An Analytical Model of Poppet Seal Leakage

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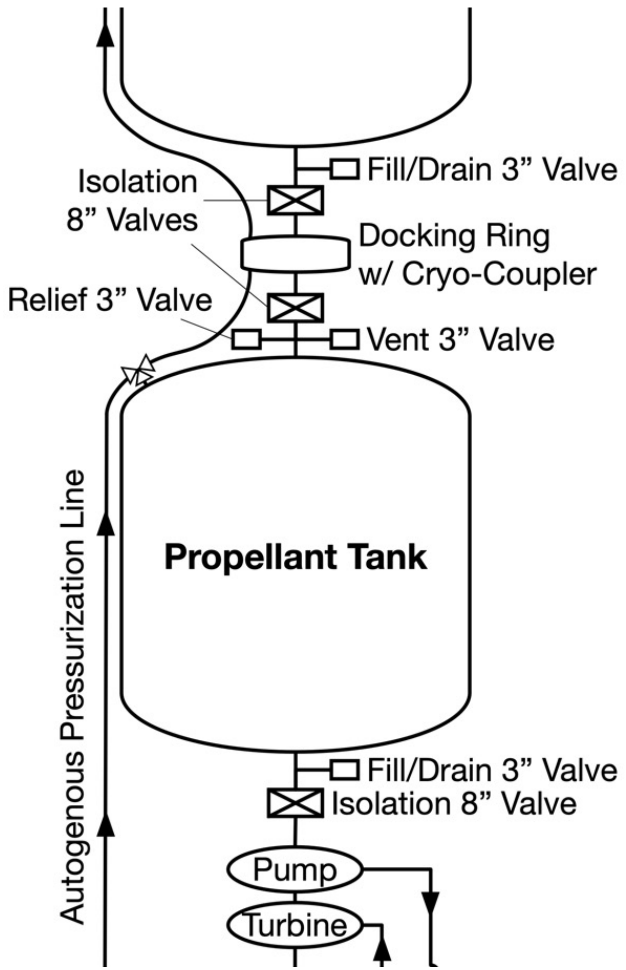
Outline

- Problem Description
- NASA-STD-7012, Leak Test Requirements
- Physics-based model for converting from gas to gas
- Extended model for converting from gas to liquid expelling to vacuum

Problem Description

- Mars mission timelines require extremely low loss valves to preserve propellant and minimize in-space propellant transfer durations.
- Poppet type valves were selected for use and valve leak rates were measured with Helium at atmospheric exit pressure at Hydrogen saturation temperature.
- Stored propellant is maintained near saturation conditions as a liquid but local heating may result in vapor in the leak path expelling to vacuum.
- **Problem**: *How to predict leak rate with gaseous and liquid Hydrogen based on gaseous Helium test data?*



Poppet Seal Description

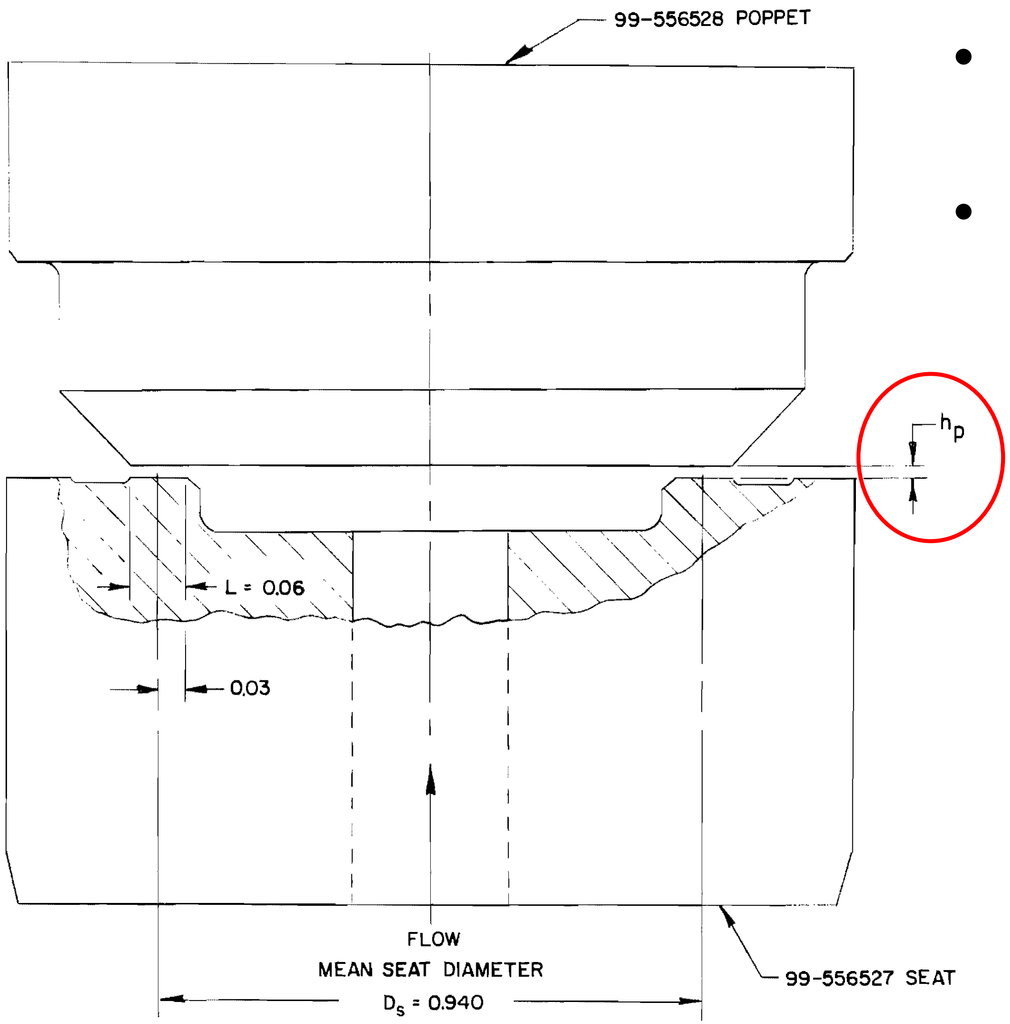


Figure 8. Typical 1.0-Inch Poppet and Seat Model

- Flat, conical, and spherical designs are common.
- The effective gap height, $\boldsymbol{h_p}$, is the length scale of interest.

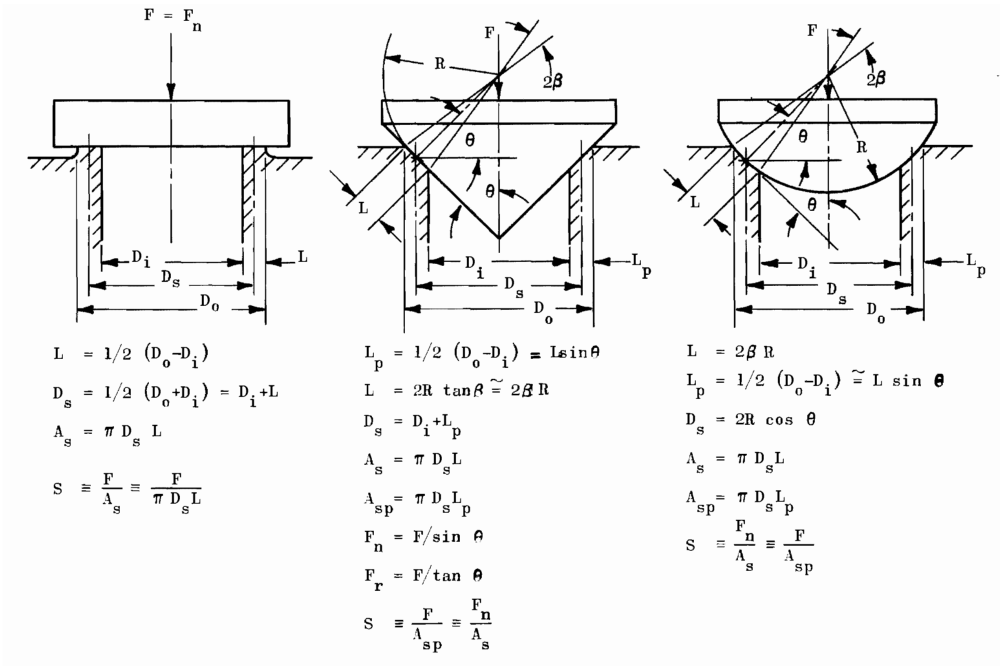


Figure 10. Flat, Conical, and Spherical Seating Equations

NASA-STD-7012, Leak Test Requirements

- Provides and simple methodology to convert leak rate in Helium to other gases based on the ratio of viscosities.
- Viscosity ratios (***VF***) are calculated at standard temperature, 70 degrees Fahrenheit.
- Standard implies leak test is done at operational temperature.
- Conversion methodology assumes laminar flow.

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.*

NASA-STD-7012, Leak Test Requirements

From NASA-STD-7012, *Leak Test Requirements*, the recommended *gas to gas* conversion is

$$Q_2 = Q_1 \frac{[p_1^2 - p_2^2]_2}{p_{1,1}^2} VF$$

This is derived from the isothermal, laminar flow equation. Here, for gas flow between parallel plates:

$$Q = \frac{Wh^3[p_1^2 - p_2^2]}{24\mu LRT\rho_{STD}}$$

where p_1 and p_2 are the upstream and downstream pressures, μ = absolute viscosity, R = gas constant, T = absolute temperature, ρ_{STD} = standard density, and W and h are the mean perimeter and gap height.

For the same geometry and a different gas, the flow rate for gas 2 can be estimated from

$$Q_2 = Q_1 \left[\frac{\mu_1}{\mu_2}\right]\left[\frac{T_1}{T_2}\right]\left[\frac{\rho_{STD,1}}{\rho_{STD,2}}\right]\frac{[p_1^2 - p_2^2]_2}{[p_1^2 - p_2^2]_1}, \rho_{STD} = \frac{P_{STD}}{RT_{STD}}, P_{STD,1} = P_{STD,2}, T_{STD,1} = T_{STD,2}$$

$$Q_2 = Q_1 \left[\frac{\mu_1}{\mu_2}\right]\left[\frac{T_1}{T_2}\right]\frac{[p_1^2 - p_2^2]_2}{[p_1^2 - p_2^2]_1} \sim Q_1 VF \frac{[p_1^2 - p_2^2]_2}{p_{1,1}^2}$$

The STD implies that the conversion assumes constant temperature but doesn't explicitly state that the helium test should be done at the hydrogen temperature.

NASA-STD-7012, Leak Test Requirements

From NASA-STD-7012, *Leak Test Requirements*, the recommended *gas to liquid* conversion is

$$Q_2 = Q_1 2P_o \frac{[p_1 - p_2]_2}{p_{1,1}^2} VF$$

This is derived from a ratio of the isothermal, laminar flow for a liquid to that for a gas, both between parallel plates:

$$Q_{LIQ} = \frac{Wh^3[p_1 - p_2]}{12\mu L}, \qquad Q_{GAS} = \frac{Wh^3[p_1^2 - p_2^2]}{24\mu LRT\rho_{STD}}$$

These reduce to

$$Q_{LIQ} = Q_{GAS}\left[\frac{\mu_{GAS}}{\mu_{LIQ}}\right]\left[\frac{T_{GAS}}{T_{GAS,STD}}\right]\frac{[p_1 - p_2]_{LIQ}}{[p_1^2 - p_2^2]_{GAS}} 2P_{GAS,STD}$$

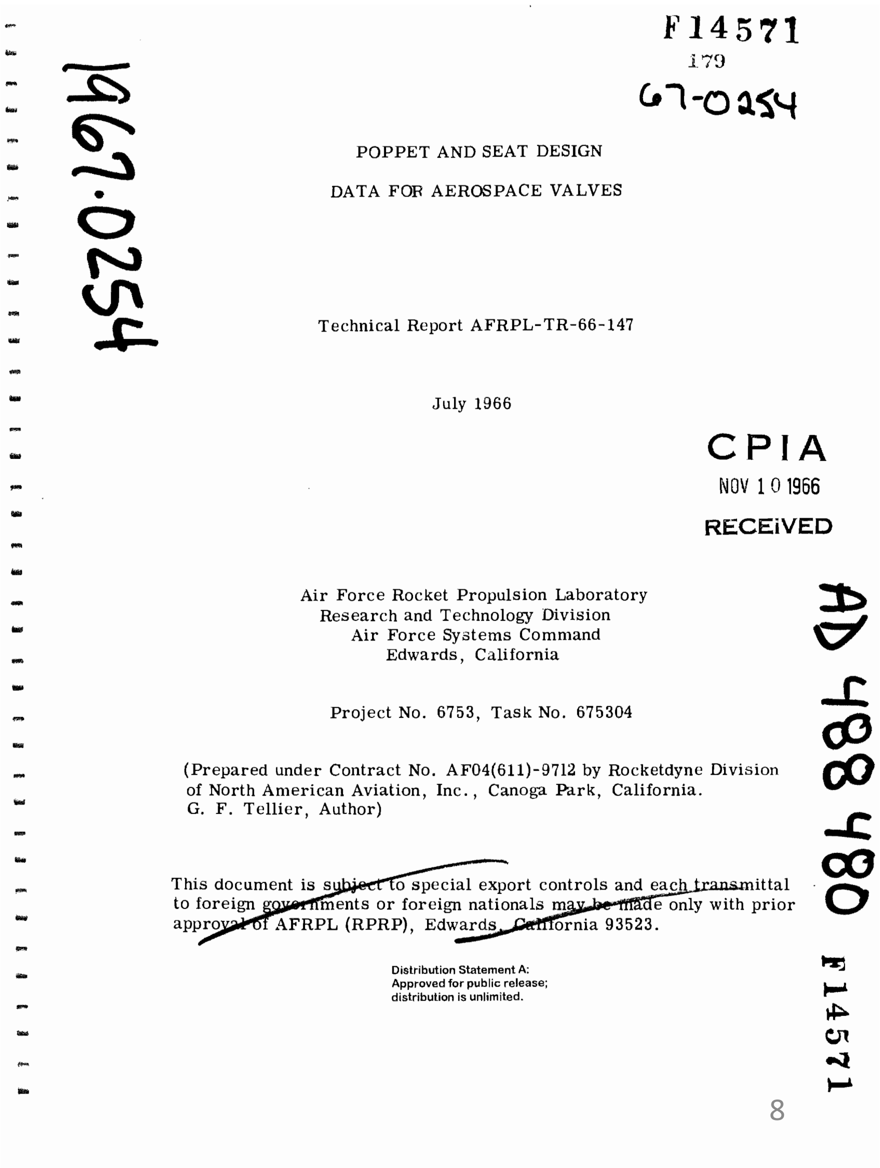
The STD further simplifies this by assuming atmospheric pressure (P_o) equals standard pressure for the gas and that the helium temperature is equal to the standard temperature.

$$Q_{LIQ} = Q_{GAS}\left[\frac{\mu_{GAS}}{\mu_{LIQ}}\right]\frac{[p_1 - p_2]_{LIQ}}{p_{1,GAS}^2} 2P_{STD} \sim Q_1 VF \frac{[p_1 - p_2]_2}{p_{1,1}^2} 2P_o$$

Both gas to gas and gas to liquid are approximations and will generally overpredict the leakage rate in the second fluid. Formulations also suggest that the liquid leakage will generally exceed the gas leakage.

Physics-Based Leakage Model

- Revisiting a methodology described and validated in 1966 by G. F. Tellier and more recently applied to long-term in-space propellant storage.
- May be used to describe valve's leak characteristic – a unique relationship between effective gap height and leakage flow rate across all flow regimes.
- Valid for converting from gas to gas and gas to liquid but fluid properties must be constant (No state change).
- Extensive validation data included in report. Permits calculation check and uncertainty estimation.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POPPET AND SEAT DESIGN

DATA FOR AEROSPACE VALVES

Technical Report AFRPL-TR-66-147

July 1966

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NOV 10 1966
RECEIVED

Air Force Rocket Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Edwards, California

AD 488 480

Project No. 6753, Task No. 675304

(Prepared under Contract No. AF04(611)-9712 by Rocketdyne Division of North American Aviation, Inc., Canoga Park, California. G. F. Tellier, Author)

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Poppet Seal Leakage Model - Geometry

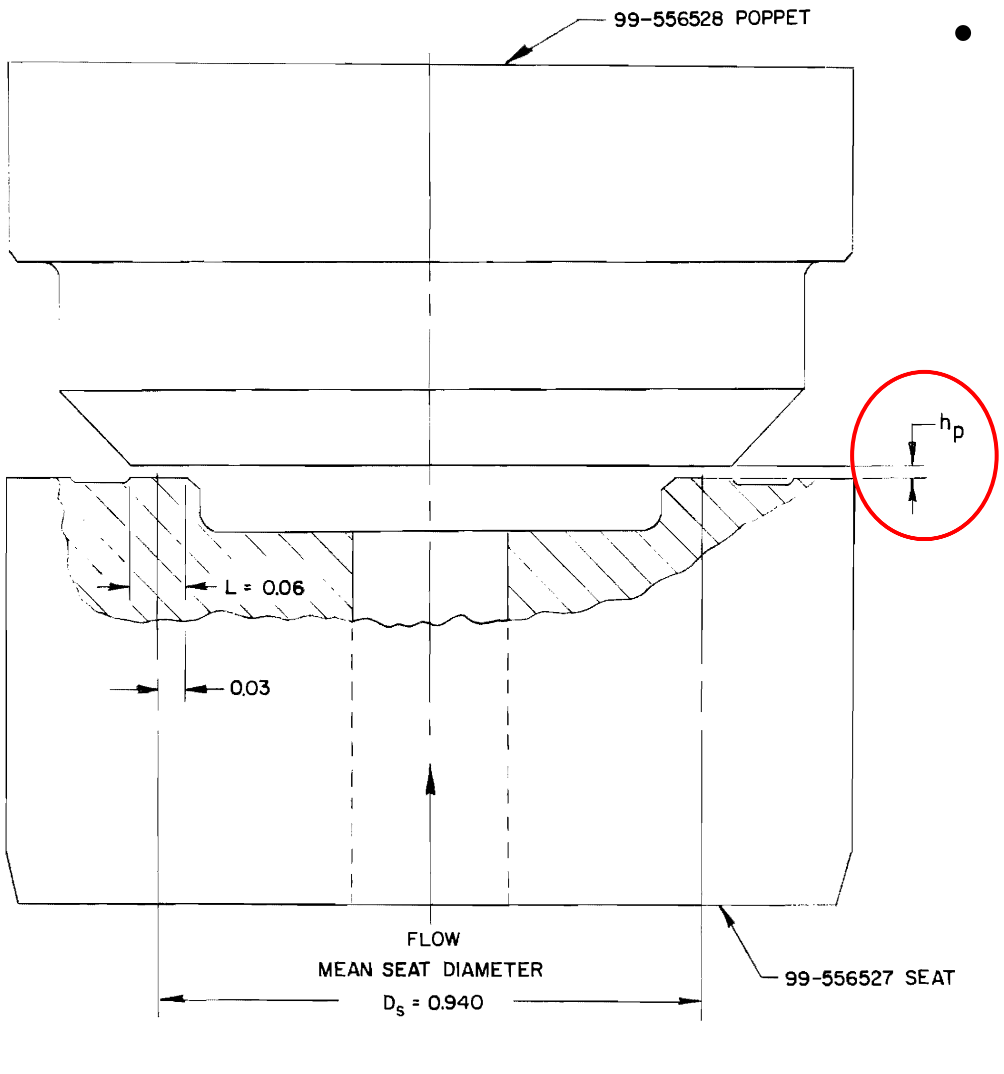
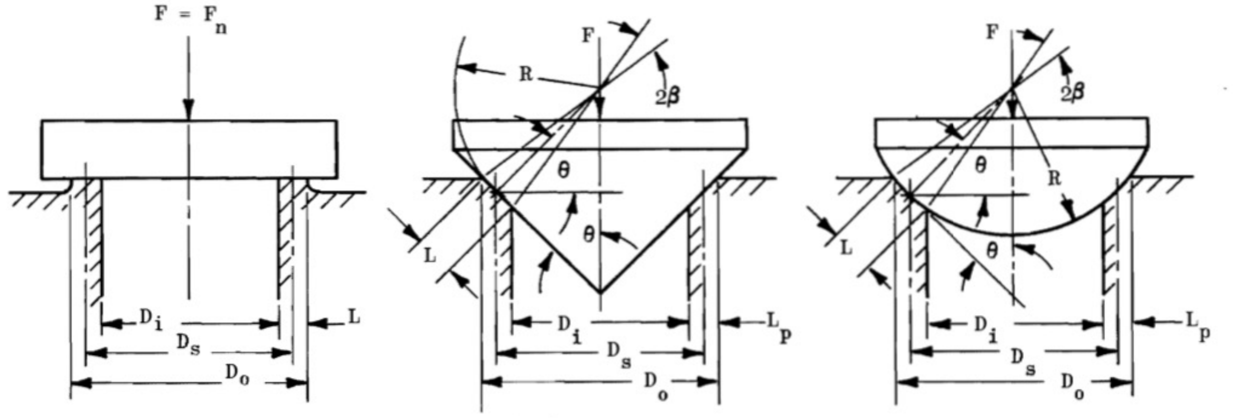
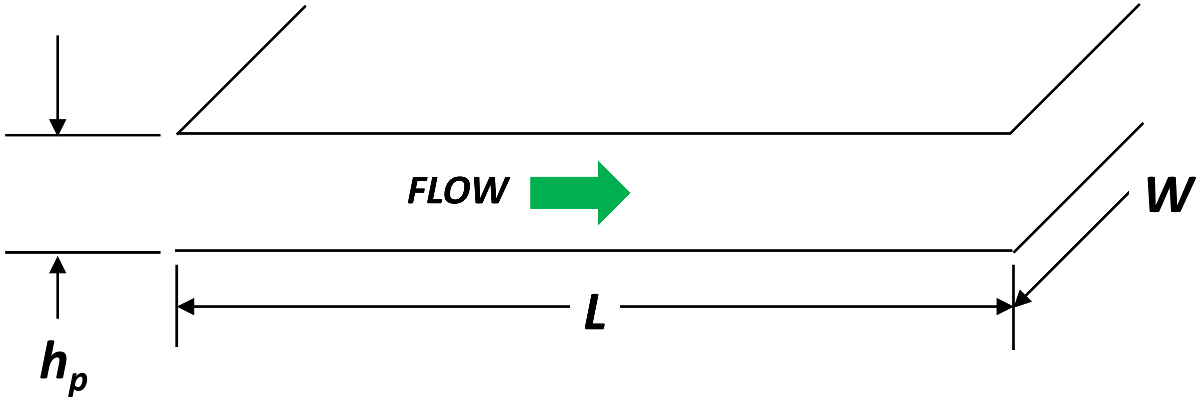


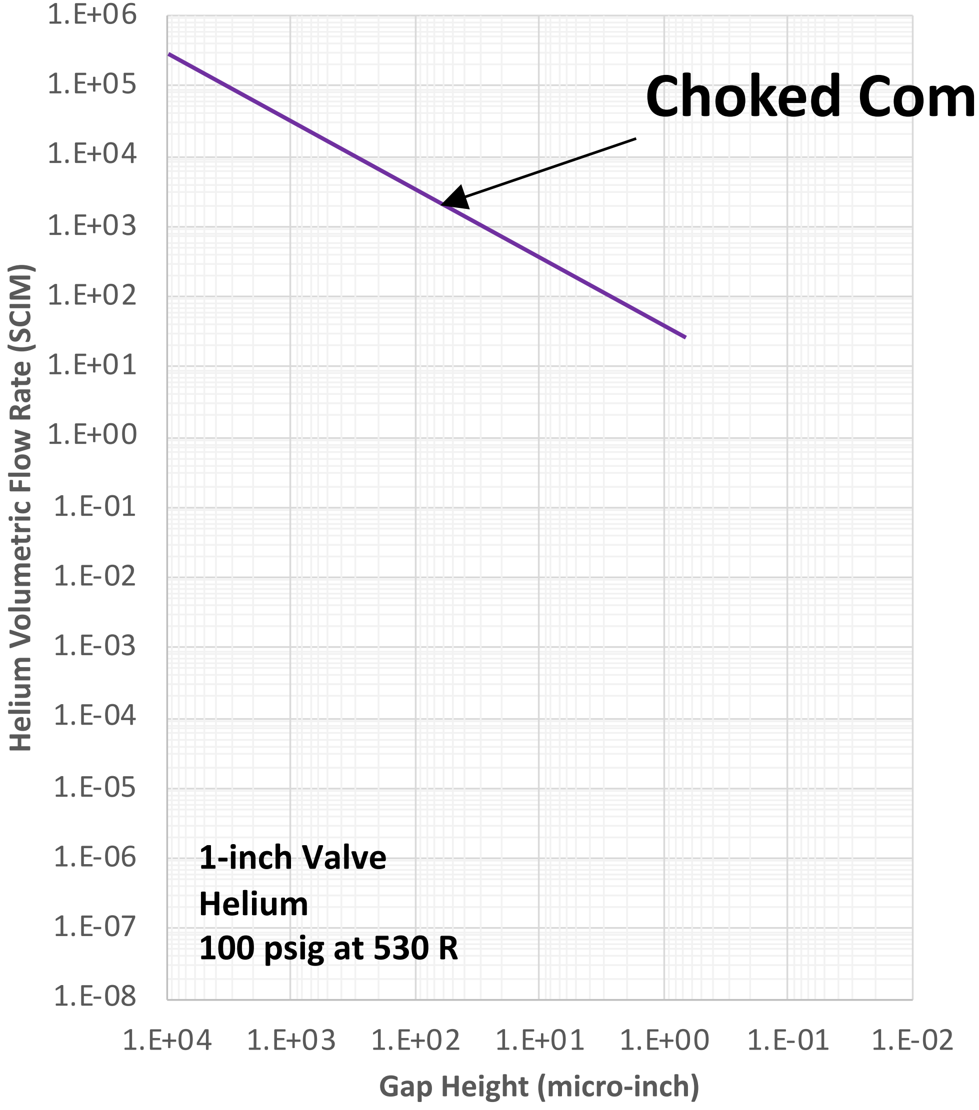
Figure 8. Typical 1.0-Inch Poppet and Seat Model

- Model assumes two parallel rings, unrolled into a long, thin rectangular passage of length *L* and width *W* (mean perimeter) with gap height h_p.





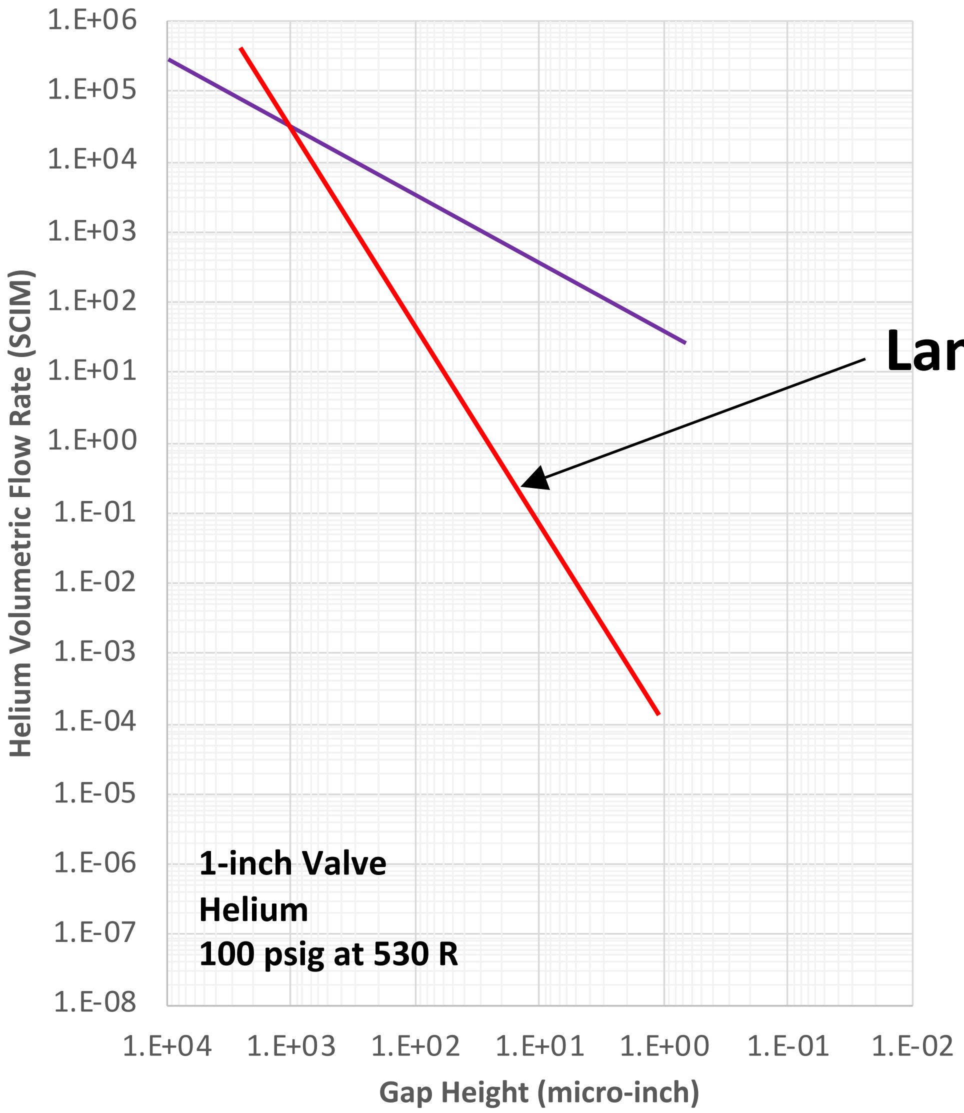
Poppet Seal Leakage Model – Gas Flow Regimes



$$\dot{m} = C_d W h_p P_o \sqrt{\frac{\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

- Example here is a 1-inch diameter valve at 530 degrees Rankine and 100 pounds per square inch discharging to standard atmospheric pressure.
- Note: A corresponding framework for liquid leakage is described in the report and summarized on chart 20.
- SCIM = standard cubic inches per minute

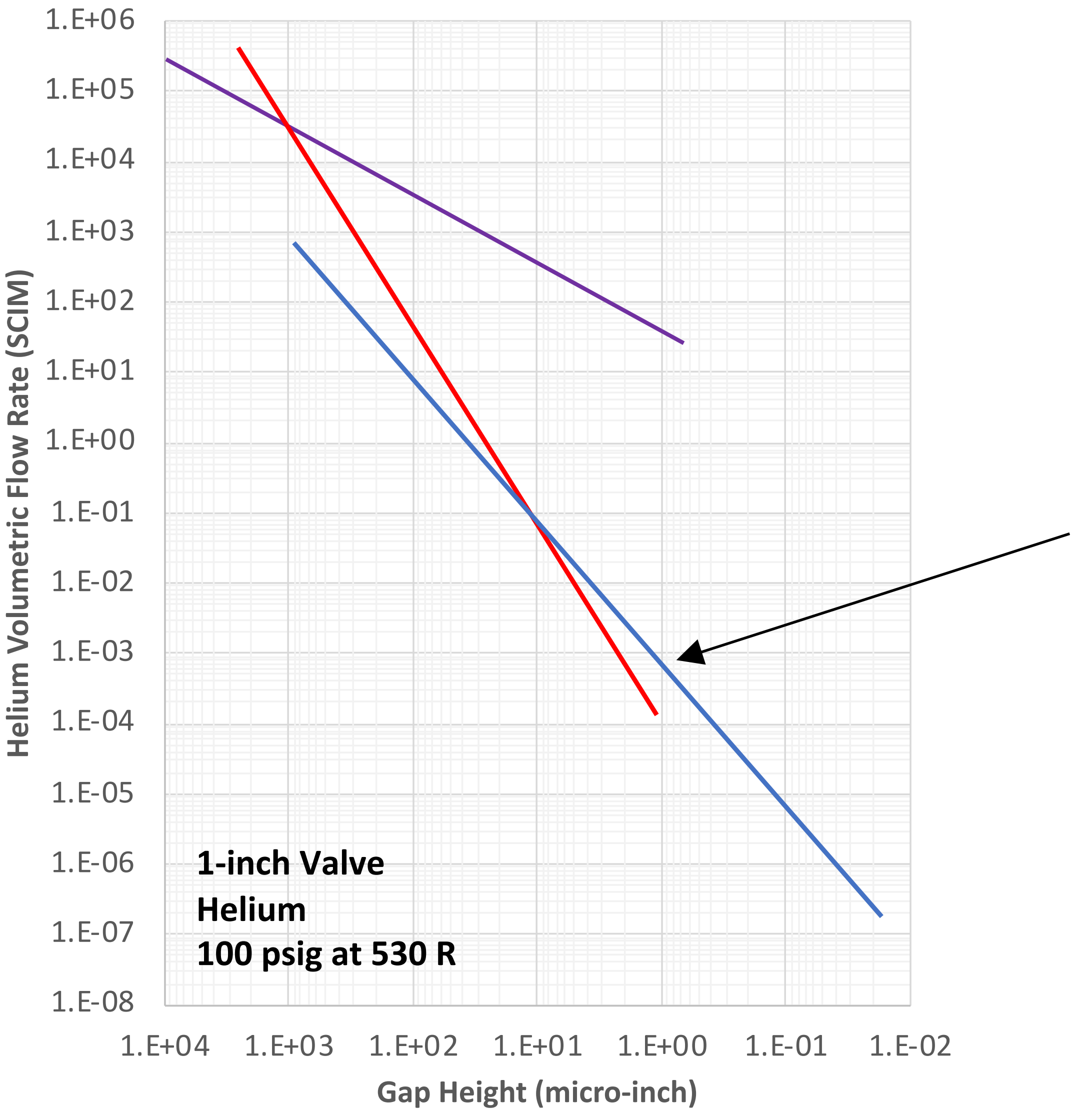
Poppet Seal Leakage Model – Gas Flow Regimes (cont)



Laminar Flow aka "Hagen–Poiseuille Flow" ~ h_p^3

$$\dot{m} = \frac{W h_p^3}{24 \mu L R T}(p_1^2 - p_2^2)$$

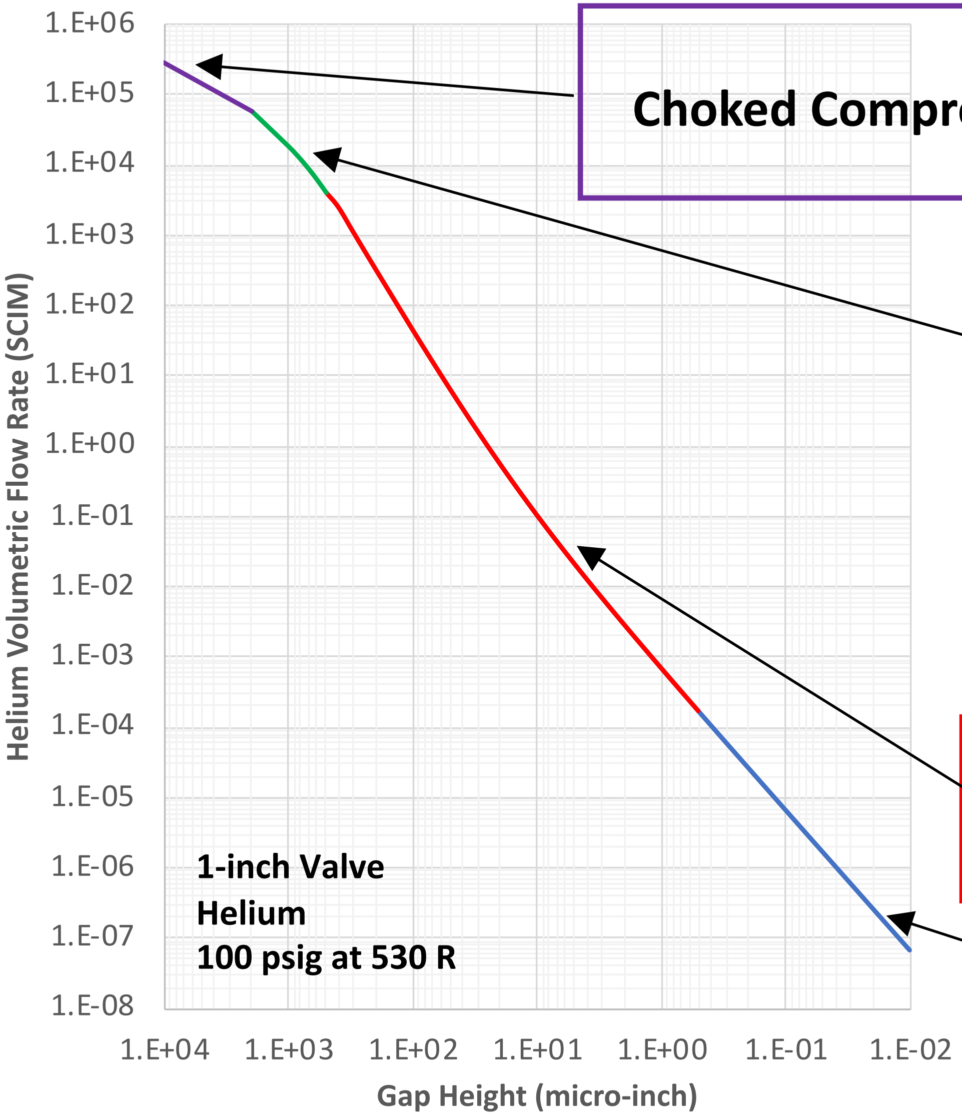
Poppet Seal Leakage Model – Gas Flow Regimes (cont)



Molecular Flow ~ h_p^2

$$\dot{m} = \frac{4}{3}\sqrt{\frac{2g}{\pi RT}}\frac{W h_p^2}{L}(p_1 - p_2)$$

Poppet Seal Leakage Model – Gas Flow Regimes (cont)



Choked Compressible Orifice aka "Nozzle Flow" $\dot{m} = C_d W h_p P_o \sqrt{\frac{\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$

Turbulent Channel Flow aka "Fanno Flow"

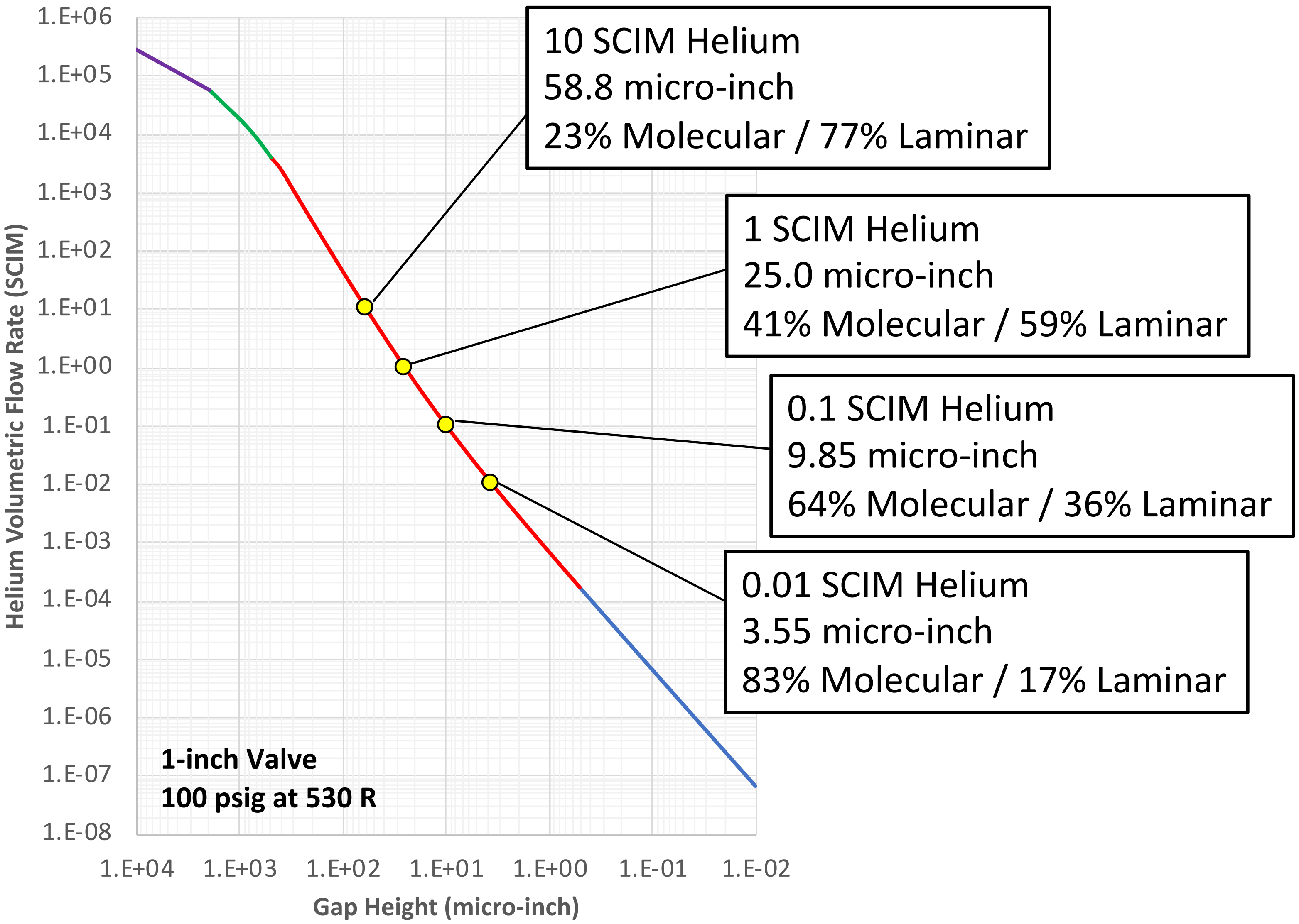
$$\dot{m} = P_o W h_p M \sqrt{\frac{\gamma}{RT_o}}\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma-1}{2-2\gamma}}$$

$$f = \left\{2log\frac{2h_p}{e} + 1.14 - 2log\left[1 + \frac{9.28}{Re\frac{e}{2h_p}\sqrt{f}}\right]\right\}^{-2} \text{ OR } f = \frac{96}{Re}$$

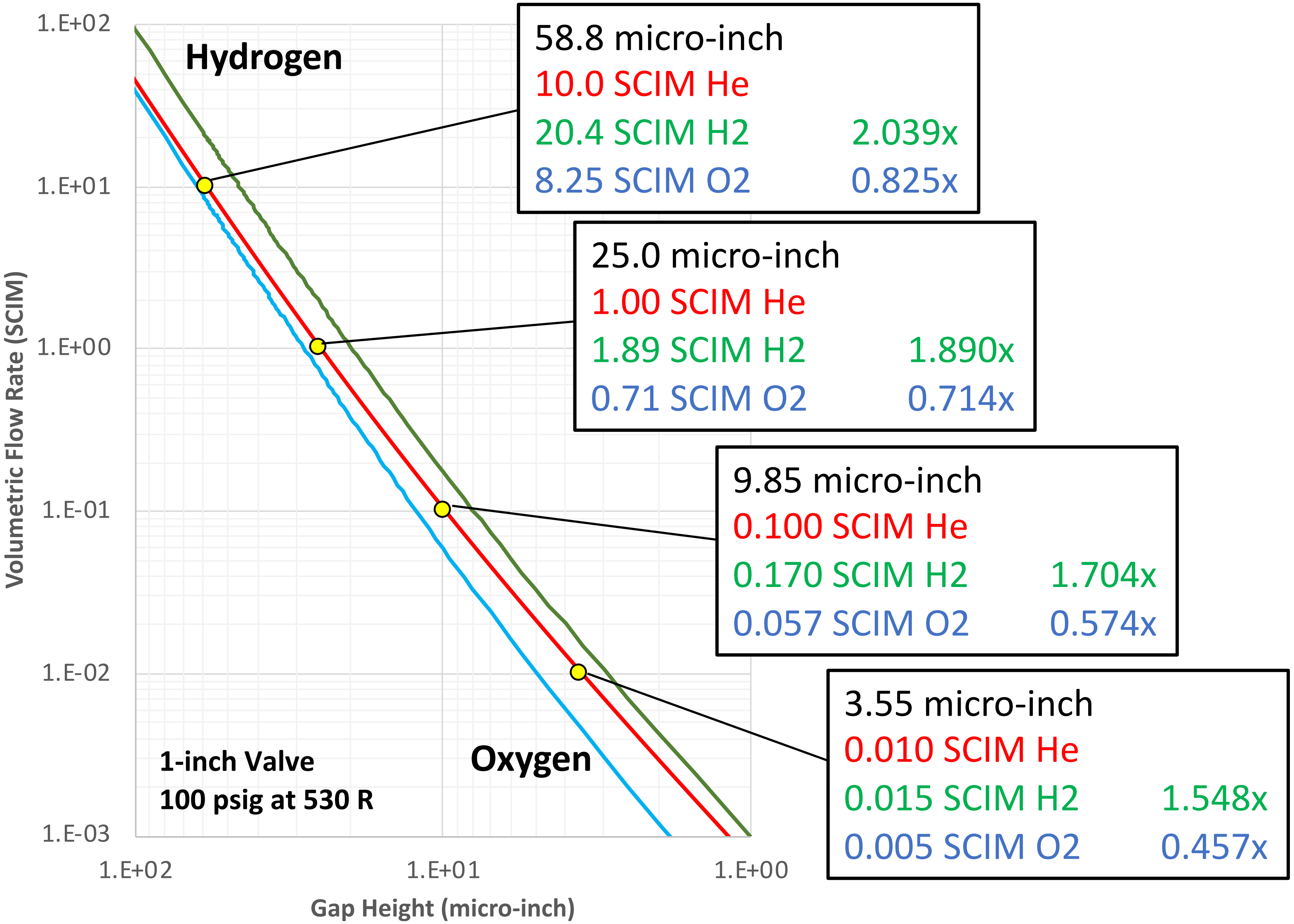
Laminar Flow aka "Hagen–Poiseuille Flow" $\dot{m} = \frac{W h_p^3}{24\mu LRT}(p_1^2 - p_2^2)$

Molecular Flow $\dot{m} = \frac{4}{3}\sqrt{\frac{2g}{\pi RT}}\frac{W h_p^2}{L}(p_1 - p_2)$

Sample Calculation – Gap Height from Helium Leak Rate

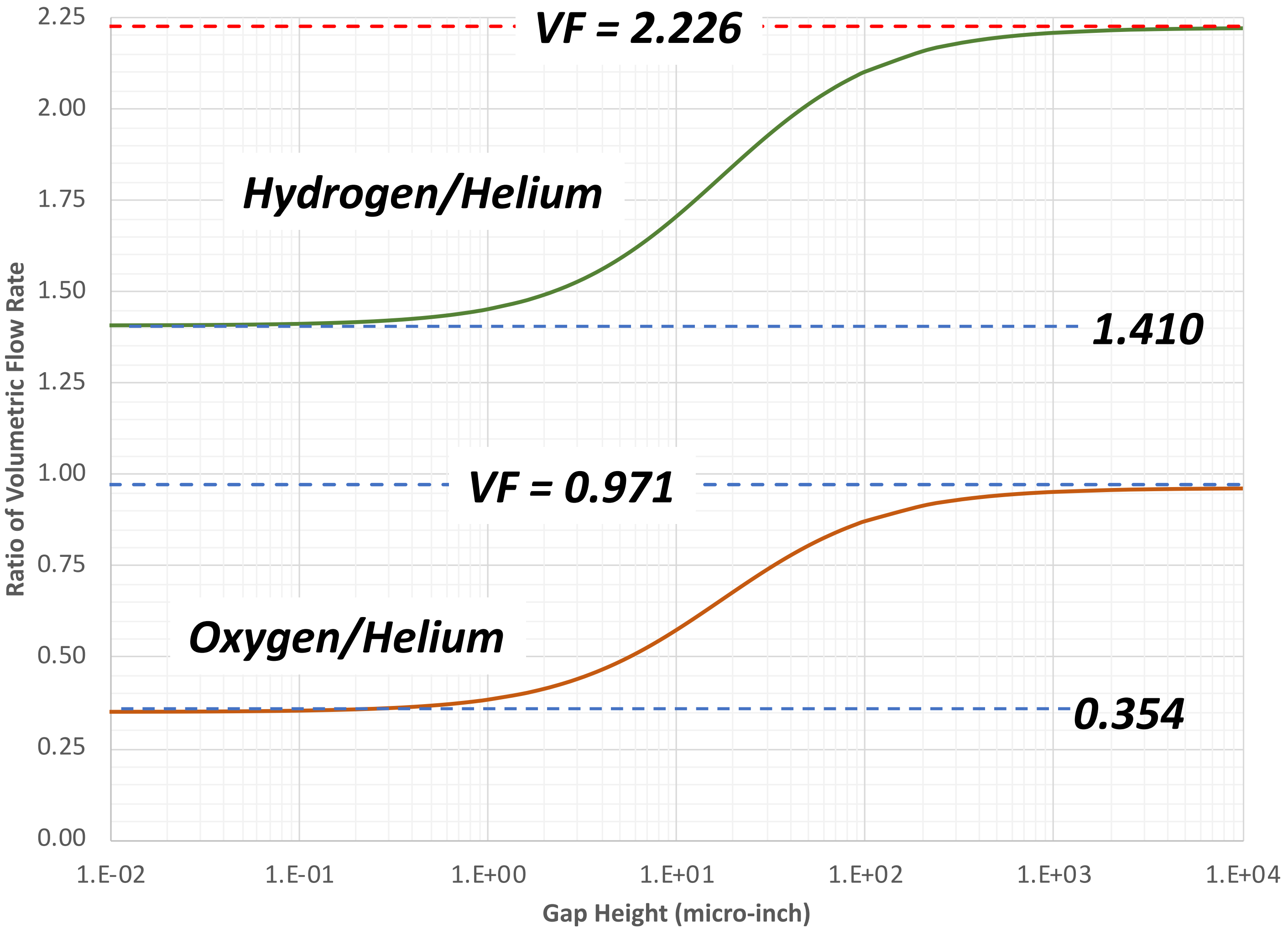


Hydrogen and Oxygen Leak Rate at Equivalent Gap Height



Comparison with NASA-STD-7012

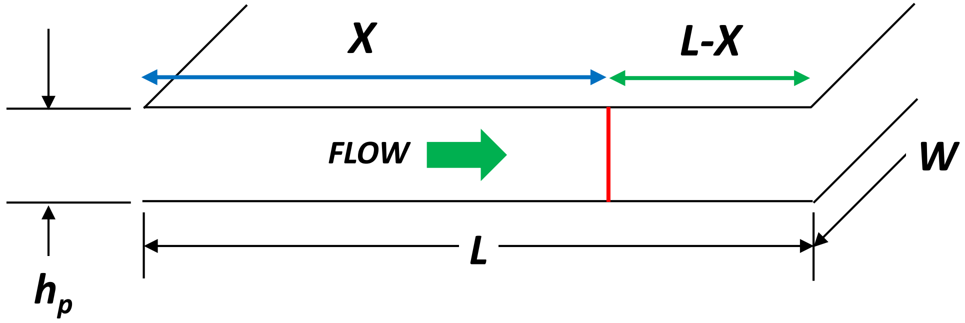
- The two methods converge at large gap heights and all laminar flow.
- At combined molecular or molecular only flow, however, the standard over predicts the leakage.
- Temperature effect on viscosity not evaluated here as identical temperatures were assumed.



Poppet Seal Leakage Model – Liquid Flow

- The model is based on isothermal, laminar flow between parallel plates:

$$Q_{LIQ} = \frac{Wh^3[p_1 - p_2]}{12\mu L}, \qquad Q_{GAS} = \frac{Wh^3[p_1^2 - p_2^2]}{24\mu LRT\rho_{STD}}$$



- If liquid is present, adiabatic or flash evaporation will occur in the leak passage if expelling to vacuum.

- The model was updated with the following:

$$\dot{m}_{LIQ} = \frac{\rho_{LIQ} W h_p^3 [p_1 - p_2]}{12\mu_{LIQ} X}$$

  - A saturation line where liquid evaporates was assumed somewhere along the passage with liquid upstream and gas downstream. Pressure at this interface is vapor pressure.

$$\dot{m}_{GAS} = \dot{m}_{LAM} + \dot{m}_{MOL} = \frac{W h_p^3 [p_1^2 - p_2^2]}{24\mu_{GAS}[L - X]RT} + \frac{4}{3}\sqrt{\frac{2g_c}{\pi RT}}\frac{W h_p^2 [p_1 - p_2]}{[L - X]}$$

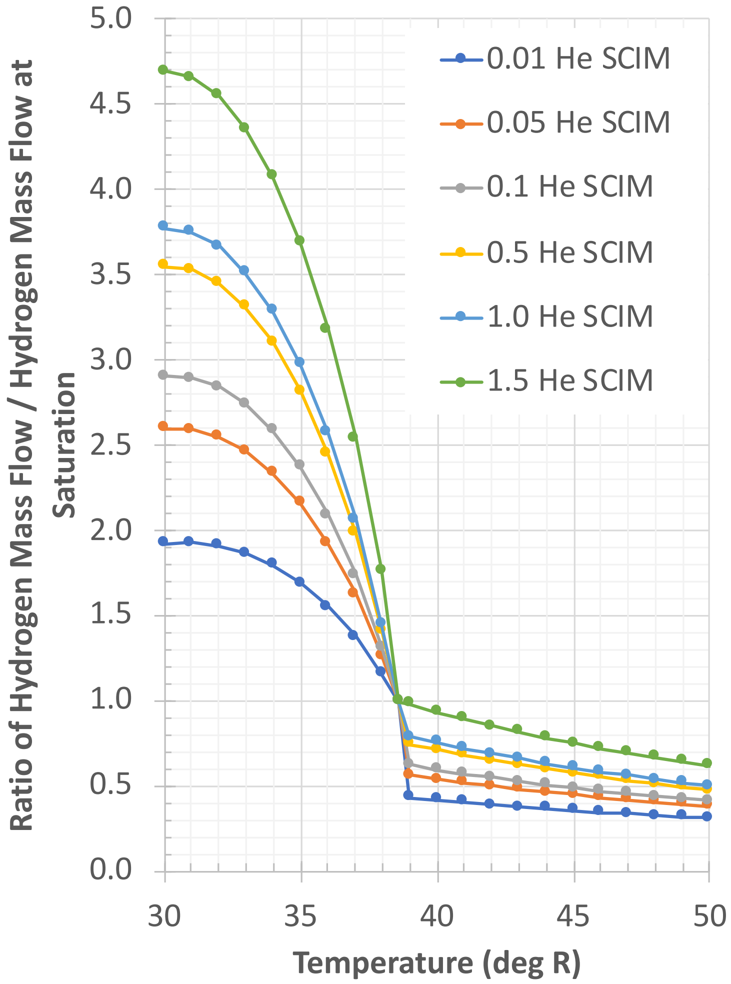
  - Downstream of the saturation line the same molecular and laminar gas flow equations described previously are assumed.

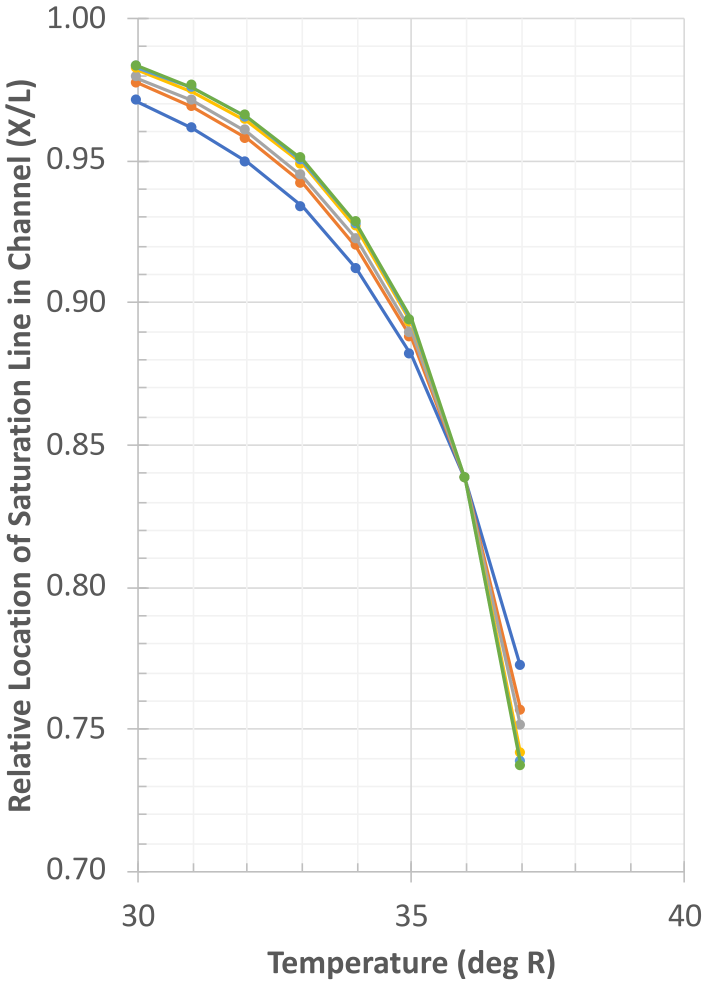
  - A bubble point type correction was added to the upstream pressure to account for surface tension effects and the “wicking” of liquid in the passage.

$$\Delta P_{EV} = \frac{4\cos\theta\ \sigma}{2h_p}$$

Poppet Seal Leakage Model – Sample Liquid Flow Results

- Same gap heights and geometry assumed with liquid at 20 psia.
- Liquid model results converge on gas-only results at saturation temperatures.
- Liquid model shows evaporation in the passage at all temperatures with saturation line approaching X = L with decreasing temperature.
- Minimum loss for propellant storage achieved at or near saturation temperature.





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- Tellier, G.F., *Poppet and Seat Design Data for Aerospace Valves*, AFRPL-TR-66-147, Rocketdyne Division, July 1966
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- Hord, J., *Correlations for Predicting Leakage Through Closed Valves*, NBS Tech Note 355, August 1967
- Blair, A.V., *Measurement and Correlation of Helium and Fluid Leak Rates*, Boeing Co, July 1970
- Tellier, G.F., *Space Shuttle Prototype Check Valve Development*, Rocketdyne Division, September 1976
- Bomelburg, H.J., *Estimation of Gas Leak Rates Through Very Small Orifices and Channels*, Battelle Pacific Northwest Laboratories, February 1977

References

- Gas and liquid leakage framework from Tellier, G.F., *Poppet and Seat Design Data for Aerospace Valves*, AFRPL-TR-66-147, Rocketdyne Division, July 1966

TABLE 2-2. GAS LEAKAGE EQUATIONS

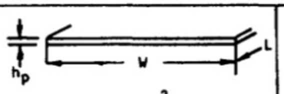
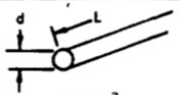
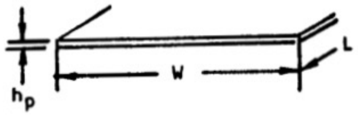
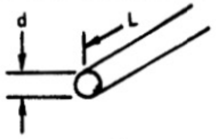
Flow Regime	Flow Equations		Boundary Parameters
Permeation	$\dot{w} = \frac{K_p A(P_1 - P_a)}{L}$, K_p is a function of seal material, fluid and temperature		No boundary; leak rate varies exponentially with temperature
Molecular Flow	 $\dot{w} = \frac{4}{3}\sqrt{\frac{2g}{\pi RT}}\frac{Wh_p^2}{L}(P_1 - P_a)$	 $\dot{w} = \frac{1}{6}\sqrt{\frac{2\pi g}{RT}}\frac{d^3}{L}(P_1 - P_a)$	$K_N = \frac{\lambda}{h_p}$ or $\frac{\lambda}{d} > 1.0$ $\lambda = \frac{3.6\mu}{P_1 + P_2}\sqrt{RTG}$
Laminar Flow	$\dot{w} = \frac{Wh_p^3 (P_1^2 - P_E^2)}{24\mu LRT}$	$\dot{w} = \frac{\pi d^4 (P_1^2 - P_2^2)}{256\mu LRT}$	$K_N < 0.01$, Re <500 $Re = \frac{2\dot{w}}{\mu Wg} = \frac{4\dot{w}}{\pi d\mu g}$
Choked Turbulent Flow	$\dot{w} = AP_1M_1\sqrt{\frac{Kg}{RT_1}}$, $\beta_1 = 1 + \frac{K-1}{2}M_1^2$ $T_1 = T_o/\beta_1$; $T^* = 2\beta_1 T_1/(K+1)$; $P_1 = P_o/\beta_1 EXP \frac{K}{K-1}$ $P^* = M_1P_1\sqrt{\frac{T^*}{T_1}}$, $f = \left\{2LOG\frac{d}{e} + 1.14 - 2LOG\left[1 + \frac{9.28}{Re(\frac{e}{d})\sqrt{f}}\right]\right\}^{-2}$ $d = 2h_p$ in f equation for plate flow, $e \cong 3$ (AA) $A = Wh_p = \pi d^2/4$, Re (see above) $L \equiv L^* = \frac{2h_p}{f}\left[\frac{1 - M_1^2}{KM_1^2} + \frac{K+1}{2K} LN \frac{(K+1)M_1^2}{2\beta_1}\right]$, ($2h_p = d$ for hole)		(1) 500 < Re < 2000 For plates f = 96/Re For hole f = 64/Re (2) Re > 2000 f = function e/d (3) L/d or $L/h_p > 10$
Nozzle Flow	$\dot{w} = \frac{CAP_o}{\sqrt{RT_o}}\sqrt{gK\left(\frac{2}{K+1}\right)EXP\frac{K+1}{K-1}}$, C is function of entrance geometry and L/d		L/d or $L/h_p < 10$

TABLE 2-3. LIQUID LEAKAGE EQUATIONS

Flow Regime	Flow Equations		Boundary Parameters
Laminar Flow	 $\dot{w} = \frac{\rho Wh_p^3 \Delta P}{12\mu L}$	 $\dot{w} = \frac{\pi\rho d^4 \Delta P}{128\mu L}$	Re < 2000 $Re = \frac{2\dot{w}}{\mu Wg} = \frac{4\dot{w}}{\pi d\mu g}$
Turbulent Flow	$\dot{w} = A\sqrt{\frac{2\rho C\Delta P}{K_{f1} + fL/d + K_{fE}}}$ $f = \left\{2LOG\frac{d}{e} + 1.14 - 2LOG\left[1 + \frac{9.28}{Re(\frac{e}{d})\sqrt{f}}\right]\right\}^{-2}$ $d = 2h_p$ in f equation for plate flow, $e \cong 3$(AA) $A = Wh_p = \pi d^2/4$, Re (see above)		Re > 2000 L/d or $L/h_p > 10$
Nozzle Flow	$\dot{w} = CA\sqrt{2g\rho\Delta P}$ $A = Wh_p = \pi d^2/4$ C is function of entrance geometry and L/d		L/d or $L/h_p < 10$