Leak Correlation

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Leakage

- Allowable leakage for systems is specified in sccs of helium – standard cubic centimeters per second
    - Derived from requirement for maximum allowable leakage of working fluid
    - Translated to sccs of He
- It’s important to understand the leak path physics to allow translation between leak rates of different fluids

Outline

- Types of leaks
- System leakage
  - Leak path
  - Leak physics
  - How to calculate equivalent leakage
    - He to other gas
    - He to liquid
    - He to two-phase fluid
    - He to volatile liquid

We won’t address permeation – just leakage

Types of Leaks

- Often people ask, “What’s the equivalent hole size?”
- This is not meaningful for a healthy system
  - The equivalent orifice diameter for nominal leakage is only a small fraction of the pressure vessel thickness
    - Orifice equivalent is not accurate for relatively tight systems
  - Orifice equivalent is accurate to predict leakage for things like micrometeoroid holes – but here the leakage rates are orders of magnitude higher

I was once asked how large a hole could be tolerated in the Orbiter radiator assuming that the FDIR could isolate the radiator in 30 seconds – the resulting hole size was orders of magnitude smaller than MMOD would create

Leak Physics

- Leakage is specified in standard cubic centimeters per second (sccs)
- sccs is not a volumetric flow rate – it's a mass flow rate
- For systems with leak rates on the order of $1x10^{-6}$ to $1x10^{-3}$ sccs, the hole size is small enough that it cannot be considered an orifice (l/d is large)
- Instead, we consider a leak path

Leak Path

- Typical leaks
  - Scratch on sealing surface
  - Weld pinhole
  - Tortuous path through a weld
- We idealize all of these as smooth cylindrical cross section leaks

Leak path roughness has no effect in laminar flow

Laminar Leak Path – Constant Density

- Laminar flow in a tube

$$Q = \frac{\pi \, \Delta p \, D^4}{128 \, \mu \, l} \qquad \dot{m} = \frac{\rho \, \Delta p \, \pi D^4}{128 \, \mu \, l}$$

  - Q = volumetric flow rate
  - $\dot{m}$ = mass flow rate
  - ρ = density
  - Δp = pressure drop
  - D = diameter
  - μ = dynamic (absolute) viscosity
  - l = length

Real Leak Paths

- Leak path cross-section can vary
- Gas flows can have non-uniform density
- Flow can be molecular (molecules are more likely to contact the wall than each other)
- Flow can be compressible (Mach number >0.3)
- Flows can be sonically limited

How do we include these effects?

Laminar Leak Path
– Isothermal Incompressible Flow

- Laminar flow in a uniform cross-section tube

$$\dot{m} = \frac{\rho_{avg}\,\Delta p\,\pi D^4}{128\,\mu\,l}$$

  - ρ_{avg} = density at average conditions $(p_{up}+p_{dn})/2$
    - results from integration of pressure gradient through the leak
    - not the same as average pressure

Laminar Leak Path

- For laminar flow of a gas in a given leak path

$$\dot{m} \propto \frac{\rho_{avg}\,\Delta p}{\mu}$$

  - ρ_{avg} is an approximation for non-uniform cross-section

We represent all leak paths by a constant cross section, circular leak path
It’s inexact, but is the best that we can do

- For a liquid in a given leak path

$$\dot{m} \propto \frac{\rho\,\Delta p}{\mu}$$

Molecular Flow

- The Knudsen number is used to define the limits of molecular flow

$$\mathrm{Kn} = \frac{\lambda}{\mathrm{L}}$$

- λ = mean free path
- L = characteristic length scale (not the same as l)

In molecular flow molecules are more likely to contact the wall than each other

Molecular Flow

- Mean free path

$$\lambda = \frac{k_B T}{\sqrt{2}\,\pi\, d^2 p}$$

  - k_B = Boltzman's constant
    - 1.380649×10^{-23} J/K
      - or $m^2 \cdot kg/(s^2 \cdot K)$
    - $5.6573016 \times 10^{-24}$ ft lbf/°R
  - T = temperature
  - d = molecular diameter (not the same as D)
  - p = pressure

Molecular Flow

- Molecular diameter is not tabulated for all gases – in that case an approximation based on viscosity can be used

$$\lambda = \frac{16}{5} \frac{\mu}{\sqrt{\rho 2\pi\, R\, T}}$$

- R = substance-specific gas constant

Limits of Molecular Flow

- Generally speaking, flow is considered
  - a continuum if Kn is small (often Kn<0.1)
  - molecular if Kn is large (often Kn>10)
- But exact limits do not exist – there is not a clean transition

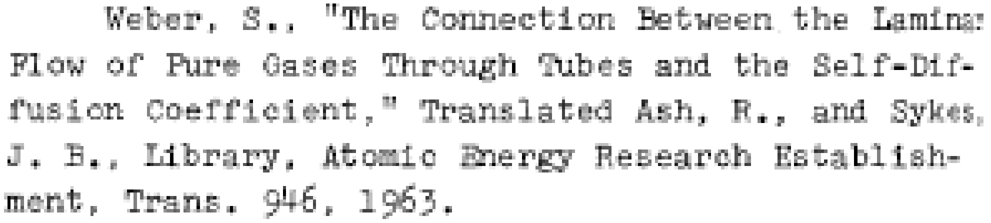
$$\mathrm{Kn} = \frac{\lambda}{\mathrm{L}}$$

Laminar Continuum and Molecular Flow in a Tube

- Using molecular theory, Weber derived an equation for flow that spans the range from continuum to molecular flow

$$\frac{\dot{n}}{\Delta p} = \frac{4}{3}\left(\frac{2\pi}{mkT}\right)^{1/2}\frac{r^3}{\ell}\left[\frac{3\pi}{128}\left(\frac{2r}{\lambda}\right) + \frac{\pi}{4}\,\frac{2r/\lambda}{1+2r/\lambda} + \frac{1}{1+2r/\lambda}\right] \qquad (1)$$

The three terms represent the continuum, slip, and self-diffusion contributions



Weber, S., "The Connection Between the Lamina Flow of Pure Gases Through Tubes and the Self-Diffusion Coefficient," Translated Ash, R., and Sykes, J. B., Library, Atomic Energy Research Establishment, Trans. 946, 1963.

Laminar Continuum and Molecular Flow in a Tube

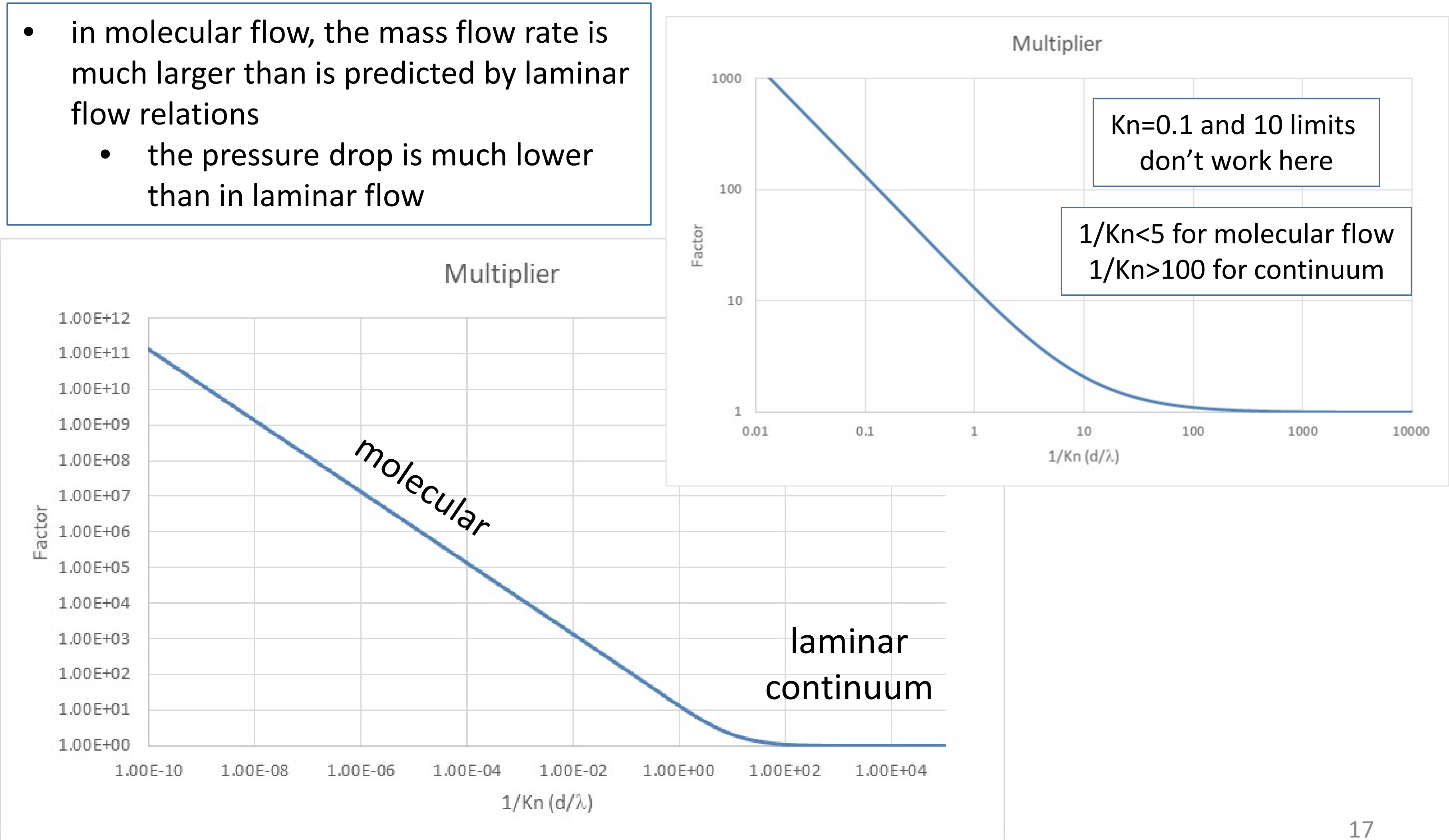
- The equation can be expressed as

$$\dot{\mathrm{m}} = \dot{\mathrm{m}}_{\mathrm{laminar}} \left[1 + \frac{32}{3} \frac{1}{1 + \mathrm{D}/\lambda} + \frac{128}{3\pi} \frac{\lambda}{\mathrm{D}} \frac{1}{1 + \mathrm{D}/\lambda} \right]$$

  - $\dot{\mathrm{m}}_{\mathrm{laminar}}$ is the mass flow rate calculated using laminar relations
- As λ/D becomes large, the factor in the brackets becomes large

Laminar Continuum and Molecular Flow in a Tube

- in molecular flow, the mass flow rate is much larger than is predicted by laminar flow relations
    - the pressure drop is much lower than in laminar flow



molecular

laminar
continuum

Kn=0.1 and 10 limits don’t work here

1/Kn<5 for molecular flow
1/Kn>100 for continuum

Laminar Compressible Flow in a Duct

- High speed flow through a constant area duct where the effect of friction is considered
  - for isothermal flow

$$\frac{\mathrm{dp}}{\mathrm{dx}} = -\frac{\mathrm{p}}{\mathrm{D}} \frac{\gamma \mathrm{M}^2}{2(1-\gamma \mathrm{M}^2)} \frac{64}{\mathrm{Re}}$$

  - x = distance along duct
  - M = Mach number V/$\sqrt{\gamma \mathrm{RT}}$
  - γ = ratio of specific heats
  - Re = Reynolds number ρVD/μ
  - V = average velocity in the duct

M>0.3 for compressible flow

- For isothermal flow, flow is limited by $\mathrm{M} = \frac{1}{\sqrt{\lambda}}$

Isothermal Laminar Compressible Flow in a Duct

$$\frac{dp}{dx} = -\frac{p}{d}\,\frac{\gamma M^2}{2(1-\gamma M^2)}\,\frac{64}{Re}$$

- Degenerates to incompressible flow model at low speeds

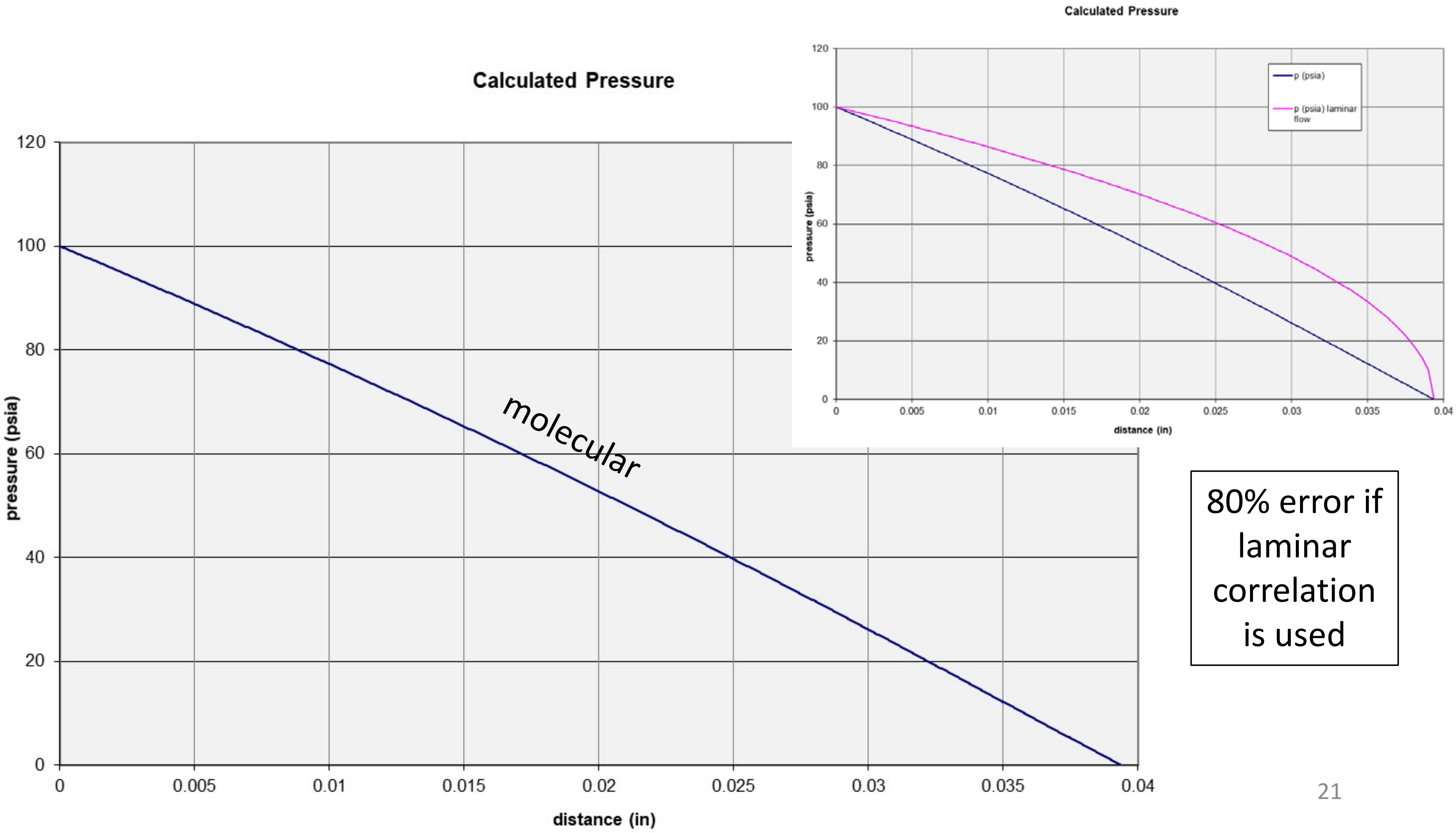
$$\frac{dp}{dx} = \frac{1}{d}\frac{1}{2}\rho V^2\frac{64}{Re}$$

Excel Leak Path Model

- Given
  - leak path length
  - mass flow rate
  - upstream pressure
  - downstream pressure
  - uniform temperature
    - low mass flow rate
  - assumed diameter
- Model
  - calculates pressure along isothermal leak path
  - checks for choking in continuum and transition regions
    - choking condition is ${}^{1}/_{\sqrt{\gamma}}$
    - no choking in molecular flow regime
- Iterate to calculate leak path diameter
- The model was exercised for helium over a wide range of upstream pressures and leak rates

70°F He from 100 psia to vacuum

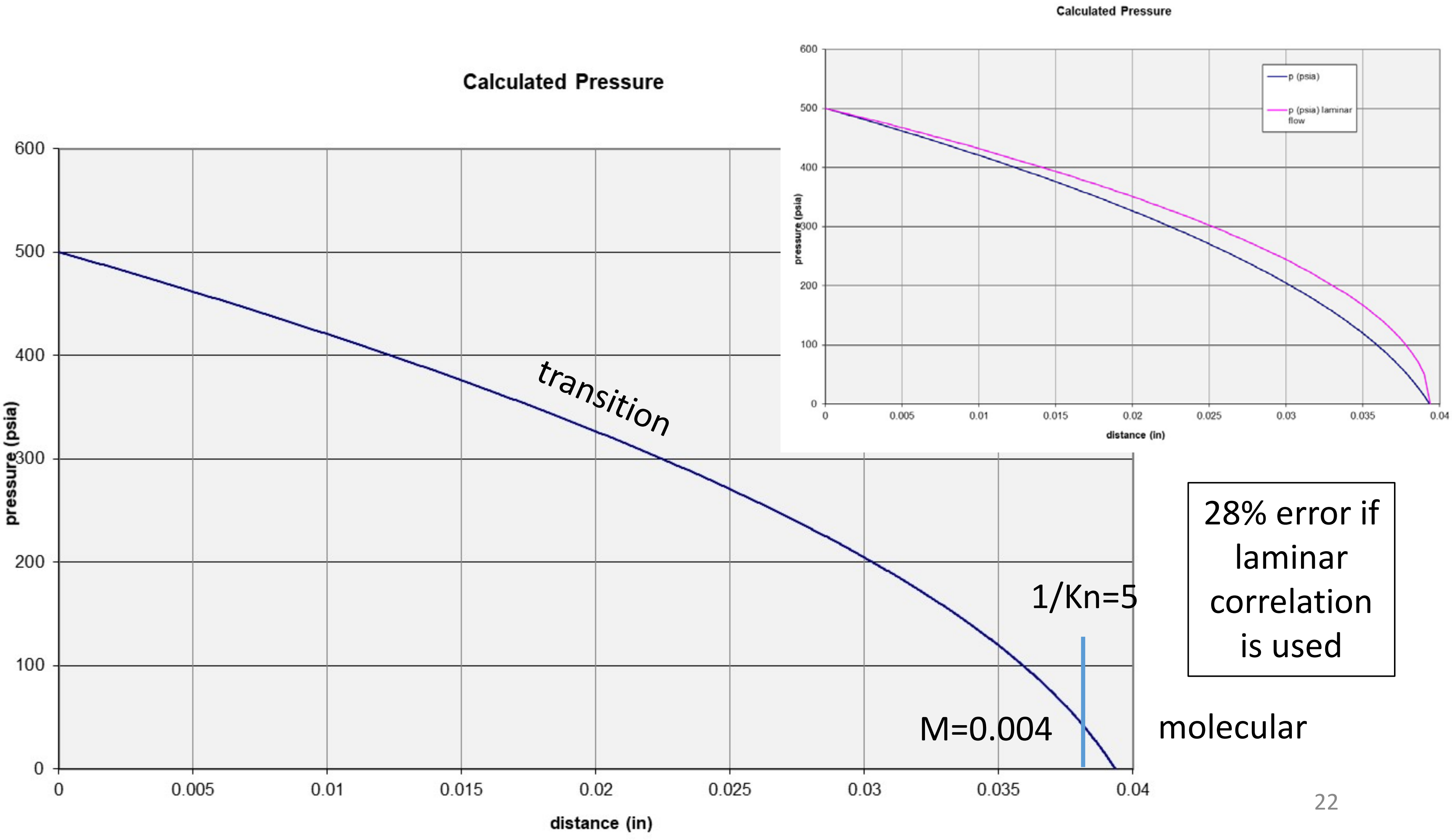
1 mm long path, 1×10^{-8} sccs, d= 6.33×10^{-6} in



80% error if laminar correlation is used

He from 500 psia to vacuum

1 mm long path, 1×10^{-6} sccs, d= 1.24×10^{-5} in



transition

1/Kn=5

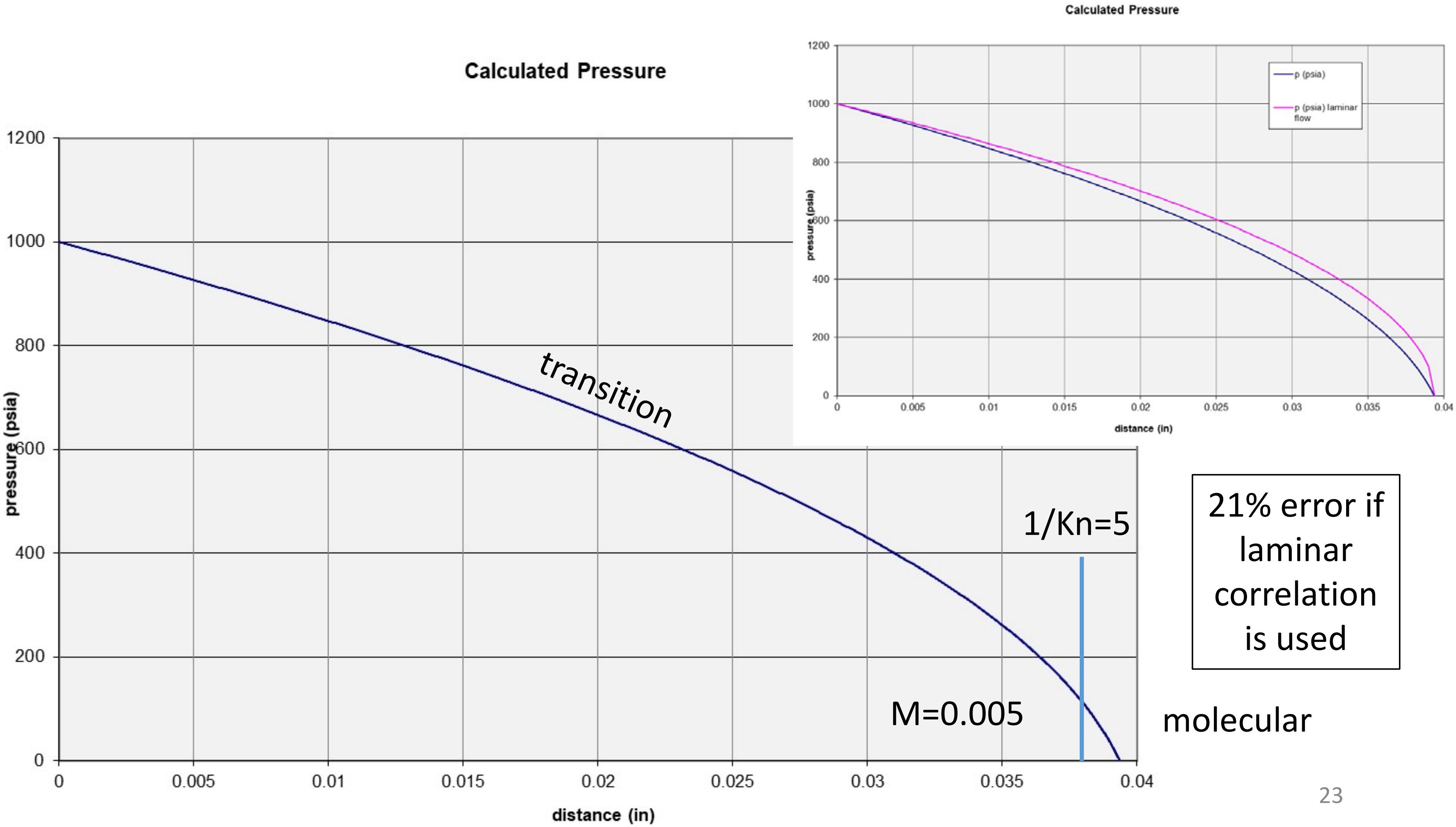
M=0.004

molecular

28% error if laminar correlation is used

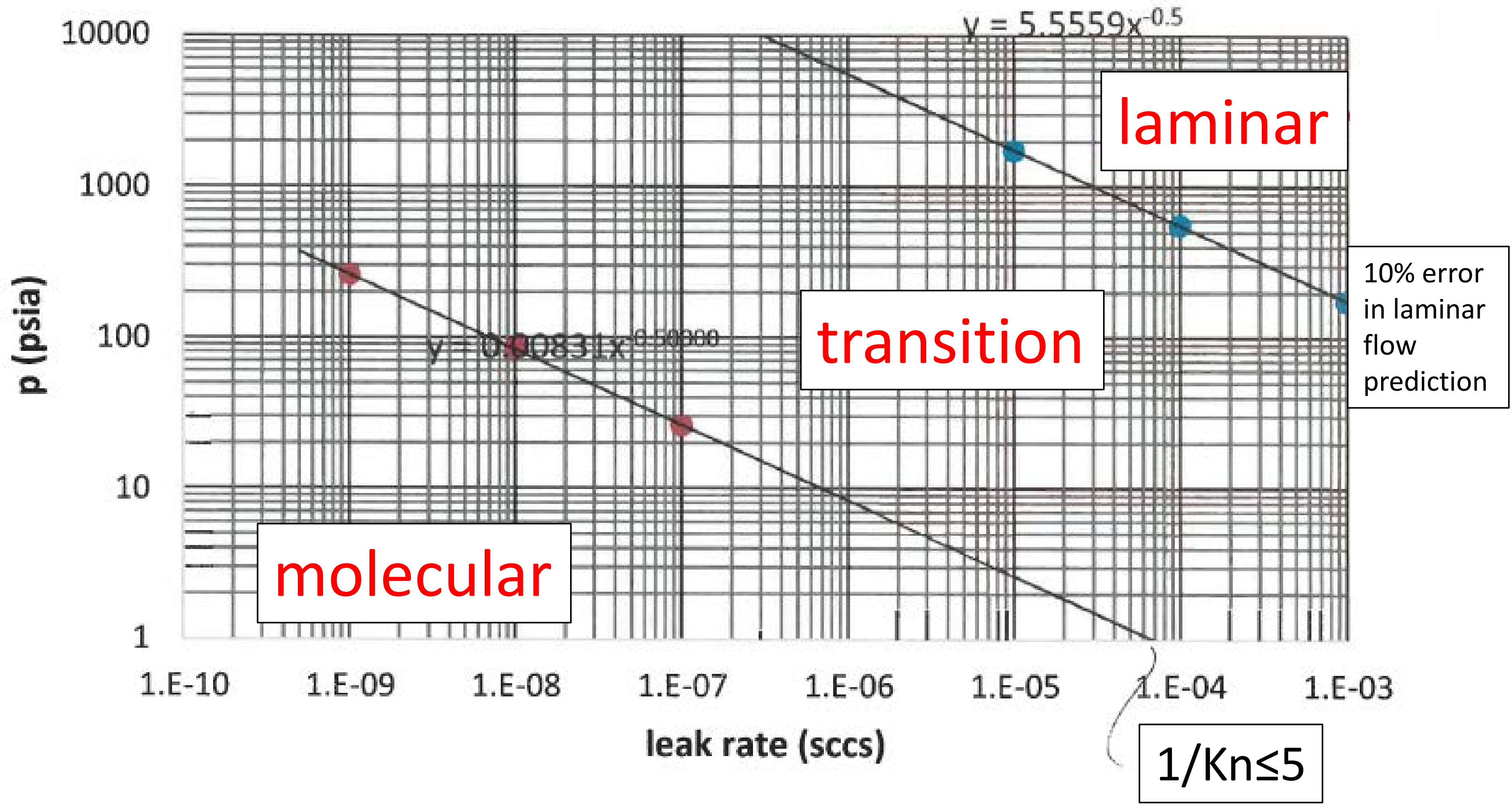
He from 1000 psia to vacuum

1 mm long path, 1×10^{-6} sccs, d= 8.96×10^{-6} in



21% error if laminar correlation is used

Helium Leak Path Regimes



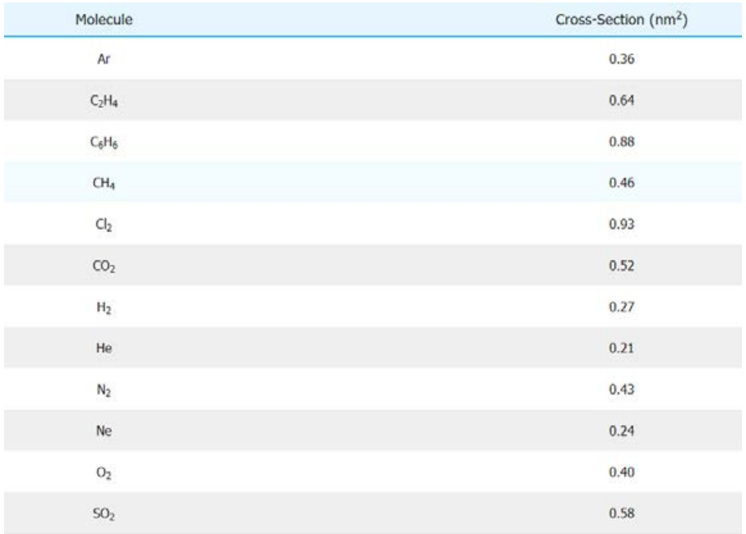
10% error in laminar flow prediction

1/Kn≤5

1 mm long circular leak path

What Does It All Mean?

- In helium leak testing
  - most cases are in the transition or molecular range
- In cases where another gas is the working fluid
  - molecular diameter is larger – He has the smallest molecular diameter of all commonly used gasses



Molecule	Cross-Section (nm^2)
Ar	0.36
C_2H_4	0.64
C_6H_6	0.88
CH_4	0.46
Cl_2	0.93
CO_2	0.52
H_2	0.27
He	0.21
N_2	0.43
Ne	0.24
O_2	0.40
SO_2	0.58

$$\lambda = \frac{k_B T}{\sqrt{2}\,\pi\, d^2 p}$$

λ is smaller for larger diameter molecules at the same conditions

What Does It All Mean?

- Can we just use laminar flow relations to work between helium leak test and gaseous working fluid?
- Consider a case where the He flow is mixed regime and the working fluid gas flow is continuum
  - True diameter of He path is smaller than predicted by laminar flow relations since mixed flow has less resistance
  - When this larger path is used in the laminar flow relations for the working fluid, it overpredicts the mass flow rate – and is conservative
- What if both cases are mixed regime?
  - The working fluid gas flow will be “less molecular” than the He in the leak test owing to its larger molecular diameter
  - Laminar flow relations again overpredict the leak rate of the working fluid – and are conservative

Using the laminar flow relations conservatively predicts the working fluid leak rate

Leak Correlation – He to Gas

- To convert $\dot{m}$ in traditional units to sccs requires that we divide by the density at standard conditions

$$\frac{\dot{m}}{\rho_{std}} = \frac{\rho_{avg}\,\Delta p\,\pi D^4}{\rho_{std}\,128\,\mu\,l} = \frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}$$

$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\left[\frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}\right]_{fluid}}{\left[\frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}\right]_{He}} = \frac{\left[\frac{p_{avg}\,\Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\,\Delta p}{\mu}\right]_{He}}$$

- For the same pressures and temperatures

$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\mu_{He}}{\mu_{fluid}}$$

Leak Correlation – He to Gas

- More generally

$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\left[\frac{p_{avg}\, T_{std}\, \Delta p\, \pi D^4}{p_{std}\, T\, 128\, \mu\, l}\right]_{fluid}}{\left[\frac{p_{avg}\, T_{std}\, \Delta p\, \pi D^4}{p_{std}\, T\, 128\, \mu\, l}\right]_{He}} = \frac{\left[\frac{p_{avg}\, \Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\, \Delta p}{\mu}\right]_{He}}$$

$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\left[\frac{\left(\frac{p_{int}+p_{ext}}{2}\right)\,(p_{int}-p_{ext})}{\mu}\right]_{fluid}}{\left[\frac{\frac{p_{int}}{2}\,(p_{int})}{\mu}\right]_{He}}$$

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$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\left[(p_{int}^2 - p_{ext}^2)\right]_{fluid}}{\left[p_{int}^2\right]_{He}} \frac{\mu_{He}}{\mu_{fluid}}$$

Leak Correlation – He to Liquid

$$\frac{\dot{m}}{\rho_{std}} = \frac{\rho_{avg}\,\Delta p\,\pi D^4}{\rho_{std}\,128\,\mu\,l} = \frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}$$

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{\left[\frac{\rho_{avg}\,\Delta p\,\pi D^4}{\rho_{std}\,128\,\mu\,l}\right]_{fluid}}{\left[\frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}\right]_{He}} = \frac{\left[\frac{\Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\,\Delta p}{p_{std}\,\mu}\right]_{He}}$$

- For the same pressure difference

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{\left[\frac{p_{std}\,\mu}{p_{avg}}\right]_{He}}{\mu_{fluid}}$$

Leak Correlation – He to Liquid

- More generally

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{\left[\frac{\rho_{avg}\,\Delta p\,\pi D^4}{\rho_{std} 128\,\mu\,l}\right]_{fluid}}{\left[\frac{p_{avg}\,T_{std}\,\Delta p\,\pi D^4}{p_{std}\,T\,128\,\mu\,l}\right]_{He}} = \frac{\left[\frac{\Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\,\Delta p}{p_{std}\,\mu}\right]_{He}}$$

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{\left[\frac{(p_{int}-p_{ext})}{\mu}\right]_{fluid}}{\left[\frac{\left(\frac{p_{int}}{2}\right)(p_{int})}{p_{std}\,\mu}\right]_{He}}$$

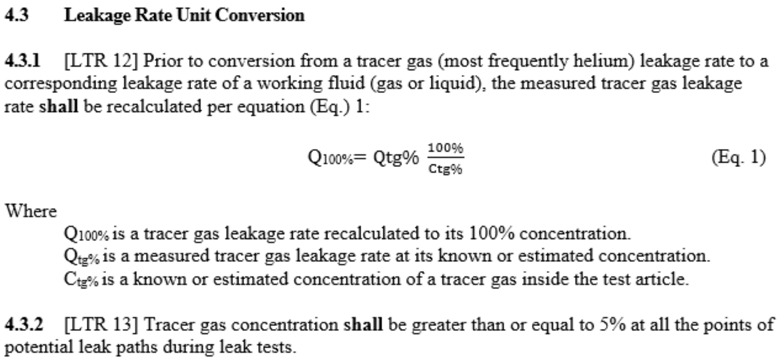
NASA-STD-7012

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{2\,p_0[(p_{int}-p_{ext})]_{fluid}}{[p_{int}^2]_{He}}\,\frac{\mu_{He}}{\mu_{fluid}}$$

NASA Standard

- These relations were used to develop the Leak Test Requirements Standard

NASA-STD-7012



4.3 Leakage Rate Unit Conversion

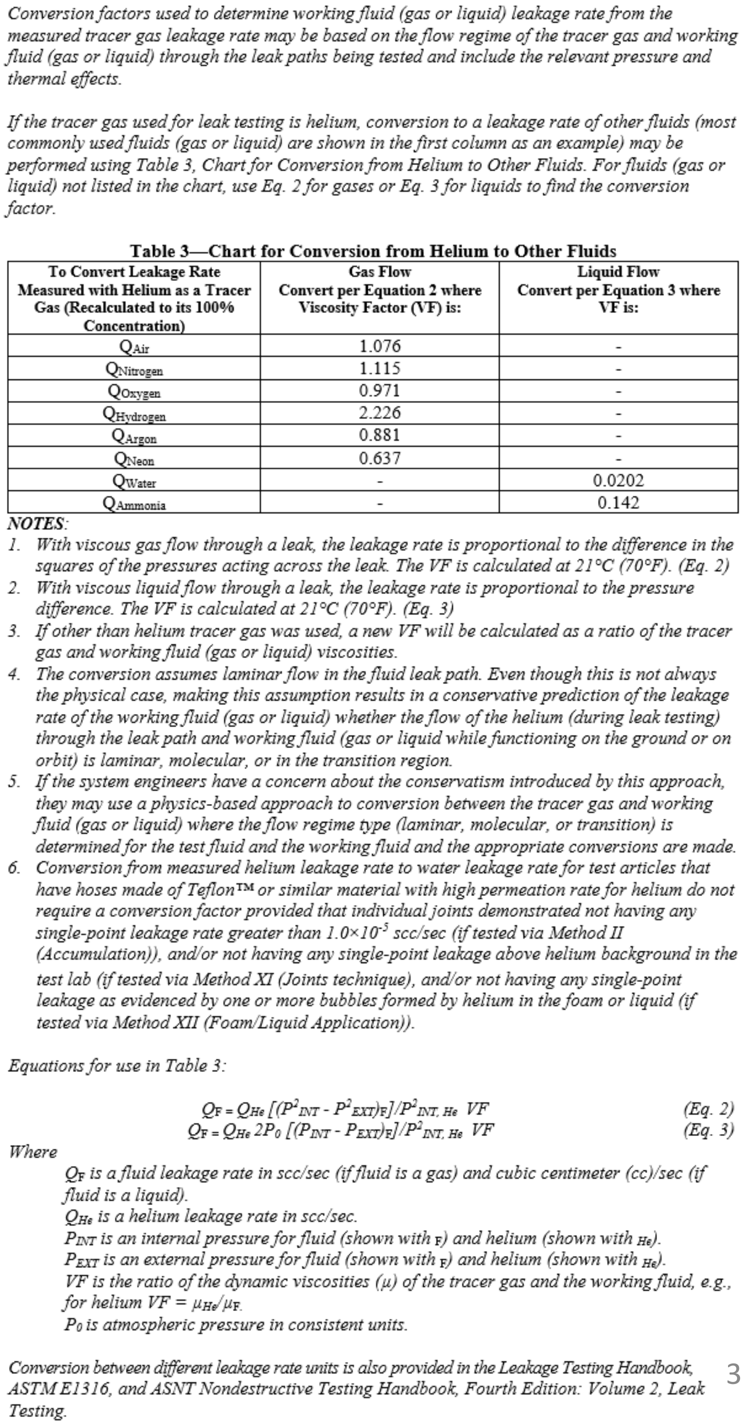
4.3.1 [LTR 12] Prior to conversion from a tracer gas (most frequently helium) leakage rate to a corresponding leakage rate of a working fluid (gas or liquid), the measured tracer gas leakage rate **shall** be recalculated per equation (Eq.) 1:

$$Q_{100\%} = Qtg\% \frac{100\%}{Ctg\%} \qquad \text{(Eq. 1)}$$

Where

$Q_{100\%}$ is a tracer gas leakage rate recalculated to its 100% concentration.
$Q_{tg\%}$ is a measured tracer gas leakage rate at its known or estimated concentration.
$C_{tg\%}$ is a known or estimated concentration of a tracer gas inside the test article.

4.3.2 [LTR 13] Tracer gas concentration **shall** be greater than or equal to 5% at all the points of potential leak paths during leak tests.



Conversion factors used to determine working fluid (gas or liquid) leakage rate from the measured tracer gas leakage rate may be based on the flow regime of the tracer gas and working fluid (gas or liquid) through the leak paths being tested and include the relevant pressure and thermal effects.

If the tracer gas used for leak testing is helium, conversion to a leakage rate of other fluids (most commonly used fluids (gas or liquid) are shown in the first column as an example) may be performed using Table 3, Chart for Conversion from Helium to Other Fluids. For fluids (gas or liquid) not listed in the chart, use Eq. 2 for gases or Eq. 3 for liquids to find the conversion factor.

Table 3—Chart for Conversion from Helium to Other Fluids

To Convert Leakage Rate Measured with Helium as a Tracer Gas (Recalculated to its 100% Concentration)	Gas Flow Convert per Equation 2 where Viscosity Factor (VF) is:	Liquid Flow Convert per Equation 3 where VF is:
Q_{Air}	1.076	-
$Q_{Nitrogen}$	1.115	-
Q_{Oxygen}	0.971	-
$Q_{Hydrogen}$	2.226	-
Q_{Argon}	0.881	-
Q_{Neon}	0.637	-
Q_{Water}	-	0.0202
$Q_{Ammonia}$	-	0.142

NOTES:

1. *With viscous gas flow through a leak, the leakage rate is proportional to the difference in the squares of the pressures acting across the leak. The VF is calculated at 21°C (70°F). (Eq. 2)*
2. *With viscous liquid flow through a leak, the leakage rate is proportional to the pressure difference. The VF is calculated at 21°C (70°F). (Eq. 3)*
3. *If other than helium tracer gas was used, a new VF will be calculated as a ratio of the tracer gas and working fluid (gas or liquid) viscosities.*
4. *The conversion assumes laminar flow in the fluid leak path. Even though this is not always the physical case, making this assumption results in a conservative prediction of the leakage rate of the working fluid (gas or liquid) whether the flow of the helium (during leak testing) through the leak path and working fluid (gas or liquid while functioning on the ground or on orbit) is laminar, molecular, or in the transition region.*
5. *If the system engineers have a concern about the conservatism introduced by this approach, they may use a physics-based approach to conversion between the tracer gas and working fluid (gas or liquid) where the flow regime type (laminar, molecular, or transition) is determined for the test fluid and the working fluid and the appropriate conversions are made.*
6. *Conversion from measured helium leakage rate to water leakage rate for test articles that have hoses made of Teflon™ or similar material with high permeation rate for helium do not require a conversion factor provided that individual joints demonstrated not having any single-point leakage rate greater than 1.0×10^{-5} scc/sec (if tested via Method II (Accumulation)), and/or not having any single-point leakage above helium background in the test lab (if tested via Method XI (Joints technique), and/or not having any single-point leakage as evidenced by one or more bubbles formed by helium in the foam or liquid (if tested via Method XII (Foam/Liquid Application)).*

Equations for use in Table 3:

$$Q_F = Q_{He}\,[(P^2_{INT} - P^2_{EXT})_F]/P^2_{INT,\,He}\ VF \qquad \text{(Eq. 2)}$$
$$Q_F = Q_{He}\,2P_0\,[(P_{INT} - P_{EXT})_F]/P^2_{INT,\,He}\ VF \qquad \text{(Eq. 3)}$$

Where

Q_F *is a fluid leakage rate in scc/sec (if fluid is a gas) and cubic centimeter (cc)/sec (if fluid is a liquid).*
Q_{He} *is a helium leakage rate in scc/sec.*
P_{INT} *is an internal pressure for fluid (shown with* $_F$*) and helium (shown with* $_{He}$*).*
P_{EXT} *is an external pressure for fluid (shown with* $_F$*) and helium (shown with* $_{He}$*).*
VF is the ratio of the dynamic viscosities (μ) of the tracer gas and the working fluid, e.g., for helium $VF = \mu_{He}/\mu_F$*.*
P_0 *is atmospheric pressure in consistent units.*

Conversion between different leakage rate units is also provided in the Leakage Testing Handbook, ASTM E1316, and ASNT Nondestructive Testing Handbook, Fourth Edition: Volume 2, Leak Testing.

NASA-STD-7012

- Gas to gas

$$\frac{\text{sccs fluid}}{\text{sccs He}} = \frac{\left[\frac{p_{avg}\,\Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\,\Delta p}{\mu}\right]_{He}}$$

$$Q_f = Q_{He}\,\frac{[(p_{int}-p_{ext})(p_{int}+p_{ext})/2]_F}{[p_{int}\,p_{int}/2]_{He}}\,\frac{\mu_{He}}{\mu_F} = Q_{He}\,\frac{[(p_{int}^2-p_{ext}^2)]_F}{[p_{int}^2]_{He}}\,\frac{\mu_{He}}{\mu_F}$$

- Gas to liquid

$$\frac{\text{ccs fluid}}{\text{sccs He}} = \frac{\left[\frac{\Delta p}{\mu}\right]_{fluid}}{\left[\frac{p_{avg}\,\Delta p}{p_{std}\,\mu}\right]_{He}}$$

$$Q_f = Q_{He}\,\frac{p_0[(p_{int}-p_{ext})]_F}{[p_{int}\,p_{int}/2]_{He}}\,\frac{\mu_{He}}{\mu_F} = Q_{He}\,\frac{2\,p_0[(p_{int}-p_{ext})]_F}{[p_{int}^2]_{He}}\,\frac{\mu_{He}}{\mu_F}$$

- Q is mass flow rate in sccs

Different Cases

- What if the working fluid is liquid but there is vaporization in the leak path?
  1. Alpha Magnetic Spectrometer CO_2 two-phase loop
  2. ISS External Active Thermal Control System subcooled liquid ammonia loop

AMS CO_2 Two-Phase Loop

- Normal operating condition is saturated liquid or vapor at 0°C (32°F)
  - Since the flow rate is very low, the flow can be considered isothermal

0°C isothermal boundary condition

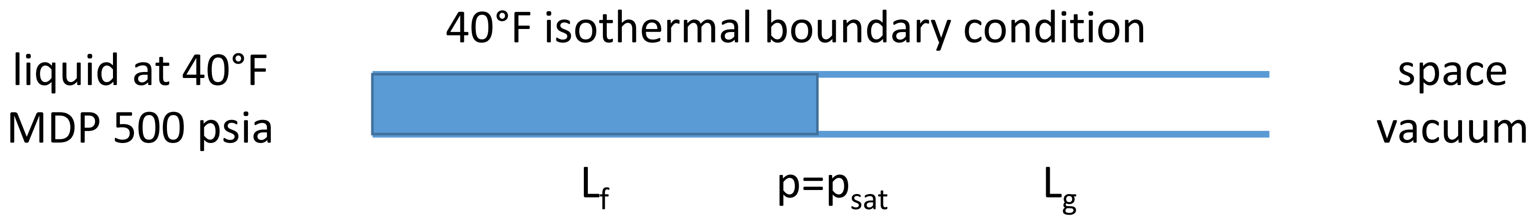
saturated liquid at 0°C

space vacuum

- Saturated liquid enters leak but vaporizes once the pressure drops slightly
  - Since the flow rate is very low, there is sufficient energy to vaporize the liquid
- Consider the flow through the leak to be pure vapor at 0°C
  - Same condition for vapor upstream of the leak path

ISS Ammonia ATCS

- Normal operating condition is subcooled liquid at 40°F
  - Since the flow rate is very low, the flow can be considered isothermal



40°F isothermal boundary condition

liquid at 40°F
MDP 500 psia

space
vacuum

L_f $p=p_{sat}$ L_g

- Subcooled liquid enters leak but vaporizes when the pressure reaches saturation
  - Since the flow rate is very low, there is sufficient energy to vaporize the liquid
    - 1 lbm/year requires less than 20 mW to vaporize

ISS Ammonia ATCS

- at 40°F
  - p_{sat}=73.22 psia
- liquid at 40°F
  - ρ_f=39.48 lbm/ft^3
  - μ_f=0.392 lbm/ft hr
- vapor at 40°F, 36.66 psia (average pressure)
  - $\rho_{avg,g}$=0.121 lbm/ft^3
  - μ_g=0.0225 lbm/ft hr (as expected, there is little change in viscosity with pressure)

$$\dot{m} = \frac{\rho_{avg}\Delta p\ \pi D^4}{128\ \mu\ l}$$

ISS Ammonia ATCS

$$\dot{m} = \frac{\rho_f \, \Delta p_f \, \pi D^4}{128 \, \mu_f \, l_f} \qquad \dot{m} = \frac{\rho_{avg,g} \, \Delta p_g \pi D^4}{128 \, \mu_g \, l_g}$$

$$\frac{\rho_f \, \Delta p_f \, \pi D^4}{128 \, \mu_f \, l_f} = \frac{\rho_{avg,g} \, \Delta p_g \pi D^4}{128 \, \mu_g \, l_g}$$

$$\frac{\rho_f \, \Delta p_f}{\mu_f \, l_f} = \frac{\rho_{avg,g} \, \Delta p_g}{\mu_g \, l_g} \qquad \frac{l_f}{l_g} = \frac{\rho_f \, \Delta p_f \, \mu_g}{\rho_{avg,g} \, \Delta p_g \mu_f}$$

Δp_f = 500-73.32 psia
426.68 psid

Δp_g = 73.32 psid

$$\frac{l_f}{l_g} = 109.0$$

~1% of the flowpath length is vapor

kinematic viscosity (μ/ρ) of vapor is 19x that of liquid – yields much higher dp/dx

Calculating Ammonia Leak Rate

Either:

1. Calculate all liquid leak based on liquid density, viscosity, and 500 psid
    - overpredicts the leakage by 15%
2. Calculate all liquid leak based on liquid density, viscosity, and 426.68 psid

Both are defensible

Summary

- Translating from measured He leak rate to working fluid leak rate using a laminar assumption is appropriate and generally conservative
- The laminar calculation results in a predicted working fluid leak rate that is higher than would actually occur