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Life Prediction for RCS Components During Severe Accidents

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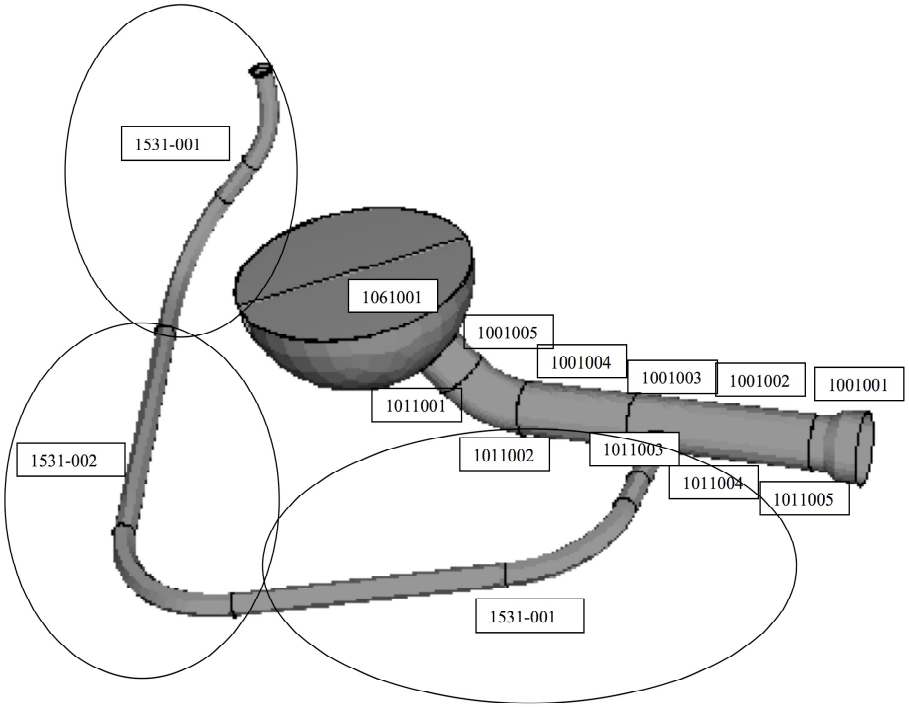
Materials for a Typical 4-loop PWR RCS Components

Component	Piping, RTD body	Hot Leg Elbow	Surge Line to Hot Leg Nozzle	RV Nozzle	SG and PZR Nozzles	Weld
Material	SA 240 Grade 316	SA 351 Grade CF8M	SA 182 Grade F316	SA 508 Class 2	SA 216 Grade WCC	308 SS

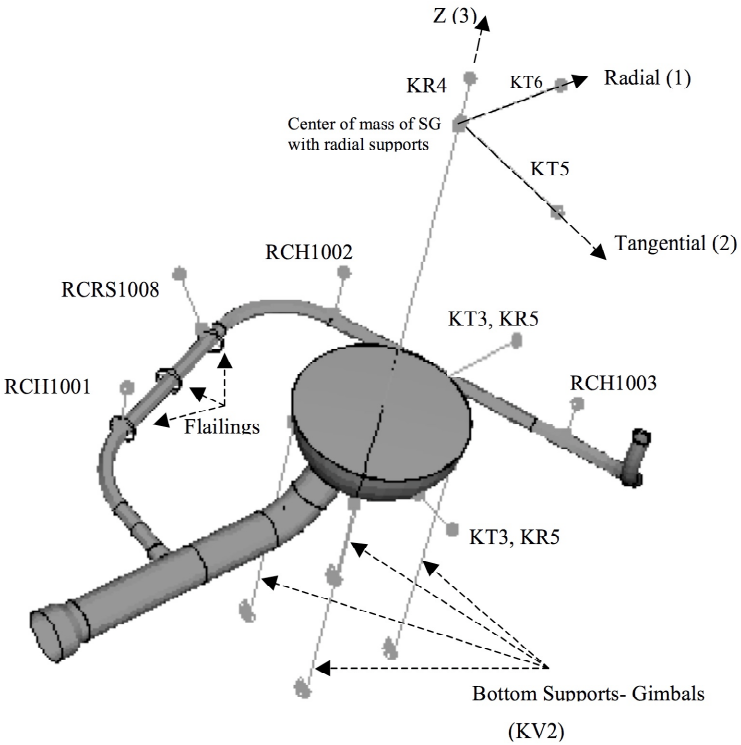
- During Phase III of NRC-sponsored severe accident program, tensile and creep tests were conducted at high temperatures on
  - SA 240 Grade 316 (SS), SA 351 Grade CF8M (Cast SS), SA 516 Grade 70 (Carbon steel).
  - SA 240/SA 516 weldment, SA 240/SA 240 weldment and SA 240/SA 351 weldment.

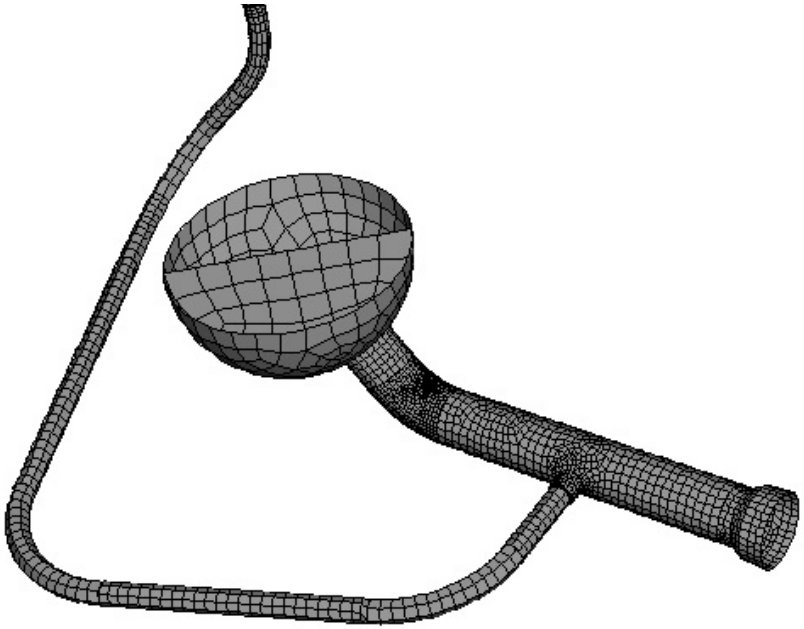
Thermal Inputs to ABAQUS from RELAP-5 Data



- Convection HTCs were augmented by entrance factors dependent on the PORV status and distance from inlet, and added to the steam-to-wall radiation HTCs.
- ABAQUS thermal conduction analyses included wall-to-wall radiation.

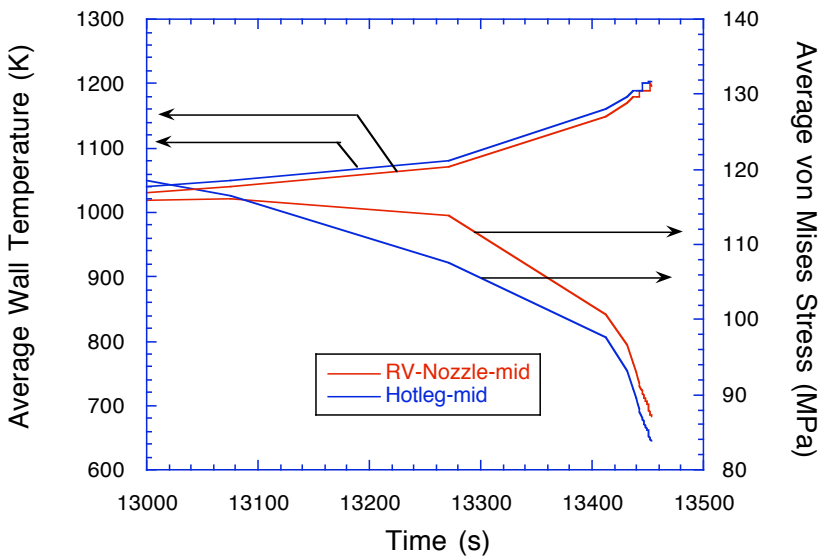
Finite Element Model of the Hot Leg/Surge Line

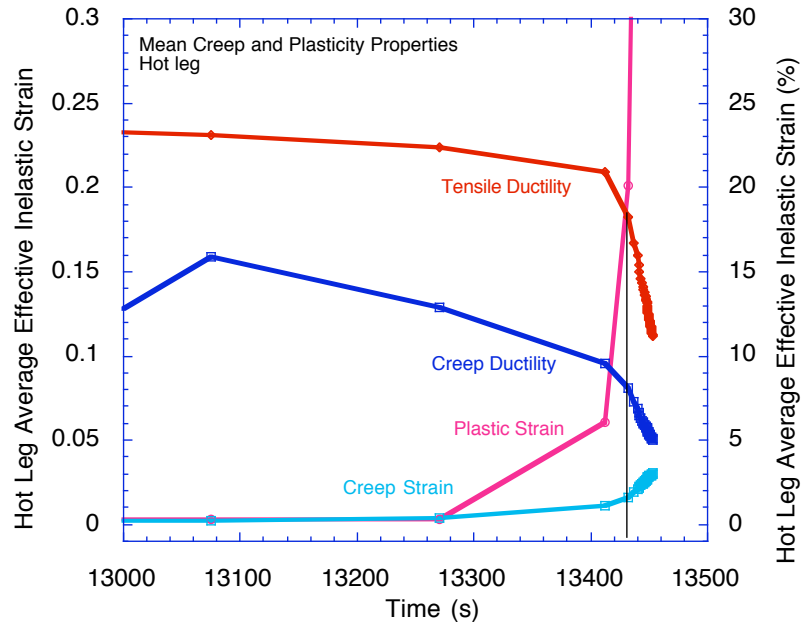




- Shell elements were used.
- Detailed boundary conditions were imposed.

Results for Base Case (March, 2006)



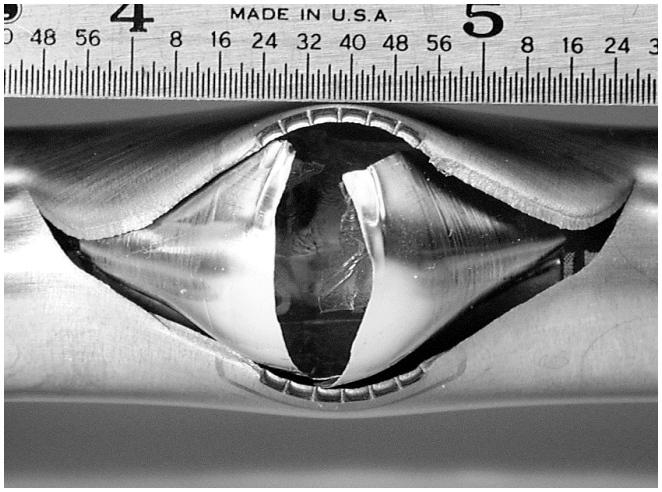


- Both locations are predicted to fail by exhaustion of tensile ductility almost simultaneously at 13,430 s.
- The accumulated creep strains in both locations are less than the available creep ductility at this time.
- The hot leg failure time reported in ISL-NSAD-TR-06-02 based on a simple creep rupture model is 13,630 s.

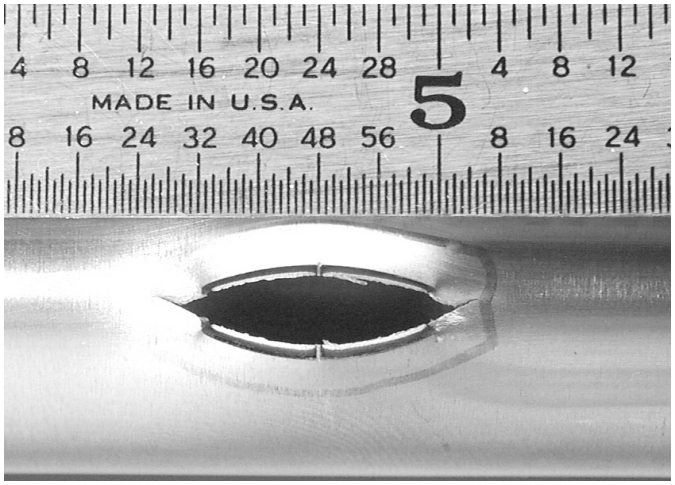
Ligament Rupture vs. Burst of Cracked SG Tubes

- Ligament rupture refers only to the rupture of the remaining ligament of part-throughwall cracks (no leakage before ligament rupture, leakage only after ligament rupture).
- Burst is defined as unstable growth of throughwall cracks with or without increasing pressure (unflawed tubes always fail by burst)
  - Burst can lead to fishmouth opening of the crack after significant crack growth
  - In test systems with limited flow/pressure capability, it is difficult to achieve fishmouth opening if the tube is tested without bladder and foil
  - Operationally, a tube is considered to have burst if there is crack tip tearing
- Ligament rupture is not necessarily burst
- Burst of PTW cracks is a two-step process, first ligament rupture then burst

Examples of Burst



Clearly a burst (Fishmouth)



This is also a burst

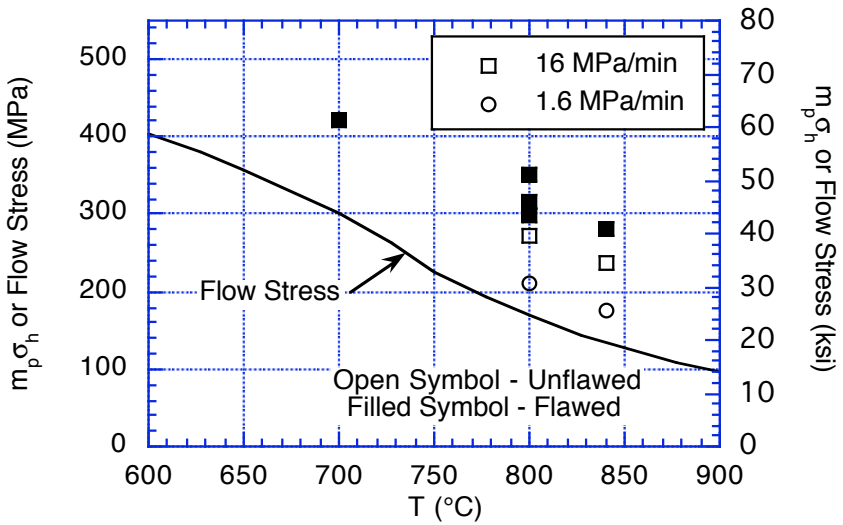
Ligament Rupture Models for SG tubes at High Temperature

- Flow Stress Model
  - $m_P\sigma = \bar{\sigma}(T)$, m_P =stress magnification factor
- Creep Rupture Model
  - $$\int_0^{t_f} \frac{dt}{t_R(T, m_P\sigma)} = 1$$

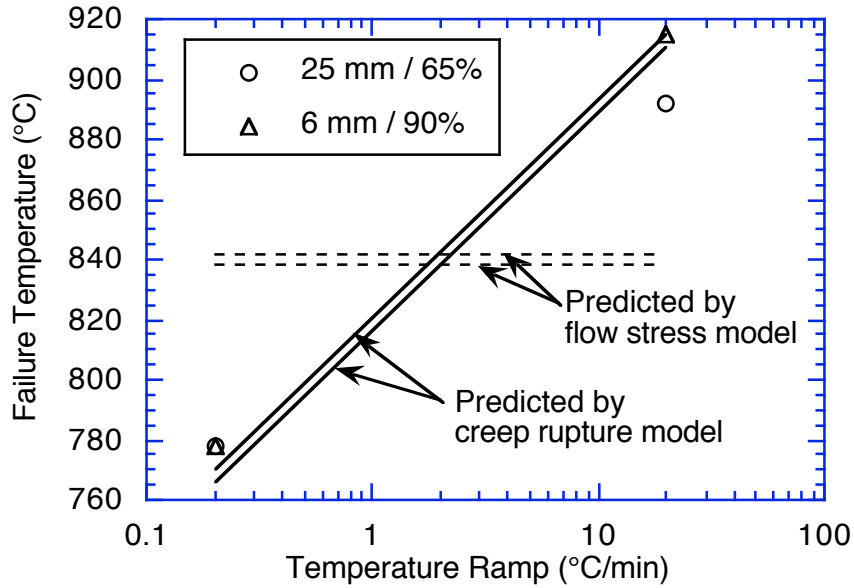
Unstable Burst Model for SG Tubes with Throughwall and Part-Throughwall Cracks

- $m\sigma_b = \bar{\sigma}(T)$, m=bulging factor (function of crack length)
- At room temperature, whether a part-throughwall crack will burst immediately after ligament rupture depends on the relative values of m and m_P.
  - If $m > m_P$, it will burst
  - If $m \leq m_P$, it will not burst.
- At high temperature, $\bar{\sigma}$ is a function of both T and strain rate.
- During ligament rupture or unstable burst, strain rates are high
  - Flow stresses measured from ordinary tensile tests are not applicable.

Rate Effect on Ligament Rupture and Burst Pressures



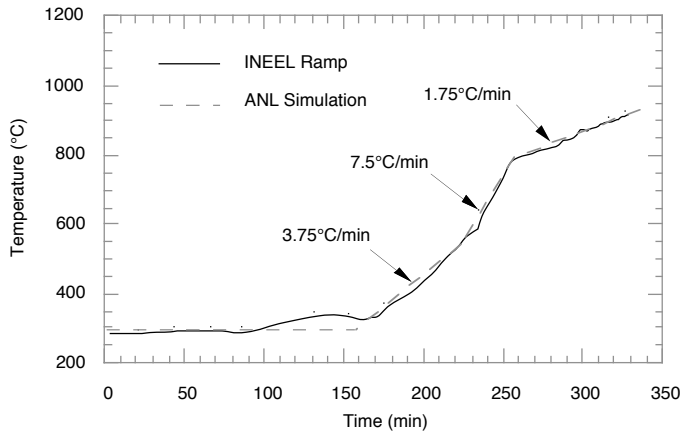
Pressure Ramp



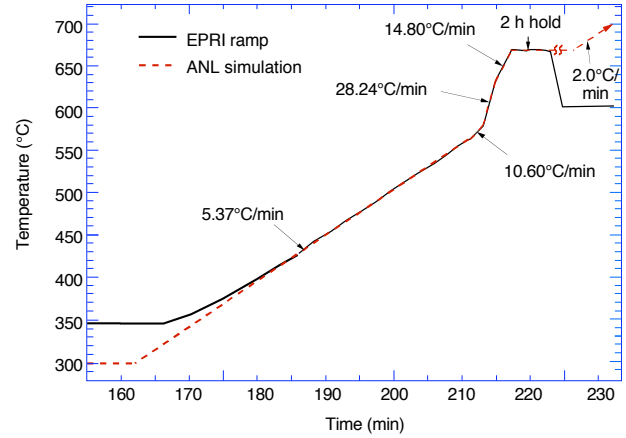
Temperature Ramp

- Flow stress on unflawed tube is rate dependent.
  - Flow stress corresponding to 2°C/min matches flow stress measured from tensile tests.
- Flow stresses derived from tensile tests may give conservative or unconservative failure predictions, depending on the rate

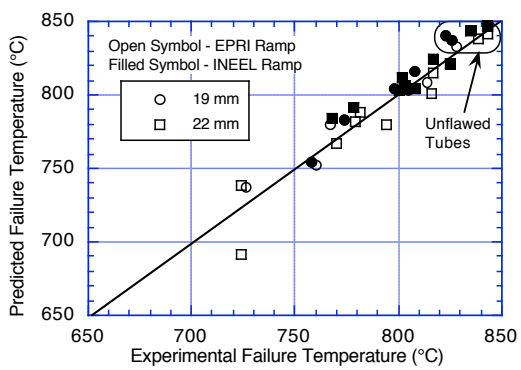
Rupture of SG Tubes During Severe Accidents



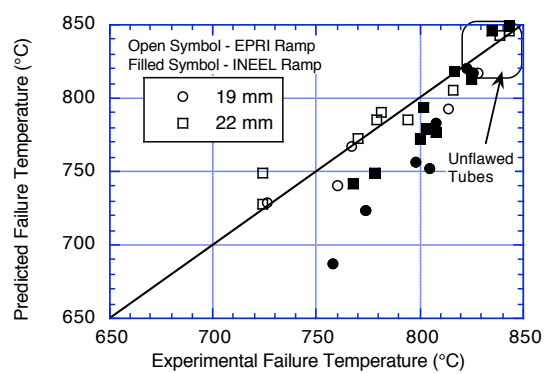
INEL Ramp



EPRI Ramp



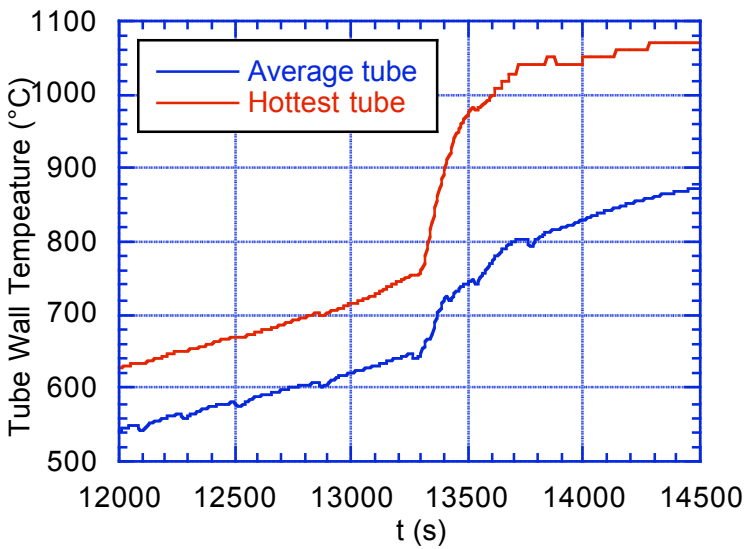
Creep Rupture Model



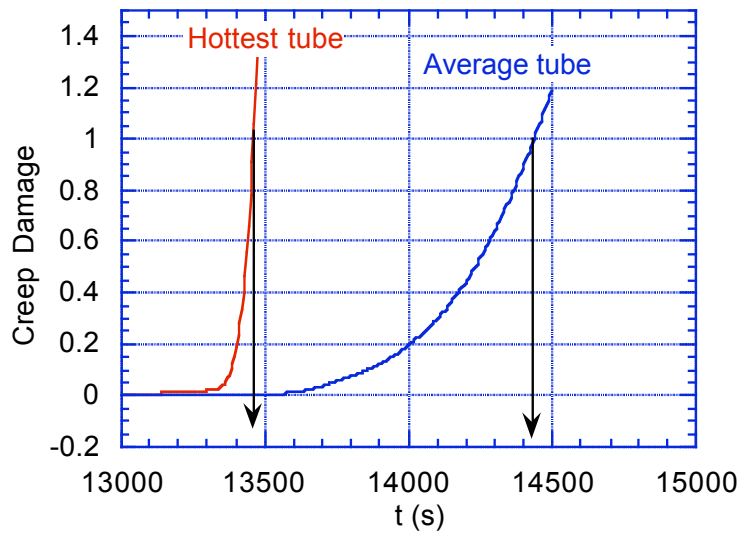
Flow Stress Model

- Note flow stress model works for EPRI ramp (2°C/min) but underpredicts the failure temperatures for INEL ramp (7.5°C/min).

Predicted Burst Time for Unflawed Tubes (Current Base Case)



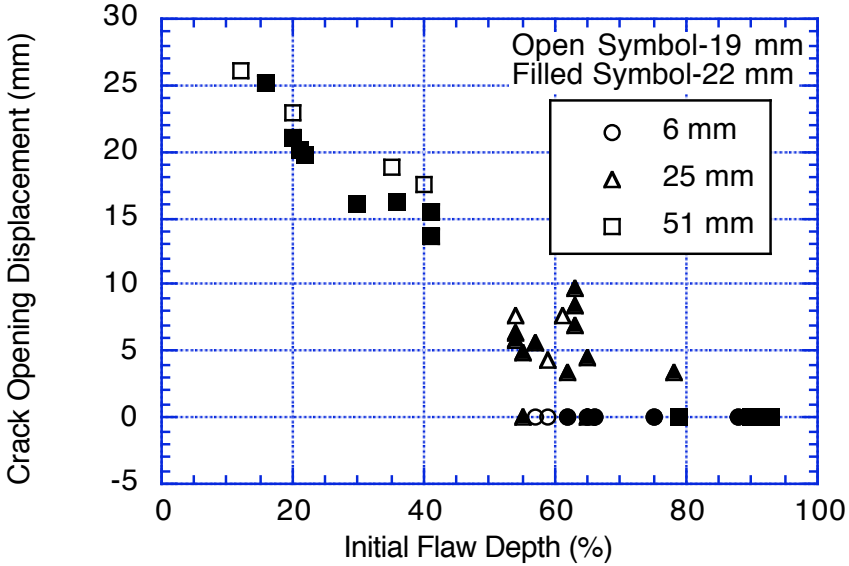
(a)

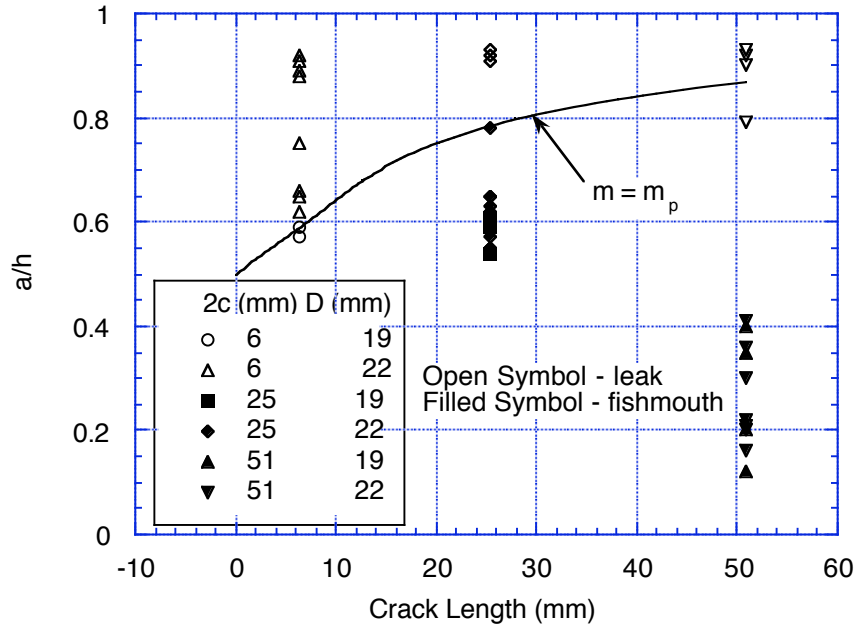


(b)

- Predicted failure time for hottest tubes is 13,475 s (cf. hot leg is 13,430 s).

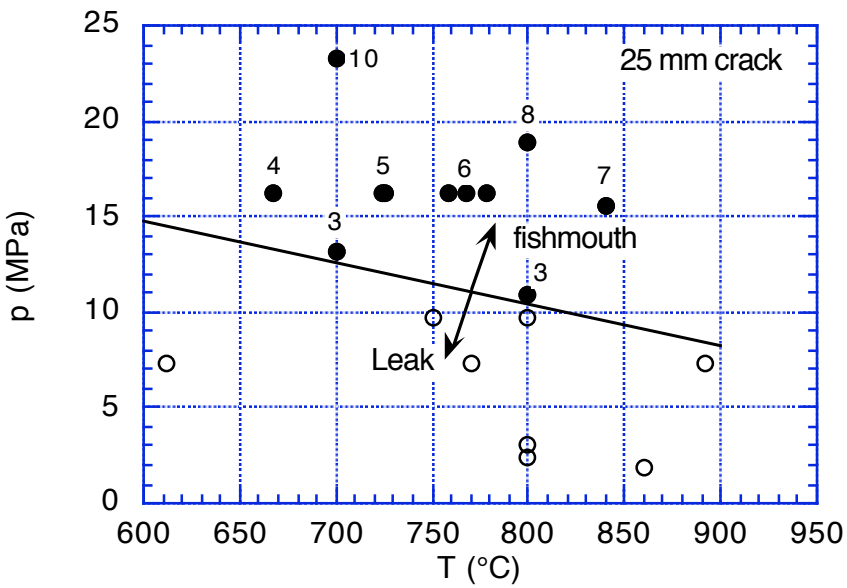
Ligament Rupture vs. Burst for PTW Flawed Tubes



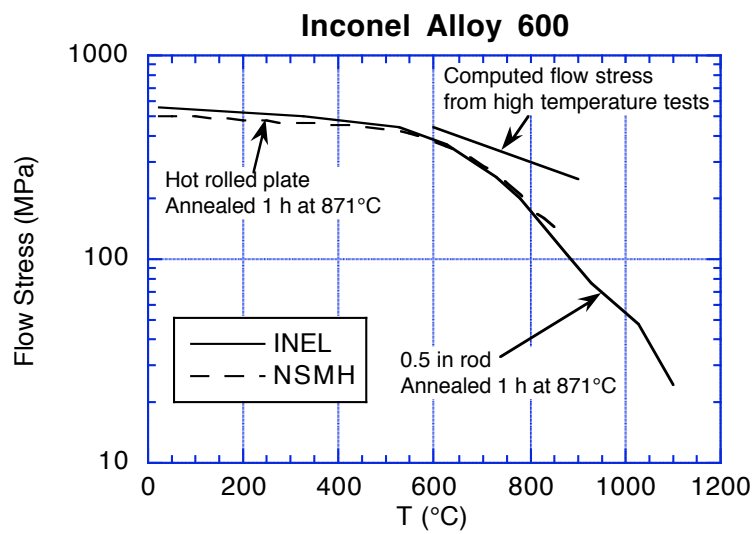


- Shallow cracks burst immediately after ligament rupture, deep cracks do not
  - This is an artifact of our test system, which depressurizes immediately after ligament rupture. Shallow cracks can have enough stored energy to cause burst
  - Long, deep cracks would have burst if the system pressure could have been maintained after ligament rupture
- The criterion $m=m_p$ separates burst from ligament rupture for the high temperature tests

Upper Bound to Flow Stress for Burst Prediction



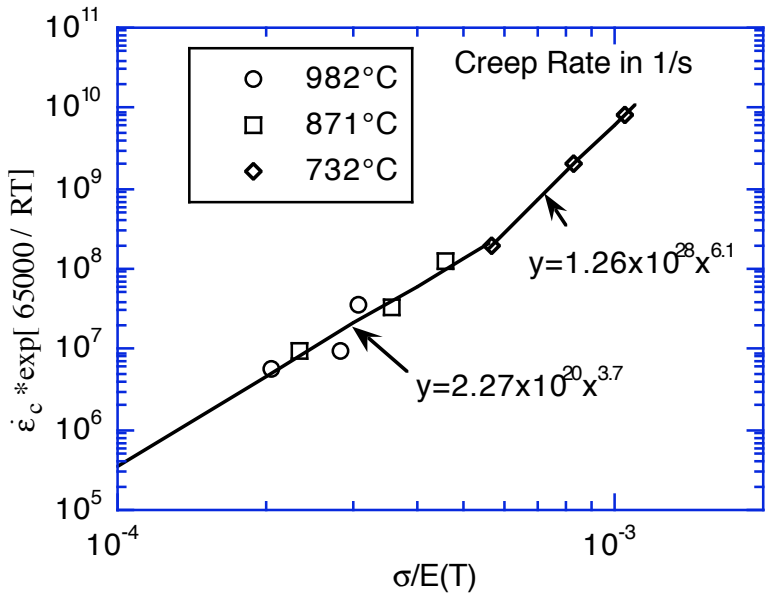
(a)



(b)

- Some of the tests lying close to the leak/fishmouth separation line would have burst if the system pressure could have been maintained after ligament rupture.

Prediction of Crack Opening Area at High Temperature



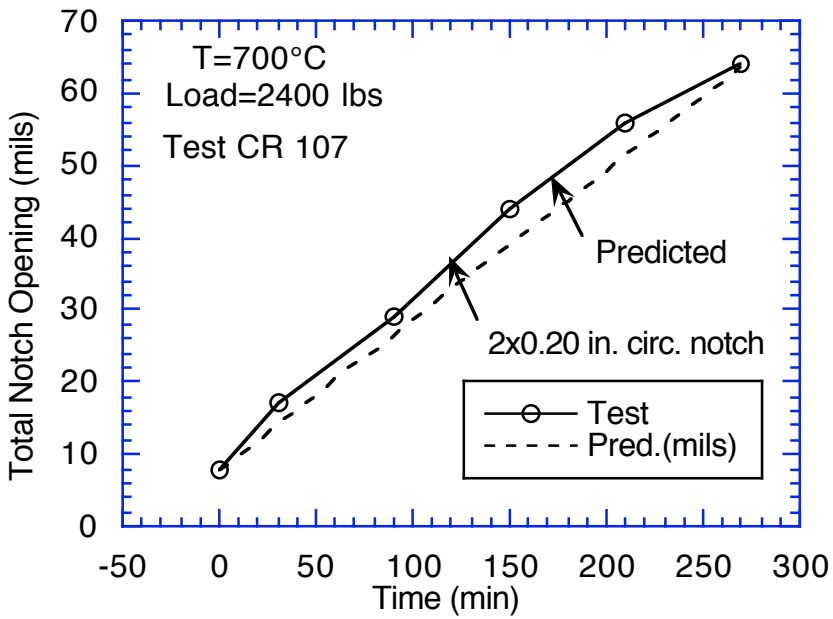
INEEL creep rate on Alloy 600 vs. stress data plotted using an activation energy of 65 kcal/mole and stress normalized by Young's modulus at temperature.

- Opening rate in a pressurized tube with an axial crack is

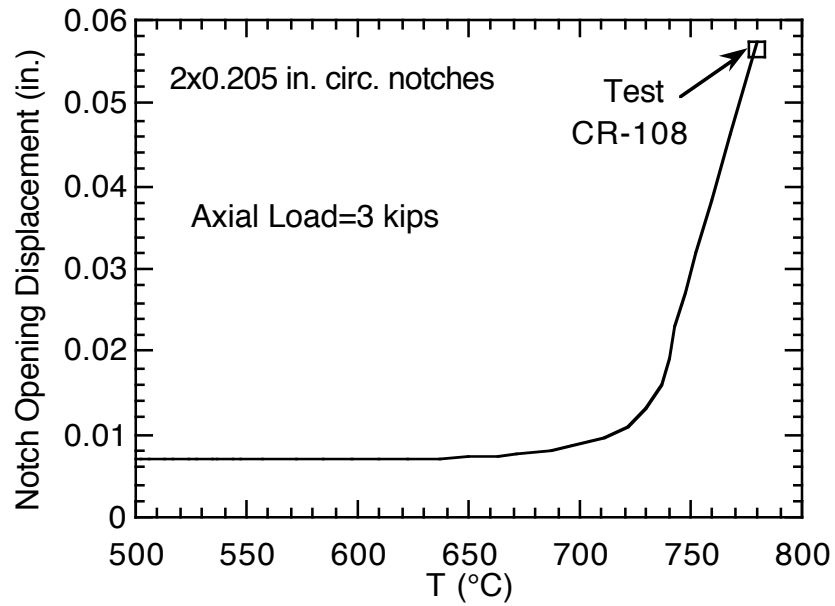
$$\dot{\delta} = \dot{\varepsilon}(\sigma) c h_2(0,n) = A c h_2(0,n) \sigma^n$$

with $\sigma = m\sigma_{hoop}$

Validation of COD by Tests on Tubes with TW Circumferential Notches Under Axial Loading

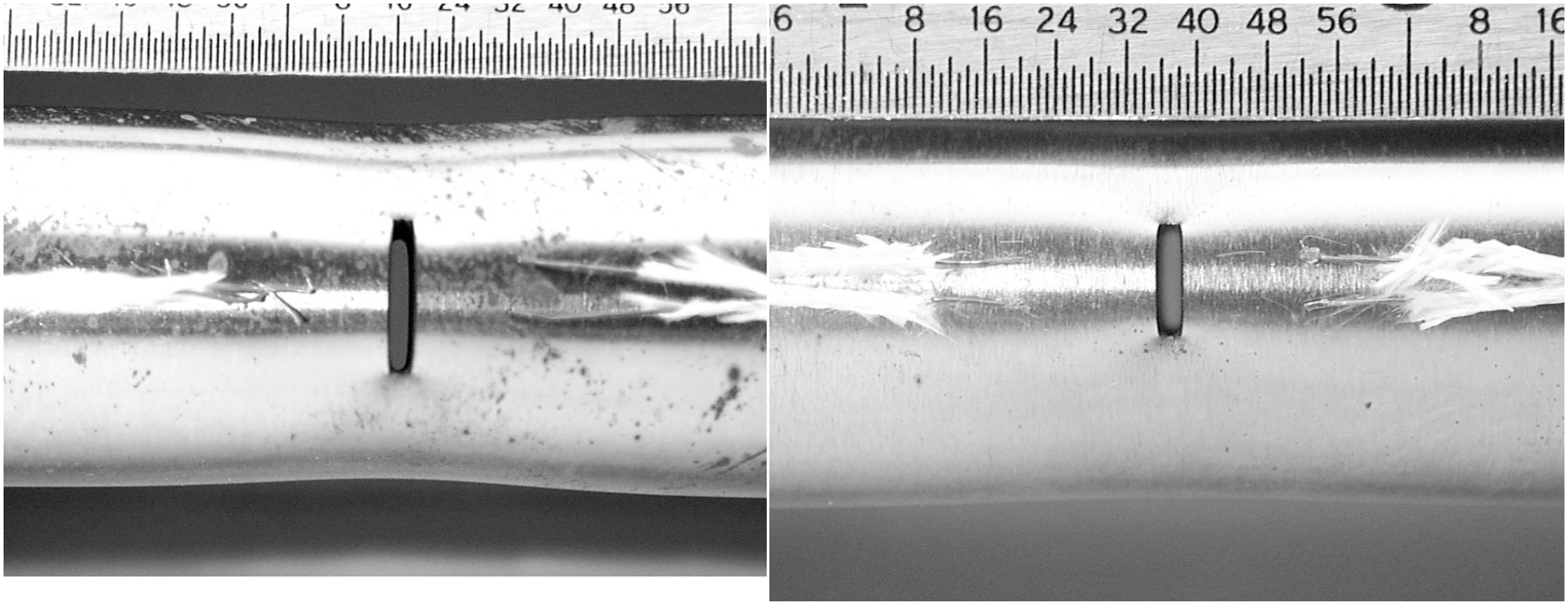


Isothermal



INEL Temperature Ramp

Crack Opening



(a) (b)

Crack opening at the end of tests for (a) isothermal loading (CR 102) and (b) Severe Accident loading (CR 108)

- No extension of notches due to creep was observed in any test.