NRC/ANL INDUSTRY MEETING

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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

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

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}:

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

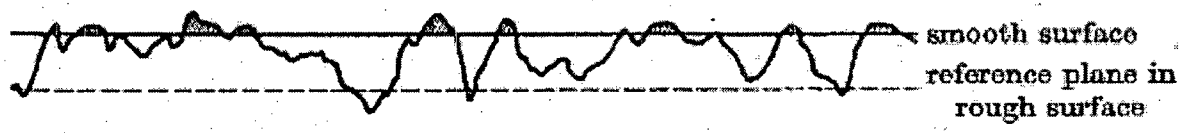
$$q = \frac{-1}{L_g} \nu_{sat} \int_{p_{sat}}^{p_2} \frac{(p_f/\rho_{sat})dp_f}{K} \text{ in the gas phase.}$$

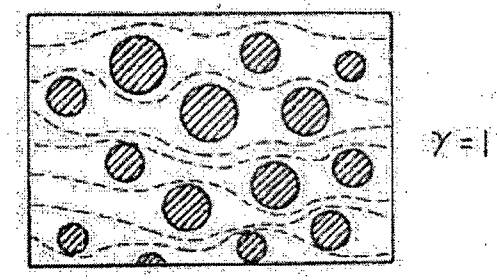
Continuity requires that the mass flow in the liquid phase and the gas phase be equal and the combined lengths of the liquid region and the gaseous region must equal the geometric length L:

$$L_\ell + L_g = L$$

- Difficult to know exactly how to match Plant C results, but roughness in the range 4-6μm (250 μ-in=6.3 μm) and ANL estimates of contact pressures (0-500 psi) seem to give results reasonably consistent with Plant C.

Flow geometries





- Rough surfaces Transverse view Top view
- 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

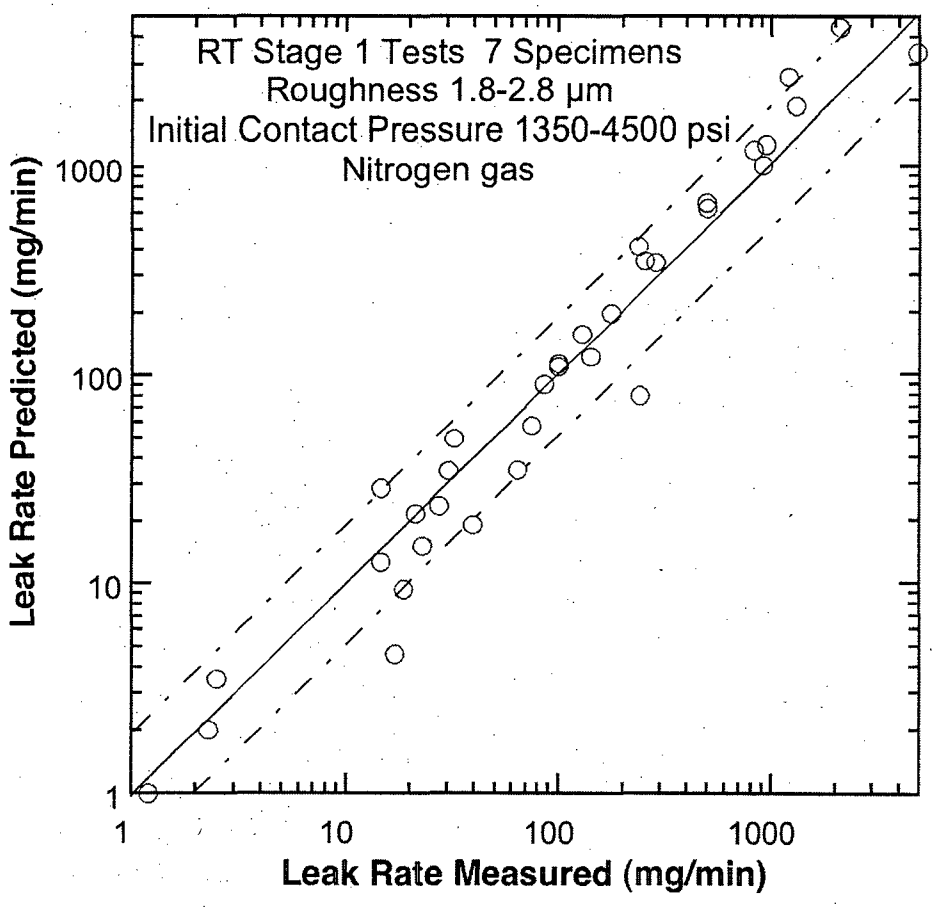
- Patir and Cheng give an estimate for the fraction of a flow channel that is blocked by the asperities when the surfaces are a distance h apart:

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

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. Average roughness 2.2 μm with standard deviation 1.0μm. After creep testing, RT annular gaps are on the order of 20 μm.
- 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.

Room Temperature Tests with Nitrogen



- Tests used to determine "universal" constant α. Values for these constants are the same for all tests on all specimens.
- Roughness truncated at 2.08 σ (roughly 95th %tile).
- Contact pressure and roughness for each specimen adjusted to get best fit. α determined so that average roughness for fitted data is close to the measured average roughness. Initial contact pressures consistent with those expected from expansion.

Design Basis Conditions

Plant C Room Temperature Tests and Parametric Studies (Roughness 4 μm)

Fluid driving pressure (psi)	Temperature °F	Total Contact pressure (psi)	Leak rate drops/min	Leak rate mg/min	
1900	70	1520	61	3079	Plant C RT
2650	70	2120	73	3689	
3100	70	2480	80	4044	
1900	70	1970	40	2020	Higher initial contact pressure
2650	70	2570	47	2386	
3100	70	2930	52	2611	
1900	70	1520	61	3079	Increasing T
1900	100	1586	82	4133	
1900	150	1696	115	5799	
1900	200	1806	145	7347	
1900	70	1520	61	3079	No thermal stress viscosity decreases
1900	100	1520	87	4390	
1900	150	1520	135	6820	
1900	200	1520	189	9556	

Design Basis Conditions (cont)

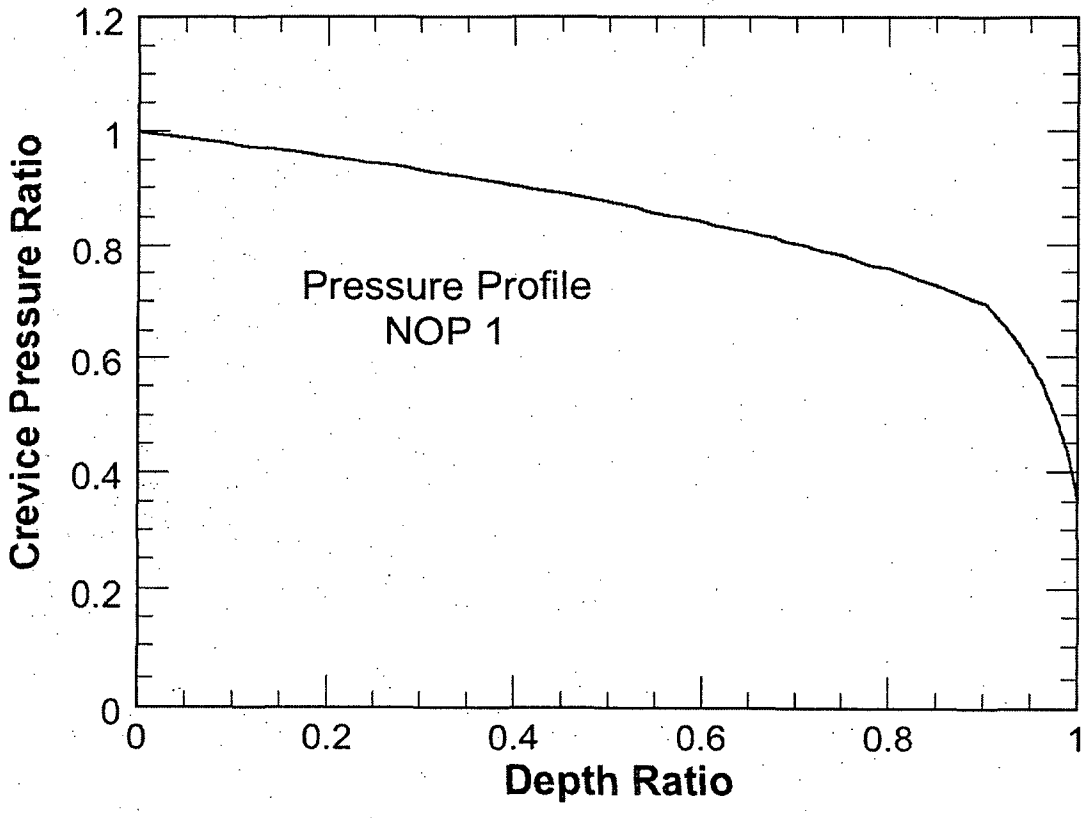
High Temp Tests, Comparison of NO and MSLB (Roughness 4 μm)

Fluid driving P (psi)	T °F	Total Contact P (psi)	Exit P psi)	Leak rate drops/min	Leak rate mg/min	L_f/L	L_g/L	
1900	600	2686	0	23	1142	0.78	0.22	Plant C HT
2650	600	3286	0	44	2216	0.95	0.05	
3100	600	3646	0	55	2779	0.97	0.03	
1900	600	3136	0	11	545	0.75	0.25	Higher
2650	600	3736	0	22	1096	0.94	0.06	contact
3100	600	4096	0	28	1393	0.97	0.03	pressure
2500	600	2795	0	75	3763	0.94	0.06	MSLB
2500	600	3295	0	32	1616	0.93	0.07	
2500	600	3795	0	15	753	0.92	0.08	
2500	600	4795	0	4	209	0.95	0.05	
2500	600	2795	1150	73	3681	0.96	0.04	Normal
2500	600	3295	1150	31	1570	0.96	0.04	Operating
2500	600	3795	1150	15	732	0.94	0.06	
2500	600	4795	1150	4	205	0.96	0.04	

Crevice Pressure

Temperature °F	Fluid pressure psi	Exit Pressure psi	Roughness µm	Contact Zone Length in.	drops /min	L_{fluid}/L	L_{steam}/L
604	2279	799	3.0	8.5	27	0.90	0.10
605	2254	792	3.0	8.5	26	0.89	0.11
590	2899	1453	3.0	8.5	42	1.00	0.00
589	2810	23	3.0	8.5	42	0.97	0.03
589	2846	23	3.0	8.5	43	0.97	0.03
589	2582	21	3.0	8.5	37	0.96	0.04

Crevice Pressure (cont)



Calculated pressure profile for test NOP 1. Flow is liquid to 0.9, steam to exit.

Comments on ANL and Industry Models

- Models agree that flow resistance is due to viscous losses and is dependent on contact pressure
  - ANL uses rough surface model to calculate local K as a function of contact pressure and integrates axially to determine overall resistance; flow is allowed to switch from liquid to steam
  - Industry determines average K from experiments by applying incompressible flow form of Darcy's law
- ANL model results agree with industry measurements that under NO and MSLB conditions that flow is liquid over most of the expansion region
  - Steam region in experiments at 1900 psi is more extensive (≈0.22 L)
  - Pressure drop in liquid region is predicted to be nonlinear because of variation in contact pressure

ANL data deeds for detailed comparisons

- Leak data currently reported in terms of K
  - How exactly was K calculated from data — what values of viscosity, density, and contact length were used?
  - Data are given in terms of index number. Would be better to have data grouped by specimen so that effect of temperature and pressure on a given specimen could be evaluated and not confounded by specimen-to-specimen variability.