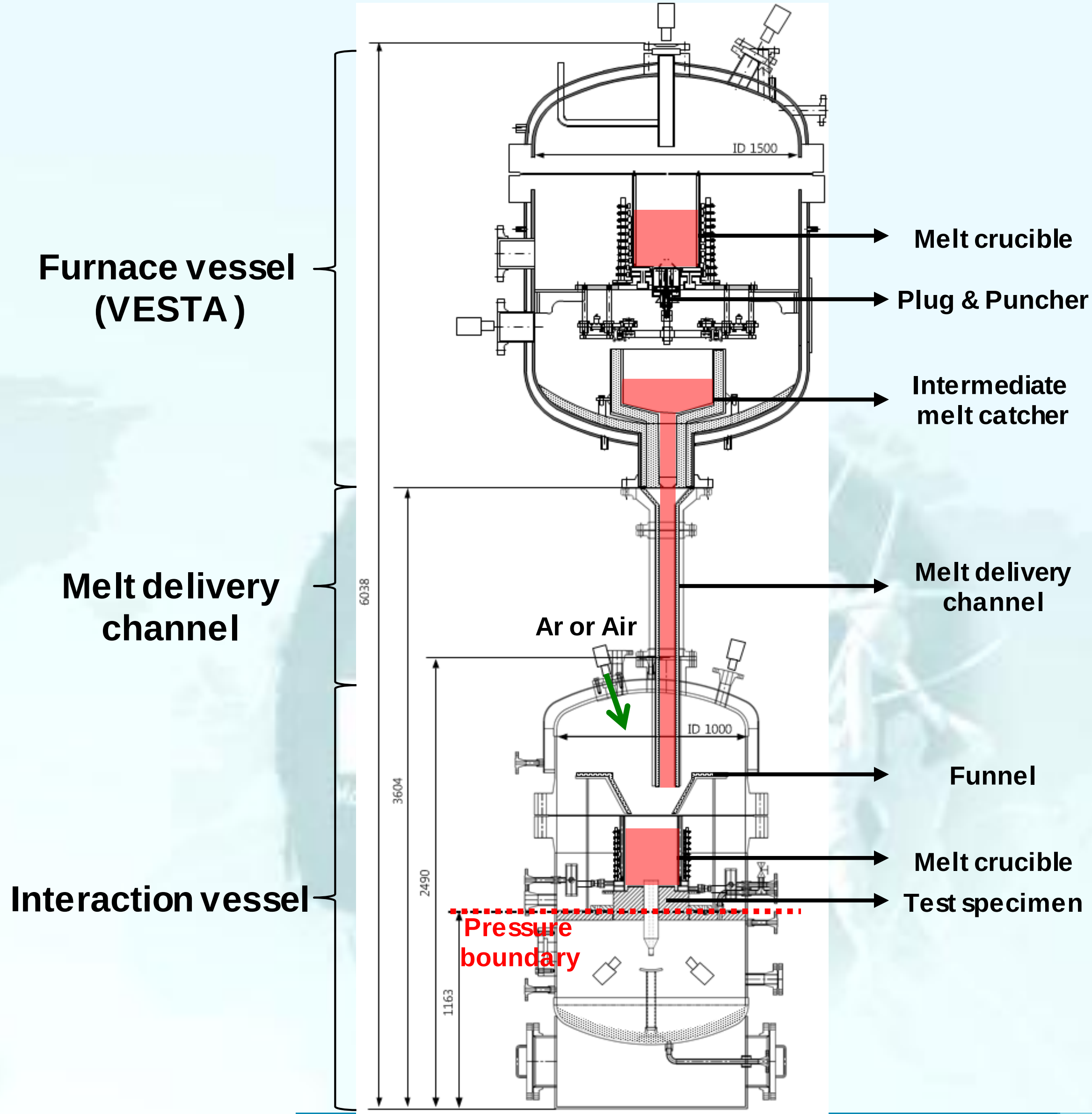


Composition:
Fe 46%, U 31%, Zr 16%, Cr 7%)
Mass:
3.129 kg



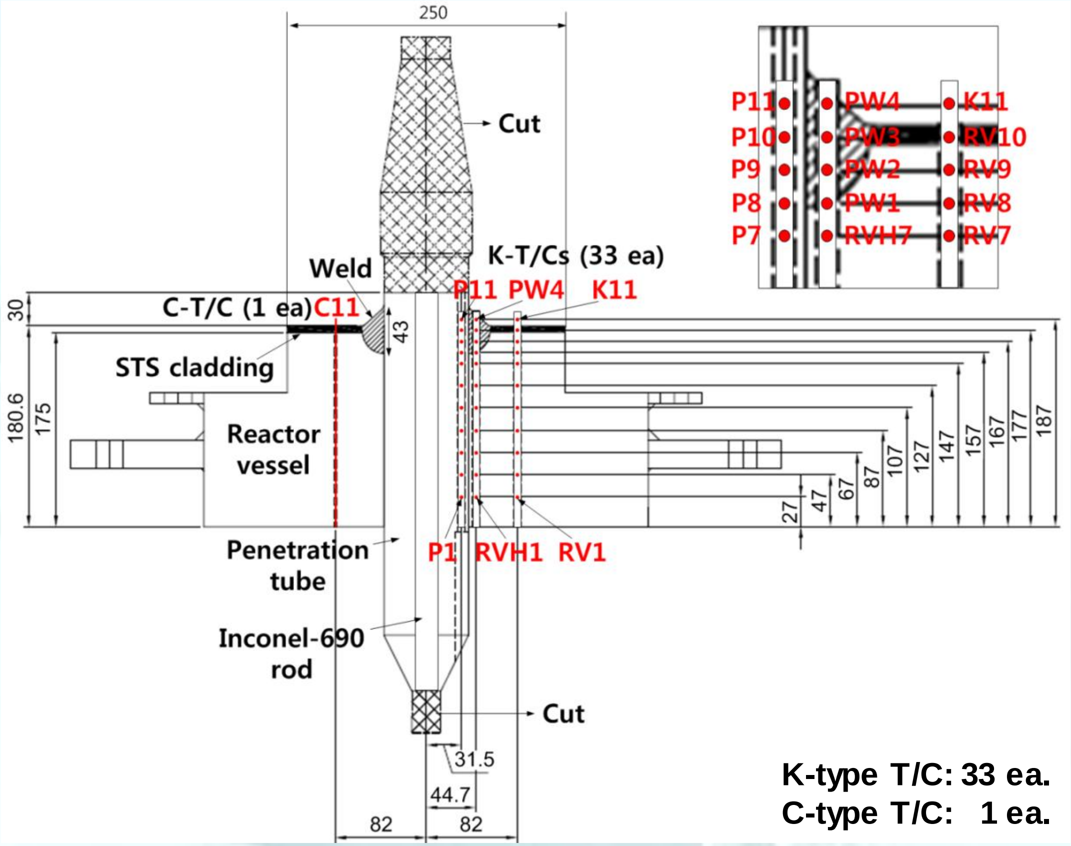
Composition:
SUS304 (Cr 19%, Ni 11%, Fe 70%)
Mass: 2.2155 kg

ICI Penetration Failure Test (1)



❑ Penetration test specimen

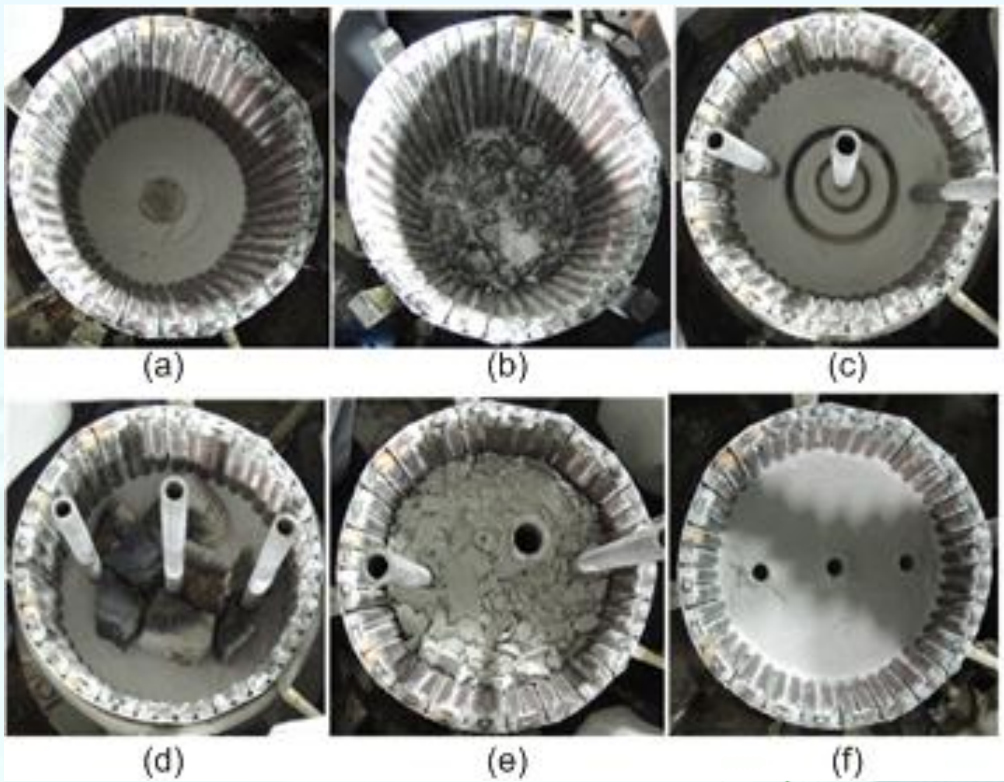
Penetration test specimen
(DOOSAN Heavy Industries and Construction. Co., Ltd.)

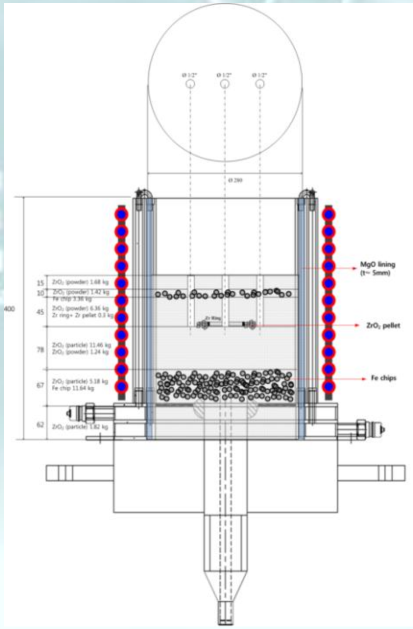


C11, K11	: Melt temperature
P1-P11	: Penetration tube temperature
PW1-PW4	: Penetration weld temperature
RVH1-RVH7	: Reactor vessel hole temperature
RV1-RV10	: Reactor vessel temperature

ICI Penetration Failure Test (3)

❑ Melt Material Charging

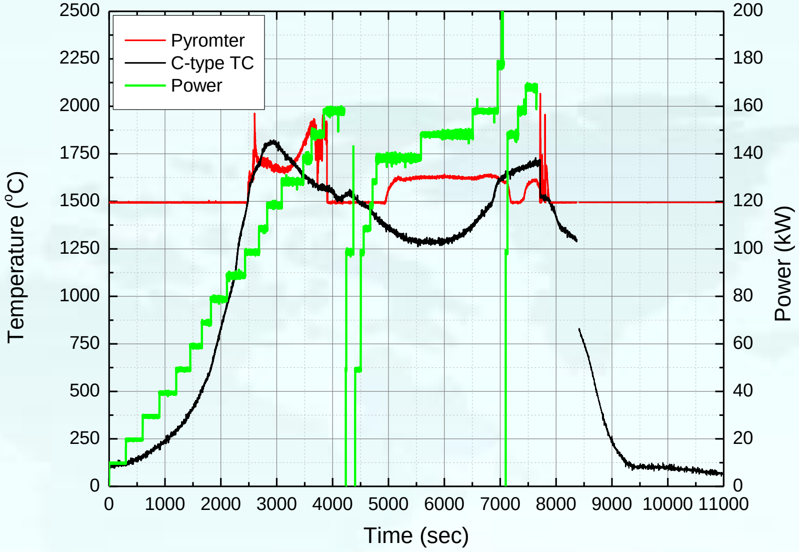




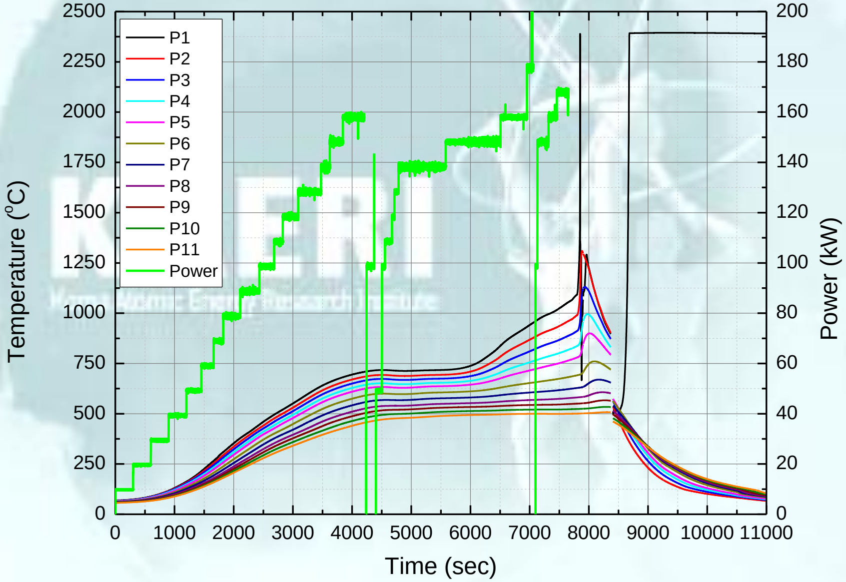
- ZrO_2 : Fe = 66 : 34 (wt%)
- Charging mass: 44.16 kg
  - ZrO_2 powder: 29.16 kg
  - Fe: 15.00 kg
  - Zr ring: small

ICI Penetration Failure Test (4)

Melt Temp.

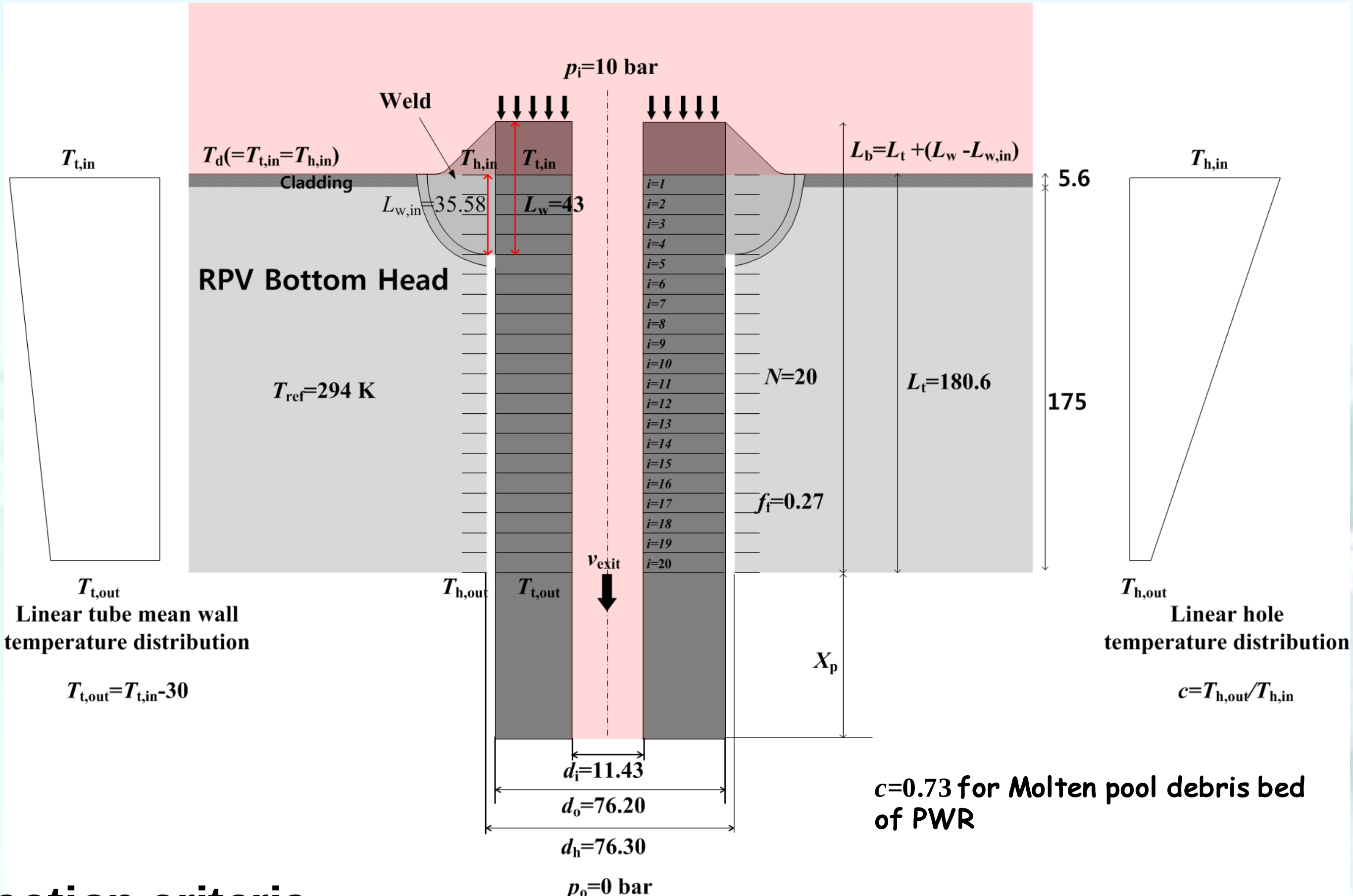


Penetration tube Temp.



Failure Models & Calculations (1)

❑ Tube Ejection (Weld failure)



- **Ejection criteria**

$$\boxed{F_p > V_T}$$

where, V_T : Total thermal binding shear force

F_p : Ejecting pressure force

Failure Models & Calculations (2)

❑ Tube Ejection

1. Free thermal expansion of tube and hole

Tube: $\Delta r_o^T = r_o \alpha_t (T_t - T_{ref}), \quad T_{ref} = 294\ \mathrm{K}$

Hole: $\Delta r_h^T = r_h \alpha_h (T_h - T_{ref}), \quad T_{ref} = 294\ \mathrm{K}$

2. Pressure expansion of tube

Tube: $\Delta r_o^P = \dfrac{p_i}{E} \cdot \dfrac{r_o r_i (2 - \nu_t)}{(r_o^2 - r_i^2)}$

Hole: $\Delta r_h^P = 0$

- The pressure expansion of hole is negligibly small.

3. Total expansion of tube

Tube: $\Delta r_o = \Delta r_o^T + \Delta r_o^P$

4. Tube-hole radial gap at temperature and pressure

$$\delta_i = (r_h + \Delta r_h) - (r_o + \Delta r_o)$$

$+ \rightarrow gap$
$- \rightarrow interface$

5. Tube-hole interface pressure

$$\delta_i < 0: \quad P_{th} = \text{lesser of} \left\{ \frac{\delta_i \cdot E (r_o^2 - r_i^2)}{r_o [r_o^2 (1 - 2\nu_t) + r_i^2 (1 + \nu_t)]}, \quad \frac{2}{\sqrt{3}} \sigma_u \ln\left(\frac{r_o}{r_i}\right) \right\}$$

(first term) Required interfacial pressure to force the outer diameter of the tube to conform to the diameter of the hole after free expansion

(second term) Required pressure to cause compression failure of the tube material

$$\delta_i \geq 0: \quad P_{th} = 0$$

6. Total thermal binding shear

$$V_T = \sum_{n=1}^{n} f \cdot P_{th} 2\pi r_o \Delta l_t$$

f : not a f (temp.), but a f (roughness)

- 0.27 for high-temperature, oxidized conditions

7. Ejecting pressure force

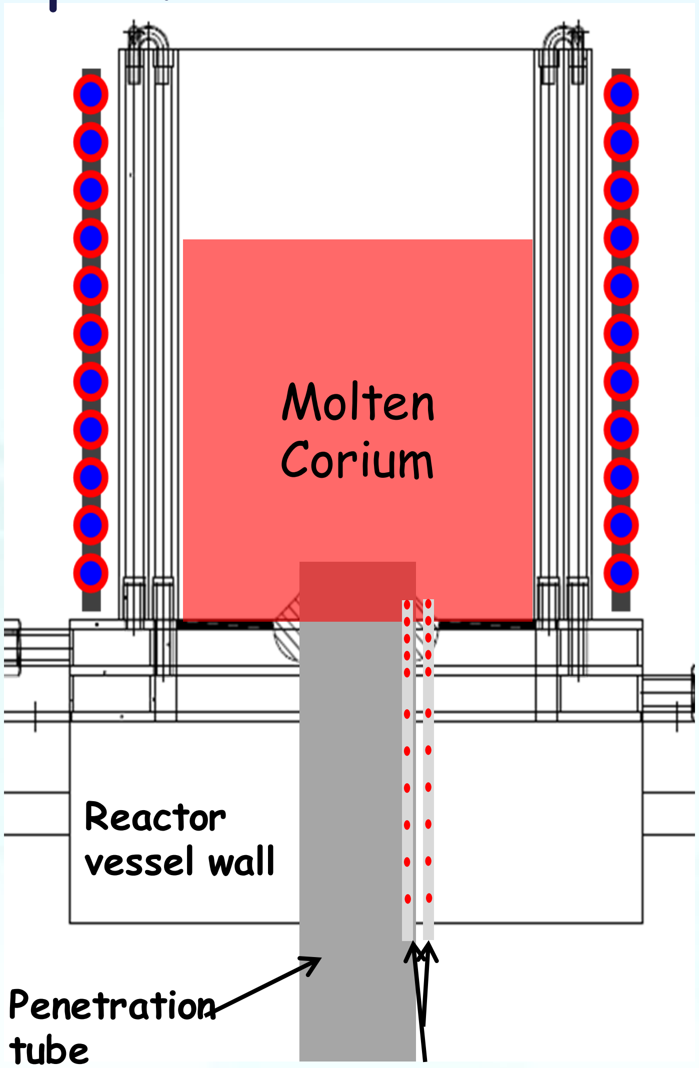
$$F_p = p_i \pi r_o^2$$

8. Ejection criteria

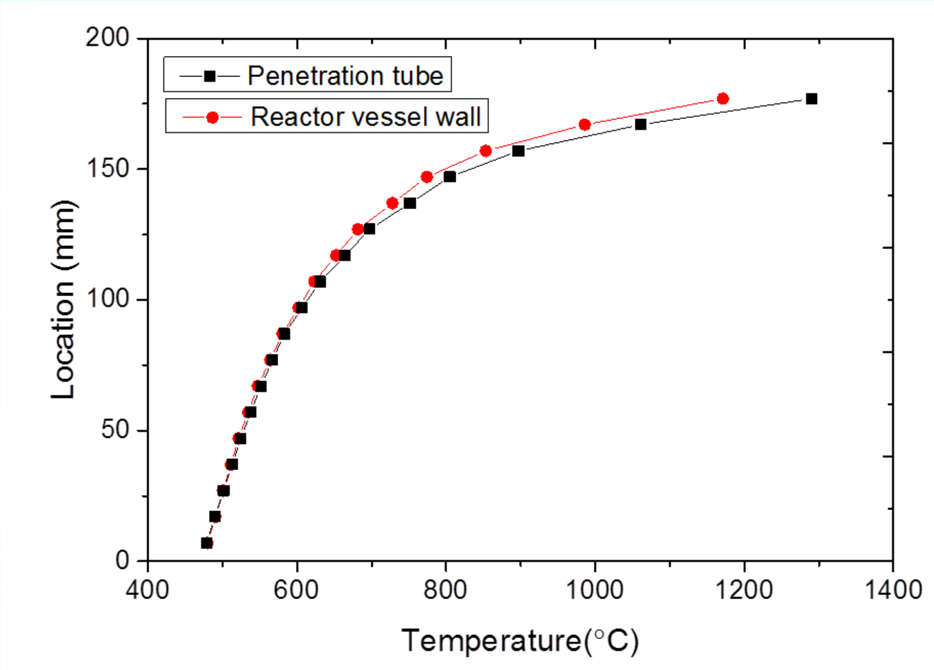
$$F_p > V_T$$

Failure Models & Calculations (3)

- Experimental results

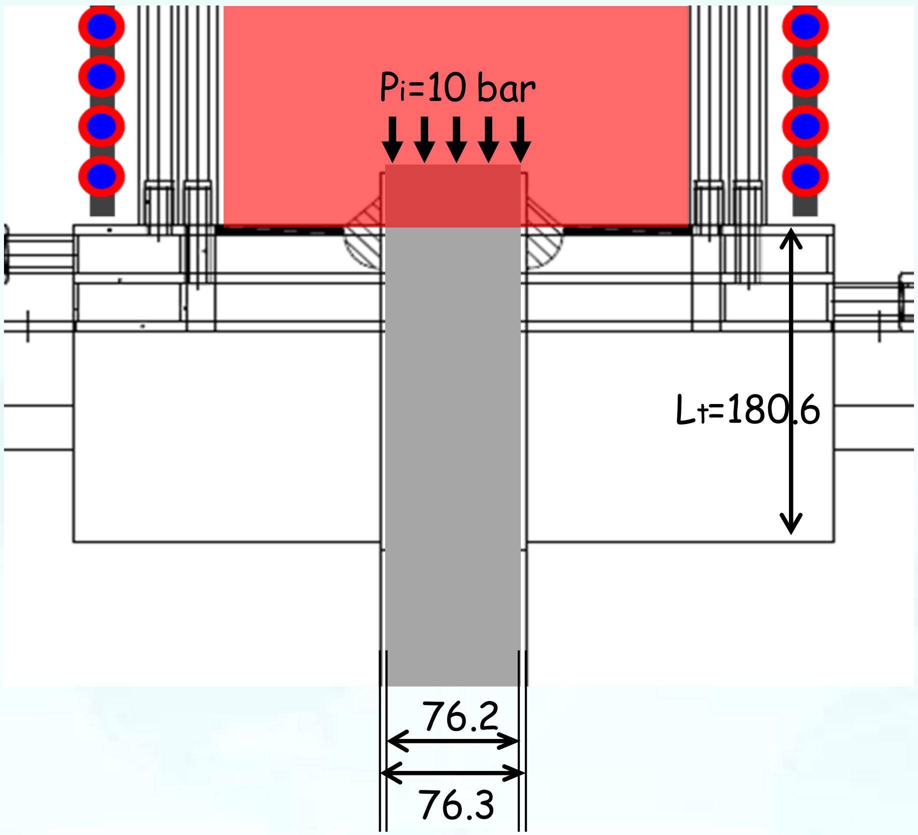


✓Temperature distribution



Failure Models & Calculations (4)

❑ Tube Ejection



❍ **Input data**

✓ Obtained temperature profile

❍ **Assumption**

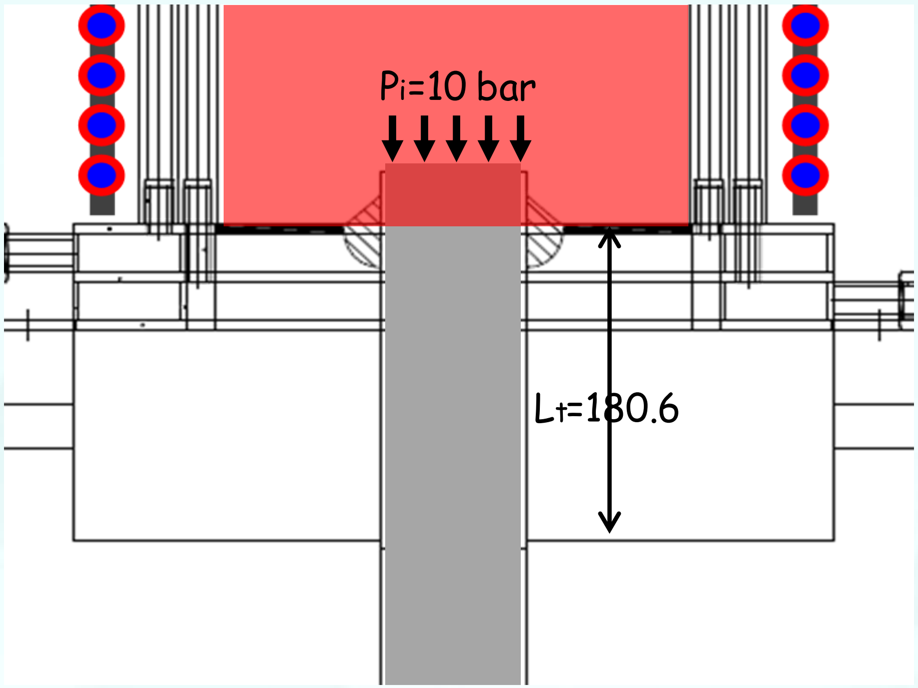
✓ P_i=10 bar

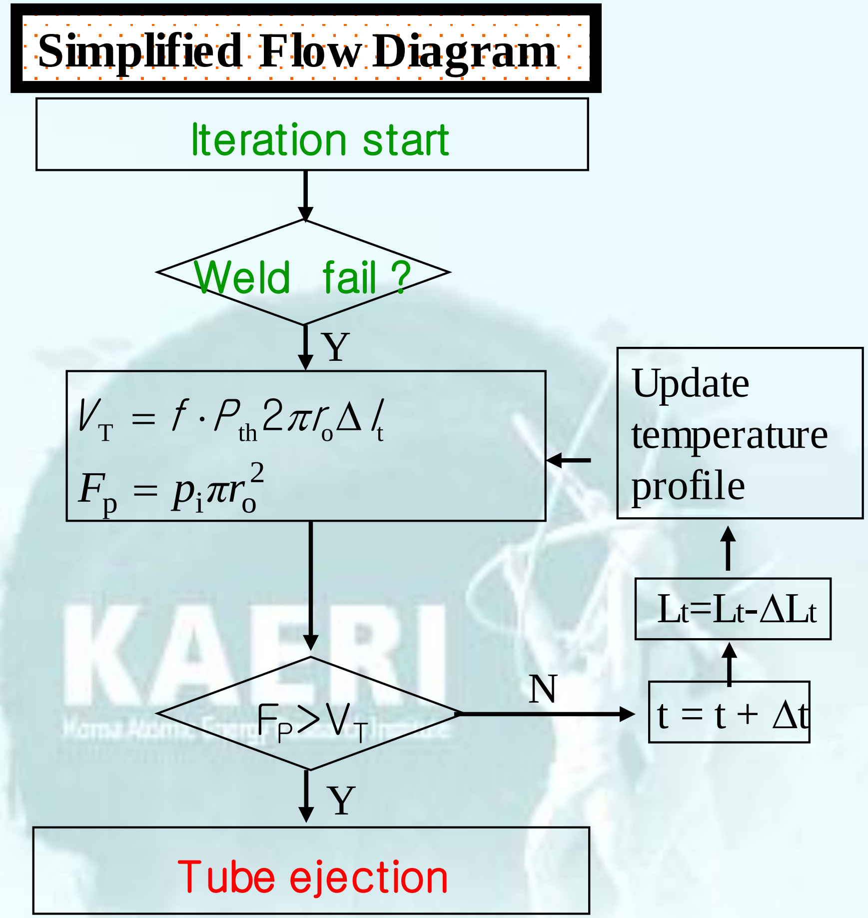
✓ Clearance gap size: same as normal operating condition

✓ Top surface temp. up to 2600 oC while maintaining similar temp. profile

Failure Models & Calculations (5)

❑ Tube Ejection (Weld failure)





- **Ejection criteria**

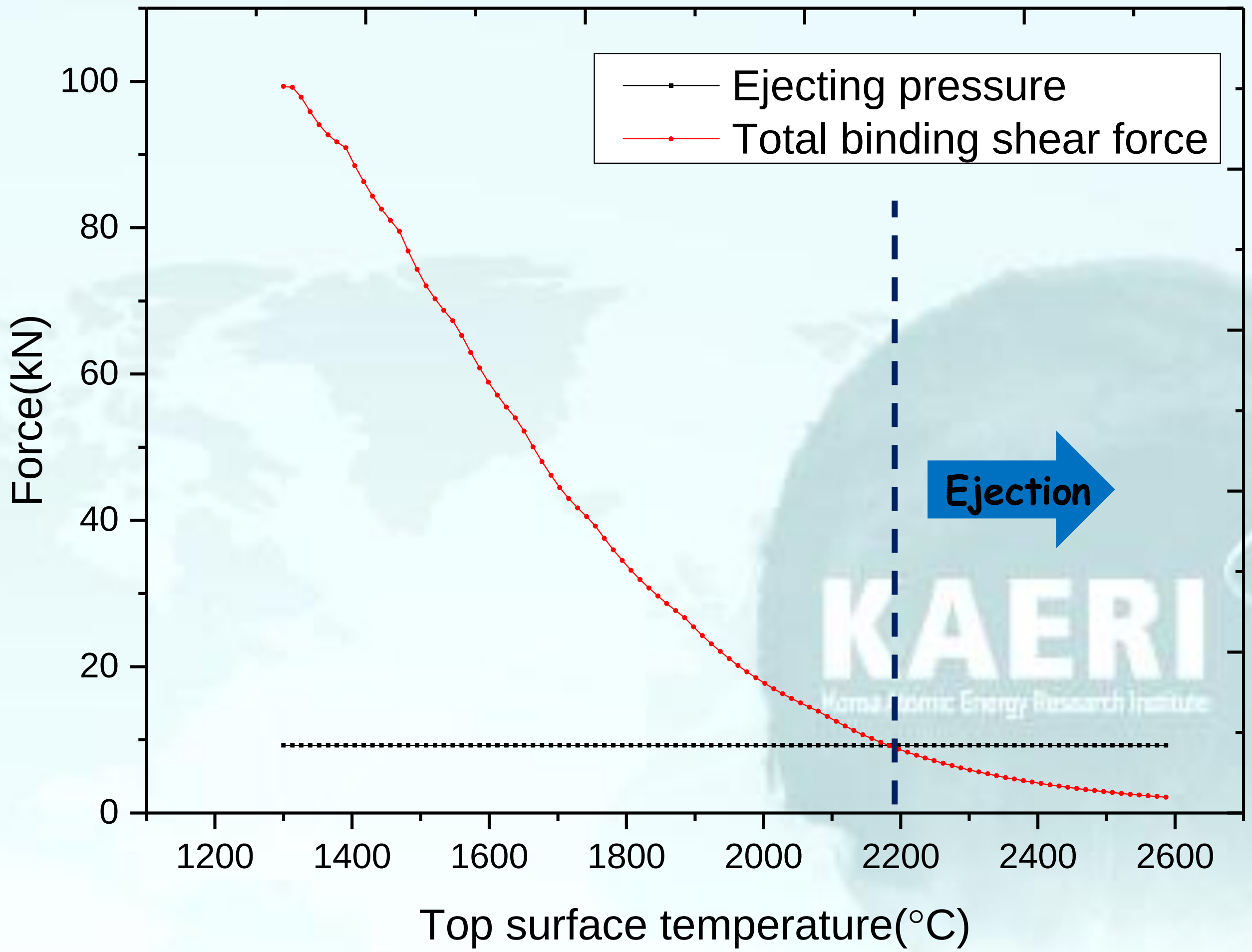
$$F_p > V_T$$

where, V_T : Total thermal binding shear force, $f \cdot P_{th} 2\pi r_o \Delta l_t$

F_p : Ejecting pressure force, $p_i \pi r_o^2$

Failure Models & Calculations (6)

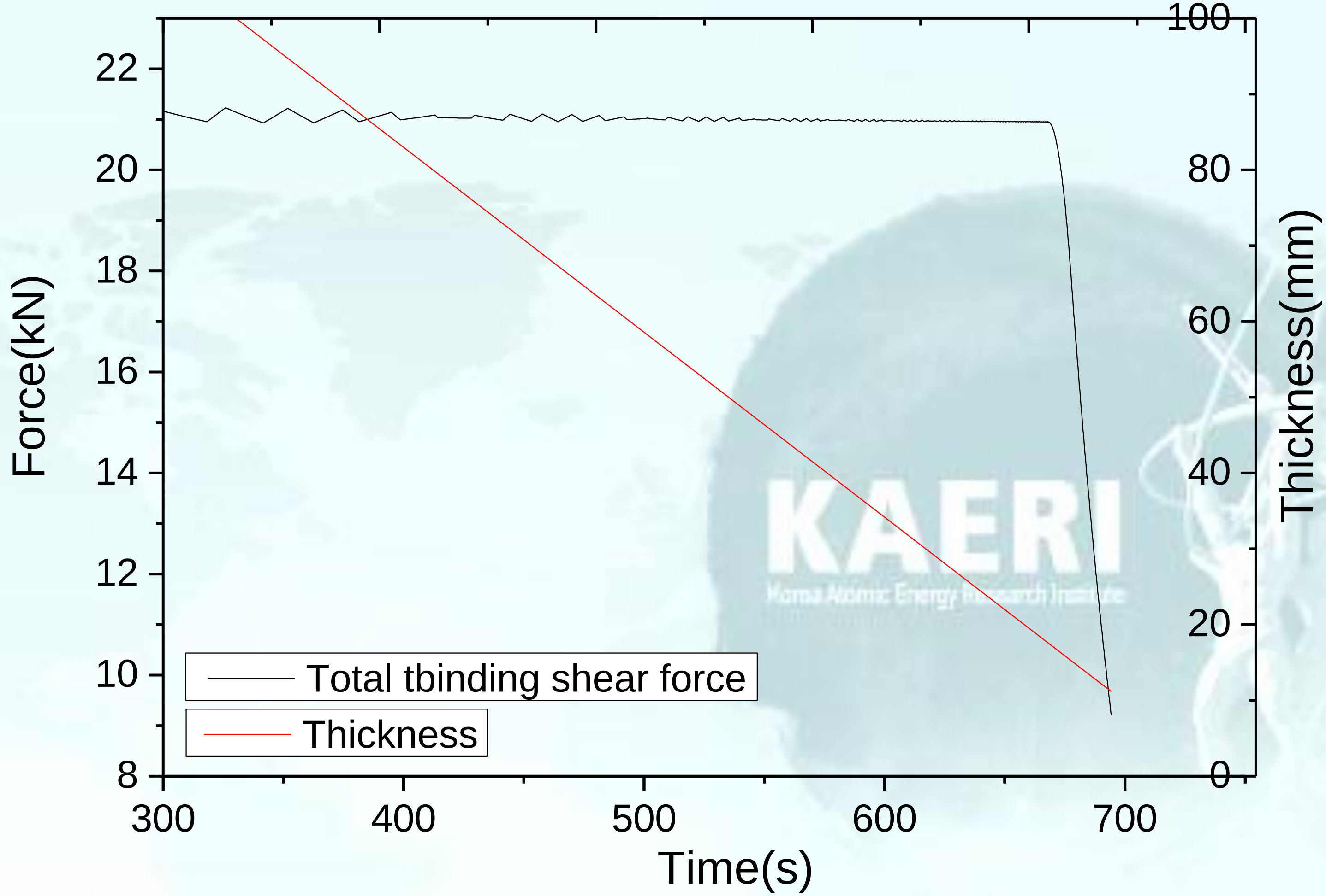
❑ Tube Ejection



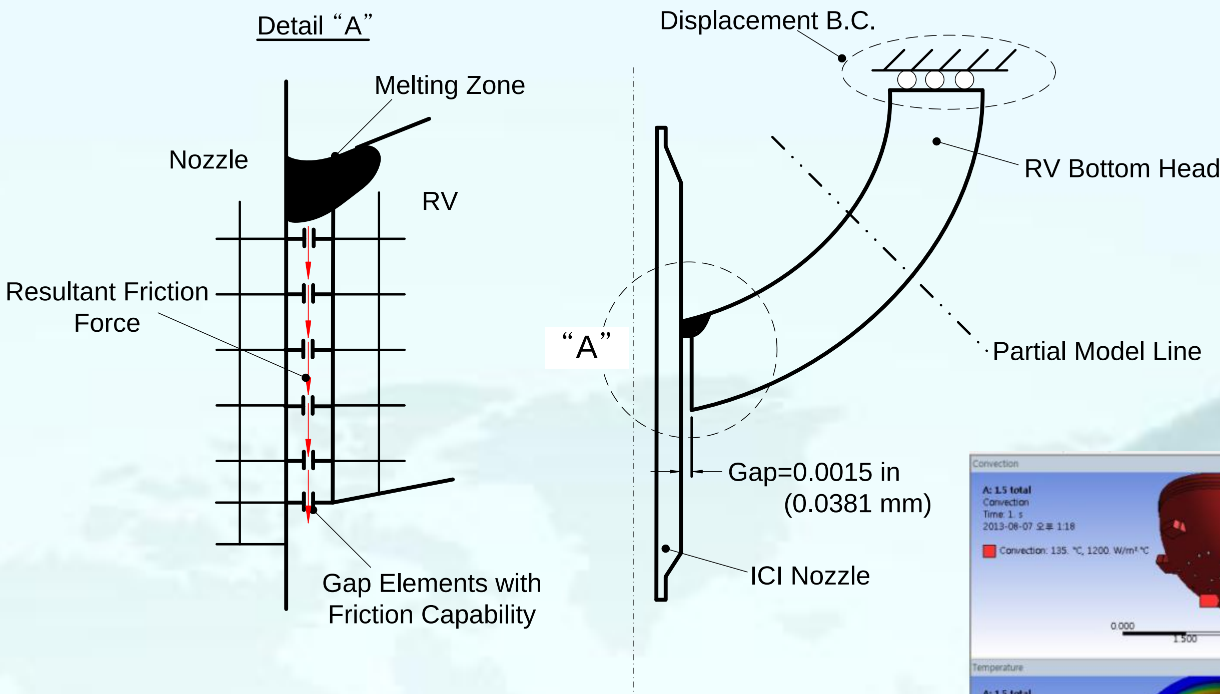
Failure Models & Calculations (7)

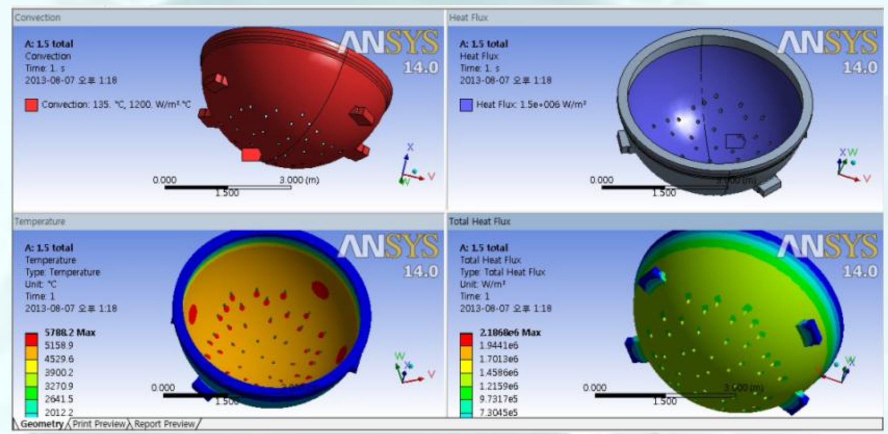
❑ Tube Ejection

✓ Top surface temperature = 1950°C



ANSYS Analysis





Deformation of reactor vessel affects the gap.
Clamping or non-clamping ICI nozzle depends on the location.
Clearance gap size may change.

Concluding Remarks

- APR1400 ICI penetration tube failure study
  - Welding material erosion test at VESTA-S facility
  - ICI penetration tube failure test at VESTA facility
  - ICI penetration tube failure calculation with suggested model

- Future work
  - Test with high heat flux and elevated pressure
  - Test under the external reactor vessel cooling condition
  - Analysis in case of clearance gap change