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 lab quantity. It might also have the largest variety of units.

SI: 1 Pa = 1 N/m^2

1 atm = 760 torr = 101,325 Pa

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

Vacuum Technology, Gas Properties

The total pressure can be (easily) measured but the microscopic makeup and behavior of the gas(es) are very important in vacuum systems. Partial pressures can be measured with a mass spectrometer: "residual gas analyzer" (RGA).

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

Humid Air: estimate of partial pressure of H_2O is 24 Torr * (relative Humidity) (note it can be up to ~3% of the air and is temperature dependent)

Mean gas velocity: $$v = \left(\frac{8k_BT}{\pi m}\right)^{1/2} = \left(\frac{8RT}{\pi MM}\right)^{1/2} = \frac{2512\, m/s}{\sqrt{MM(g/mol)}}$$ at 298 K

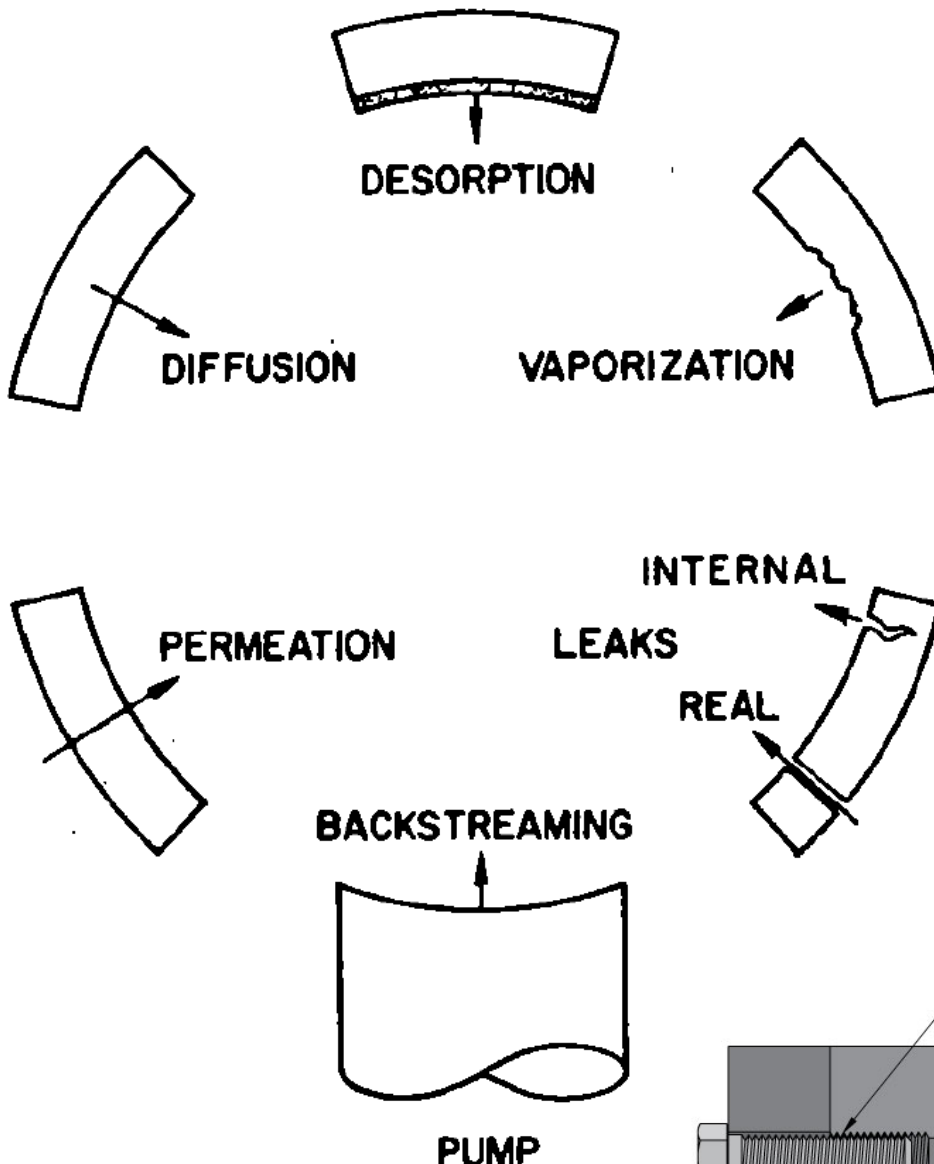
Effusion: $$\frac{v_1}{v_2} = \left(\frac{MM_2}{MM_1}\right)^{1/2}$$

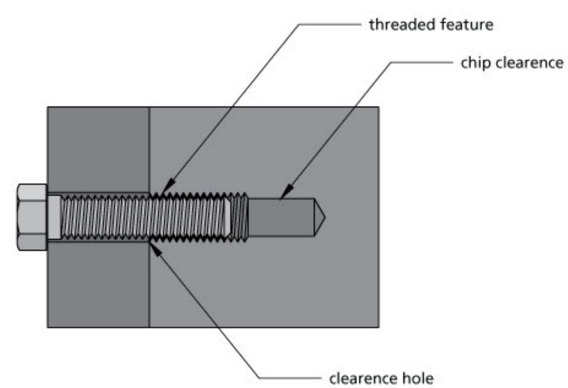
Mean Free path: $$\lambda = \frac{1}{\sqrt{2}\,\pi\, d^2 \rho_n} = \frac{6.6\, mm\, Pa}{P}$$

Vacuum Technology, Gas Sources

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

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





Most important residual gas of a system with no leaks varies with time …
First H_2O then ultimately H_2

Vacuum Technology, Gas Flow –1–

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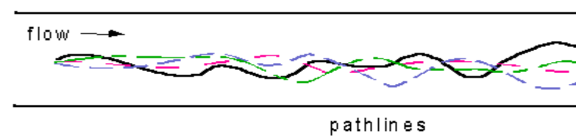
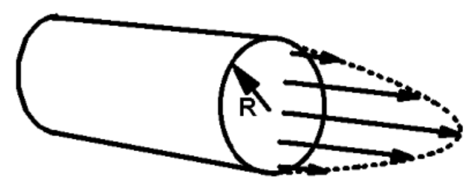
Two dimensionless numbers are used to characterize gas flow regimes:

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

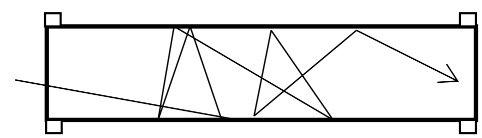
Reynold's Number: Re = U ρ d / η U – stream velocity, ρ – density, η – viscosity

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

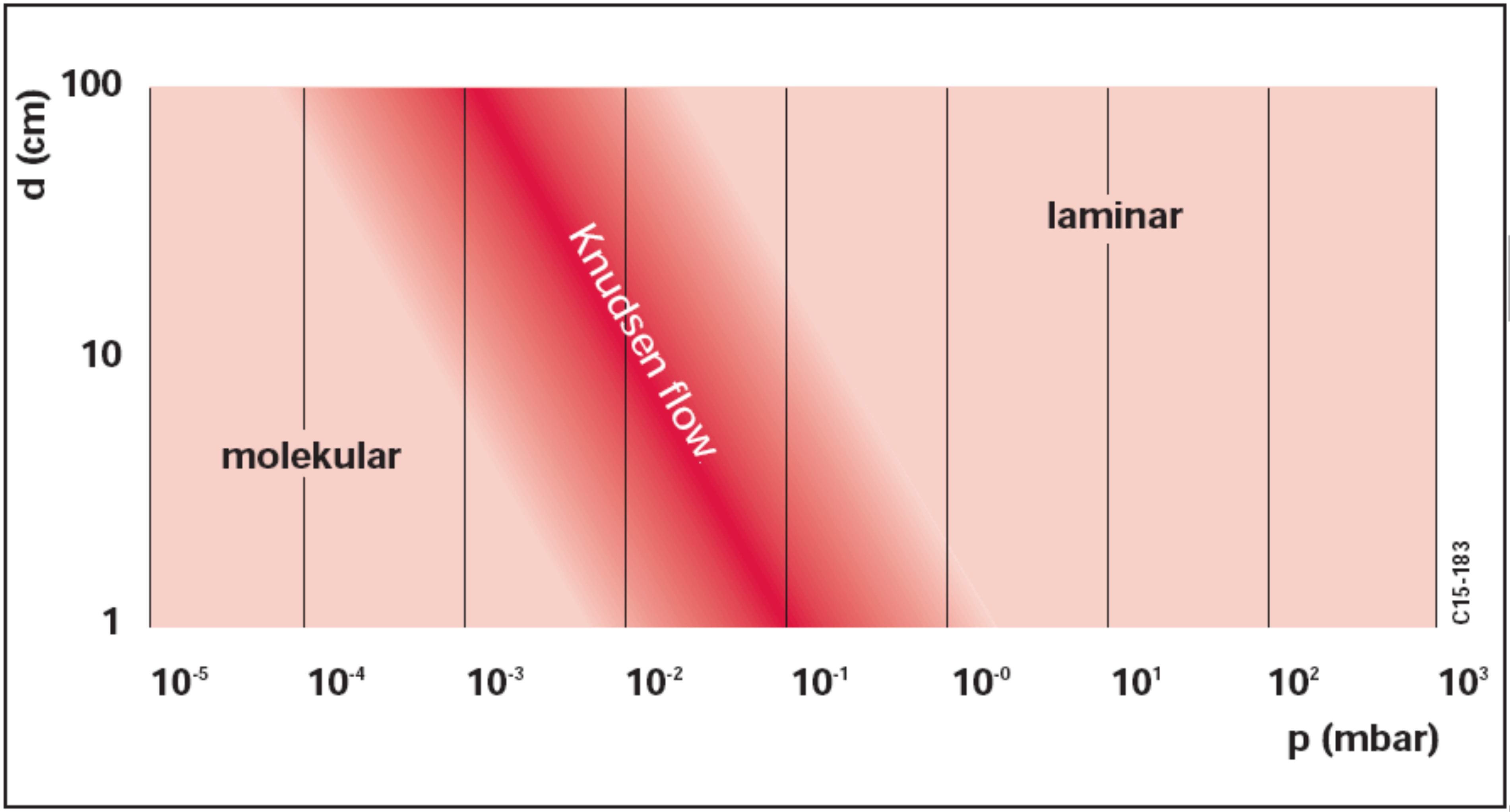




visco8



Durschflussregelungen von einem deutschen Unternehmen



From: Pfeiffer Vacuum, "Working with Turbopumps" on class website.
See revised website by manufacturer:
https://www.pfeiffer-vacuum.com/en/know-how/vacuum-generation/turbomolecular-pumps/

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 lab conditions.

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

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:

$$Q = P\frac{dV}{dt} = P\,S$$

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

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

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

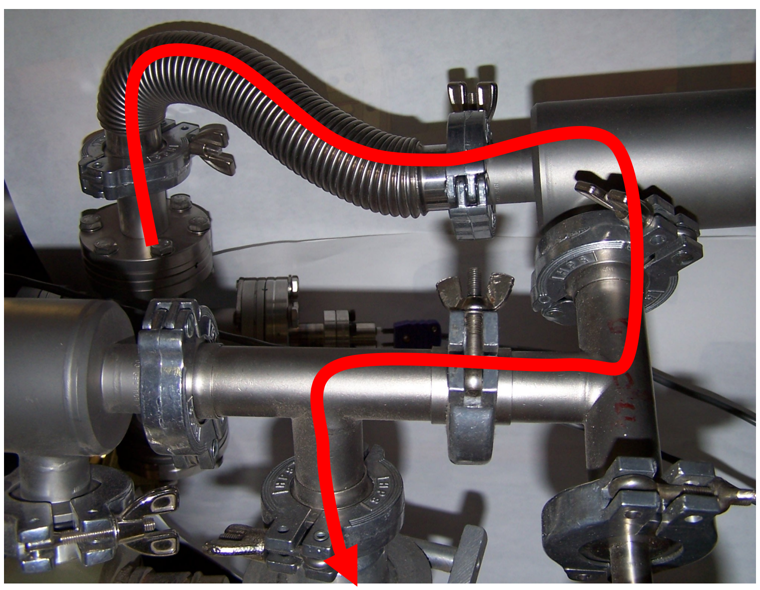
C is the *Conductance* of the pipe, e.g. liter/s

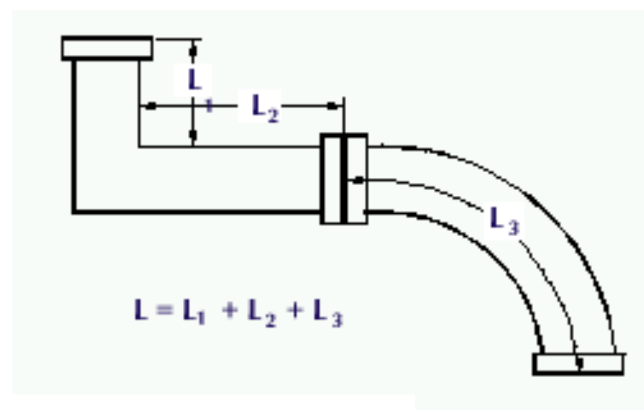
Vacuum Technology, Gas Flow –3–

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, the pressure and the gas.

	Laminar	**Molecular**
Aperture	(complicated, called choked flow)	$A\,v/4$
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: $1/C_{total} = 1/C_1 + 1/C_2 + \ldots$





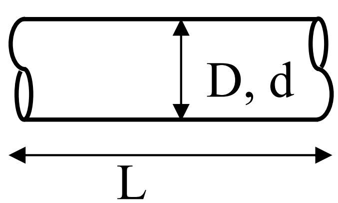
Vacuum Technology, Gas Flow –4–

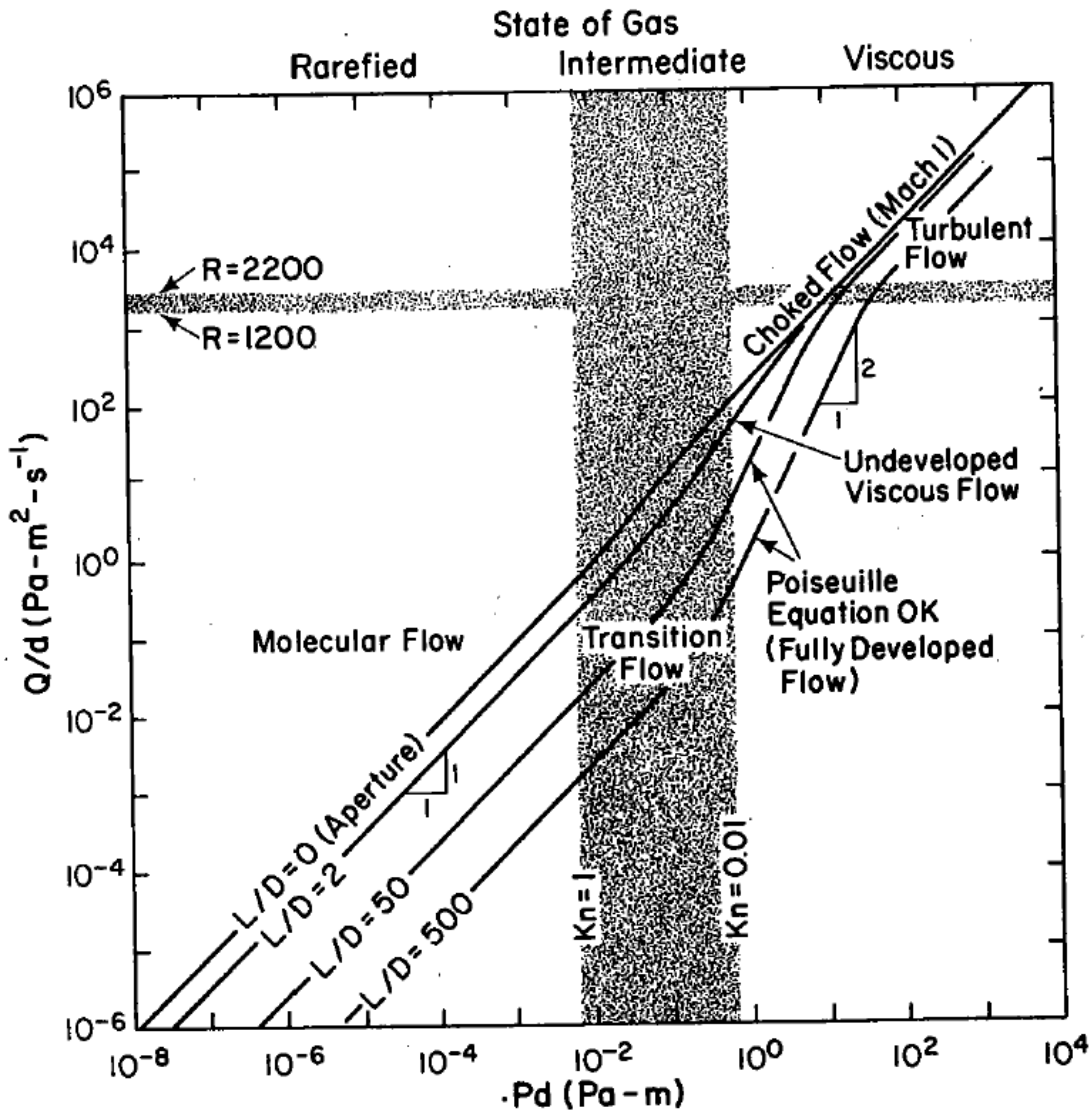
Flow Summary

Figure 3.17
O' Hanlon, 2^{nd} Ed.

Figure 3.18
O' Hanlon, 3^{rd} Ed.

Round tube





Vacuum Technology, Production –1–

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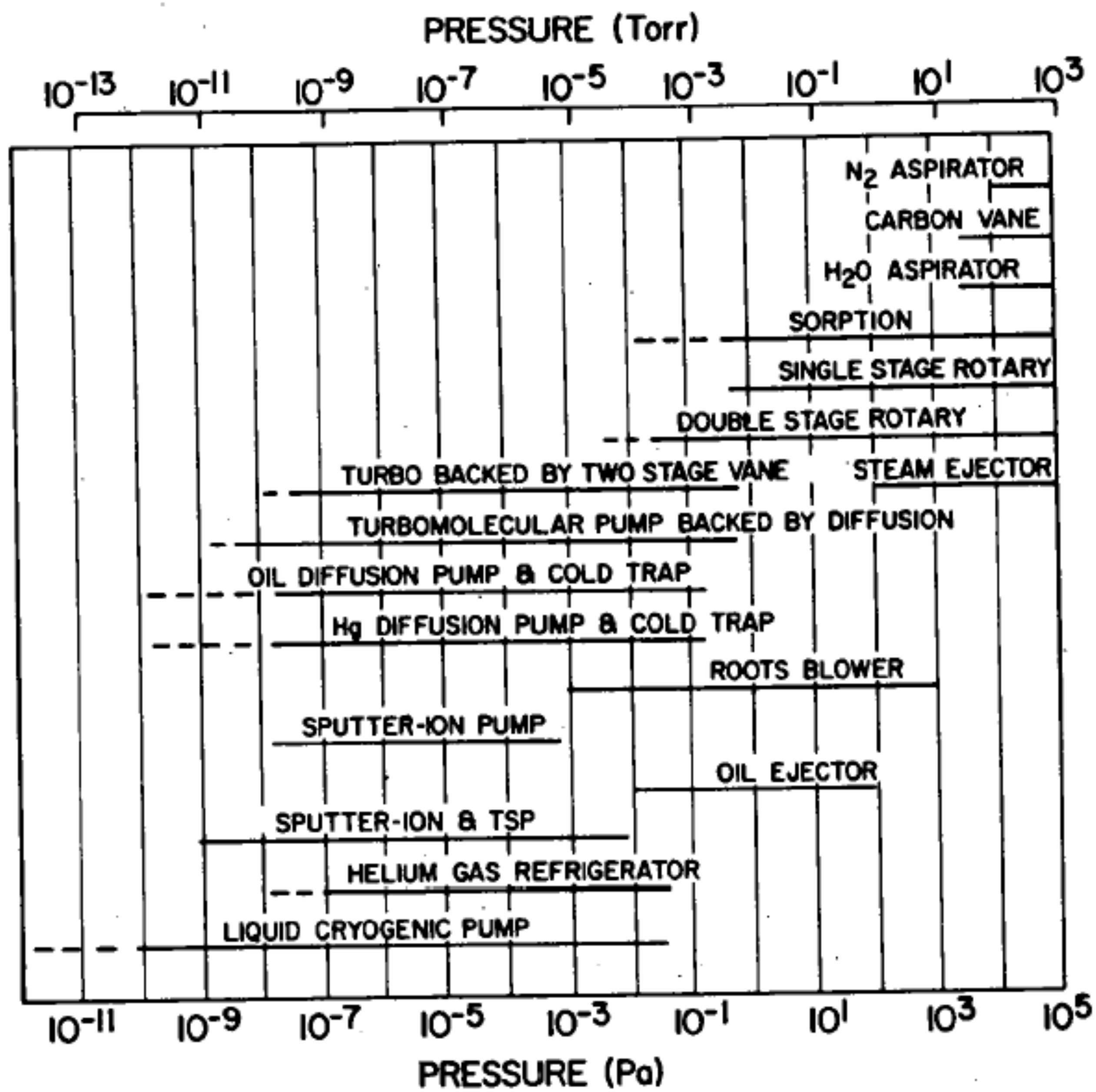
A huge variety of vacuum pumps have been developed over time that use various physical techniques to trap, and in a few cases move, the gas. In general, their usefulness is limited to certain pressure ranges.

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

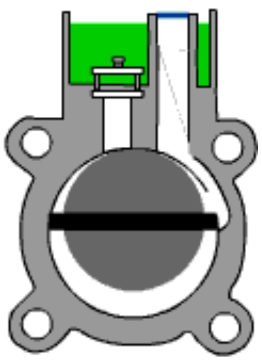
Another distinction is: Are there moving parts or not?

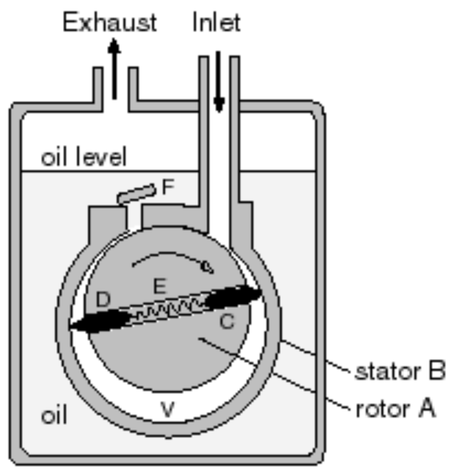


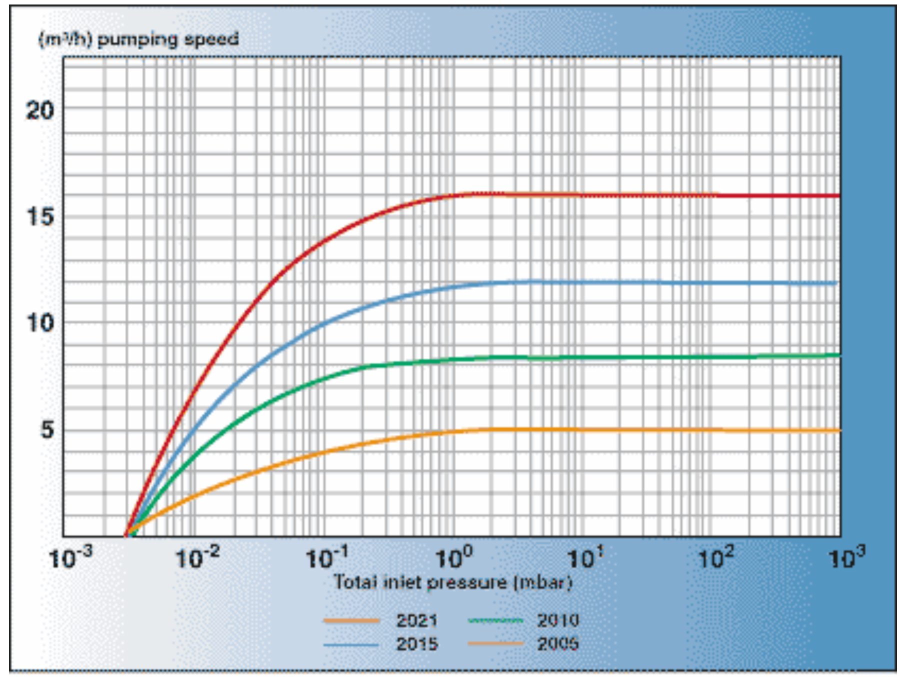
Vacuum Technology, Production –2–

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

Oil-sealed





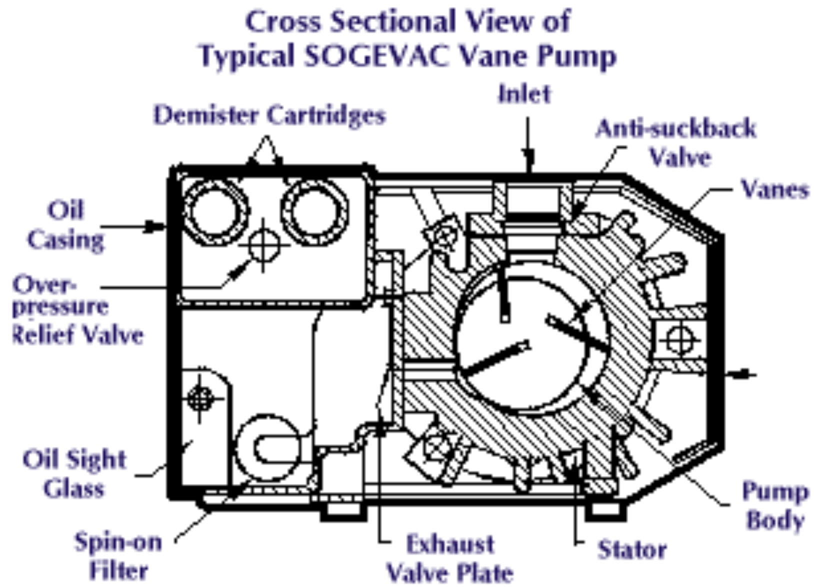


Alcatel Vane pump

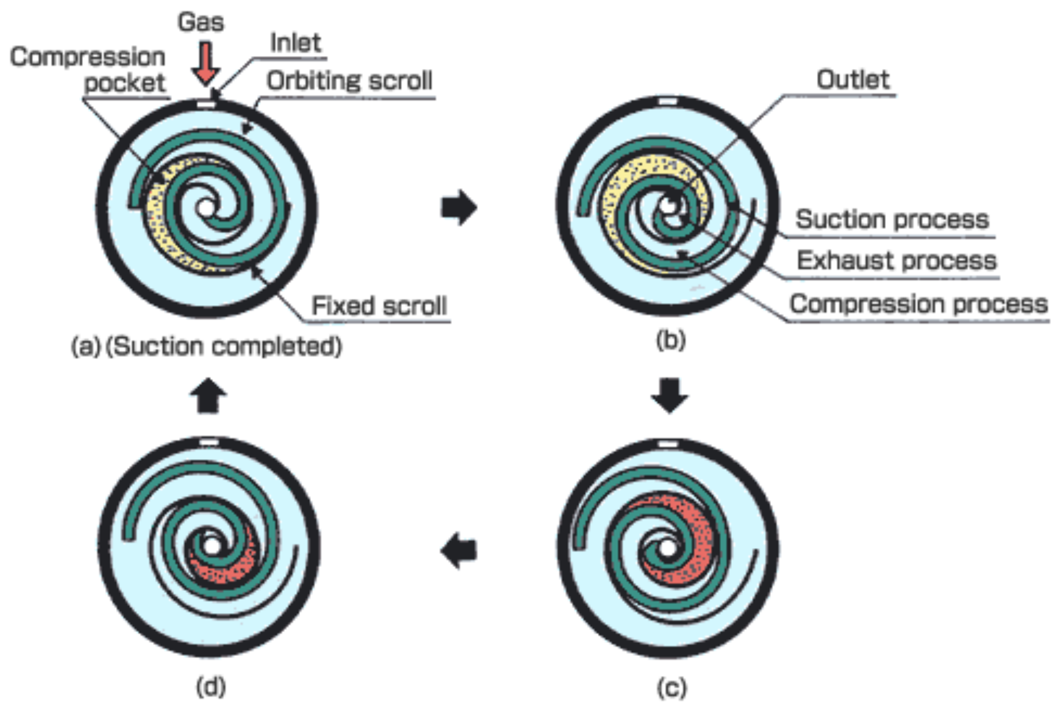
$$S = \frac{dV}{dt} \approx \frac{\Delta V}{\Delta t}$$

Mechanical pumps: oil free

Dry Vane

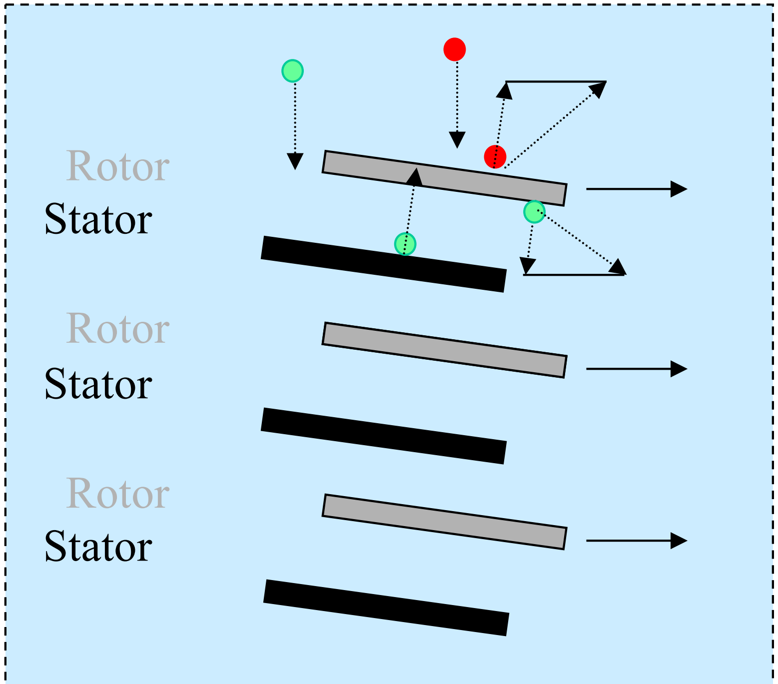


Dry Scroll



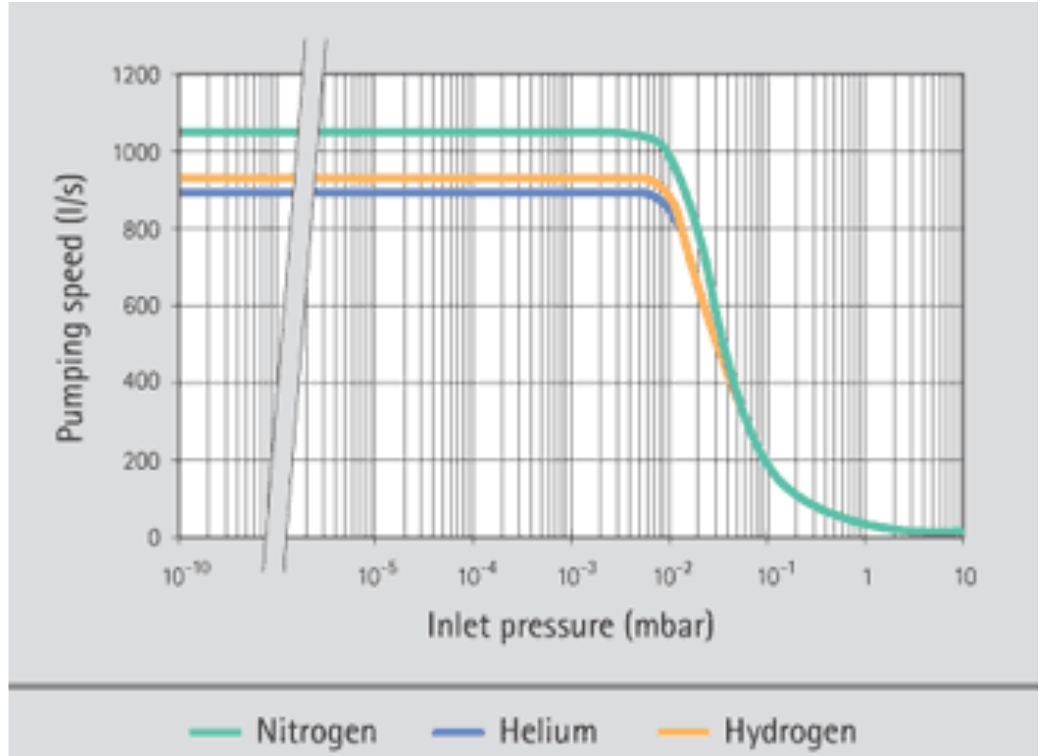
High Vacuum pumps: TMP

Chamber Side
(in Molecular flow!)



Pump outlet Side

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



Varian Turbo-V 1001

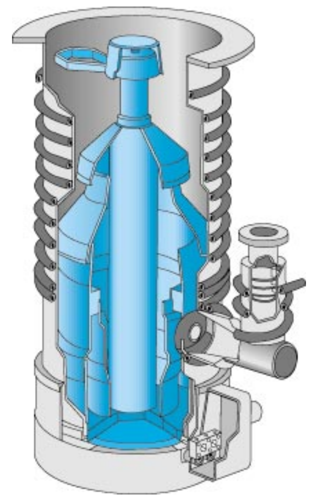
High flow

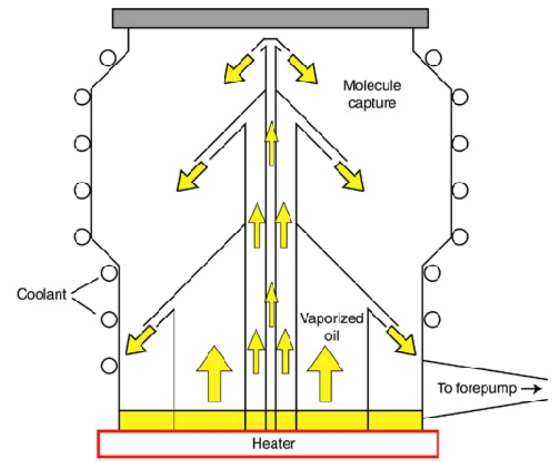
High Compression

Vacuum Technology, Production –4–

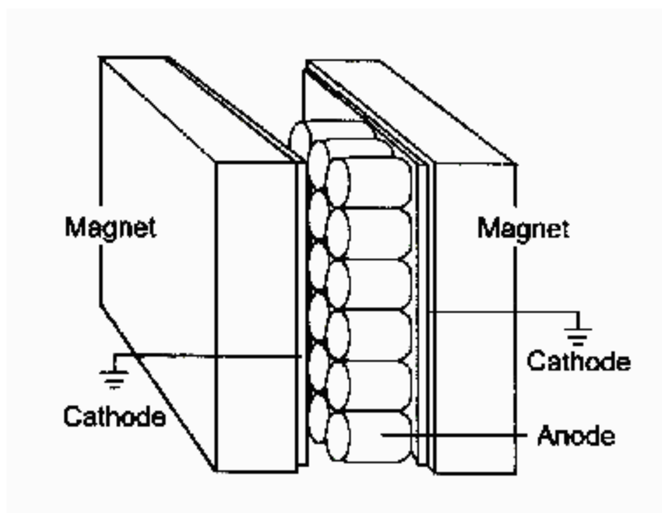
High Vacuum pumps: Diffusion pumps

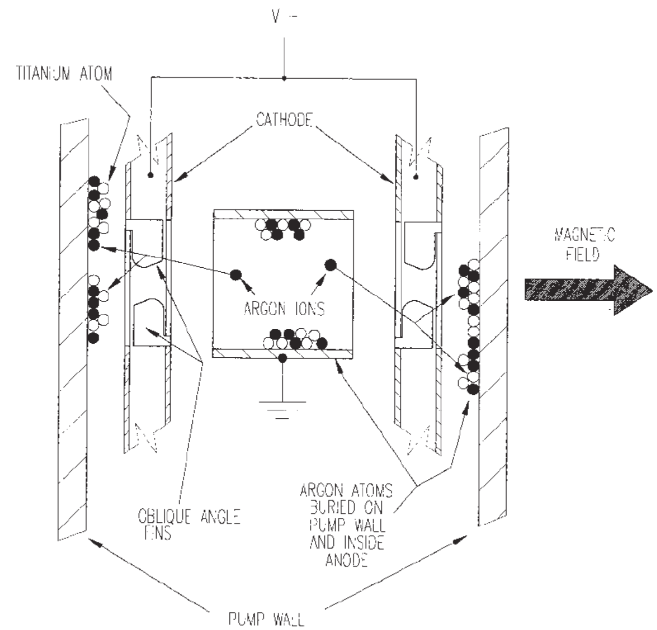
- Hot oil-filled, need cold traps
- Highest pumping speeds for He
- No real limit to size





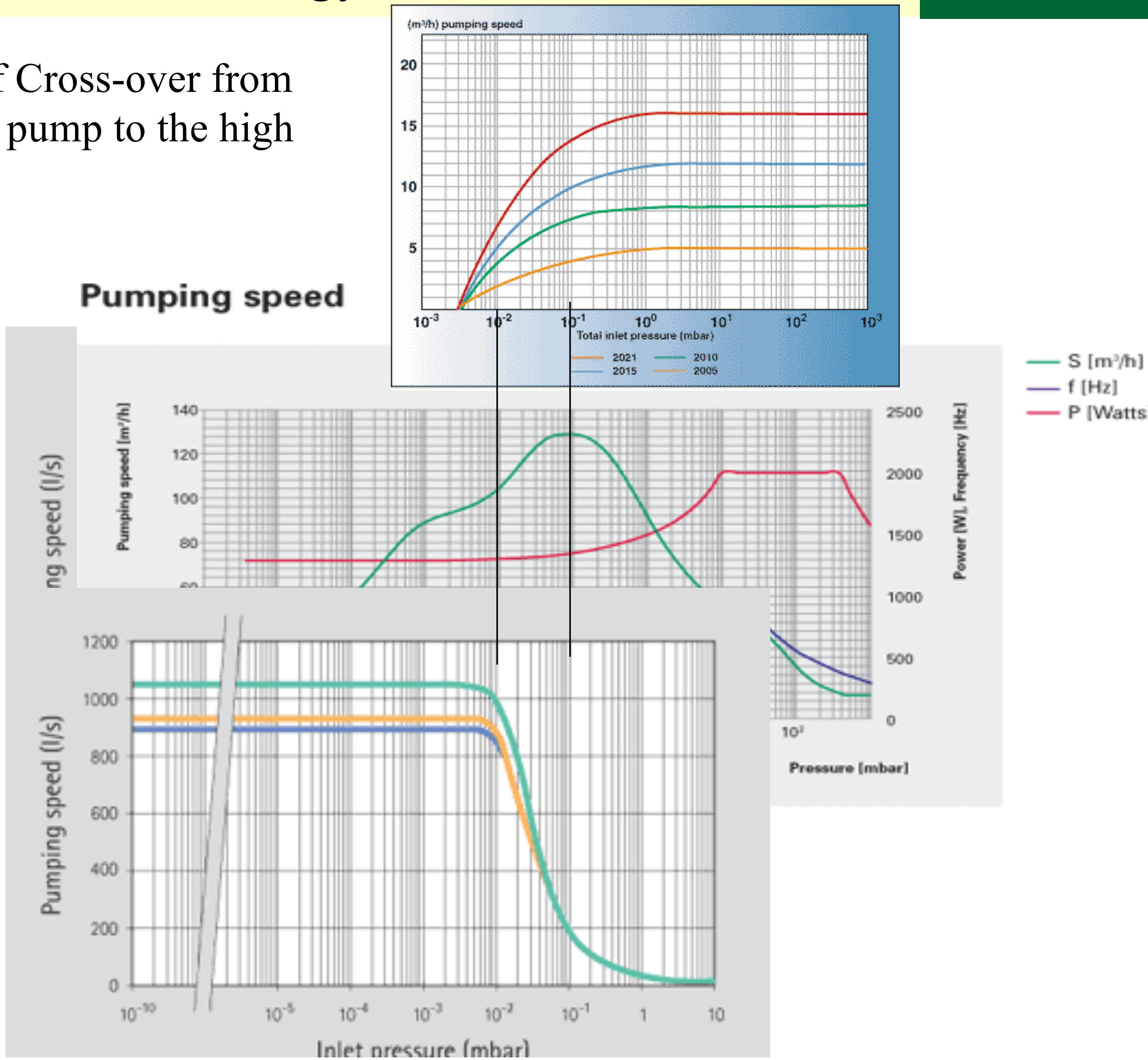
High Vacuum pumps: Ion pumps – closed system





Vacuum Technology, Production –5–

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



Vacuum Technology, Measurement –1–

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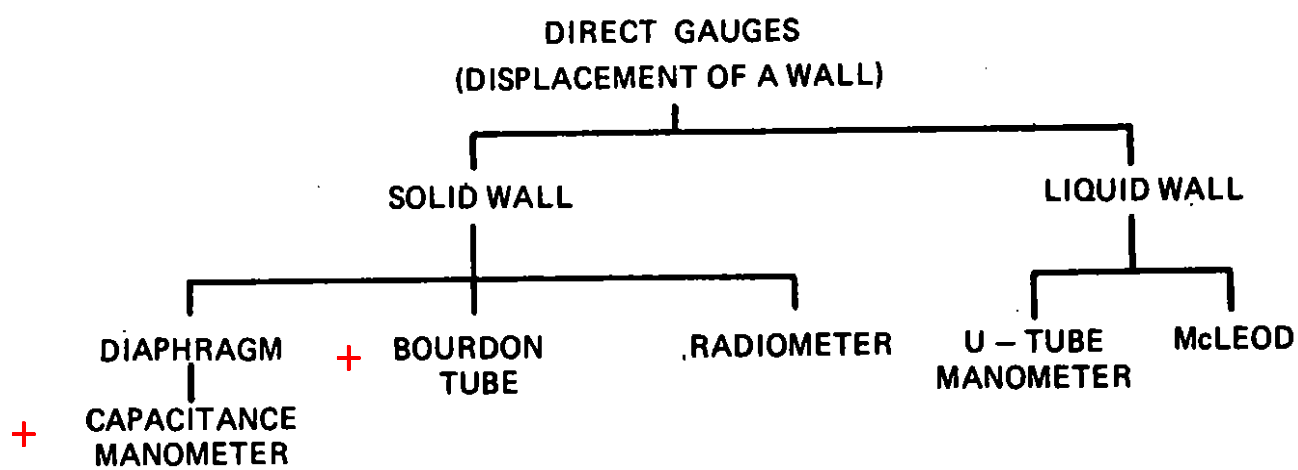
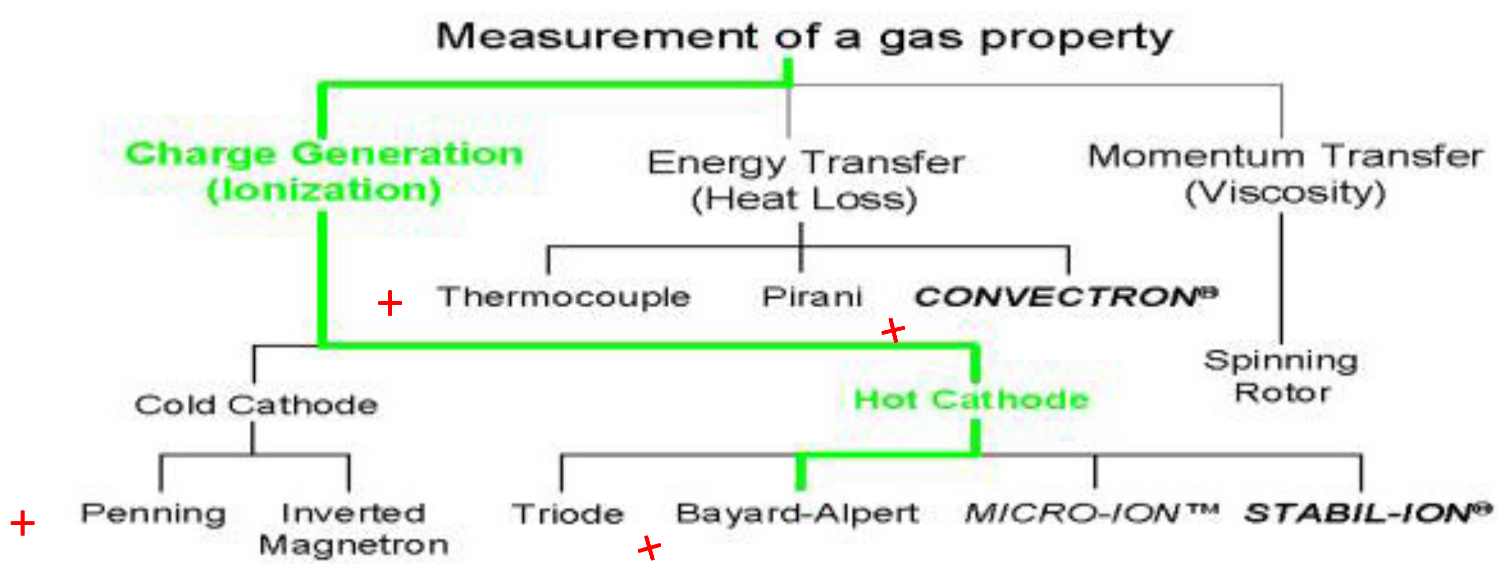
Categorization of Vacuum Gauges

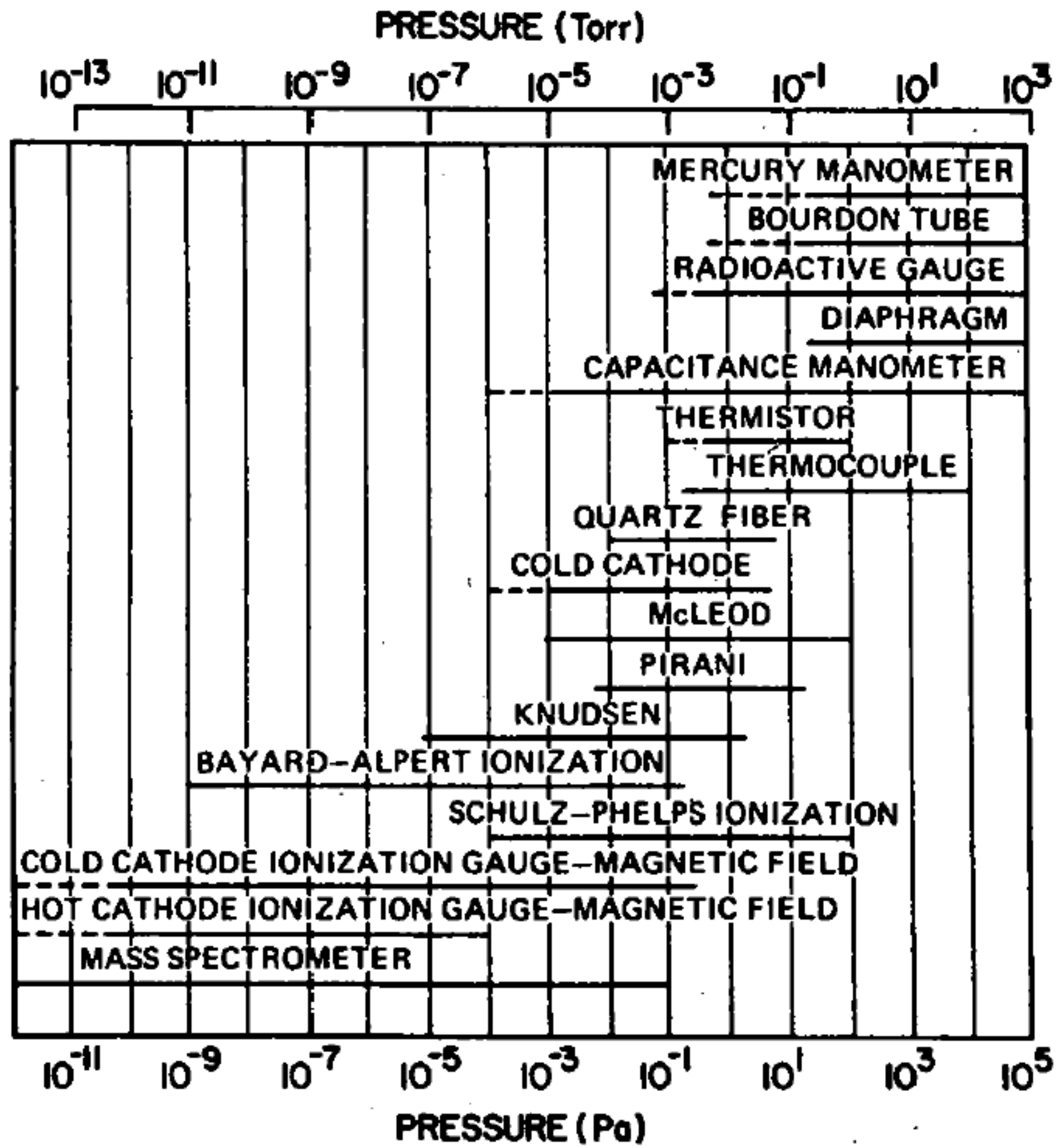
Figure 5.1
O' Hanlon,
2nd or 3rd Ed.



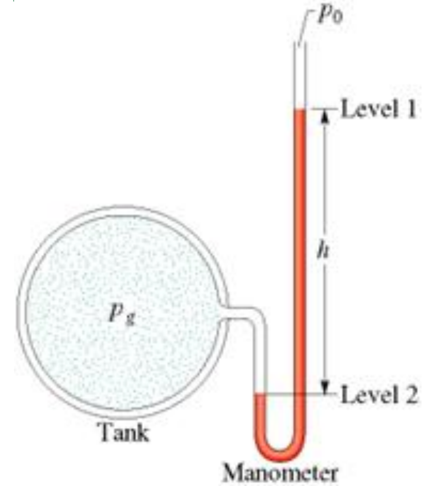


Ranges of Vacuum Gauges

Figure 5.2
O' Hanlon,
2^{nd} or 3^{rd} Ed.



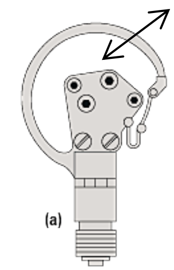
High pressure:



<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 being able to read small differences in column heights.

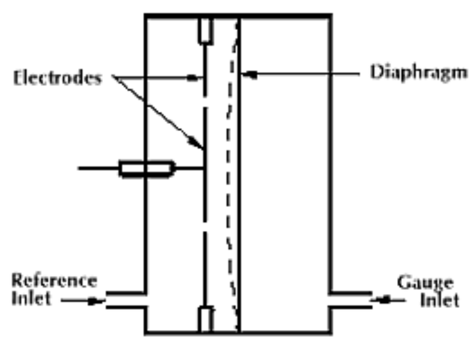
Solid wall – key feature is stiffness of the metal wall (can be tuned to the pressure region), low pressure limit again due to detection of smallest physical motion. Recent devices use pizeoresistive chips.

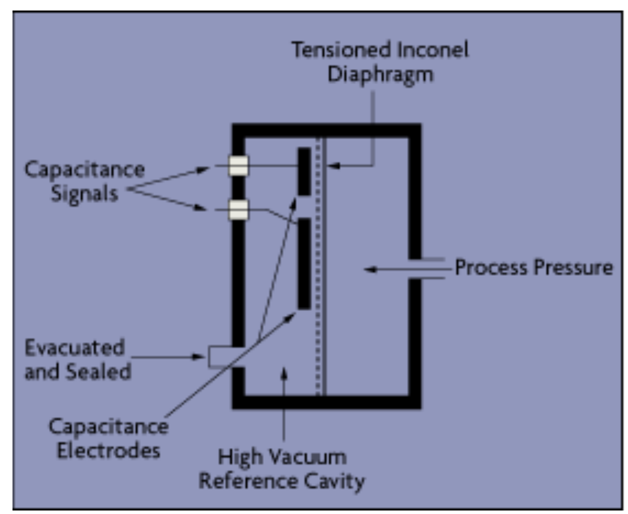


Bourdon tubes measure relative to external pressure connected to a mechanical gauge.

Capacitance manometers, Electronic readout, compatible with UHV

MKS device





Vacuum Technology, Measurement –4–

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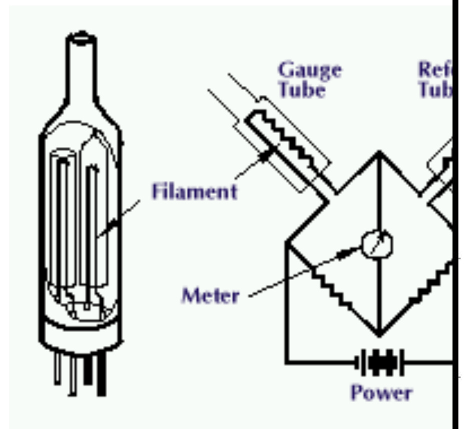
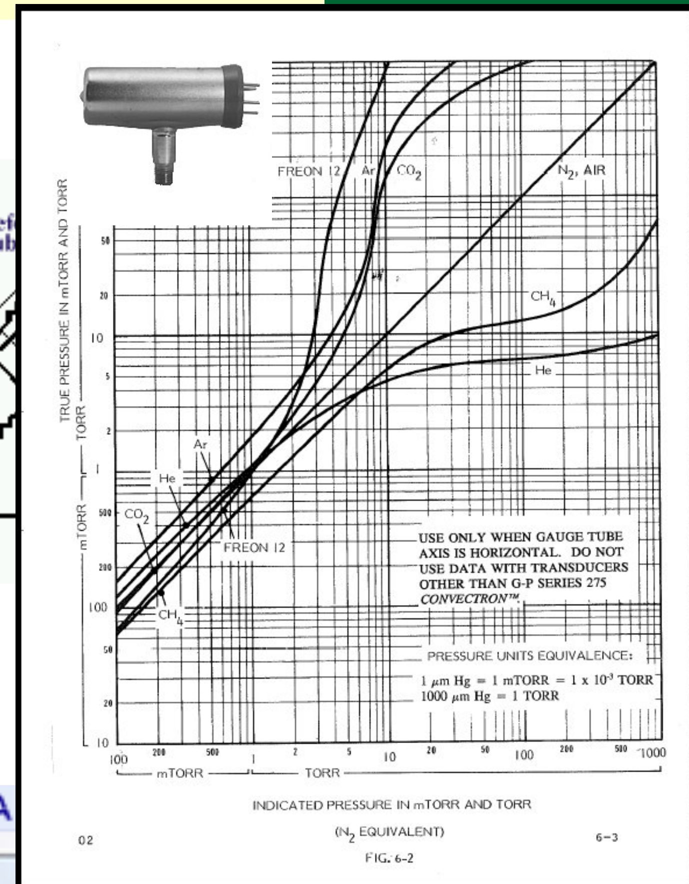
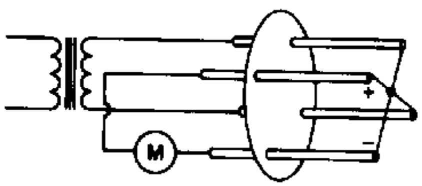
Medium pressure: measure heat transport

<u>Pirani gauge</u> – thermal transpiration



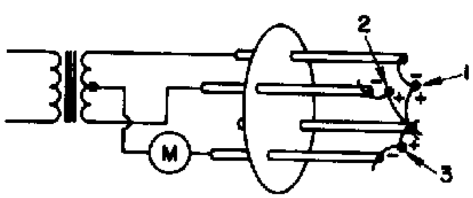


<u>Thermocouple gauge</u> – simple TC

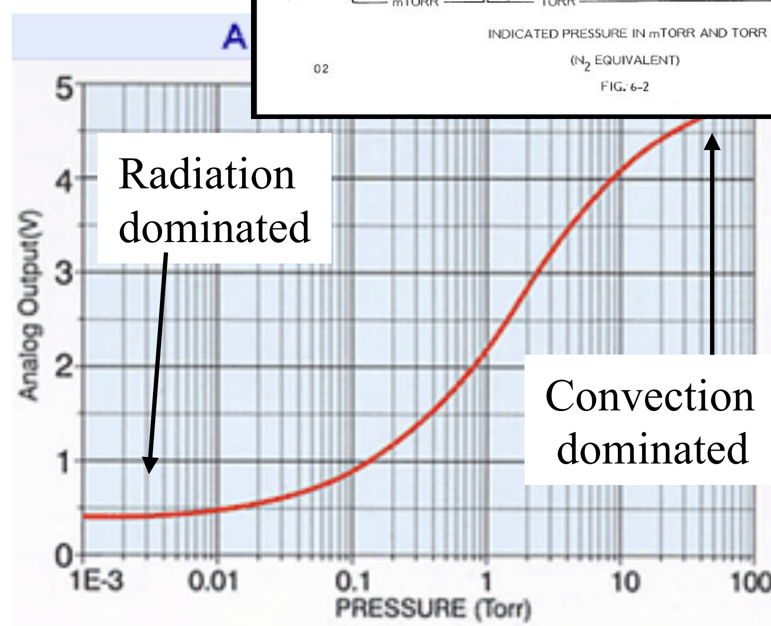


(A)

or Compensated <u>Hastings Gauge</u>



(B)



Vacuum Technology, Measurement –5–

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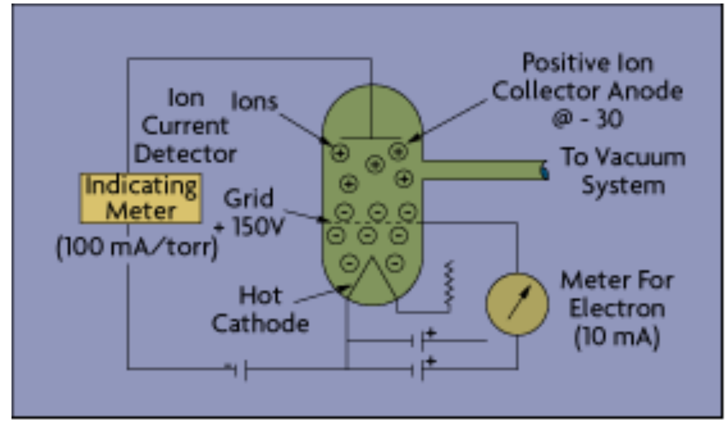
Low pressure: create & measure positive ion current and thus the ρ_n or number density of the gas (T dependent because n/V = P/RT).

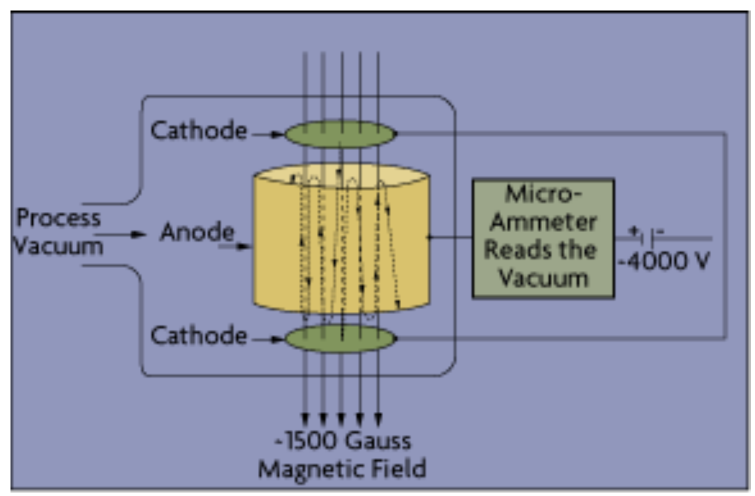
Hot filament gauge – hot cathode, Bayard-Alpert …

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

s ~ 1 for N_2, 5 Acetone, 0.2 He



Cold filament gauge – cold cathode, Penning Gauge, inverted magnetron



Gauge-ology, Now for an example

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Vacuum Technology
-- Principles
-- Gas Flow
-- Pumps
-- Gauges

Vacuum Technology
-- Example System
Calculation

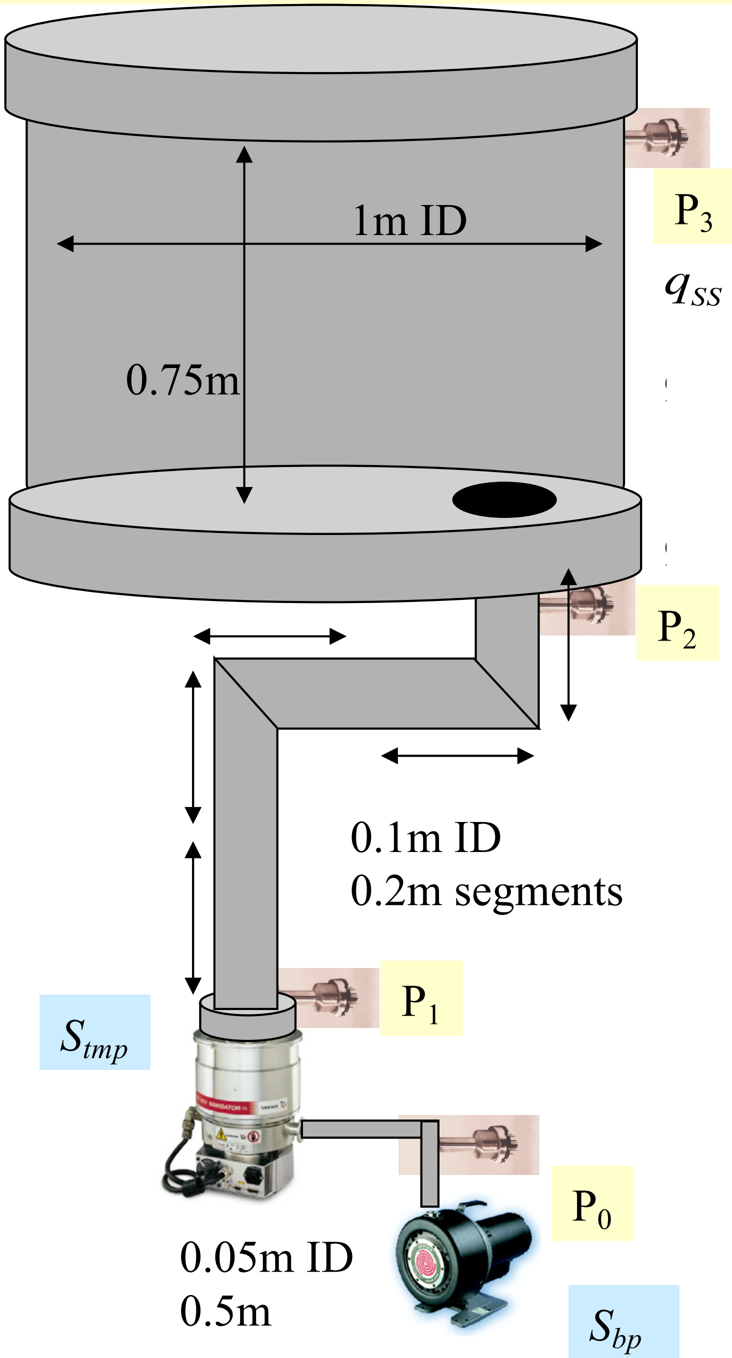
General use of Statistical Distributions in Radiation Measurements
-- Fluctuations in Number
--- distribution models
-- Fluctuations in Time

Vacuum Technology, Simple System –1–

Complete system: Molecular Flow & no leaks!

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

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



Vacuum Technology, Simple System –2a–

Conductance in Molecular Flow

Best approach is to Monte Carlo the flow …

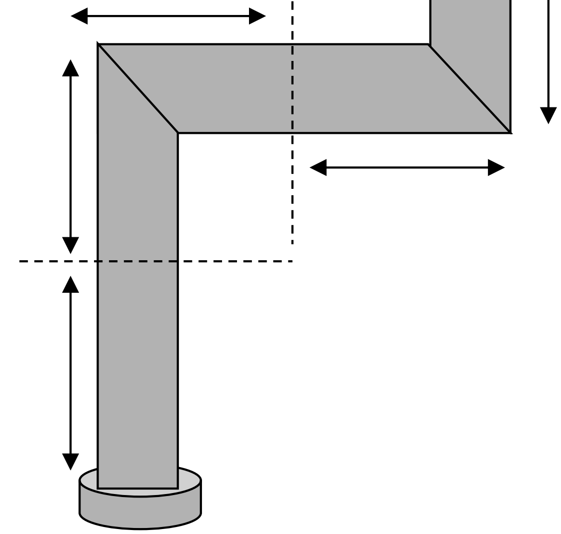
Oatley Method to combine conductances

$C = a\, C_{aperature}$

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

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

0.2m segments



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

Two elbows with L=0.2 m arms, L/r =4, $a_1 = a_2 \sim 0.25$

One pipe with L=0.2 m , L/r = 4, $a_3 \sim 0.35$

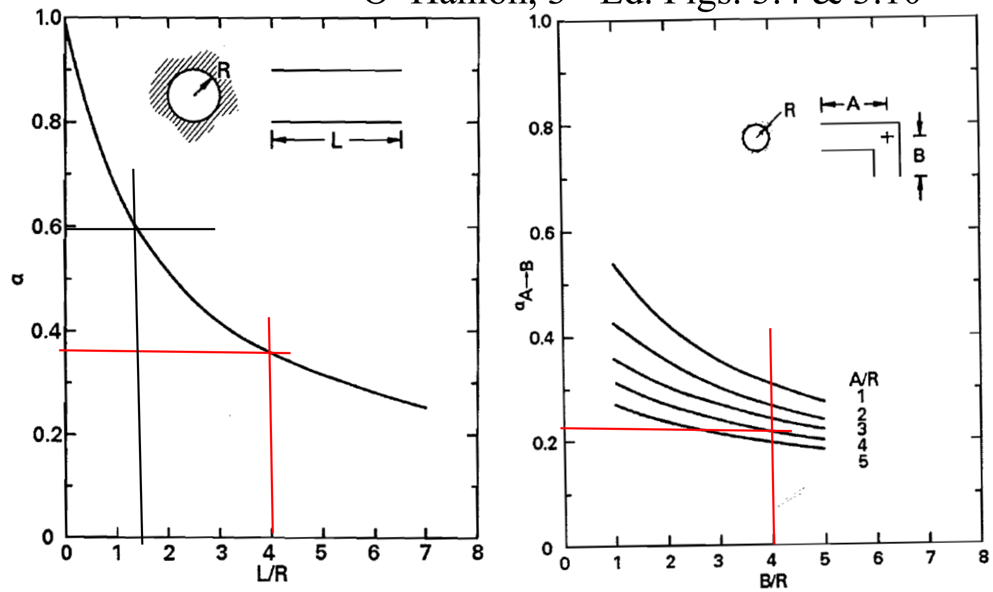
$(1- a) / a = 0.75/0.25 + 0.75/0.25 + 0.65/0.35 = 7.86$

$a = 0.113$

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

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

O' Hanlon, 3rd Ed. Figs. 3.4 & 3.10



Vacuum Technology, Simple System –2b–

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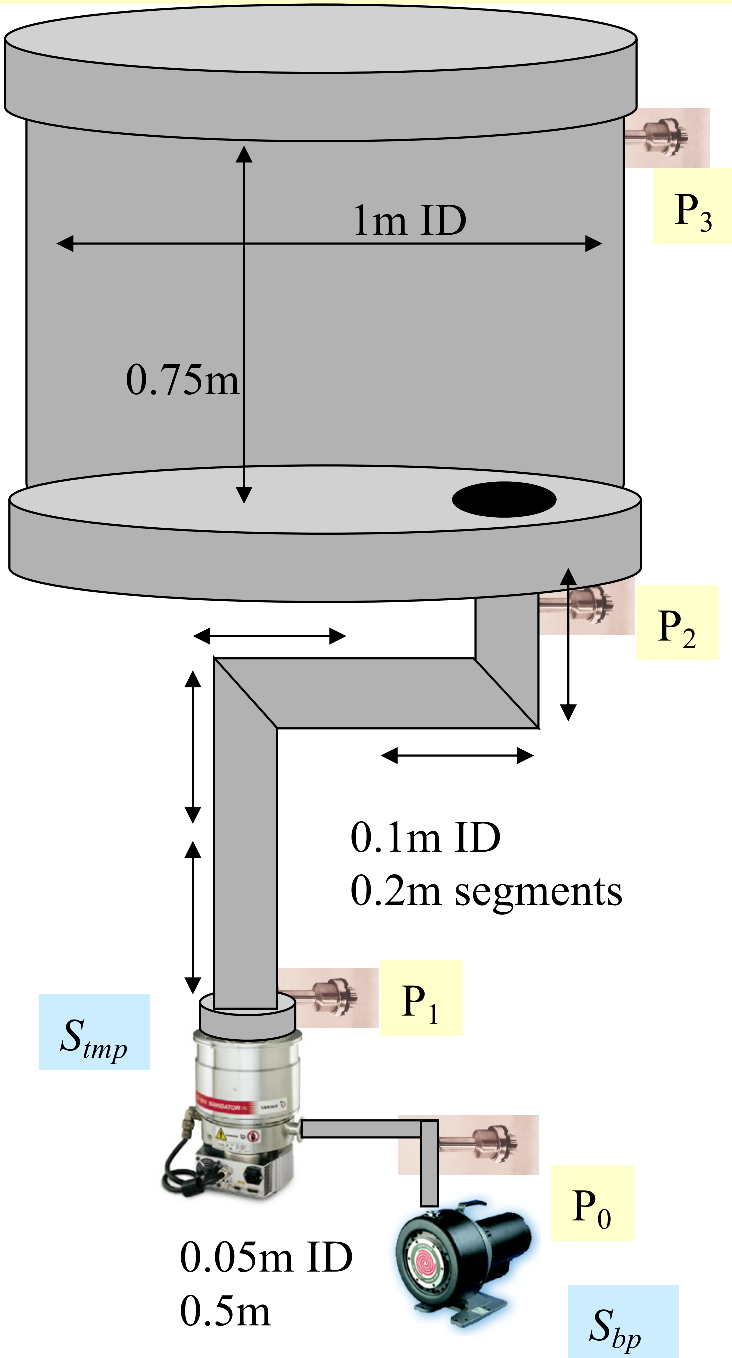

Complete system: no leaks!

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

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

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

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

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 –2b–

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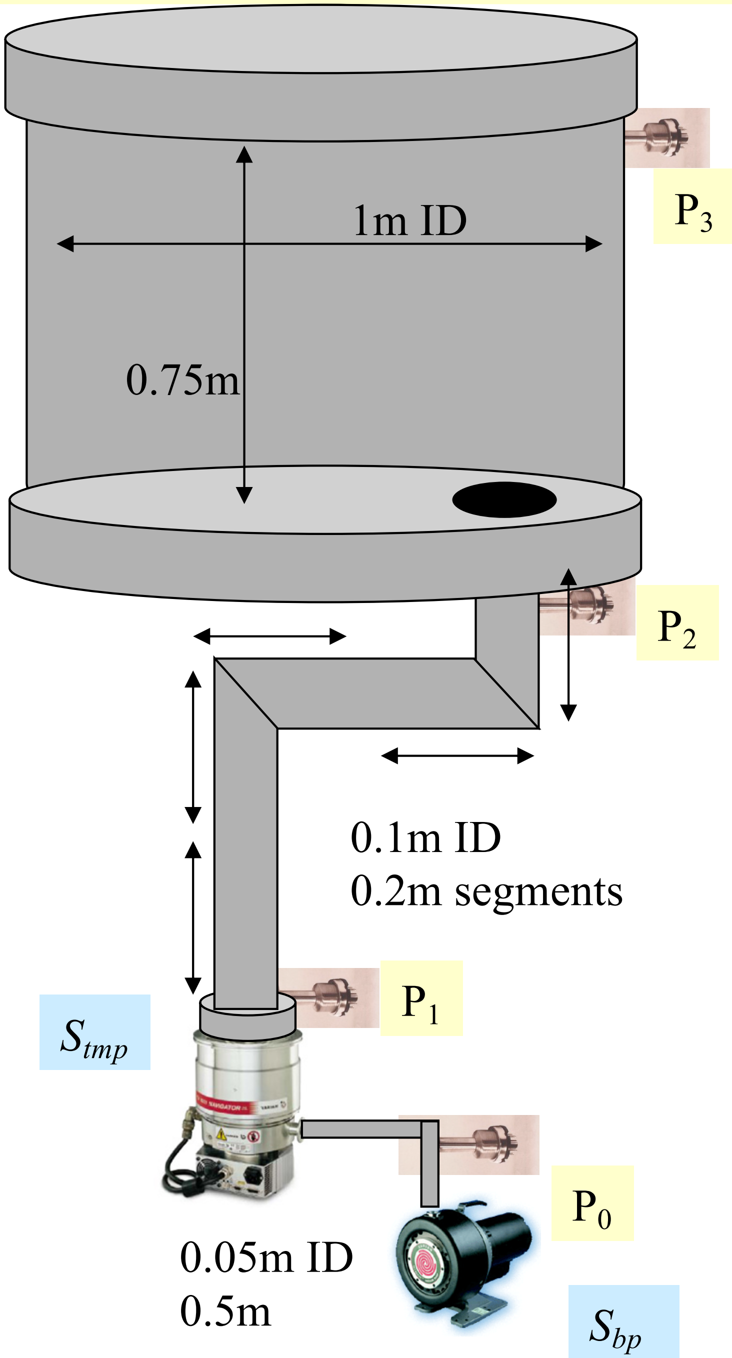

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P_2=6.9x10^{-6} torr

Chamber top: P_3

One "pipe" with L=0.75 m , L/r = 1.5, a ~ 0.6

C = 0.6 * 11.6 A l/s-cm^2 , A= π (50)^2
C = 0.6 * 91,106. l/s = 54,663 l/s

N.B. λ = 6.6 mm-Pa/P → 7.1 m

Vacuum Technology, System Summary

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Complete system:

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

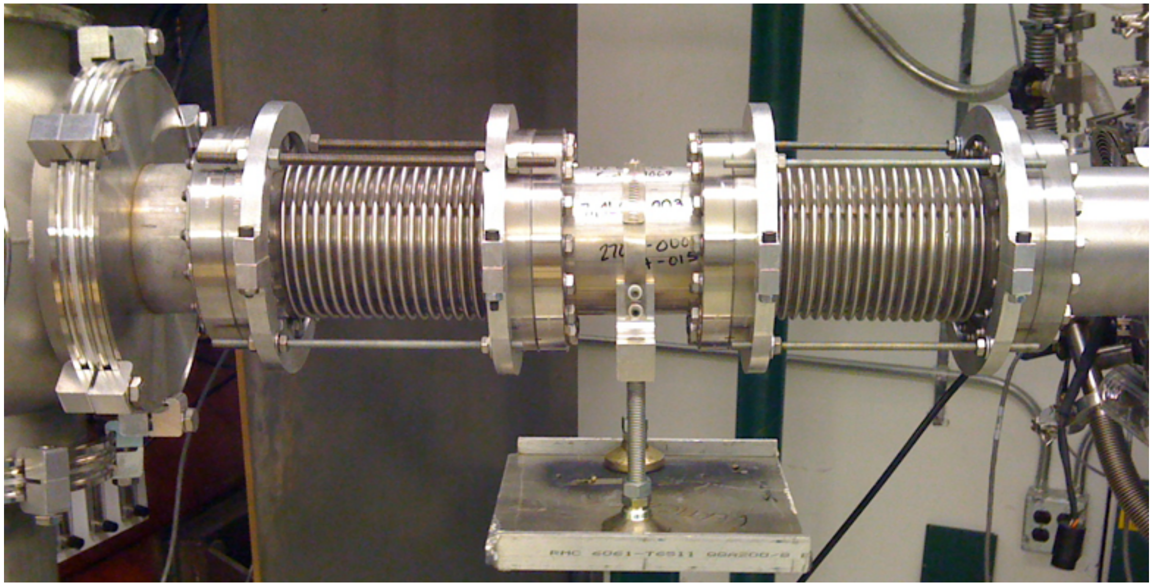
Gauges & pressure: measurement principle? – range is limited by technique and is probably the most over interpreted aspect of vacuum technology.

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

Chamber: seals – better know as "leaks"

Pipes & valves: conductance – limited by size and shape of plumbing, probably the most overlooked concept

in vacuum technology.



Week 4: Chap. 3 Statistics of Radioactivity

Vacuum Technology

General use of Statistical Distributions in Radiation Measurements

-- Fluctuations in Number

--- distribution function models

-- Fluctuations in Time

General Detector Properties

"Without deviation from the norm, progress is not possible."
Frank Zappa, 1986