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Leak Rate Models for Tube–Tubesheet Junctions

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Leak Rate Models and Results

- Operation and Design Basis Accidents
  - Leakage is through rough surfaces under contact pressure.
  - Applicable to tubes as fabricated and up until creep relieves all the contact pressure and opens a gap between tube and TS collar.
- Severe Accidents
  - Tube and tube sheet collar separated by an open annular gap. The gap varies with tube internal pressure and the external fluid driving pressure due to elastic deformation of the tube. Grows with time due to creep.
  - Applicable to RT testing of specimens after exposure to high temperature and creep and to prediction of leak rate after creep has opened annular gap.
- All leak rate models to date assume fluid flow is dominated by viscous forces. Assumption appears valid even in high leak rate tests

Leak Rate Models

- The mass flow per unit length around the circumference q is

$$q = -\frac{1}{K}\frac{\rho(p_f)}{\mu}\frac{dp_f}{dz}$$

where p_f is the fluid pressure, μ the viscosity, ρ the density, and $K = 12/d^3$ where d is the height of the opening between the tube and tubesheet.

  - For rough surfaces d is a function of surface roughness and contact pressure
  - For annular flow d is the gap between the two surfaces
  - Nitrogen and high–temperature steam assumed to act as perfect gases; for given p, T nitrogen mass flow about 30% greater than steam

- Annular flow between rigid cylinders can be solved analytically for perfect gases. For both isothermal and adiabatic flows, pressure drop is

$$\frac{p_f}{p_1} = \sqrt{1-\left(\frac{z}{L}\right)}$$ compared to $$\frac{p_f}{p_1} = 1-\left(\frac{z}{L}\right)$$ for incompressible flows

Two phase flows

- Flow is assumed incompressible as long as p_f is greater than the saturation pressure p_{sat} and to flash instantly to steam and act as perfect gas once p_f is less than p_{sat}:

$$q = \frac{-1}{\mu L_\ell} \int_{p_1}^{p_{sat}} \frac{\rho(p_f) dp_f}{K} \text{ in the liquid phase and}$$

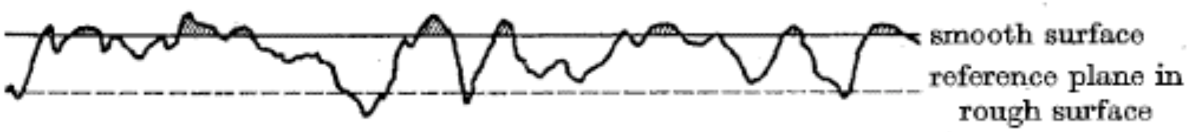
$$q = \frac{-1}{L_g} \nu_{sat} \int_{p_{sat}}^{p_2} \frac{\left(p_f / \rho_{sat}\right) dp_f}{K} \text{ in the gas phase.}$$

Continuity requires that the mass flow in the liquid phase and the gas phase be equal and the combined lengths of the liquid region and the gaseous region must equal the geometric length L:

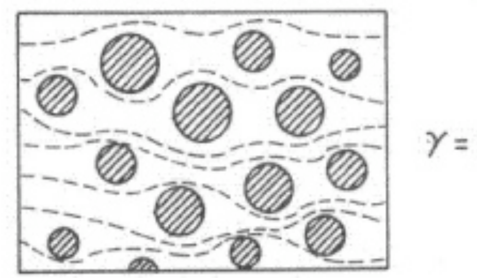
$$L_\ell + L_g = L$$

Flow geometries

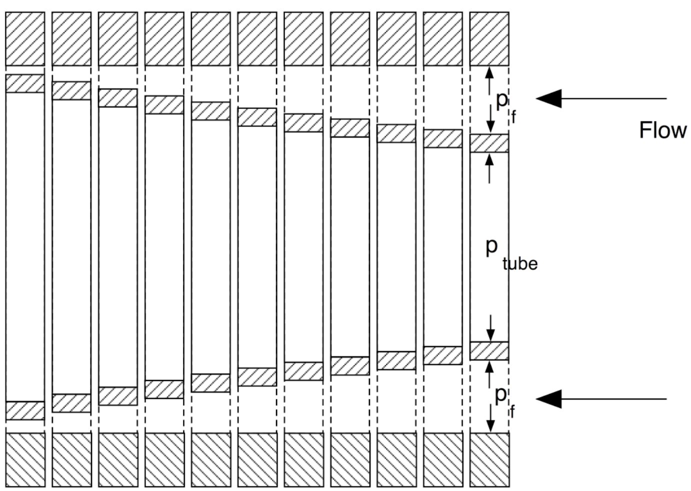
- Rough surfaces



Transverse view



Top view



- Ring model assumes segments can deform independently. Majumdar has performed iterative solutions which suggest ring approximation is reasonable for specimen geometries

Rough surfaces

- Greenwood and Williamson provide a relation between contact pressure and the distance between rough surfaces:

  $p_c = \alpha e^{-h}$

  where $h = d/\sigma$, d is the actual distance, and σ is the standard deviation of the surface roughness. This form assumes Gaussian roughness distribution is approximated by exponential distribution

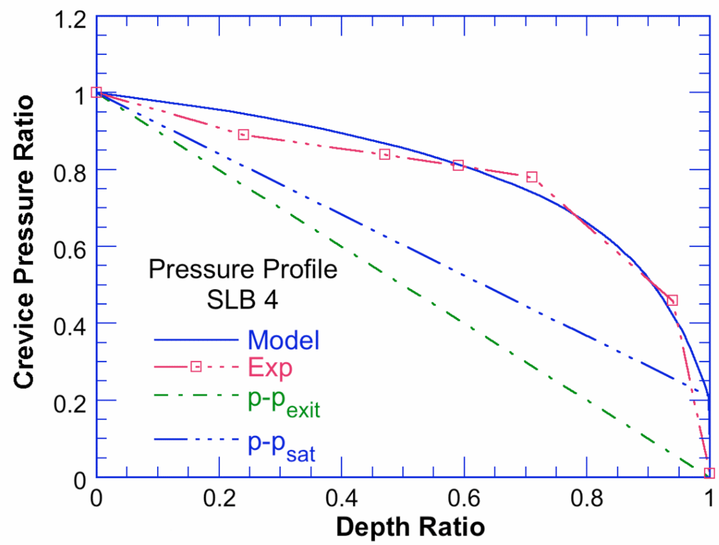
- Patir and Cheng give an estimate for the fraction of a flow channel that is blocked by the asperities when the surfaces are a distance h apart:

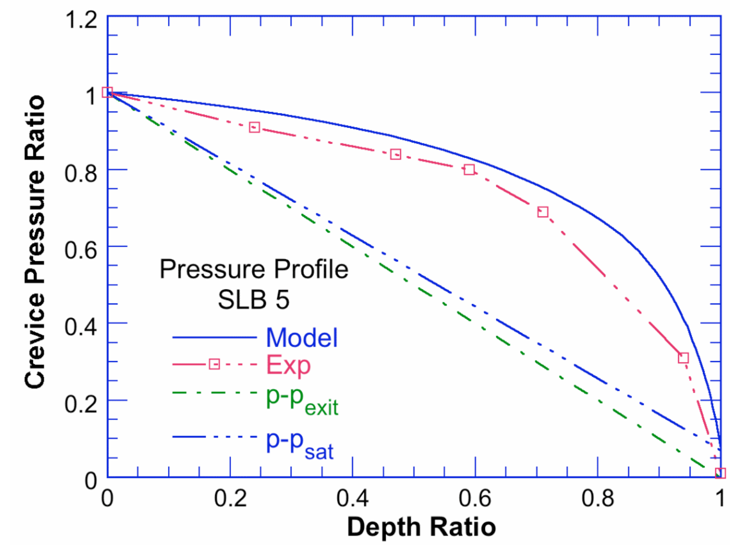
  $\varphi = 1 - 0.90e^{-0.56h}$

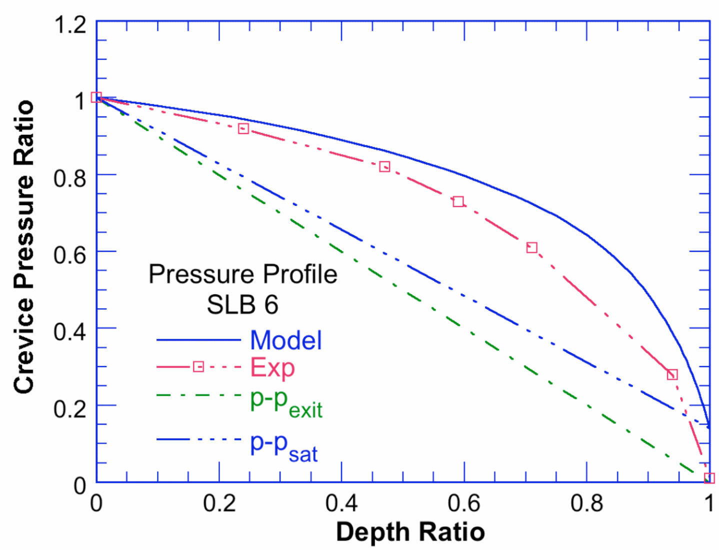
Rough surface model

- Model contains 2 “universal” constants: α and a parameter describing the roughness value at which the roughness distribution is truncated. Values for these constants are the same for all tests on all specimens.
- Roughness truncated at 2.08 σ (roughly 95th %tile). α is determined so that average roughness for fitted data is close to the measured average roughness
- Roughness dominated by machined surface of tube sheet.
- For each specimen, one must also estimate initial contact pressure and roughness. These are obtained from fits to initial RT data, but values are somewhat constrained — we don’t know contact pressure exactly, but we know a range; we don’t know roughness exactly, but we know a range.
- Contact Pressure Dependence of Flow Resistance—Experimental Results

Comparisons with Data for Two Phase Flows



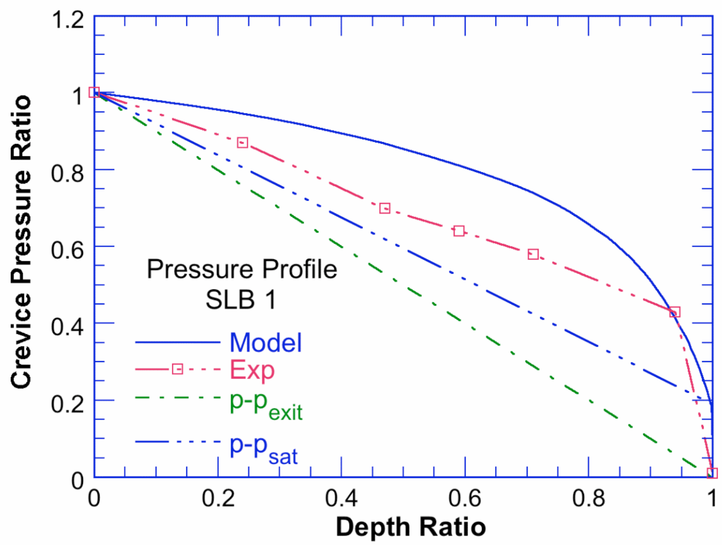


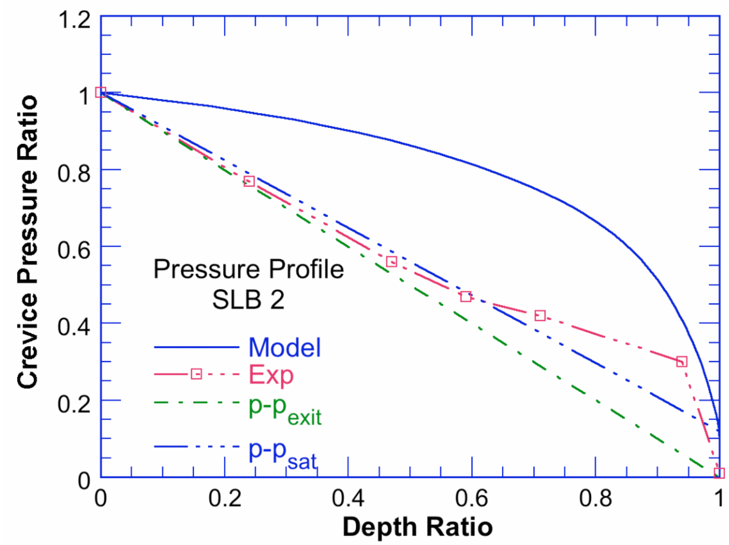


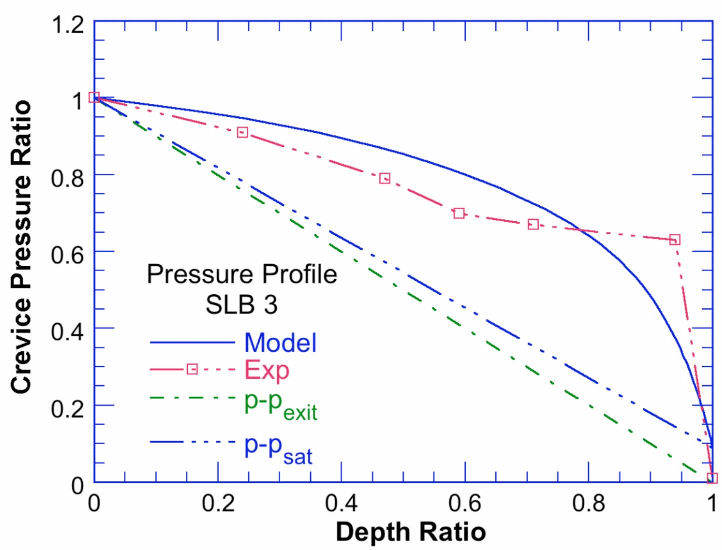
Good agreement between model and data for these tests (Specimen 8)

Neither linear dependence on p-p_{sat} or p-p_{exit} correlates well with observed data, although dependence on p-p_{sat} is somewhat closer to data

Comparisons with Data for Two Phase Flows (cont)





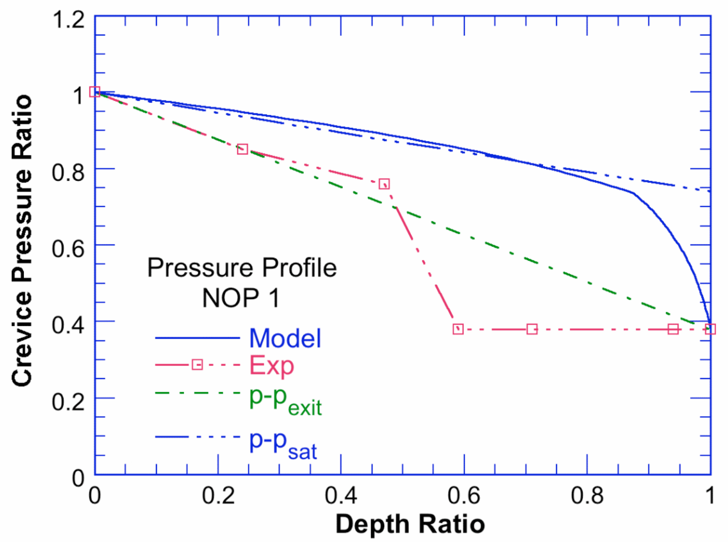


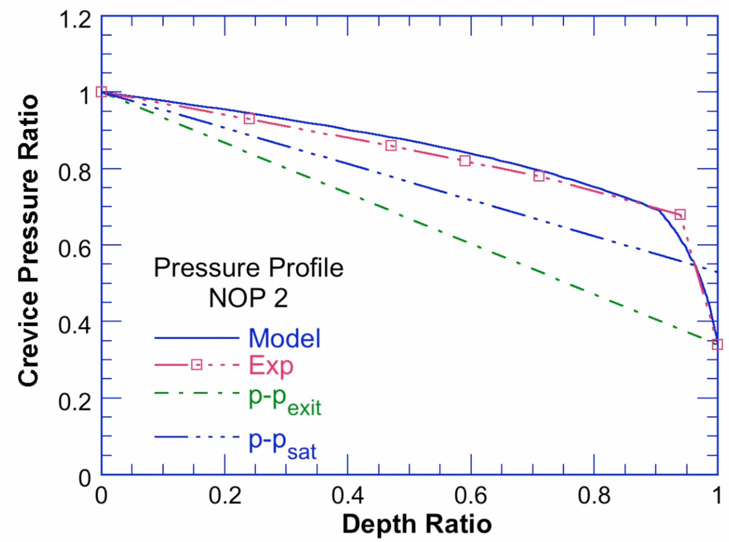
Agreement between model and data for these tests (Specimen 7) is not as good for tests with Specimen 8.

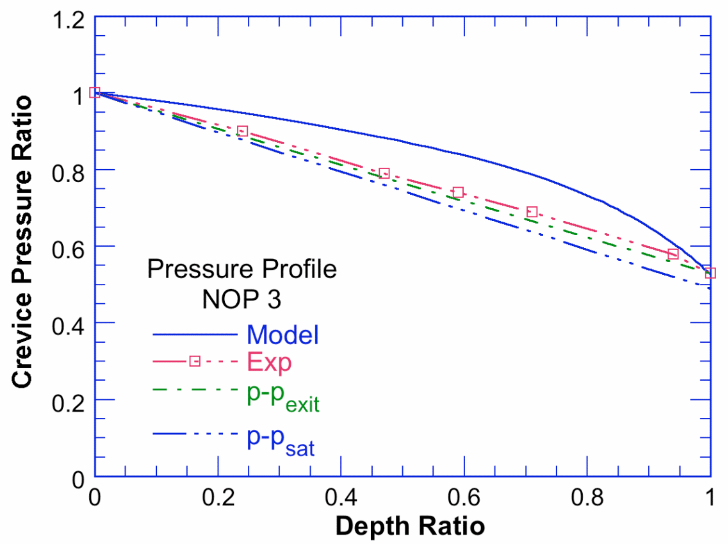
Linear dependence on p-p$_{sat}$ or p-p$_{exit}$ correlates better with observed data than for tests SLB 4, 5, 6

Dependence on p-p$_{sat}$ is somewhat closer to data

Comparisons with Data for Two Phase Flows (cont)



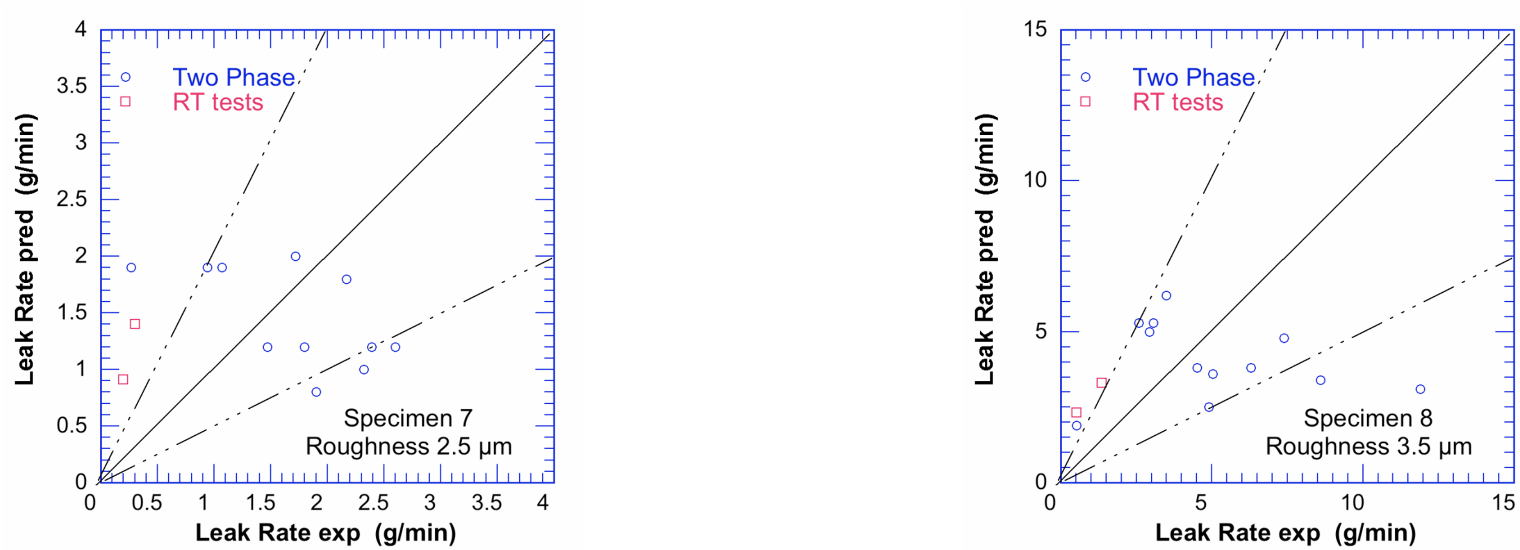




Agreement between model and data is again reasonably good for tests on Specimen 8 (NOP 2 and NOP 3)

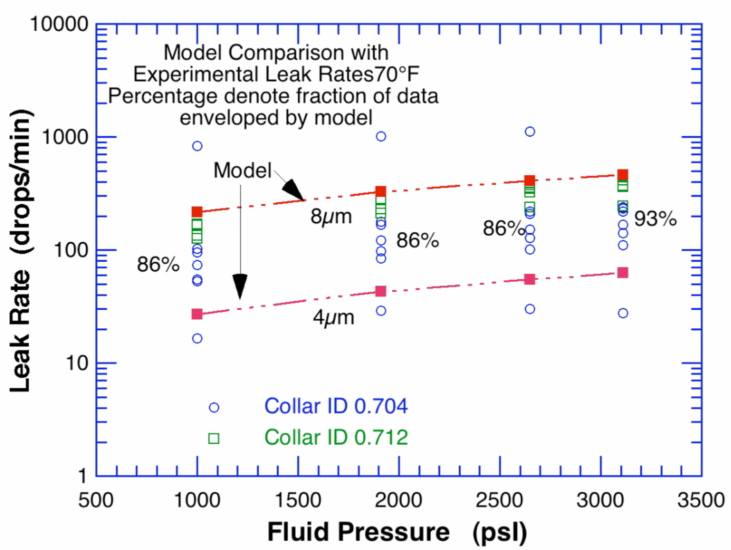
Profiles from Specimen 7 seem to have a concave upward profile indicating more resistance in the lower half of the expansion zone

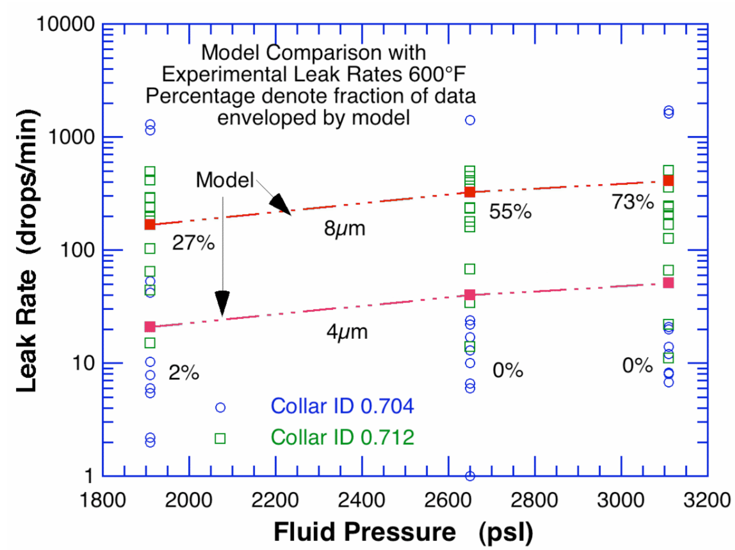
Comparisons with Data for Two Phase Flows (cont)

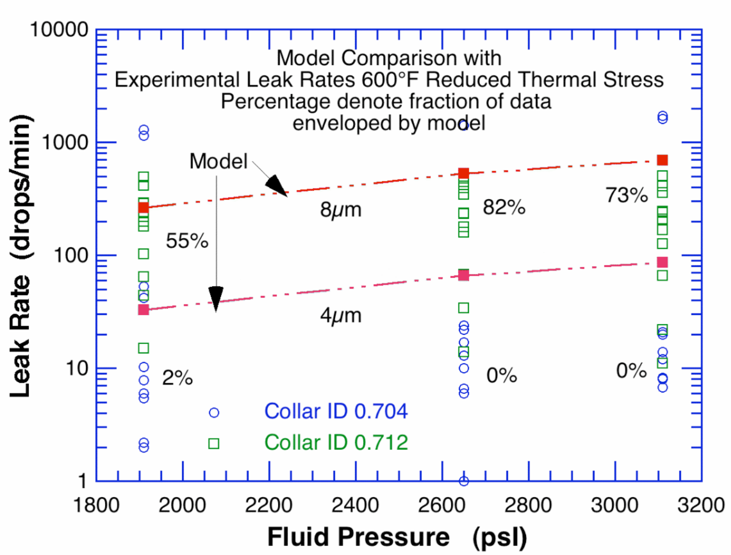


- Predicted leak rates are typically within a factor of 2 of observed leak rates. Experimental measurement of leak rates is difficult and pressure profiles may be more robust comparison
- Correlations for these two specimens for p-p_{exit} and p-p_{sat} are as good as those of the model.

Comparisons with Data for Two Phase Flows (cont)



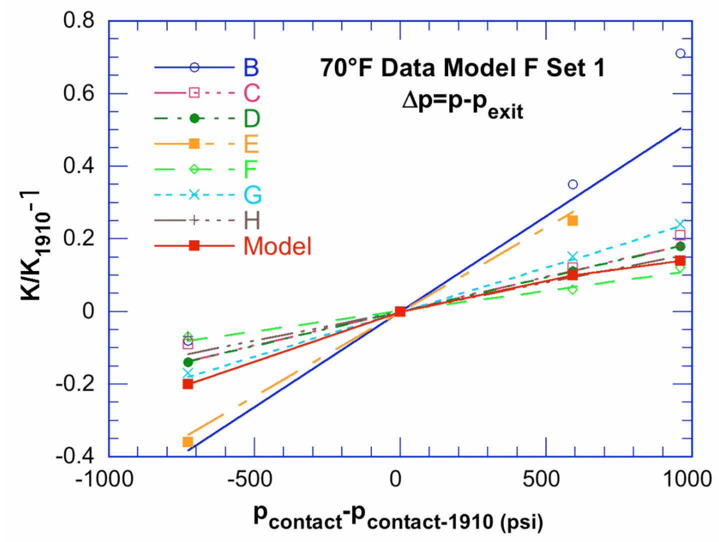


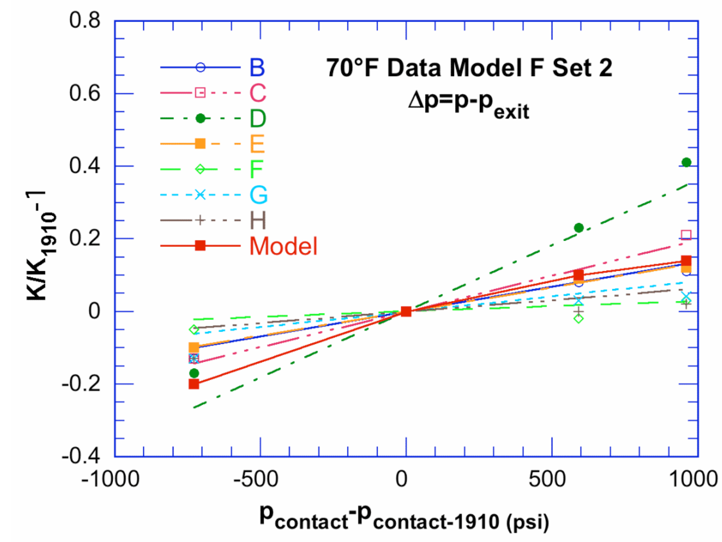


Leak rate data at 70°F is encompassed by assuming roughness in the range 4-8μm

Leak rates are somewhat higher for oversize collars

At 600°F, for tight collars leak rates are lower than predicted—oxide formation? For oversize collars leak rates larger than predicted—thermal stresses overestimated?

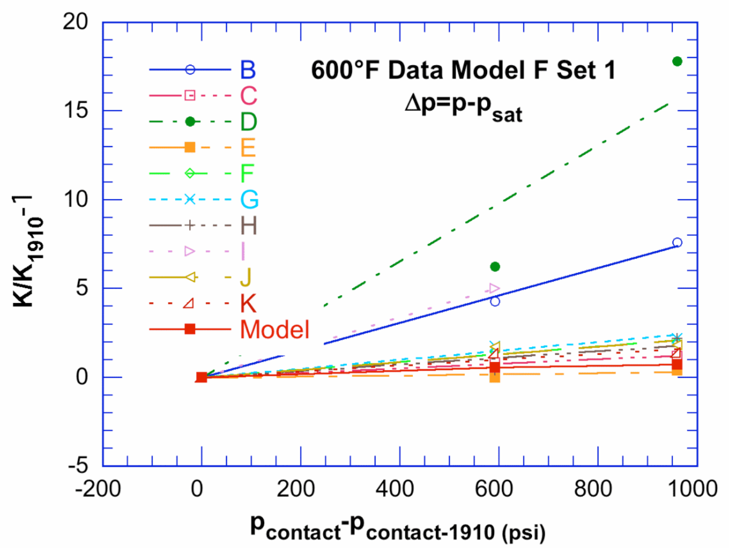


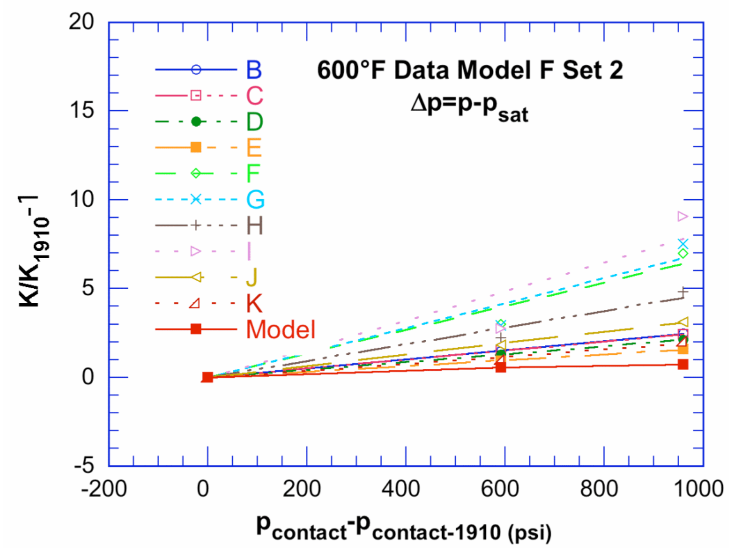


Leak Rate Dependence on Contact Pressure

- For each specimen compute K at each internal pressure from data. Normalize values to K at 1910 psi. Contact pressures from Majumdar calculations which give low initial contact pressures.
- There is scatter but a fairly consistent trend is observed and is in reasonable agreement with model predictions

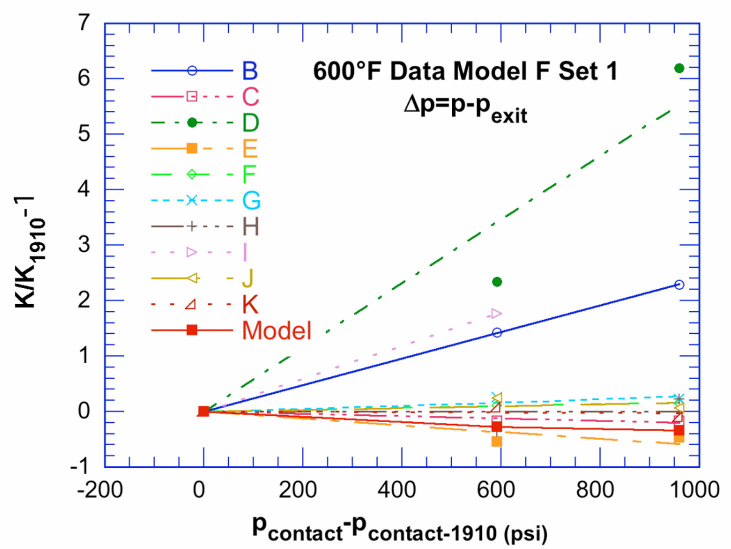
Leak Rate Dependence on Contact Pressure (cont)

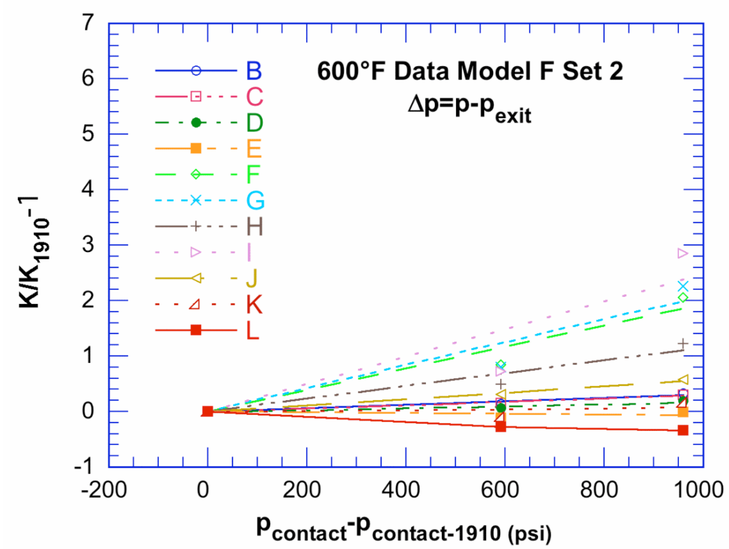




- At 600°F, K values computed based on $Q/(p-p_{sat})$ and $Q/(p-p_{exit})$
- Scatter but model and data seem to suggest effects of contact pressure are modest
- Tests involve changes in both contact pressure and fluid driving pressure simultaneously and are non-prototypical for case of interest. In case of tube sheet bowing, fluid driving pressure is held constant, while contact stress may change. Does this affect apparent dependence on contact pressure?

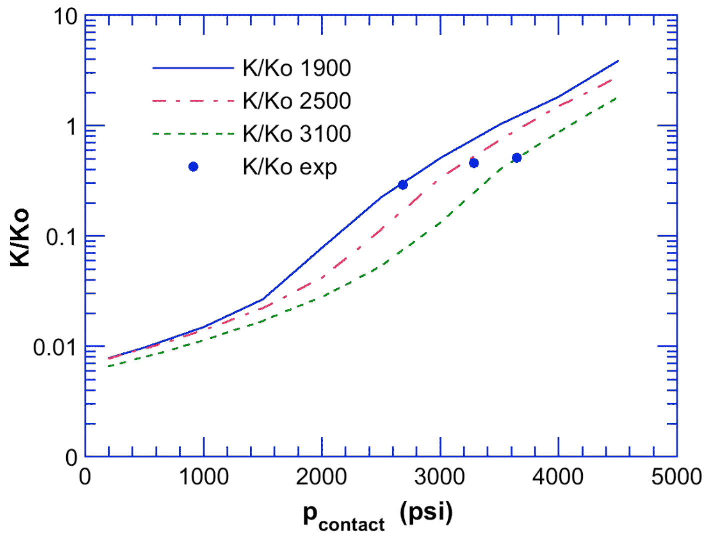
Leak Rate Dependence on Contact Pressure (cont)

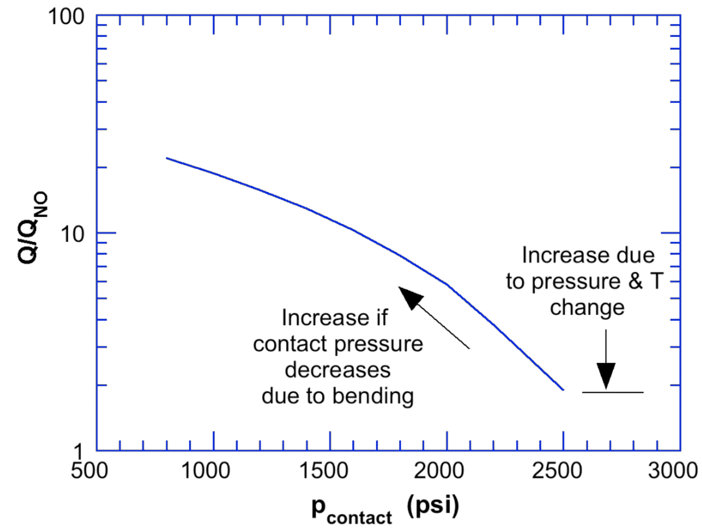




- Basing K on p-p$_{exit}$ gives reduced dependence on contact pressure. Model predicts a slight decrease in K with increasing contact pressure which is seen in some tests
- Pressure profile and model predictions suggest using p-p$_{exit}$ is not good scaling for two-phase flows. Resultant prediction of decreased resistance with increasing contact pressure further evidence that p-p$_{exit}$ is not a good scaling parameter for this problem

Leak Rate Dependence on Contact Pressure (cont)





- As noted previously, experiments are non-prototypical in that contact pressures and fluid driving pressure are changed simultaneously. We attempt to account for this through introduction of K and scaling by either $p-p_{exit}$ or $p-p_{sat}$ but pressure profile tests suggest this scaling is not particularly accurate
- Model predictions suggest there is an increase < 2 in leak rate due to changes in pressure drop, temperature, and associated change in thermal stress. However, additional decreases in contact pressure due to tubesheet deformation could produce greater increases in leak rate

Summary

- Pressure profile tests suggest $p-p_{exit}$ or $p-p_{sat}$ provide poor scaling of two phase flows through tight contacts, although leak rate predictions using $p-p_{exit}$ and $p-p_{sat}$ for the two specimens for which data is available over a range of temperatures and exit pressures are as good as those of the model.
- Rough surface model gives reasonable predictions of pressure profiles
- Rough surface model probably overestimates leak rate through tight contacts since it ignores effects like corrosion
- Available test data may give non-prototypical (and non-conservative) estimates of the change in leak rate due to a change in contact stress