Interlude: Vacuum Technology in a Nutshell

Topics:
Chamber: materials, seals
Pump: speed, pressure range
Pipes, valves: conductance, material

Component missing from photo?

Pressure has one of the largest dynamic ranges of any measured quantity. It also has a variety of units.

SI: 1Pa = 1 N/m^2

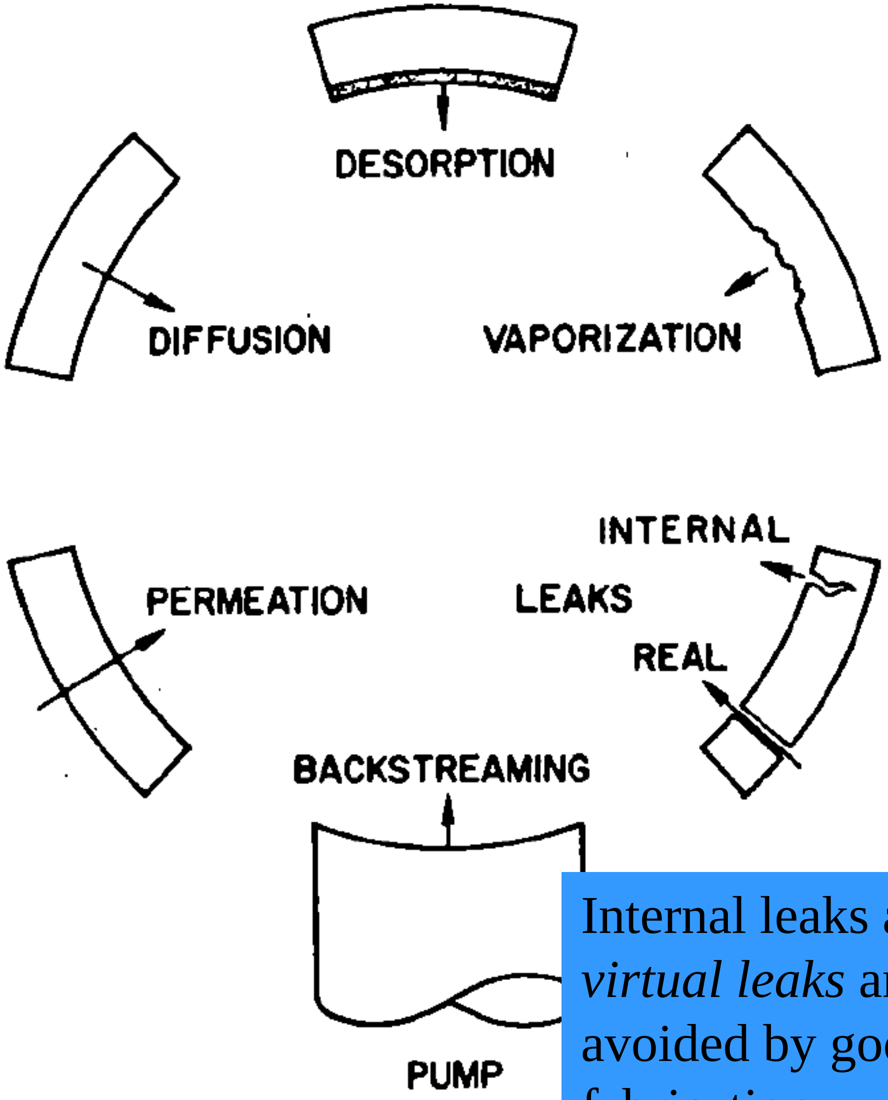
1 atm = 760 torr = 101,325 Pa

1 bar = 10^5 Pa   1.33 mbar = 1 torr

Vacuum Technology, Gas Sources

Summary Figure 4.1 in O'Hanlon, 2nd Ed. & 3rd Ed.

Sources of residual gas after the bulk filling gas has been removed.



Internal leaks are often called *virtual leaks* and can only be avoided by good design and fabrication.

Vacuum Technology, Gas Properties

The total pressure can be measured but the microscopic makeup and behavior of the gas(es) are very important in vacuum systems.

Dry Air: 78.08 % nitrogen, 20.94 % oxygen, 0.93% Ar, 0.03% CO_2 …

Humid Air: estimate partial pressure of H_2O as 24 Torr * (relative Humidity) (up to ~3% and is temperature dependent)

Mean gas velocity:

$$v = \left(\frac{8k_B T}{\pi m}\right)^{1/2} = \left(\frac{8RT}{\pi\, MM}\right)^{1/2} = \frac{2512\, m/s}{\sqrt{MM\,(g/mol)}}$$

Effusion:

$$\frac{v_1}{v_2} = \left(\frac{MM_2}{MM_1}\right)^{1/2}$$

Mean Free path:

$$\lambda = \frac{1}{\sqrt{2}\,\pi\, d^2 \rho_n} = \frac{6.6\, mm\, Pa}{P}$$

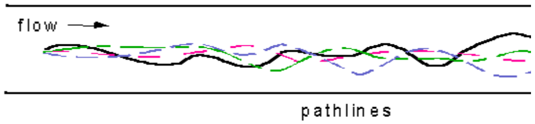
Vacuum Technology, Gas Flow –1–

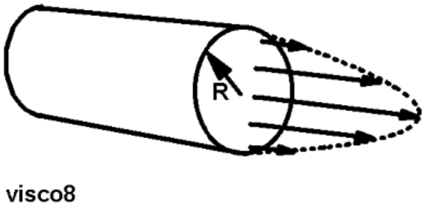
Two dimensionless numbers are used to characterize gas flow regimes:

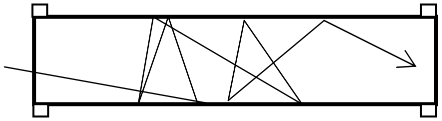
Knudsen’s Number: Kn = λ / d λ – mean free path, d – pipe diameter

Reynold’s Number: Re = U ρ d / η U – stream velocity, ρ – density, η – viscosity

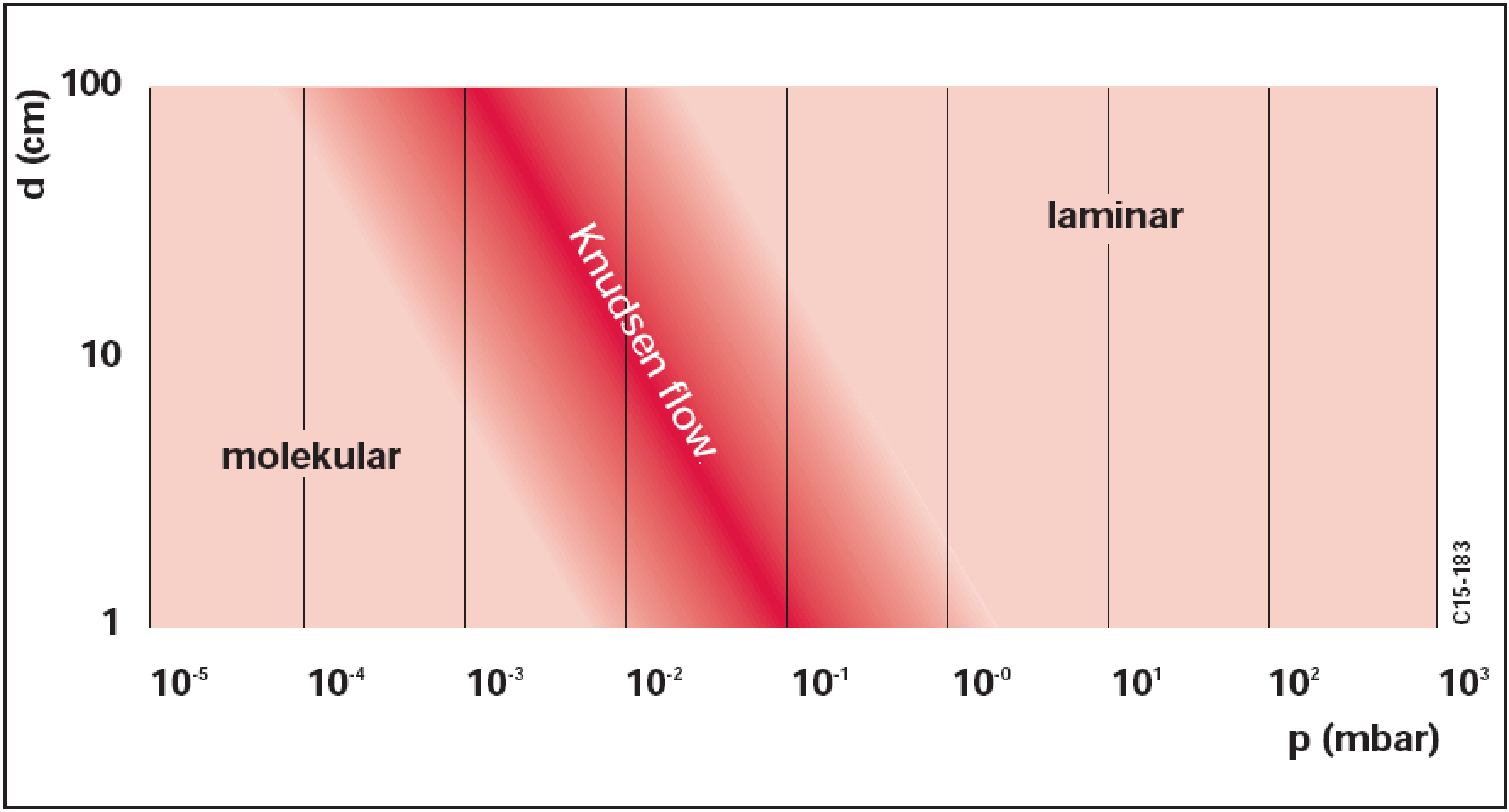
	Kn	Re
Turbulent	< < 0.01	> 2200
Viscous Laminar	< 0.01	< 1200
Molecular	>1	< 1200







Flow Regimes auf deutsch



Pfeiffer Vacuum, “Working with Turbopumps”

http://www.pfeiffer-vacuum.de/cnt/en/706/ “Literature”

Vacuum Technology, Gas Flow –2–

Gas flow can be analyzed in terms of the volume of gas, at some pressure, that passes a plane in a fixed period of time: $Q = d(PV)/dt$ where Q is called the "throughput" and has many sets of dimensions along the lines of torr-l/s .

All gases behave ideally at low pressure and nearly ideal under standard conditions.

$$Q = \frac{d\,PV}{dt} \qquad PV = nRT \rightarrow Q = RT\,\frac{d\,n}{dt} \qquad \text{(if isothermal)}$$

Thus, Q also has units of energy/time = power (i.e. watts).

(A) When the system is in a steady state with a constant pressure:

$$Q = P\,\frac{d\,V}{dt} = P\;S$$

S is the *Speed* of the pump, e.g. liter/s

(B) Whereas for continuous flow through a pipe with a pressure difference:

$$Q = C\left(P_2 - P_1\right)$$

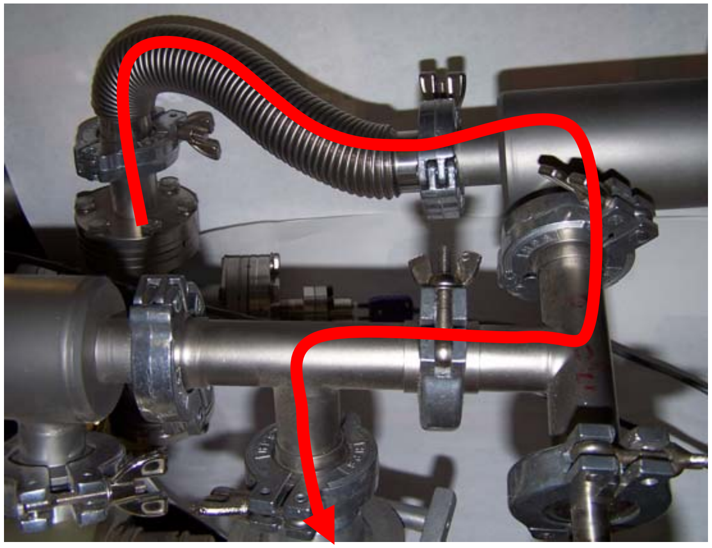
C is the *Conductance* of the pipe, e.g. liter/s

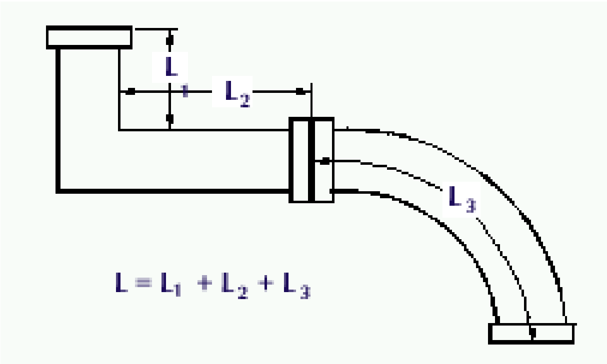
Vacuum Technology, Gas Flow –3–

The so-called fundamental vacuum equation is **PS = C ΔP**   The pump speed, S, is a function that depends on the design of the pump *and* the pressure. Similarly, the conductance, C, depends on the design of the plumbing and also on the pressure.

	Laminar	**Molecular**
Aperture	(complicated)	$A\,v/4$
Long Pipe	$\frac{\pi d^4}{128\eta l}\,\frac{P_1+P_2}{2}$	$(\pi/12)\,v\,d^3/l$

Conductances are combined in reciprocal: $1/C_{total} = 1/C_1 + 1/C_2 + \ldots$





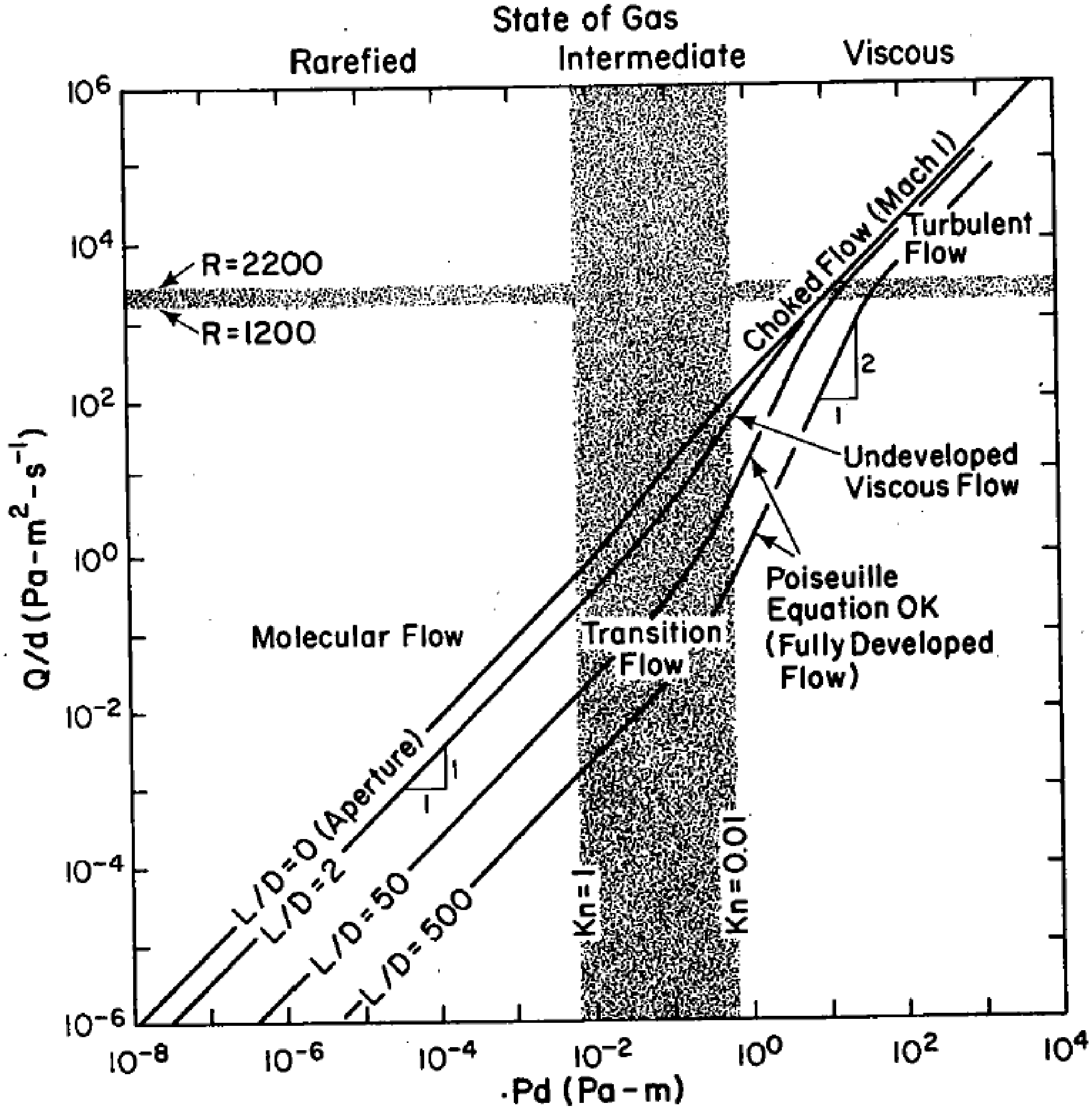
Want: the shortest, straight tubes with largest diameters connected by rounded corners.

Vacuum Technology, Gas Flow –4–

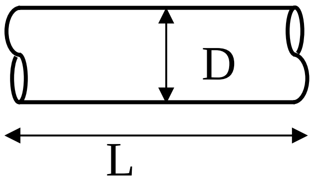
Flow Summary

Figure 3.17
O'Hanlon, 2nd Ed.

Figure 3.18
O'Hanlon, 3rd Ed.



Round tube



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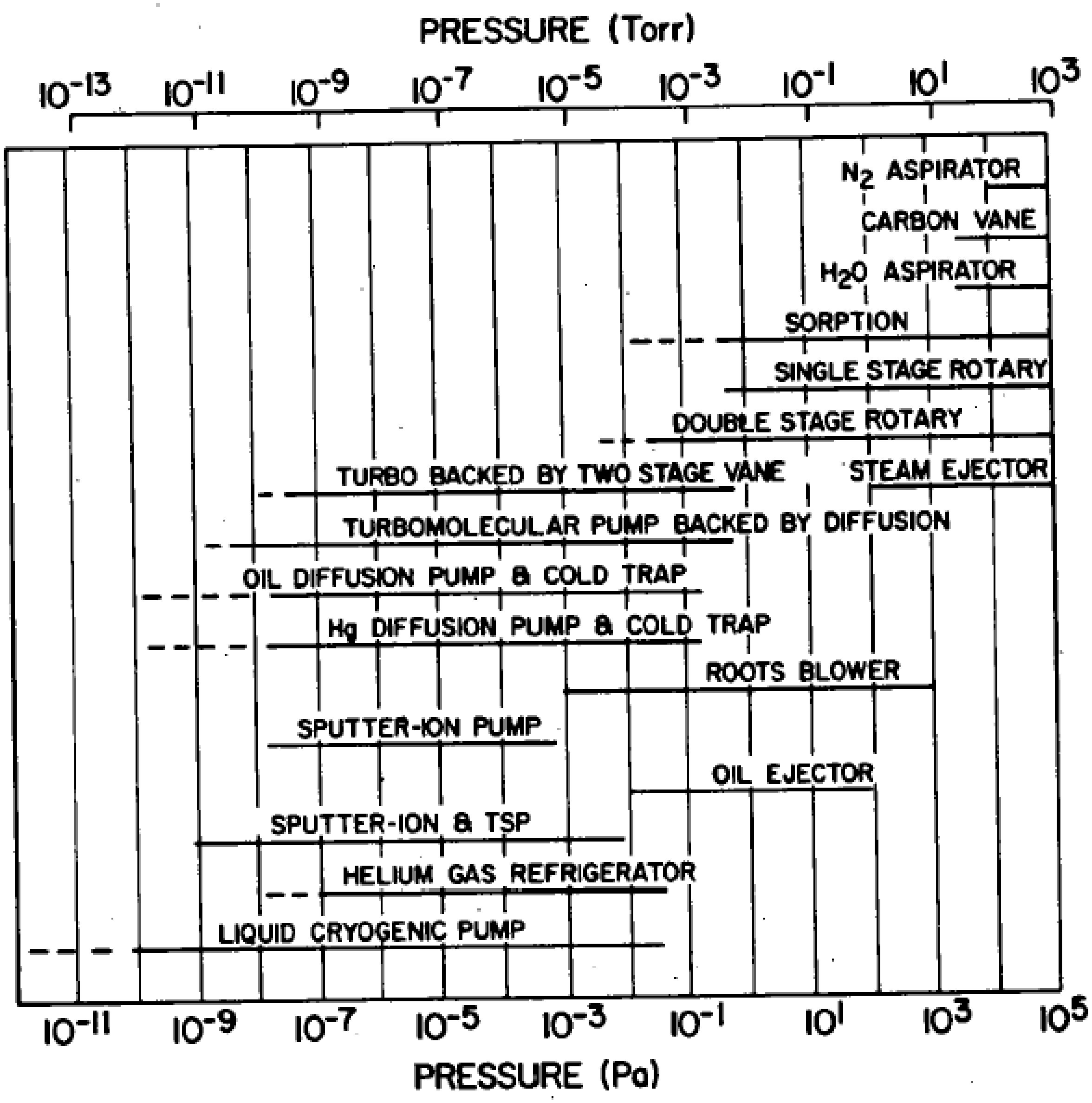
Vacuum Technology, Production –1–

A huge variety of vacuum pumps have been developed over time that use various physical techniques to trap, and in a few cases move, the gas and so are limited to certain pressure ranges.

An important distinction among pumps: Is it sealed or does it have a path from inside to outside during operation?

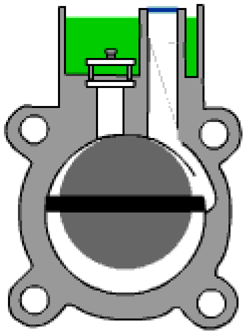
Another distinction is: Are there moving parts or not?

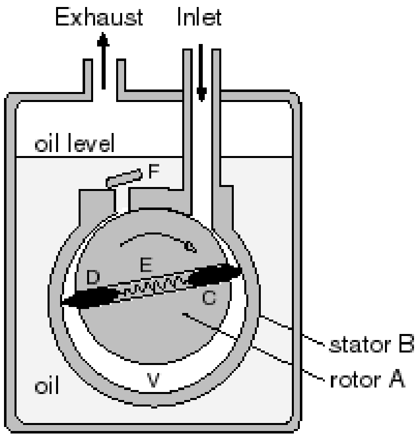


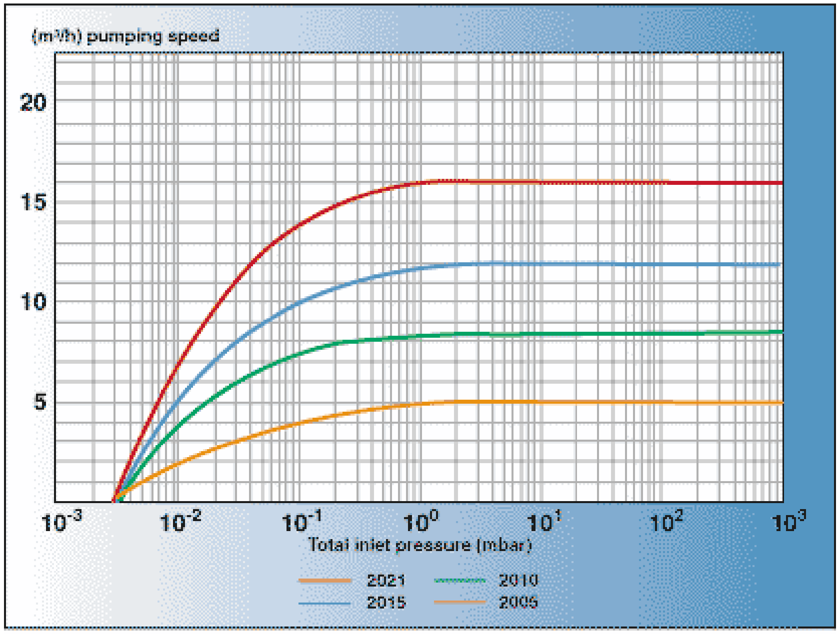
Vacuum Technology, Production –2–

Mechanical pumps: characterized by an eccentric rotor, vanes and stages

Oil-sealed







Alcatel Vane pump

$$S = \frac{dV}{dt} \approx \frac{\Delta V}{\Delta t}$$

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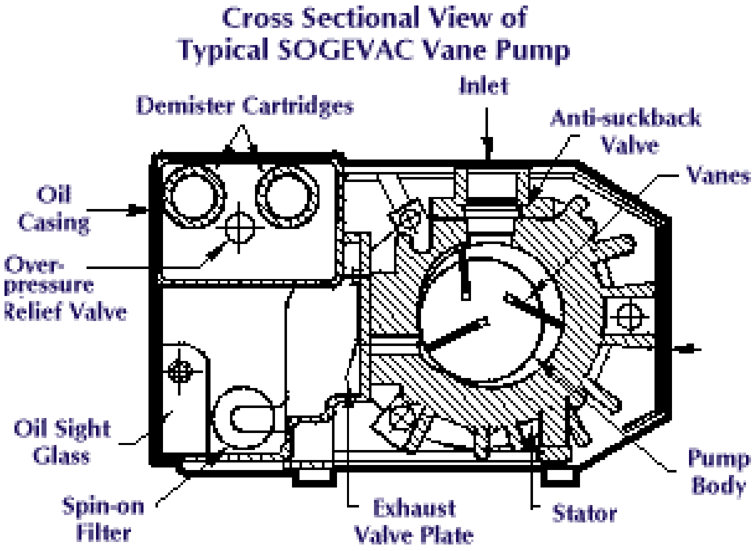
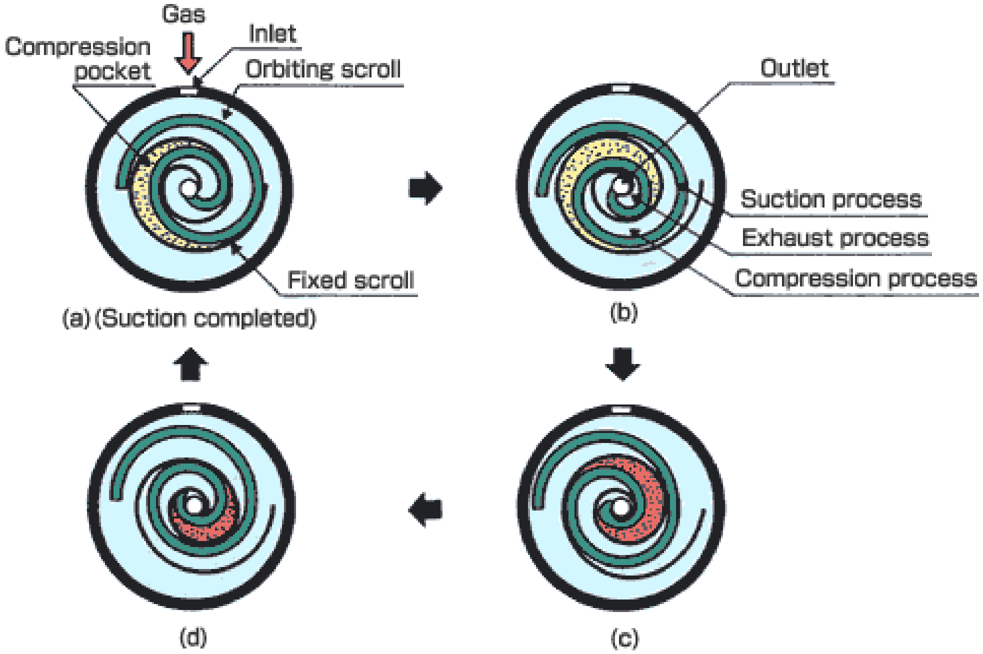
Vacuum Technology, Production –2a–

Mechanical pumps: oil free

Dry Vane



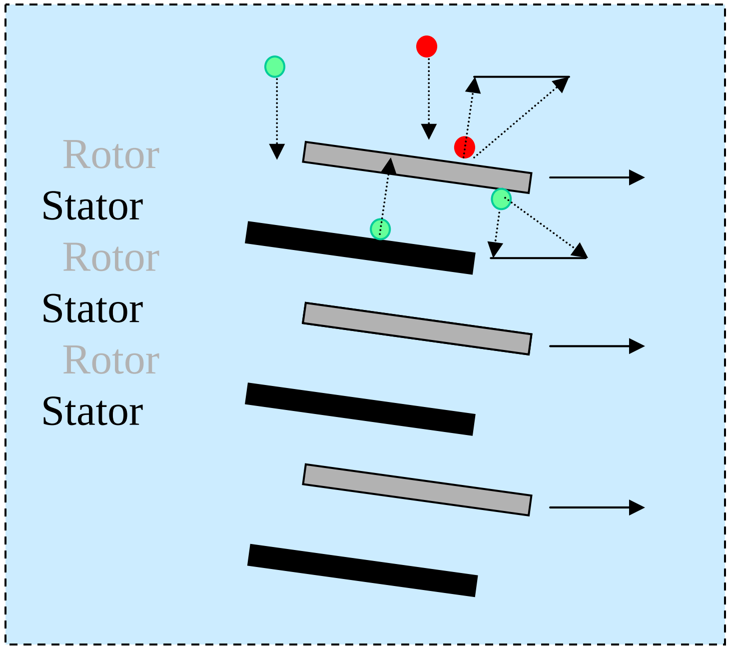
Dry Scroll



Vacuum Technology, Production –3–

High Vacuum pumps: TMP

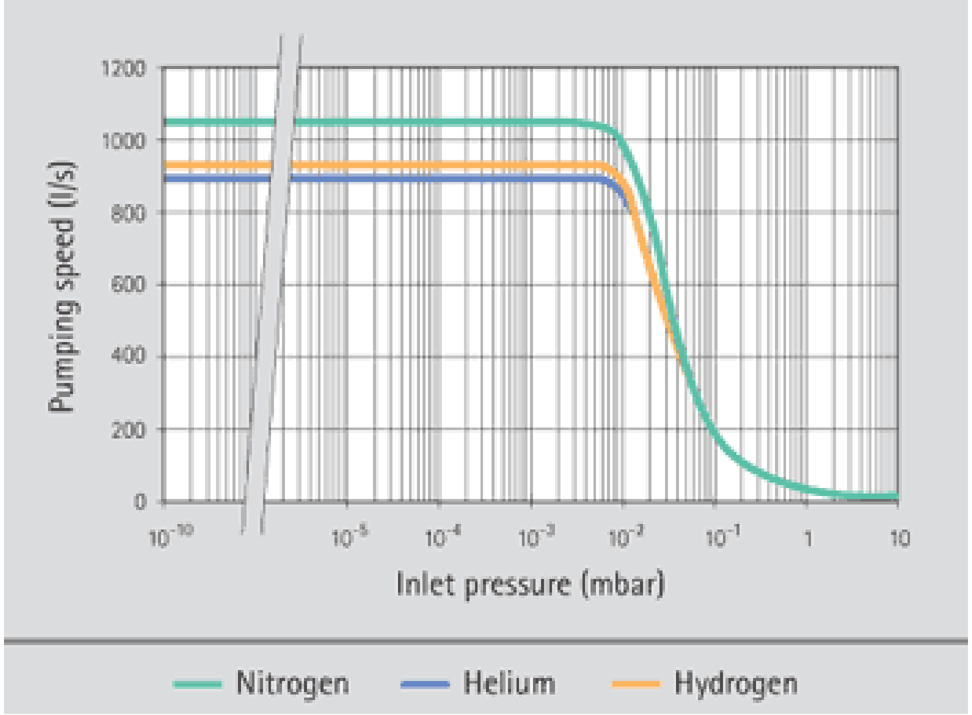
Chamber
(in Molecular flow!)



Pump outlet

$$S_{\max} < C_{aperture} / 2$$

Speed drops with the gas velocity



Varian Turbo-V 1001

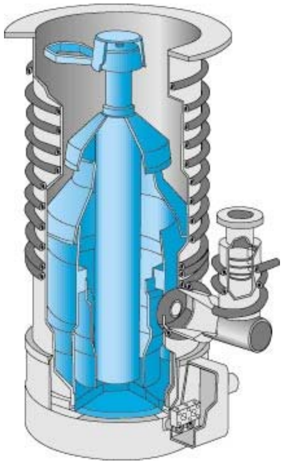
High flow

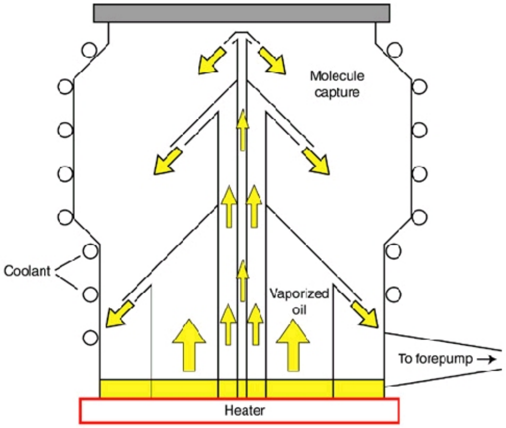
High Compression

Vacuum Technology, Production –4–

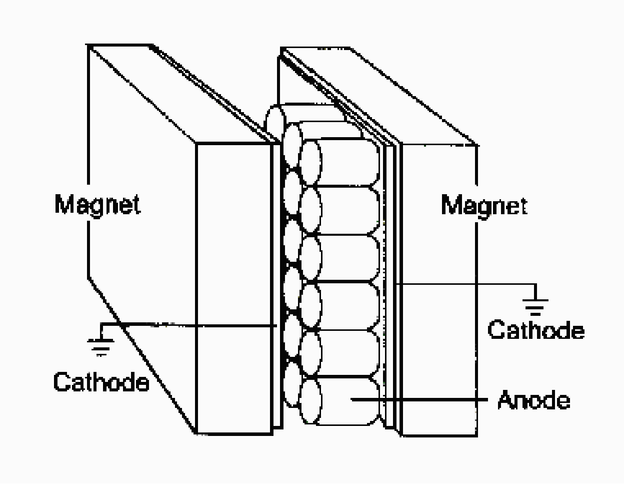
High Vacuum pumps: Diffusion pumps

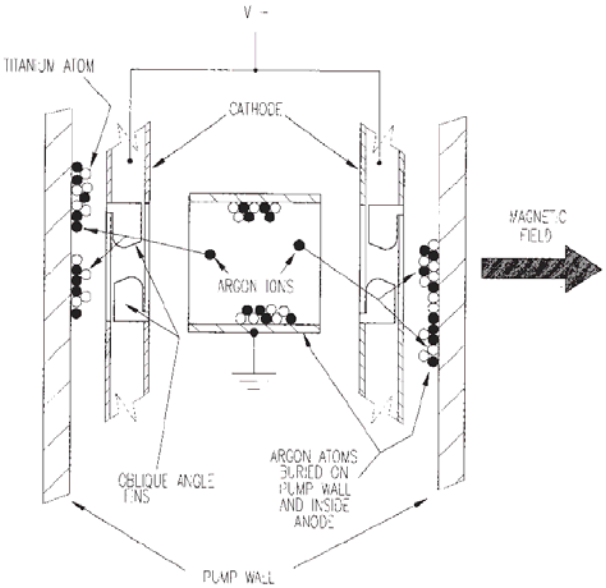
Hot oil-filled, need cold traps
Highest pumping speeds for He
No real limit to size





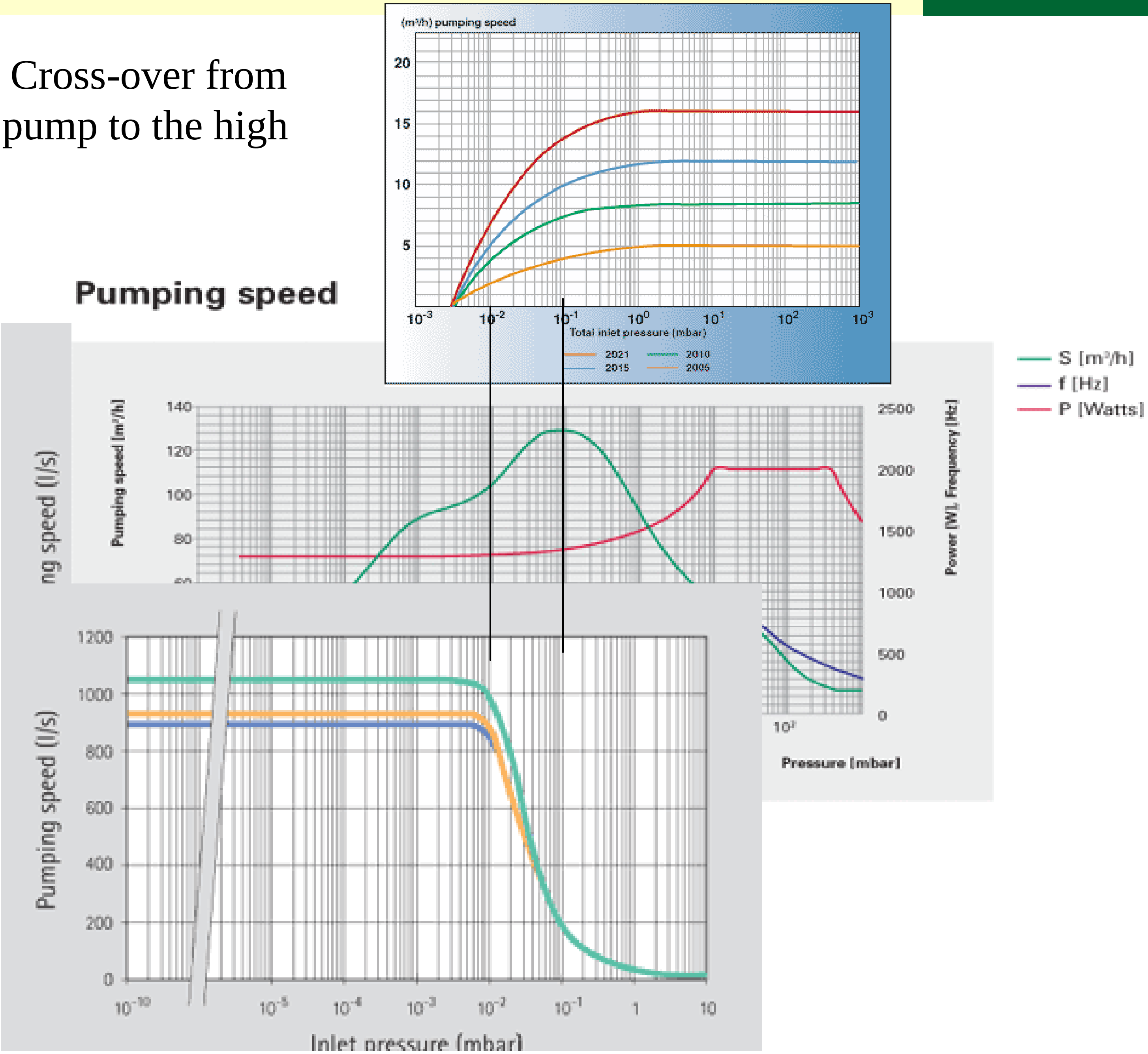
High Vacuum pumps: Ion pumps – closed system





Vacuum Technology, Production –5–

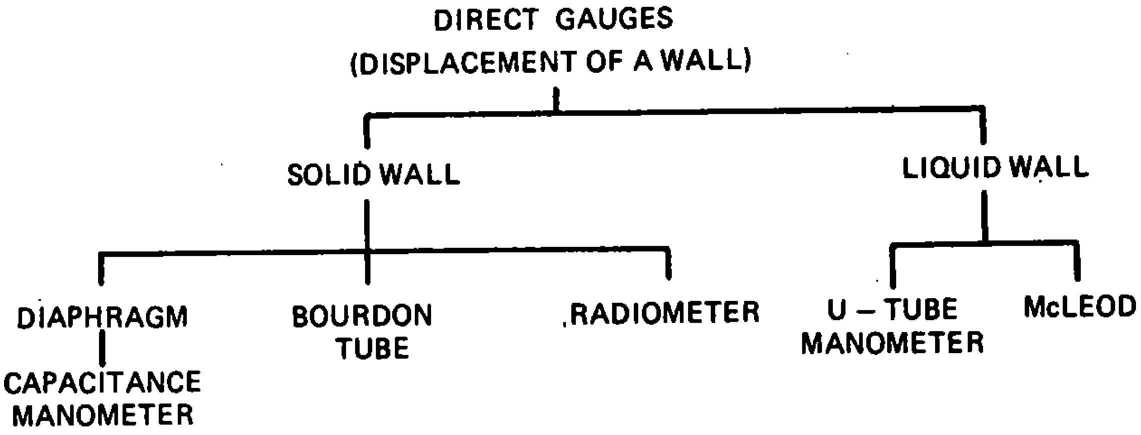
The problem of Cross-over from the mechanical pump to the high vacuum pump:

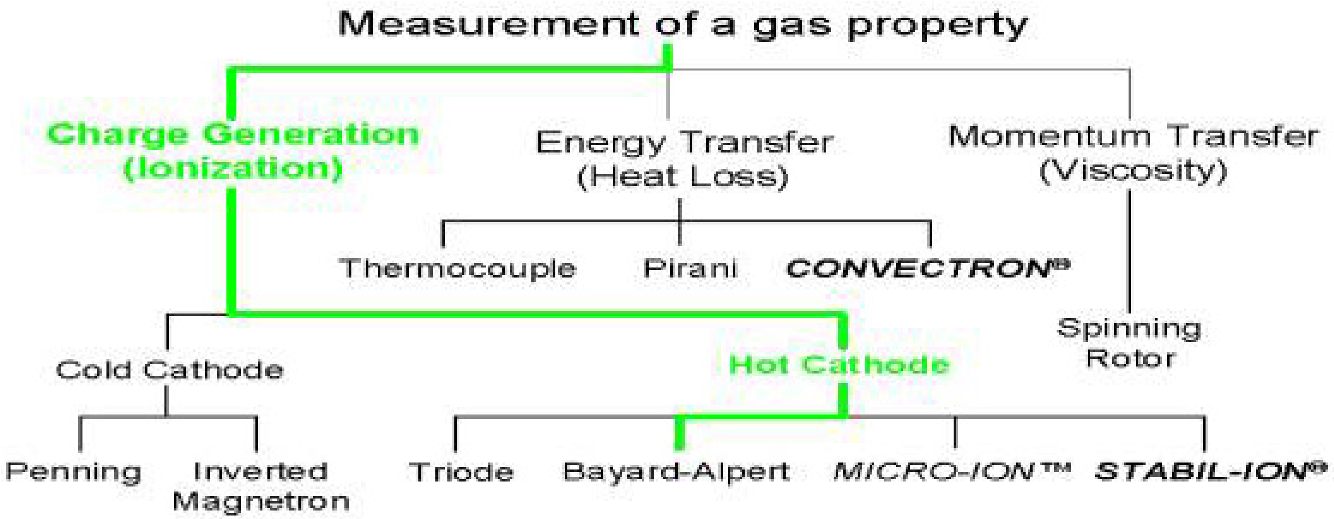


Vacuum Technology, Measurement –1–

Categorization of Vacuum Gauges

Figure 5.1
O’Hanlon,
2nd or 3rd Ed.

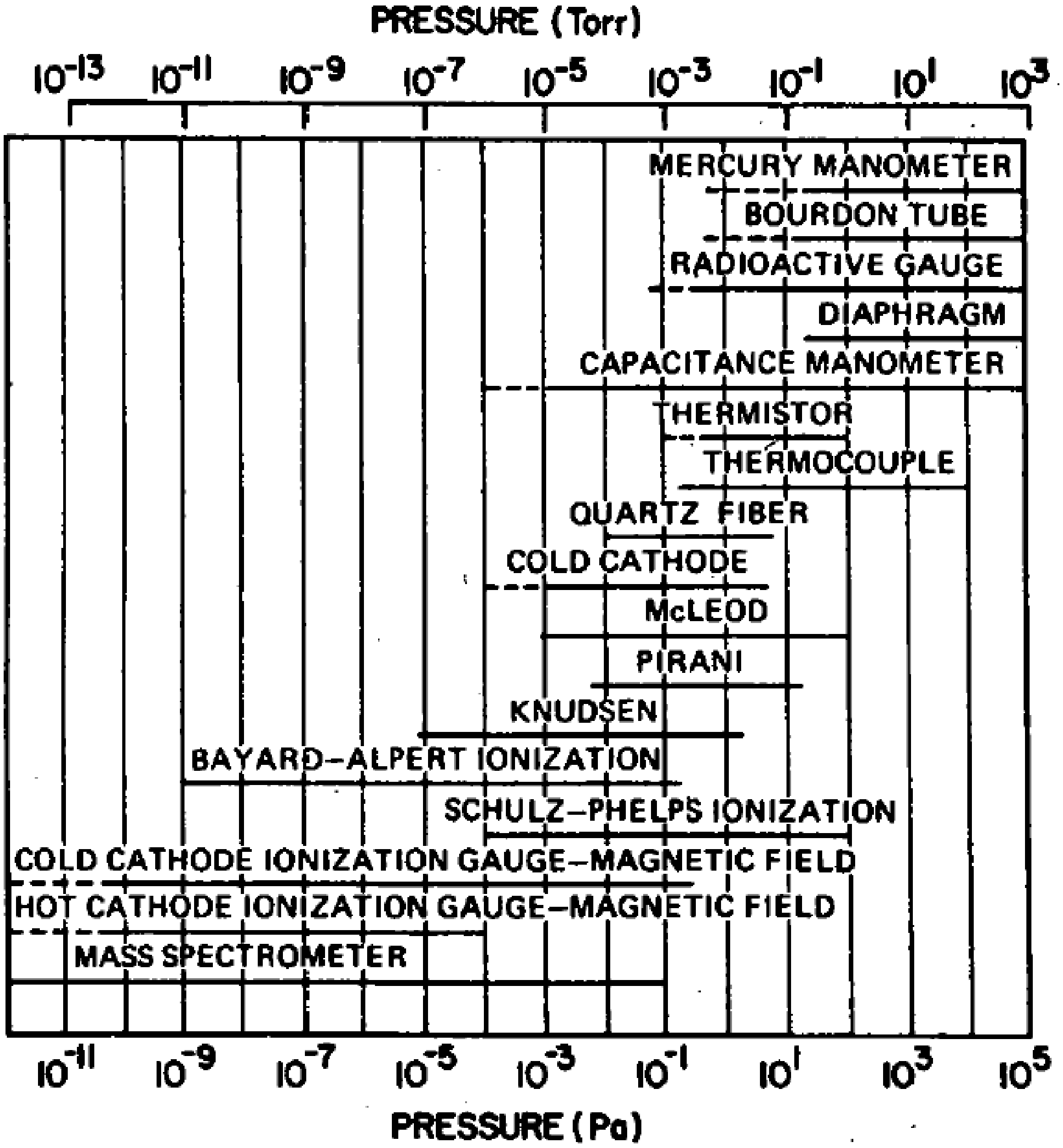




Vacuum Technology, Measurement –2–

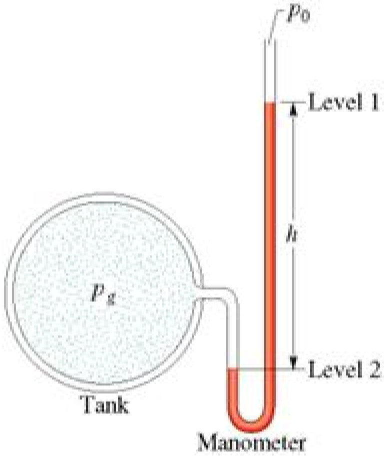
Ranges of Vacuum Gauges

Figure 5.2
O’Hanlon, 2nd Ed.



Vacuum Technology, Measurement –3–

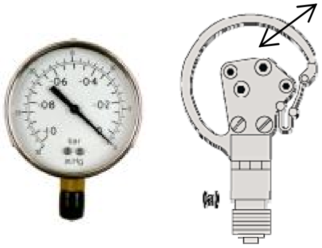
High pressure:



<u>Mechanical or Moving wall</u>

Liquid wall – classical manometer, key feature is the density of the liquid, low pressure limit is set by the vapor pressure of the liquid, p_0, and small differences in column heights.

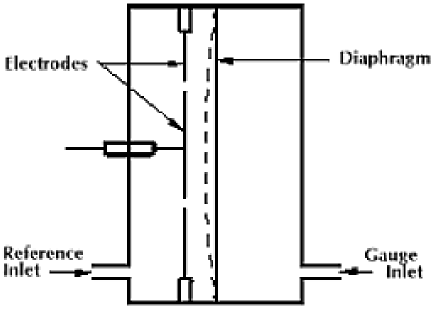
Solid wall – key feature is stiffness of the metal wall (tuned to the pressure region), low pressure limit due to small physical motion.

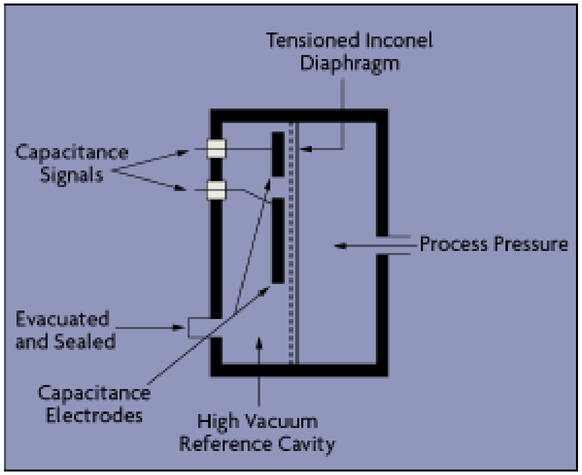


Bourdon tubes measure relative to external pressure connected to a mechanical gauge.

Capacitance manometers, Electronic readout, compatible with UHV

MKS device

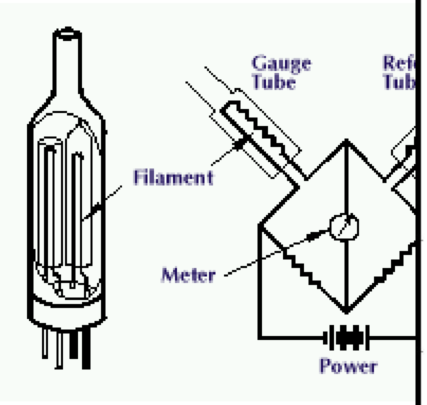




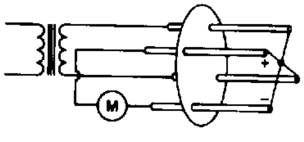
Vacuum Technology, Measurement –4–

Medium pressure: measure heat transport

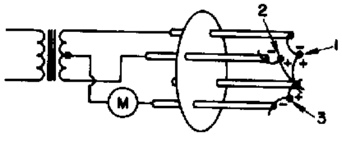
Pirani gauge – thermal transpiration



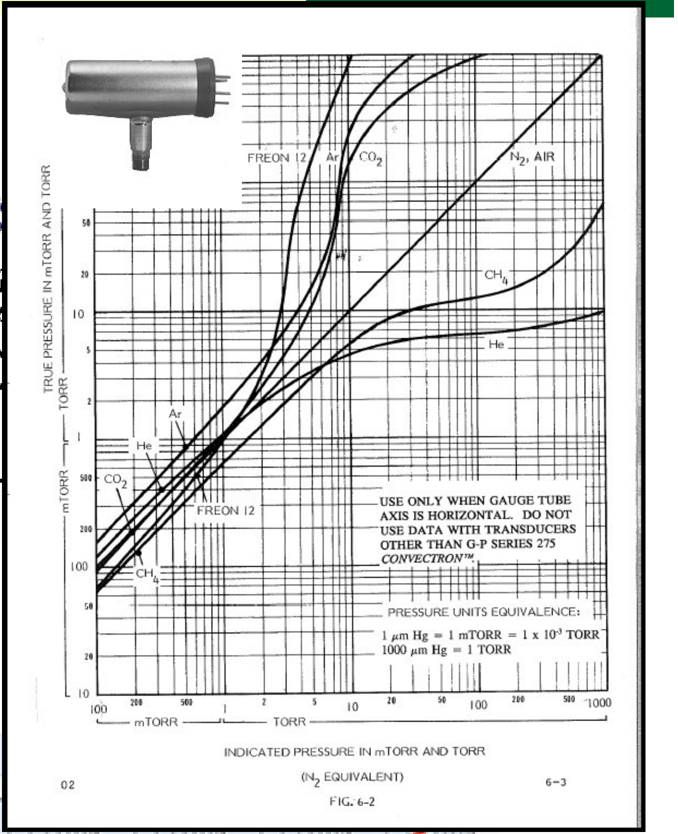
Thermocouple gauge – simple TC


(A)

or Compensated Hastings Gauge

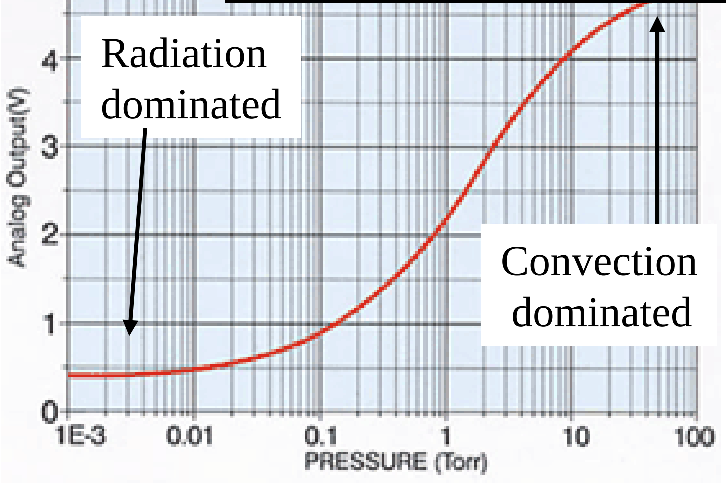


(B)



USE ONLY WHEN GAUGE TUBE AXIS IS HORIZONTAL. DO NOT USE DATA WITH TRANSDUCERS OTHER THAN G-P SERIES 275 *CONVECTRON™*

PRESSURE UNITS EQUIVALENCE:
1 μm Hg = 1 mTORR = 1 x 10^{-3} TORR
1000 μm Hg = 1 TORR



Radiation dominated

Convection dominated

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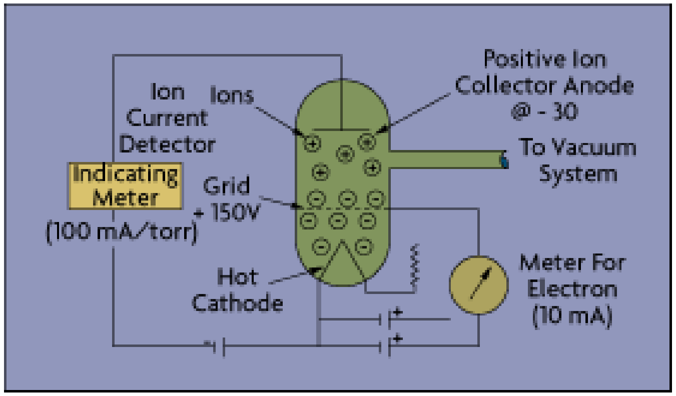
Vacuum Technology, Measurement –5–

Low pressure: create & measure ion current and thus the ρ_n or number density of the gas (T dependent because n/V = P/RT).

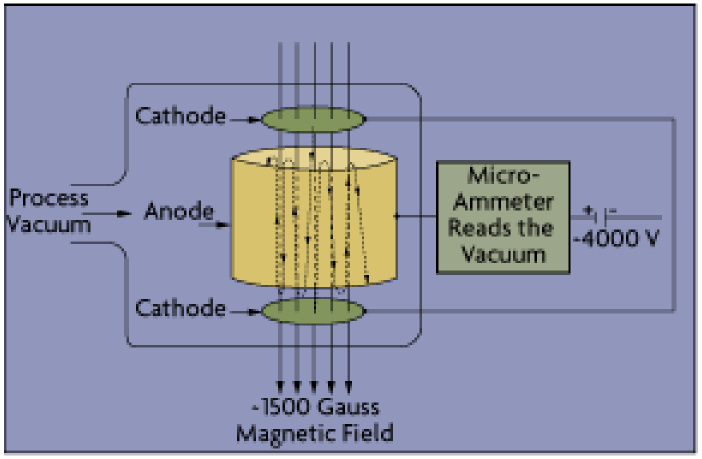
<u>Hot filament gauge</u> – hot cathode, Bayard-Alpert …

$$I^+ \propto s\, I^- P$$

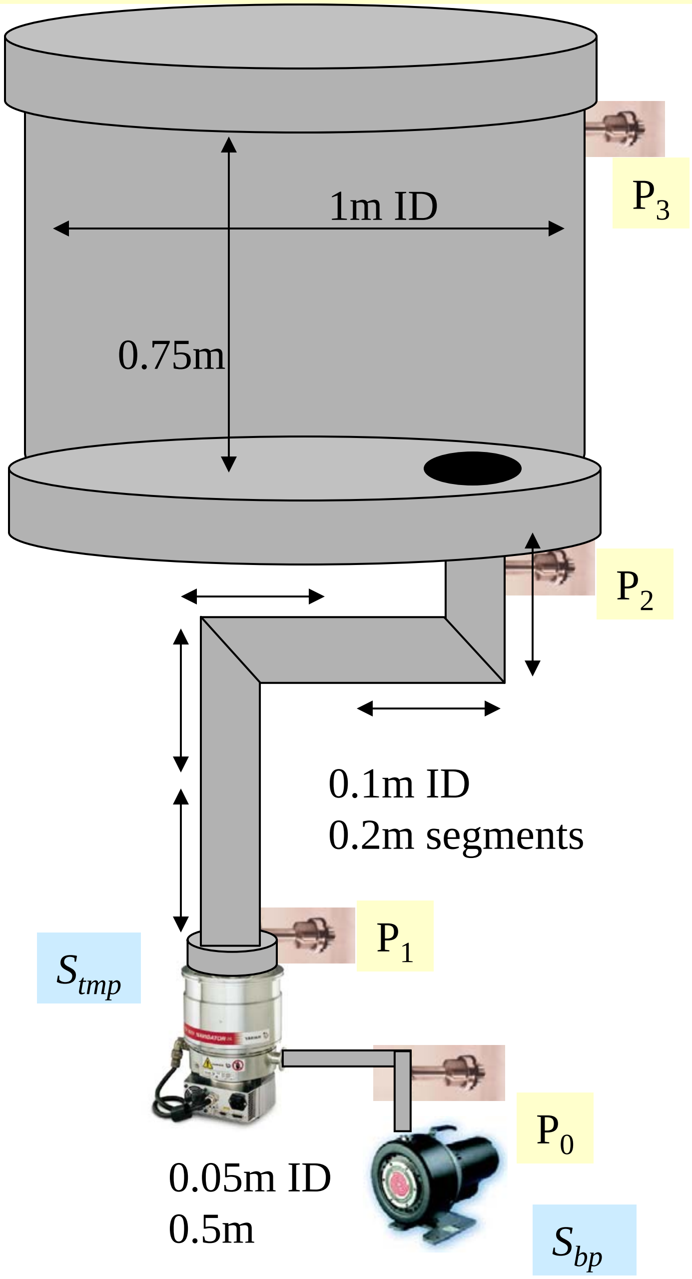
s ~ 1 for N_2, 5 Acetone, 0.2 He



<u>Cold filament gauge</u> – cold cathode, inverted magnetron



Vacuum Technology, Simple System –1–



Complete system: Molecular Flow & no leaks!

SS chamber, S_{tmp} =300 l/s, (S_{bp} = 200 l/min)

$$q_{SS} \sim 2x10^{-5} t^{-1.3} \left(W/m^2\right) \qquad Q_{off-gas} = q_{SS}\, A_{Total}$$

$$Q_{off-gas} \sim 2x10^{-5}\left[\left(\underbrace{\pi(0.5)^2}_{\text{Top}} + \underbrace{2\pi(0.5)0.75}_{\text{Wall}} + \underbrace{\pi(0.5)^2}_{\text{Bottom}}\right) + \underbrace{\pi(0.1)1}_{\text{Pipe}}\right]$$

$$Q_{off-gas} = 7x10^{-5} t^{-1.3}\, W$$

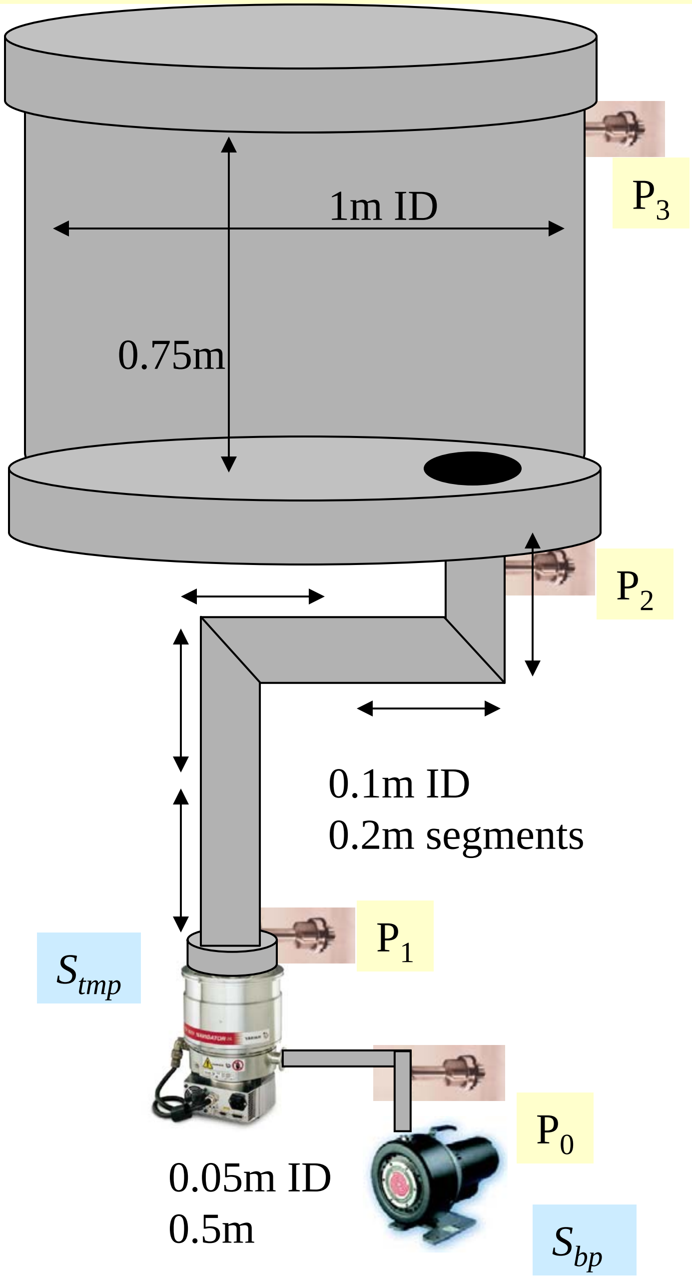
Pump entrance: P_1 [ignoring time dependence]

$$Q_{off-gas} = P_1\, S_{tmp}$$

$$P_1 = \left(\frac{7x10^{-5} W}{300\, l/s * 10^{-3} m^3/l}\right) = 2.4x10^{-4}\, Pa$$

760 torr/101,325 Pa → P_1=1.8x10^{-6} torr

Vacuum Technology, Simple System –2–



Complete system: no leaks!

SS chamber, S_{tmp} =300 l/s, (S_{bp} = 200 l/min)

P_1= 2.4x10^{-4} Pa → 1.8x10^{-6} torr

Chamber entrance: P_2

$$Q_{off-gas} = C\left(P_2 - P_1\right) \rightarrow P_2 = P_1 + \left(Q_{off-gas} \big/ C \right)$$

$$C_{line} \sim 103.\ l/s \qquad \left(C_{aperture} \sim 910\ l/s\right)$$

$$P_2 = 2.4x10^{-4}\,Pa + \left(\frac{7x10^{-5}W}{0.103\,m^3/s}\right) = 9.2x10^{-4}\,Pa$$

P_2=6.9x10^{-6} torr

Effective Speed: S_{eff}

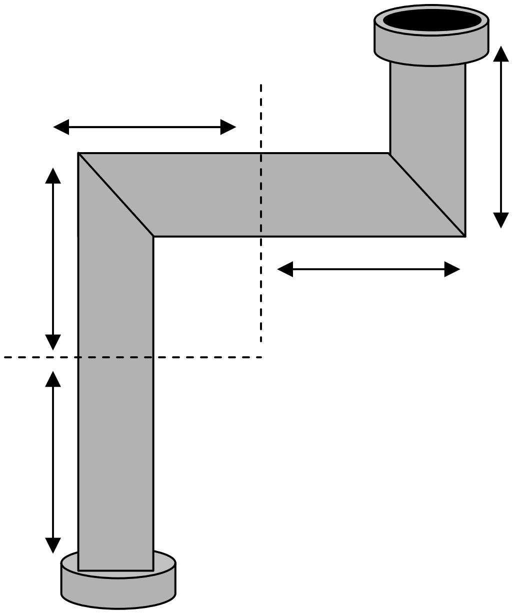
$$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S_{tmp}} \rightarrow \frac{1}{103} + \frac{1}{300} \sim \frac{1}{77}$$

Vacuum Technology, Simple System –2a–

Conductance in Molecular Flow

Oatley Method to combine conductances

0.1m ID, i.e., r = 0.05 m
0.2m segments



$C = a\, C_{aperature}$

$\quad = a\, Av/4$ where "a" is a transmission coefficient

$(1- a) / a = (1- a_1) / a_1 + (1- a_2) / a_2 + (1- a_3) / a_3 + \ldots$

Two elbows with L=0.2 m arms, L/r =4, $a_1 = a_2 = 0.35$

One pipe with L=0.2 m , L/r = 4, $a_3 = 0.25$

$(1- a) / a = 0.75/0.25 + 0.75/0.25 + 0.65/0.35$

$(1- a) / a = 7.86$

$a = 0.113$

$C = 0.113 * 11.6\ A$ l/s-cm^2 , $A= \pi\, (5)^2$

$C = 0.113 * 911.$ l/s $= 103$ l/s

Vacuum Technology, System Summary

Complete system:

Chamber: materials – unless you are very careful, off-gassing generally determines the lowest pressure the system will attain.

Chamber: seals – better know as “leaks”

Pumps: speed – depends on the design, gas, and pressure. Is higher pumping speed always the best answer?

Pipes & valves: conductance – limited by size and shape of plumbing and is probably the most ignored concept in vacuum technology.

Gauges & pressure: measurement principle? – range is limited by technique and is probably the most over interpreted aspect of vacuum technology.