Reliability requirements for joints

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Leak rates

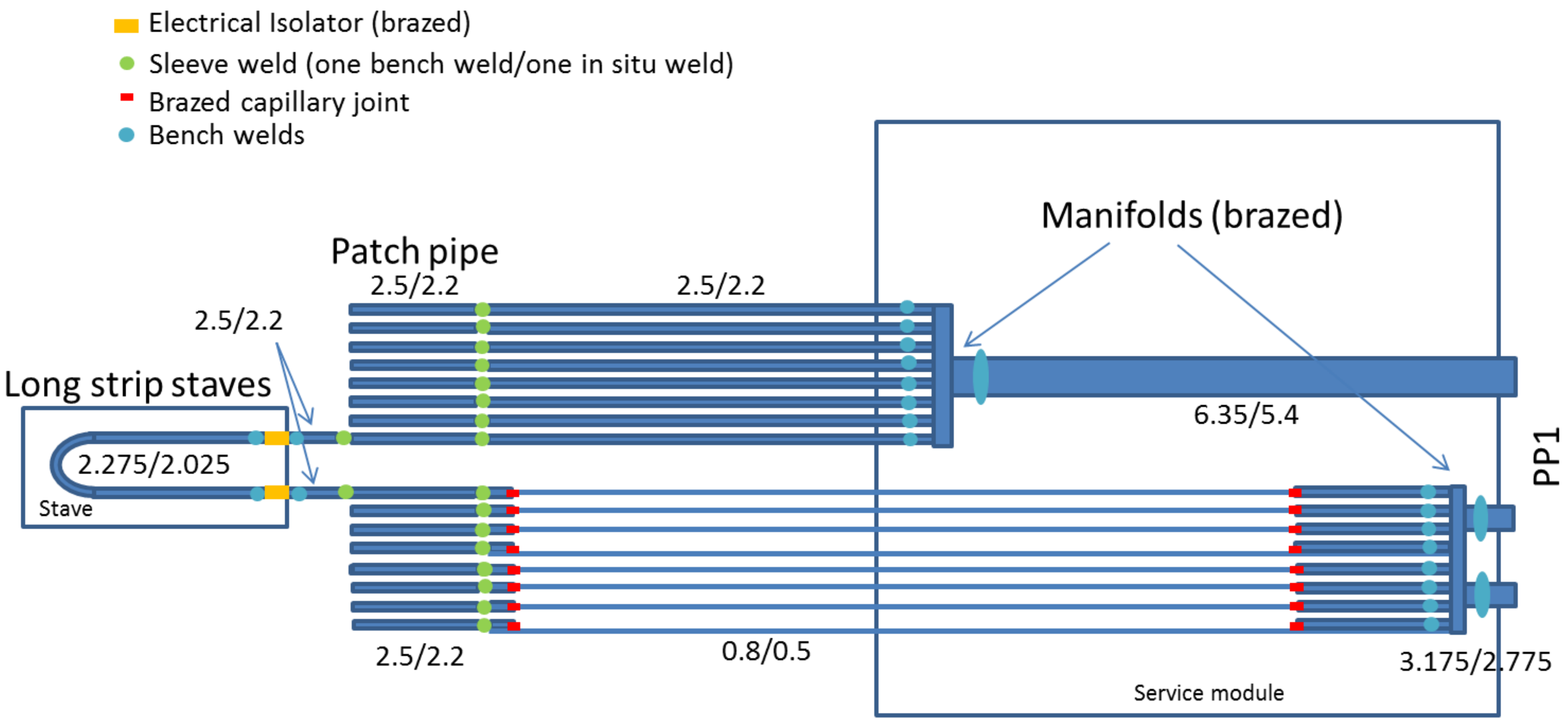
- No gas vessel (pipe, etc.) is absolutely leak tight
  - And actually it does not need to be
- The leak rate must be low enough that the required operating pressure is maintained and that the lost fluid is not doing any damage to the environment (immediate or general) or incurs a large financial loss
  - Operating pressure
    - If evaporating CO_2 at -35°C p_{sat}~12bar. Assume that a pressure drop corresponding to 1°C is acceptable, that's a Δp~0.4bar (3%)
  - Lost fluid: Accept 100kg loss of CO_2 per year
    - Cost is marginal
    - Impact on general environment is null (GWP = 1)
    - Impact on immediate environment small
      - Low dew point environment → little acid formation
      - Mechanical impact negligible (see later)

Size of system

- All estimates must be seen in the context of a system size (number of joints)
- Conclusions will be different for smaller systems
- Here: look at a large tracking system (ATLAS barrel strips)
  - 392 staves (=evaporators) with electrical breaks (2 each)
  - Internal (within ITk) 1:8 (1:9) manifolding
  - Patch pipes to allow connection to staves to services during integration

7248 joints within the ITk thermal enclosure (effectively inaccessible)

Example: ATLAS barrel strips



Tube dimensions are OD/ID for illustration only – final numbers slightly different
Units of measurement in mm

Some equations

- Leak rate usually quoted in mbarl/s (or equivalent) – pressure drop rate in volume of 1l
- To get to a mass leak rate

$$\frac{\Delta m}{\Delta t} = \frac{r_l M}{RT}$$

Leak rate (in units above)
Molar mass
83.14 mbarl/molK
Temperature (in K)

- Leak rate typically quoted for He. To translate to other gas:
  - For >10^{-4}mbarl/s: Laminar viscous $r_{l_A}\eta_A = r_{l_B}\eta_B$
    - For He (20°C) → CO_2 (-35°C): $r_{CO_2} = 1.6 r_{He}$
  - For <10^{-6}mbarl/s: Molecular $r_{l_A}\sqrt{M_A} = r_{l_B}\sqrt{M_B}$
    - For He → CO_2: $r_{CO_2} = 0.3 r_{He}$
  - Between: pick worse ($r_{He} = 0.61 r_{CO_2}$)

Viscosity

What leak rate does this imply?

- Pressure criterion:
  - Assume 10 m length → volume per loop of 50 ml, need 3g/s. Estimate time needed to push liquid through this volume: 20s

$$r_l \sim \frac{\Delta p V}{t} = \frac{400 \times 0.05}{20} \frac{1}{n_{joints}} = 0.05 \mathrm{mbarl}/s$$ (CO_2) for n_{joints}=20

- Lost mass criterion:

$$r_l \sim \frac{\Delta m}{\Delta t} \frac{RT}{M} \frac{1}{n_{joints}} = 1.4 \times 10^{-4} \mathrm{mbarl}/s$$ (CO_2) for n_{joints}=10^4

- Force on environment:

$$F \sim \frac{\Delta m}{\Delta t} v_{sound}$$ ~0.7µN for r_l=10^{-4} mbarl/s (CO_2)

From this: 10^{-4} mbarl/s (He) is entirely adequate

Reliability

- So, what is really the (challenging) requirement we need to achieve?
- It’s reliability
  - The absence of a joint with a significantly higher leak rate than any of the above, which potentially requires a disconnect of a section of the detector
  - Because of a failure of the fitting which prevents it from achieving design and test performance
  - Often because of stress (typically mechanical, but also thermal, corrosion or gasket erosion) or improper joining technique
- This is what
  - During installation costs money, time and nerves
  - During operations costs acceptance (if we would loose one manifold in the ATLAS strip barrel that’s about 2m^2 of Silicon)

Verification of reliability

- How do we quantify reliability?
  - By a failure rate
- Need to establish
  1. What failure rate do we need
  2. How can we establish this performance for a given design/part?

Setting the requirement…

- The probability to get exactly n_f failures in a sample of n components, which all have a failure rate of 1 in m is given by

$$p = \frac{n!}{n_f!\left(n - n_f\right)!}\left(\frac{1}{m}\right)^{n_f}\left(1 - \frac{1}{m}\right)^{n-n_f}$$

- Probability to encounter at least one failure in this sample

$$p = 1 - \left(1 - \frac{1}{m}\right)^{n}$$

  - For $m = n$ this probability tends to 63% for large n
  - To achieve a 10% probability the individual failure rate needs to be lowered by a factor 10 (e.g. for n = 1,000 the individual failure rate needs to be 1 in 10,000)

…and verifying it,…

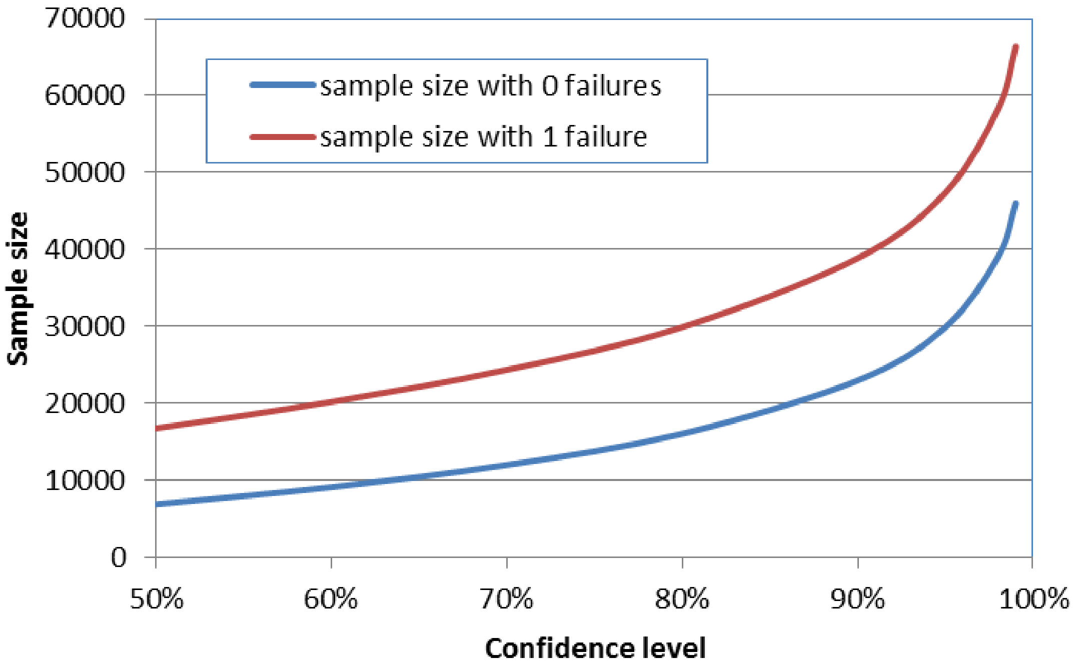
Estimate the sample size needed in a series of pass/fail tests to set a limit of the failure rate with a confidence level of *c*:

With no fail:

$$n = \frac{\ln(1-c)}{\ln\left(1-\frac{1}{m}\right)}$$

With 1 fail:

$$\frac{1-c}{1+\frac{n-1}{m}} = \left(1-\frac{1}{m}\right)^{n-1}$$



pass/fail test sample size to demonstrate a failure rate of 1 in 10,000

…an impossible task?

- We should bear in mind that this pass/fail test would need to be performed under realistic conditions, with realistic loads etc.
- It should be clear that such a verification for any system larger than 10-100 fittings is beyond our means, so what can we do?
  1. Use industry standard connection techniques
     - Not because they are smarter, but because they have a much larger use statistics
     - The problem is that for the tube dimensions we aim for there is no industry standard – not even brazing or welding
  2. In the qualification think carefully about the loads for which the joining technique needs to be qualified and perform controlled tests using these loads
     - I think this will need to include tests at increased stress levels to find faults without the need of excessive statistics (HALT/HASS)