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Structural Integrity Research for Reactor Pressure Vessel under In-Vessel Melt Retention

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Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

1. Background

- *In-Vessel Retention (IVR)* of molten core debris via water cooling on the external surfaces of the reactor vessel is an inherent severe accident management feature of the AP1000/CAP1400 passive *Nuclear Power Plants (NPPs).*
- Main failure modes associated with *IVR*: Thermal Failure / Structural Failure.
- The Structural Failure assessment is also necessary because high temperature induced creep damage are the immediate threats to the RPV, especially with the sustained pressure loads existence

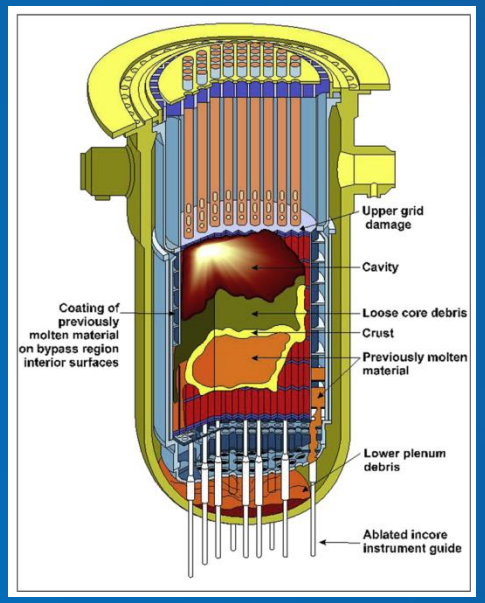


Fig.1 Schematic diagram of reactor core following TMI-2 accident.

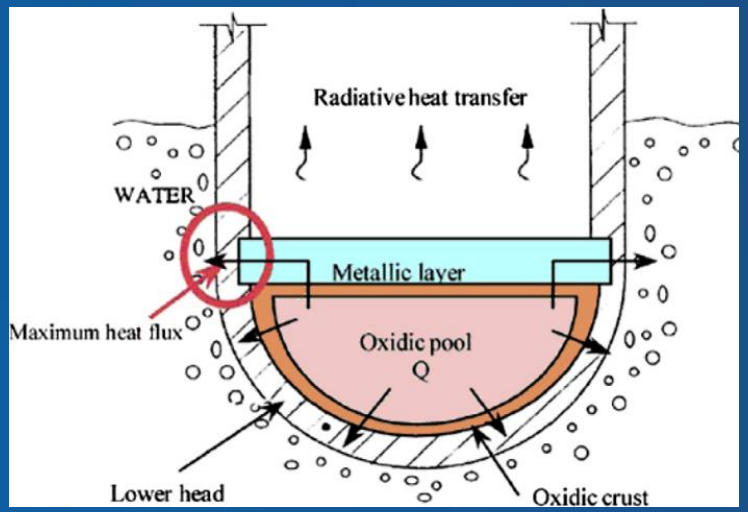


Fig. 2 Schematic diagram of IVR strategy.

Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

2. Load and Material Properties

- ***Load***
  - ✓ Temperature (inner and outer)

【Cylinder】

【Lower head】

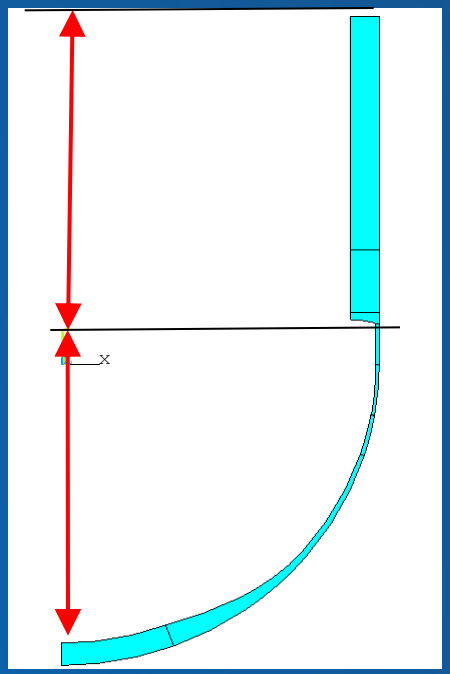


Fig.3 Temperature distribution of inner wall

  - ✓ Internal Pressure (Pressure Differential between inner and outer of lower head)

2. Load and Material Properties

- ***Material Properties (SA-533 B Cl.1)***
  - ✓ Mechanical and Physical Properties

    The relationship of Young's modulus , Yield strength, coefficient of expansion , thermal conductivity and temperature are presented

    - *Young's modulus*
    - *Yield strength*
    - *coefficient of expansion*
    - *thermal conductivity*

2. Load and Material Properties

- ***Material Properties (SA-533 B Cl.1)***

✓ Creep Constitutive Model

A time hardening creep model is chosen.

$$\varepsilon = A\sigma^m t^n$$

where ε is the creep stain, σ is the stress (ksi), and t is the time (hr).

Table 1 Creep Constitutive Model of SA-533 B Cl.1

T (°C)	$\varepsilon = A\sigma^m t^n$ (primary and secondary stage)		
	A	m	n
399	3.17E-16	7.01	0.243
627	1.06E-6	2.83	0.836
777	6.62E-4	2.66	0.704
877	1.08E-3	3.00	0.788
977	8.56E-3	3.67	0.536
1100	0.236	4.74	0.714

Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

3. Analyses Approach

- ✓ The Larson-Miller Parameter (*LMP*) correlation: $LMP = 0.001(20.0 + \lg t_r)T$
- ✓ *LMP* vs. σ_{oe} correlation: $LMP = b \ln \frac{\sigma_{oe}}{a}$ $a = 5272$ $b = -5.7241$

where σ_{oe} *is the effective stress (ksi) which generalize the unixial constant-load creep data to multiaxial stress conditions,* $\sigma_{oe} = \frac{1}{\sqrt{2}}\left[(\sigma_{o1} - \sigma_{o2})^2 + (\sigma_{o2} - \sigma_{o3})^2 + (\sigma_{o3} - \sigma_{o1})^2\right]^{1/2}$

Table 2 Creep Stress-rupture Test Data of SA-533 B Cl.1

T(℃)	σ (ksi)	t_r (hr)	*LMP*
627	10.1	190	36.09
777	3.8	18.9	40.21
877	1.8	54.7	45.00
877	3.8	4.1	42.67
977	1.2	61.2	49.02
1100	1.0	0.65	48.98

3. Analyses Approach

- ✓ The incremental damage is defined as follows:

$$\Delta D = \frac{\Delta t}{t_r(\sigma, T)}$$

where $t_r(\sigma, T)$ is the rupture time obtained from a constant-load creep-rupture test conducted for the stress σ and the temperature T.

- ✓ The total damage at certain duration can be expressed as follows:

$$D = \sum \frac{\Delta t}{t_r}$$

When $D \geq 1.0$, the failure by creep rupture is indicated.

Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

4. Analyses and Discussions

- ***Finite Element Model (FEM)***
  - ✓ An ANSYS FEA model of the partially melted lower head with 2D axis-symmetric elements

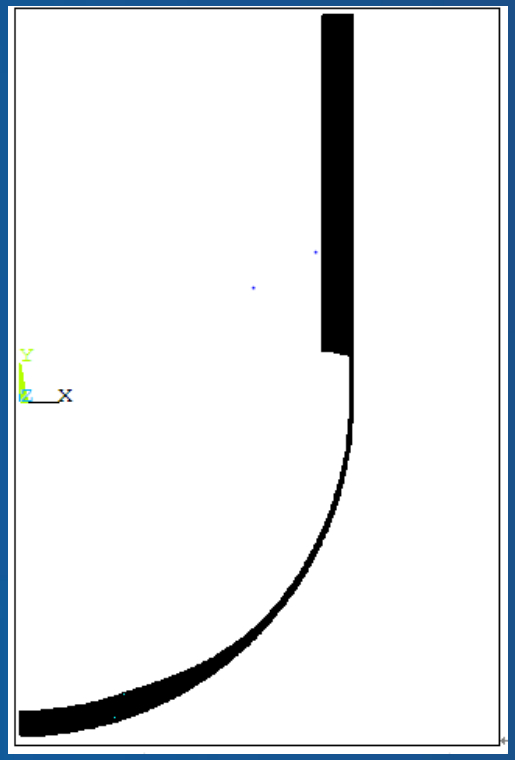


Fig.5 FEA model

4. Analyses and Discussions

- ***Discussion and Evaluation***

  - ✓ The overall displacement of the vessel cylinder is approximately equal to 10 mm, which is half of that of lower head (approximately 20 mm).
  - ✓ The maximum total deformation happens at the structural discontinuity between the lower head and the vessel cylinder, with the maximum displacement value of 25.69mm.

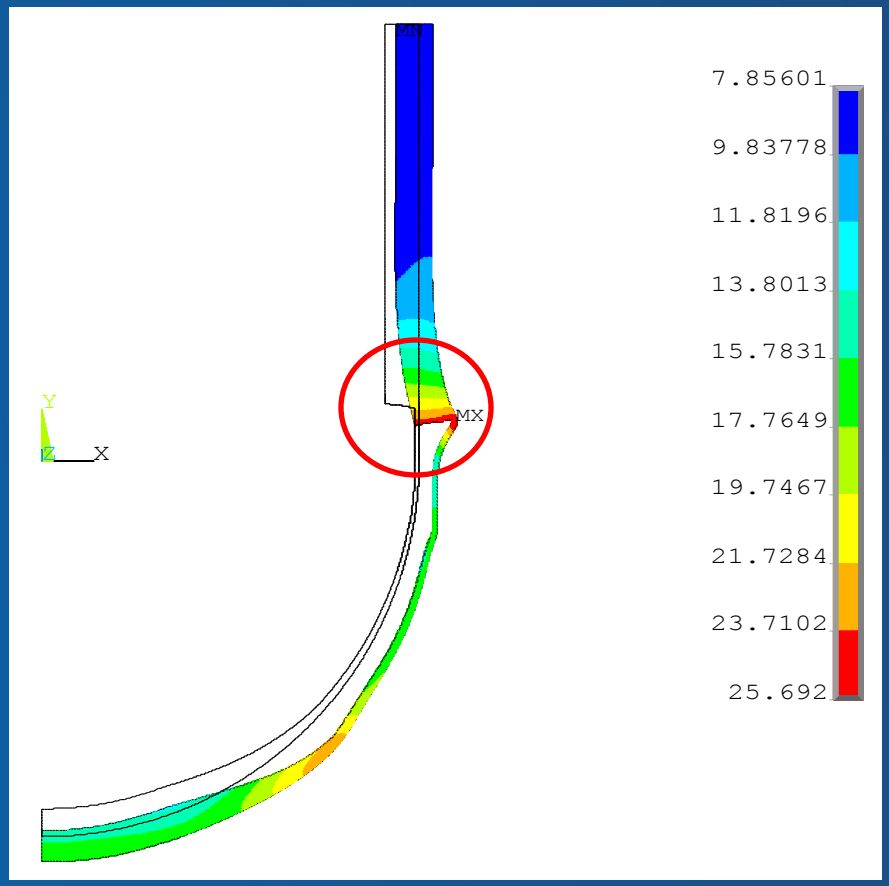


Fig. 6 deformation under loadings (*unit: mm*)
(magnified 10 times for clarity)

4. Analyses and Discussions

- ***Discussion and Evaluation***

  - ✓ Based on creep calculations, the distributions of hoop stress and meridian stress along the wall thickness at different times are obtained, then the critical temperatures defined as $T_{critical}$ where the hoop and the meridian stresses transform from compressive to tensile are captured.
  - ✓ According to ASME B&PV Code, Section III, NB-1120, if the temperature exceeds the its limit, the creep characteristics of materials become significant factor. The limit temperature defined as T_{creep} of ferrite materials is 370 ℃.

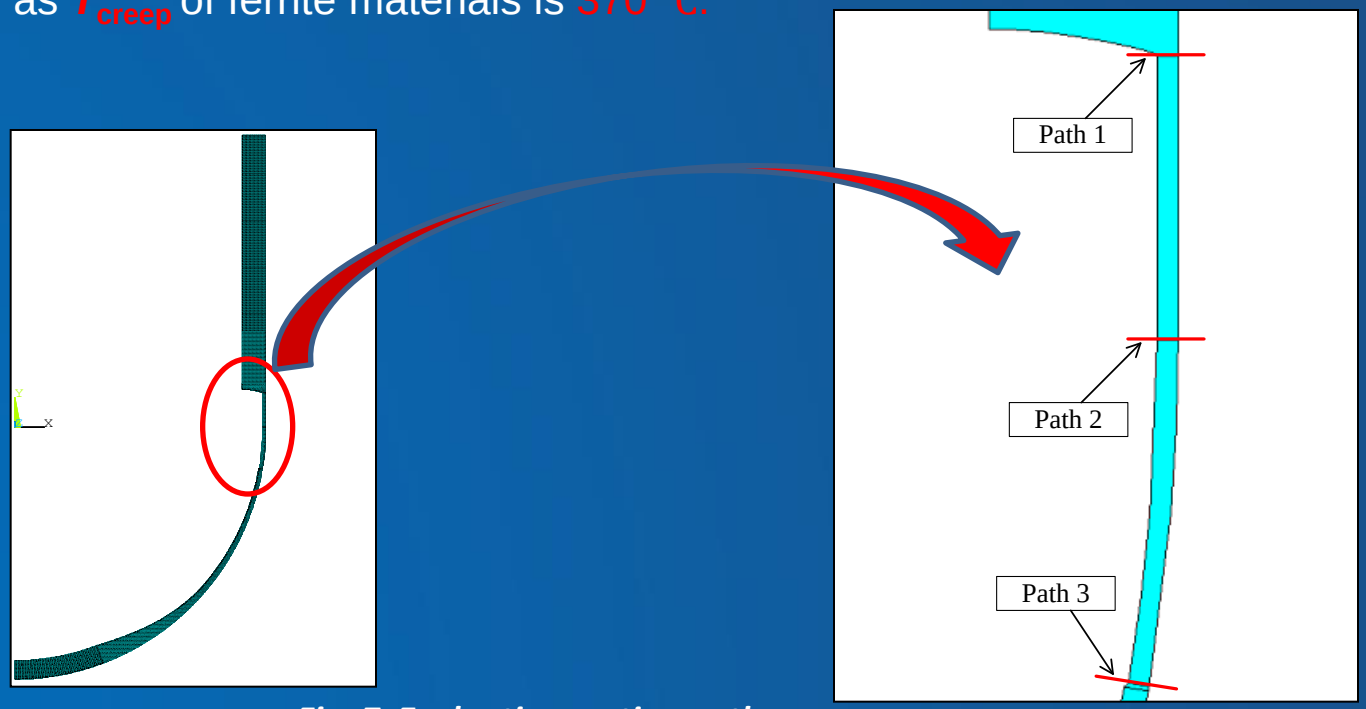


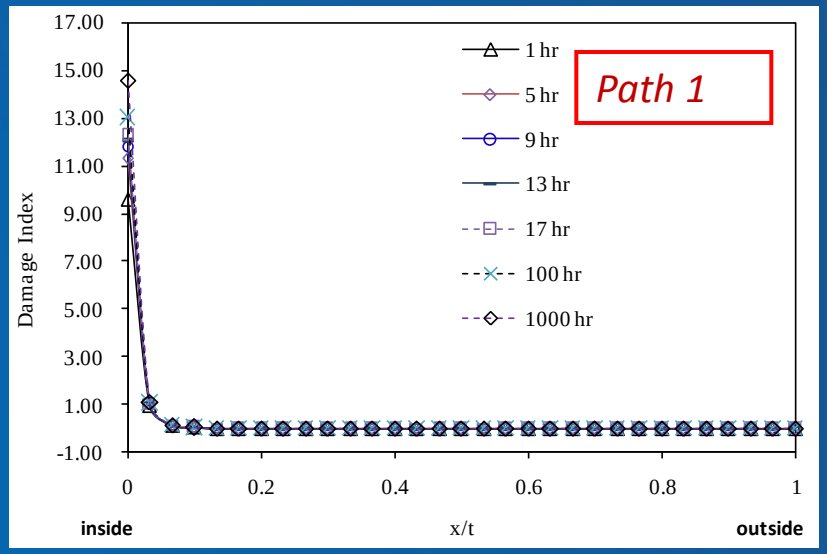
Fig. 7 Evaluation section paths

4. Analyses and Discussions

- ***Discussion and Evaluation***

✓ The damage factor varied by time

The damage factor of a very little part of inner region exceed 1.0, while that of the rest of thickness is nearly zero, which shows that the creep failure maybe only happen in pretty local region through the thickness.

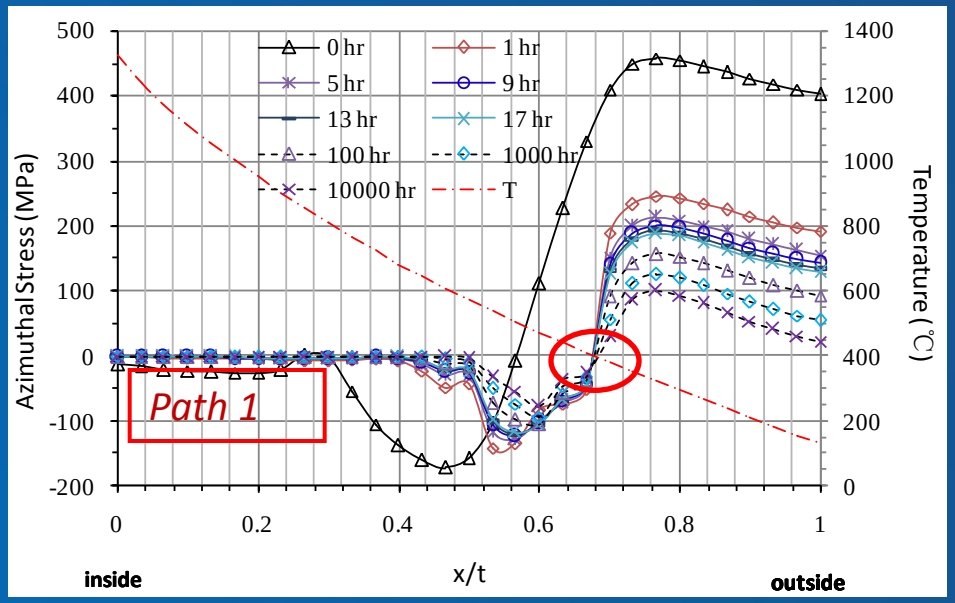


4. Analyses and Discussions

- ***Discussion and Evaluation***

✓ The hoop stress varied by time

- a thick inner part of the wall is in the compressive stress condition, while the left outer part is in tensile condition.
- Path *1*, $T_{critical}$ = 400℃ > T_{creep} = 370℃

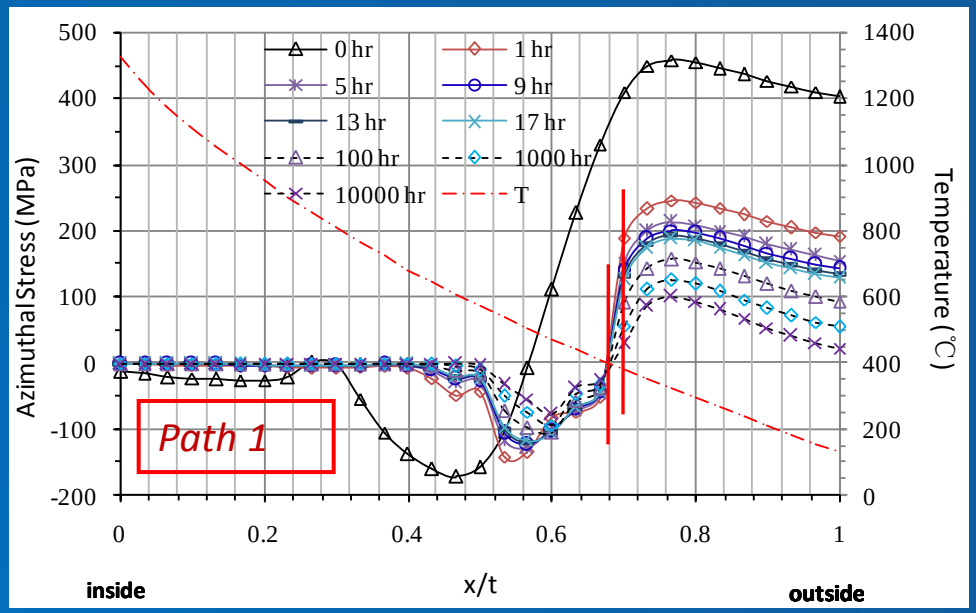


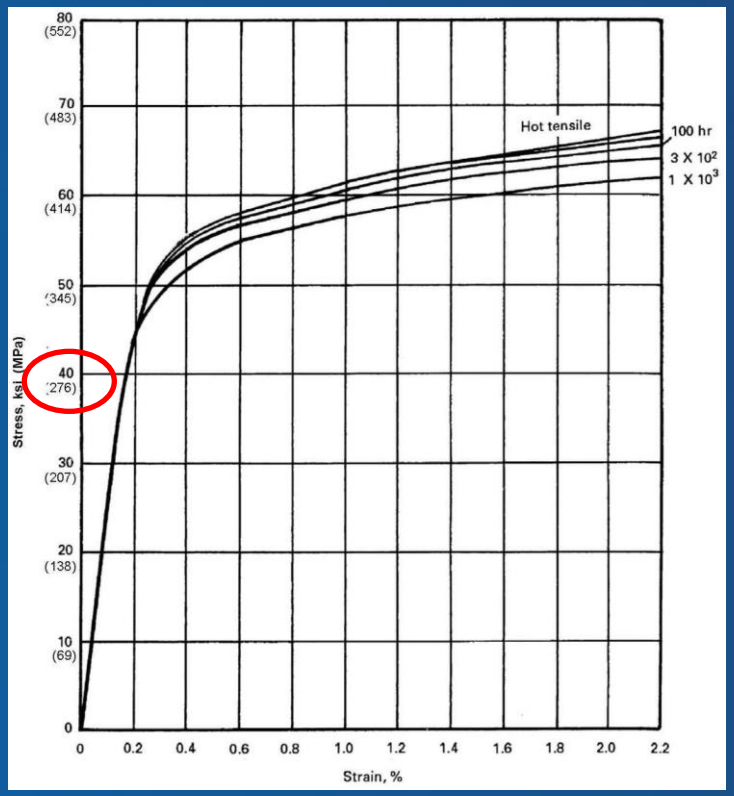
4. Analyses and Discussions

- ***Discussion and Evaluation***

✓ All the critical temperatures $T_{critical}$ are less than the limit temperature T_{creep} with exception of *Path 1*. It means that the regions, where the temperatures exceed the limit temperature, are almost in the compressive stress condition, so the creep crack could not propagate.

✓ For the exception of *Path 1*, the stresses of "compressive to tensile" is less than 276MPa, and it would further reduce with the time, so the creep effect could be negligible.





Isochronous stress-strain curves at 400℃

Contents

1. Background

2. Load and Material Properties

3. Analyses Approach

4. Analyses and Discussions

5. Conclusions

5. Conclusions

✓ The achieved results are as follows:

Although there is some possibility of creep crack initiations at the inner regions of the lower head wall, the cracks would not propagate to induce the leakage of the wall. The failure modes associated with creep rupture would not happen even when a certain amount of pressure sustained.

The approaches introduced could be utilized in structural integrity evaluation of RPV under IVR for other new types of NPPs.

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Thanks For Your Attention！

Any Comments Are Welcomed！

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