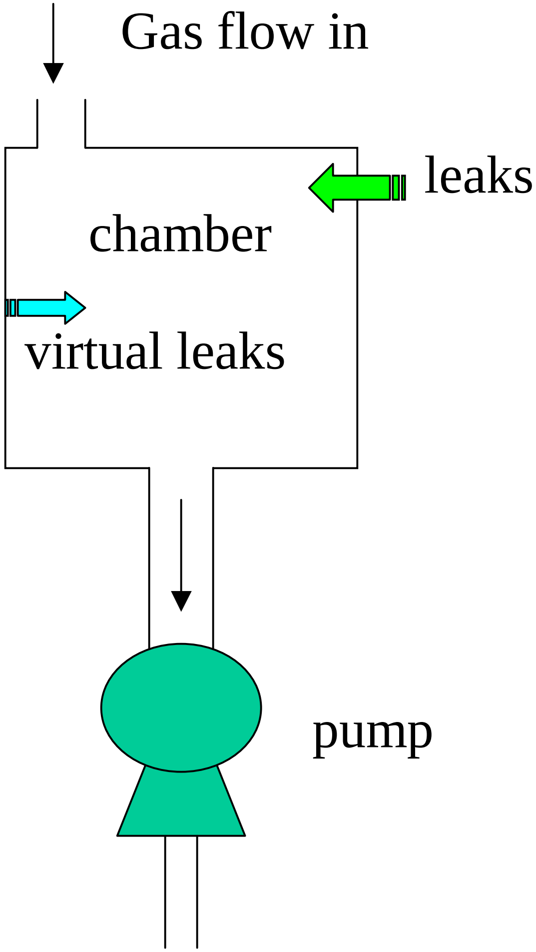
Vacuum Science and Technology

- Most CVD , Epitaxy and Plasma processes use vacuum
- Vacuum : < 1 atm = 760 Torr
- ~ 0.1-760 Torr : Rough Vacuum
- ~ 10^{-4}-0.1 Torr : Medium Vacuum
- ~ 10^{-8}- 10^{-4} Torr : High Vacuum
- $< 10^{-8}$ Torr : Ultrahigh Vacuum (UHV)
- Base pressure: the lowest pressure the chamber can be pumped down to without any gases flowing.
- Processing pressure (with gases flowing) maybe higher than the "base pressure"

Why doesn't pressure go to 0?



- Even if gas flow is 0, there are always leaks. They may be very small but they are always there.
- Virtual leaks are leaks that are not associated with transport across the chamber wall but act as a gas source (e.g. , desorption from gas walls, slow leak of gas trapped inside crevices and cracks.)
- Pumps are characterized by pumping speed (liters/second, m^3/h, etc.)
- They are called vacuum pumps but they are really compressors.
- Think of pumping speed as volume captured per unit time and displaced out of the chamber. Amount of gas depends on how much gas is inside that volume (Pressure).

Pumping Speed, Throughput and Flow rate

Throughput (torr liters/sec) → $Q = PS$

Pressure (torr) → P; Pumping speed (liters/s) → S

$$n = \frac{PV}{RT} \quad \Rightarrow \quad \dot{n} = \frac{P}{RT}\dot{V} = \frac{P}{RT}q$$

$$Q = PS = \dot{n}RT$$

$$\dot{n} = \frac{P_s}{RT_s}\dot{V}_s$$

760 Torr → P_s

0 °C → T_s

Specifying flow rate in std cm³/min (sccm) is equivalent to specifying molecular (or molar) flow rate → $\dot{V}_s$

$$1\ sccm = 2.69 \times 10^{19}\ molecules/minute$$

$$1\ torr\ lit/s = 79.05\ sccm$$

Residence time and chamber pressure

$$\frac{d(PV_R)}{dt} = -Q = -SP$$ ➡ $$\frac{dP}{P} = -\frac{S}{V_R}dt \quad \Rightarrow \quad P = P_o e^{-t/\tau}$$

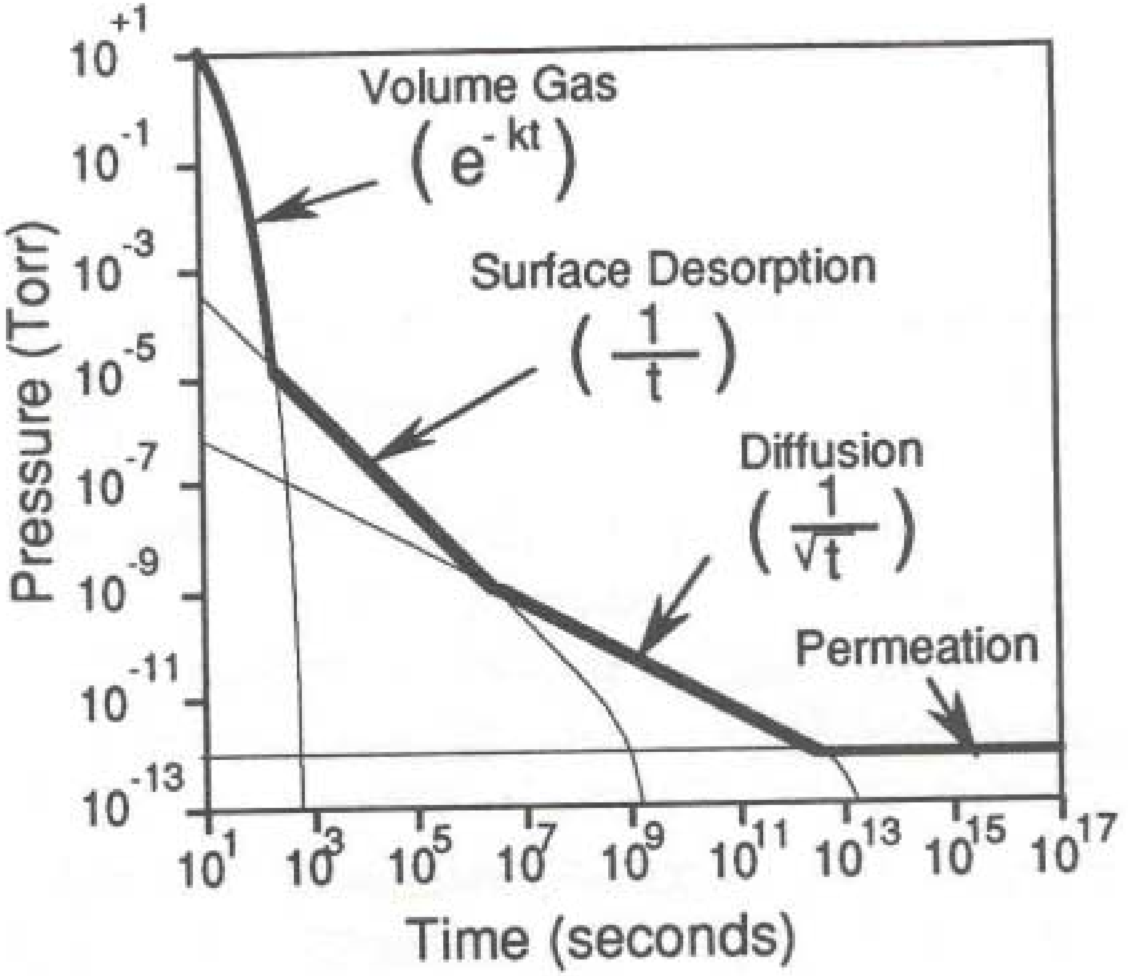
Residence time ➡ $$\tau = \frac{V_R}{S}$$

$$\frac{d(PV_R)}{dt} = Q_{gas} + Q_{leak} - Q = Q_{leak} - SP$$

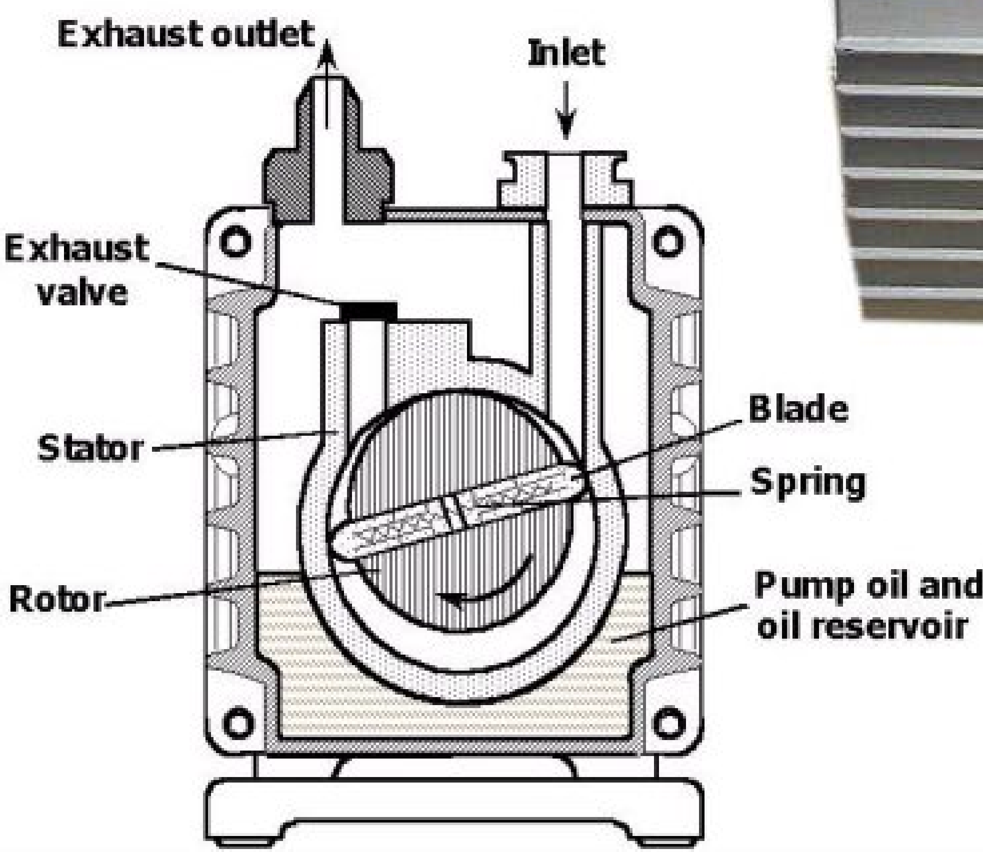
Steady state no gas flow $$P_{min} = \frac{Q_{leak}}{S}$$

Steady state with gas flow $$P = \frac{Q_{gas} + Q_{leak}}{S}$$

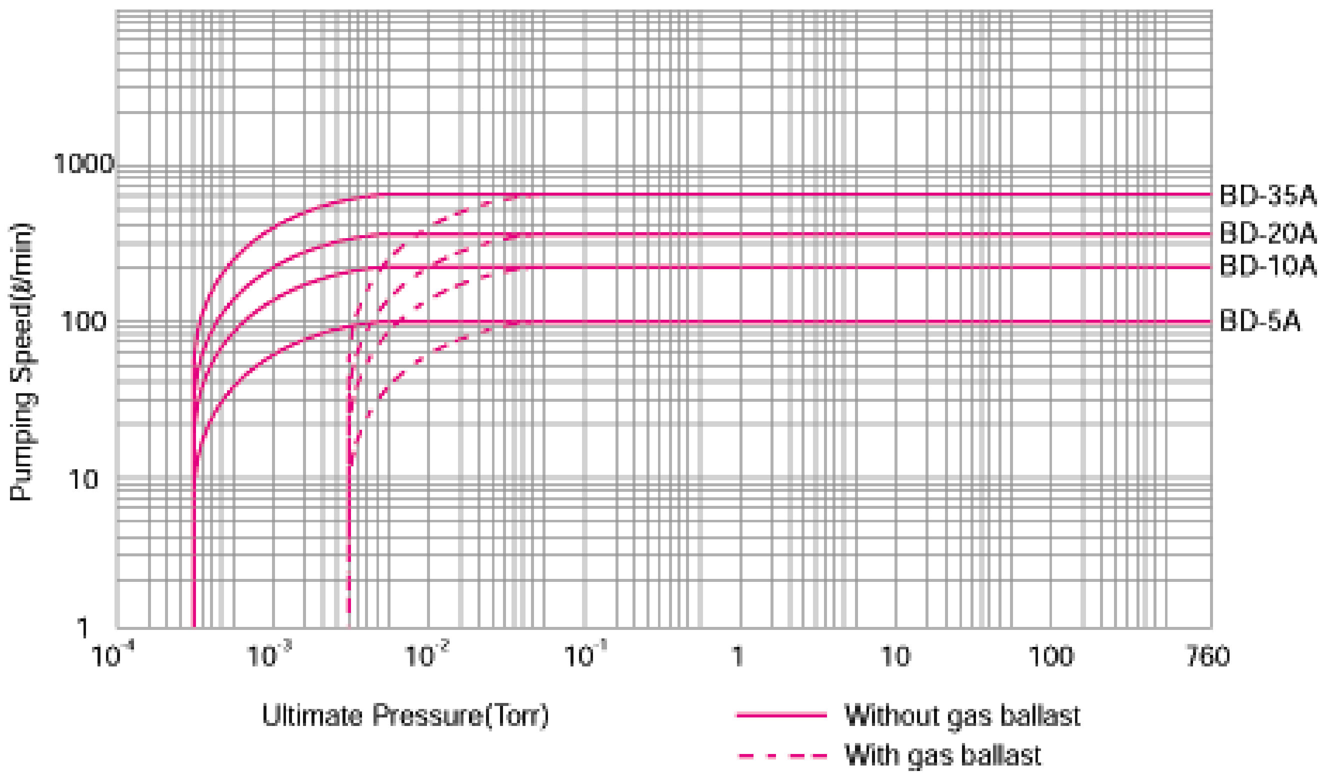
Typical pump down curve

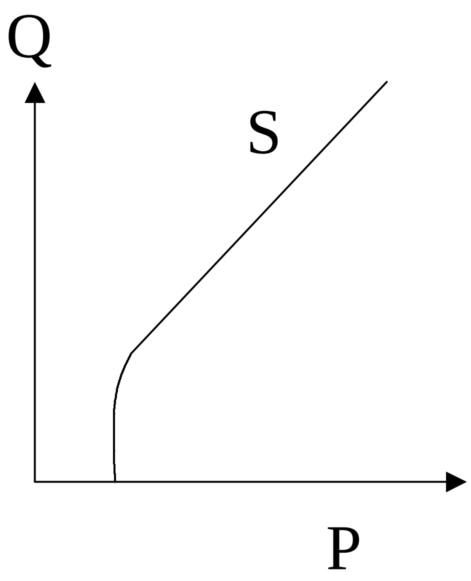


“Mechanical” Roughing Pumps

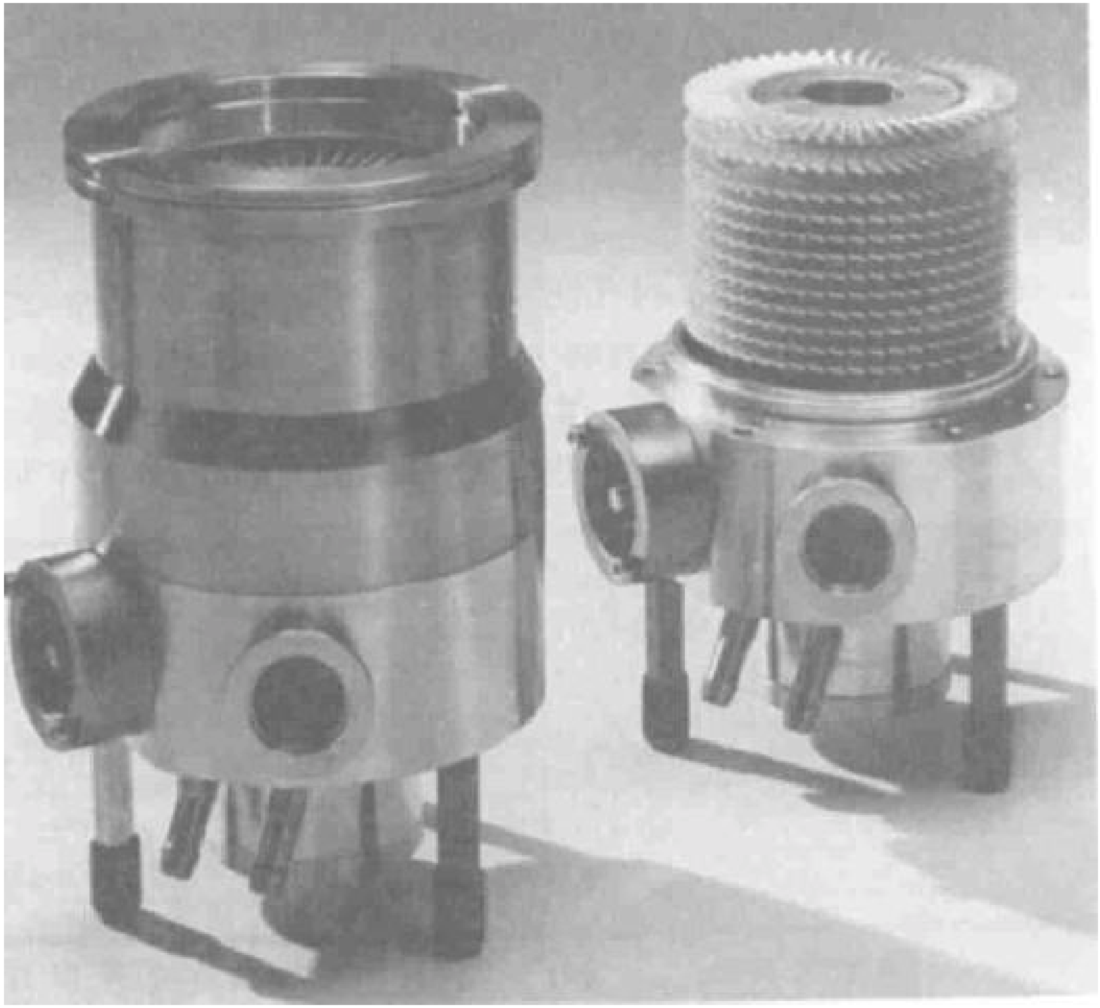


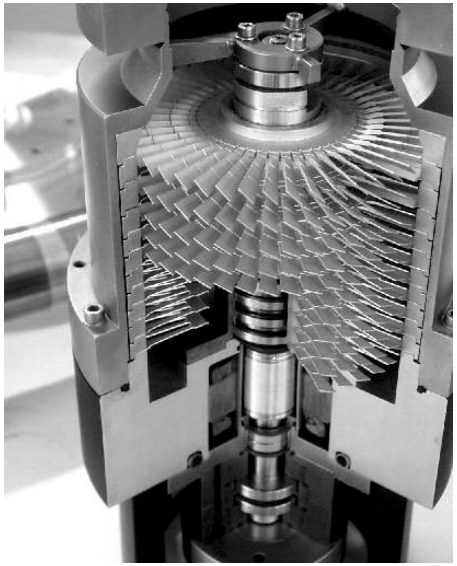
Pumping speed

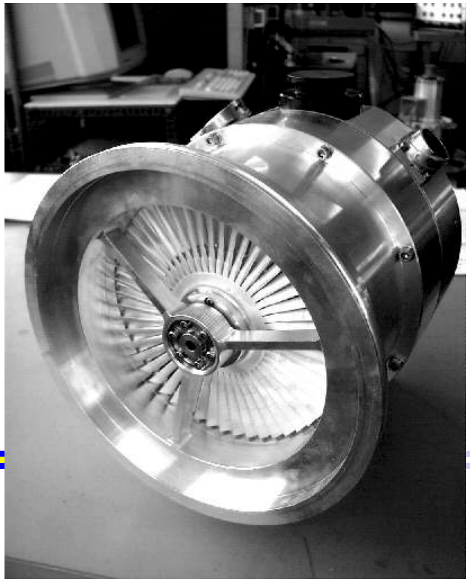




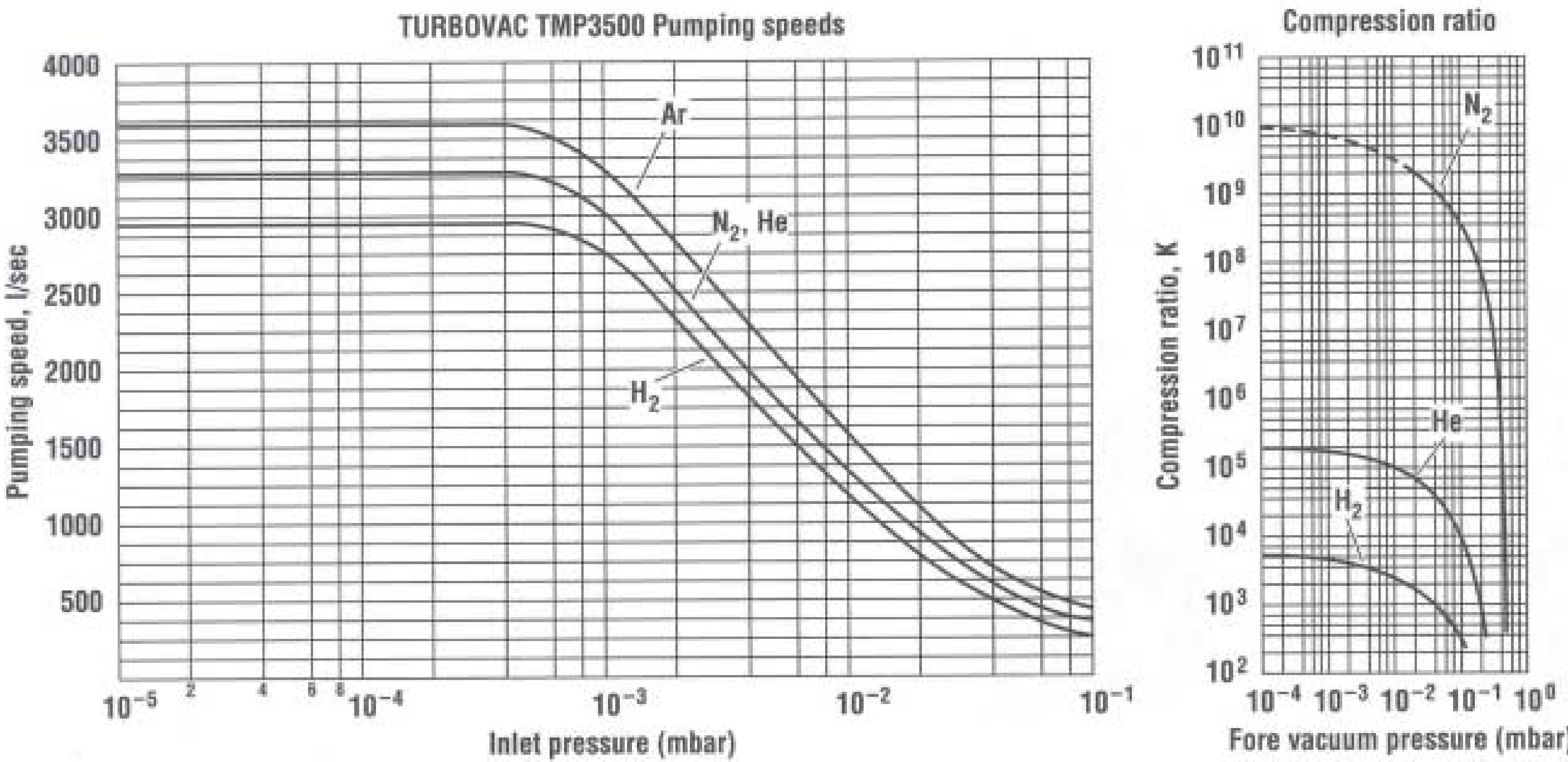
Turbomolecular pump (turbopump)



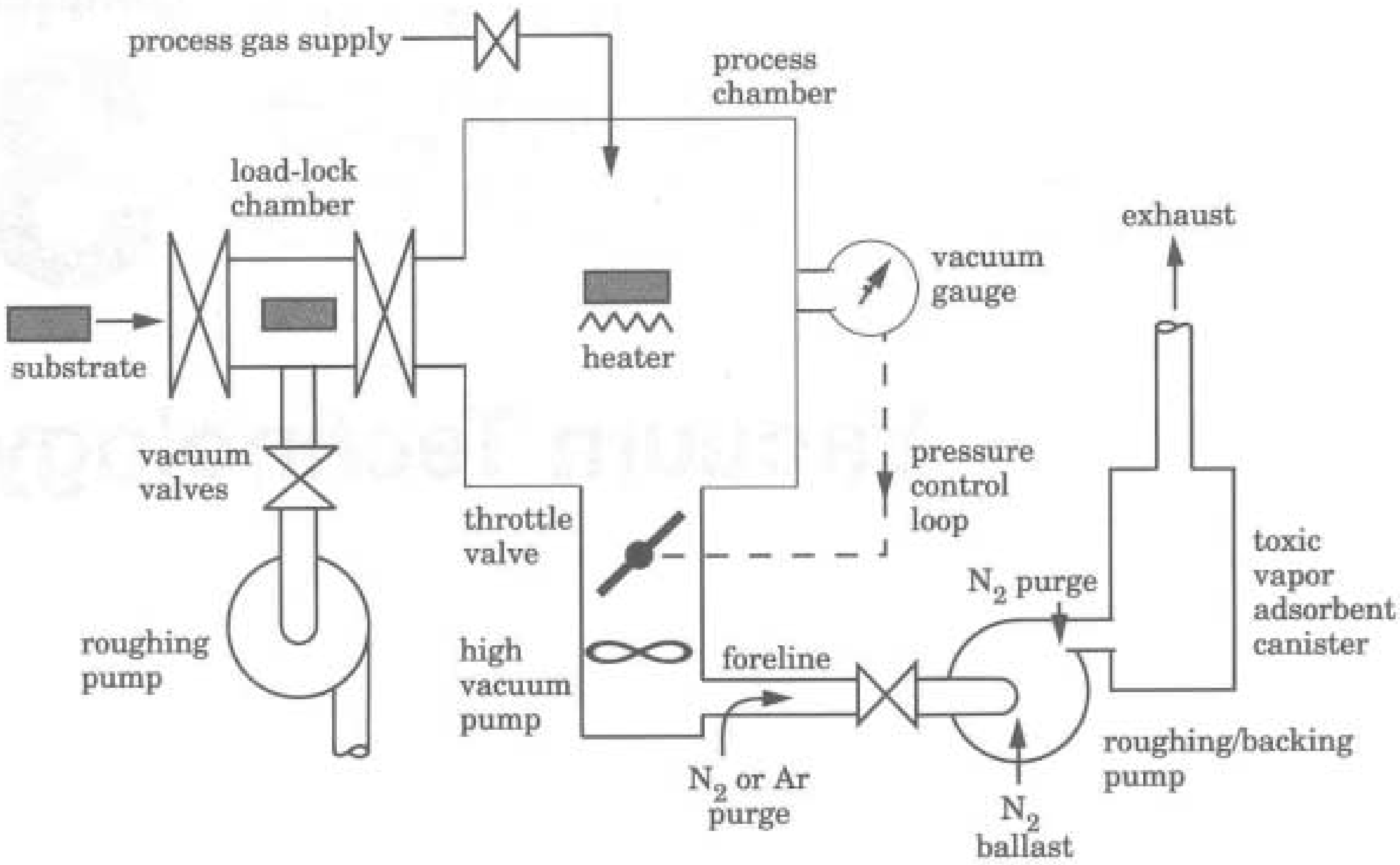




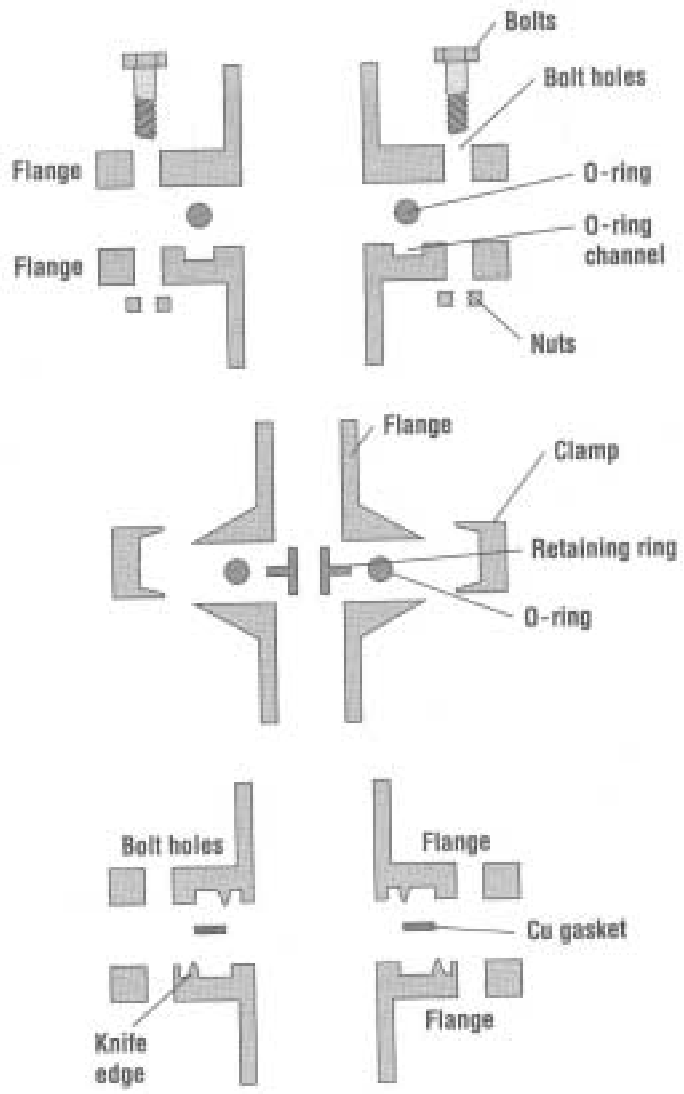
Turbomolecular pump speed curves



Typical Vacuum Apparatus



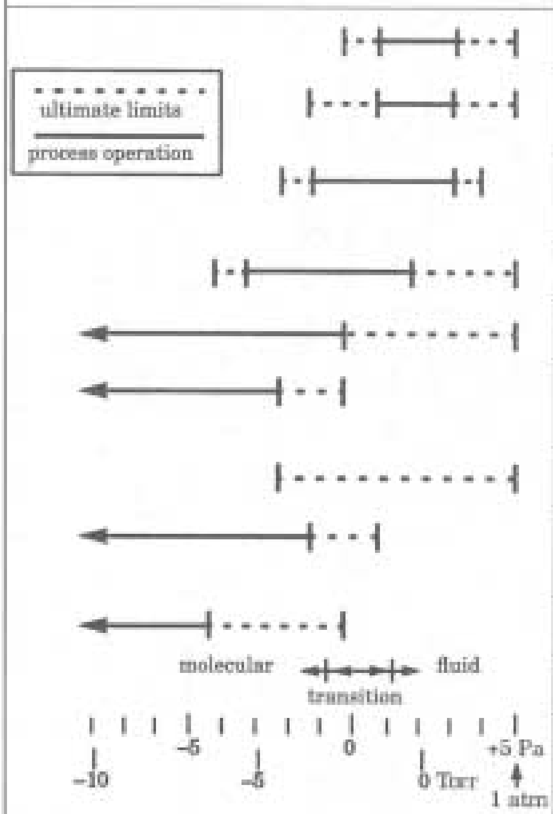
Vacuum Seals



Pumps

Pump	Principle of operation	Typical operating range in torr	Remarks
Rotary oil forepump	Displacement of gas by rotary piston or vanes	10^{-3}–760	Common for pumpdown from atmospheric pressure; oil backstreaming has to be prevented
Sorption forepump	Sorption on cooled zeolite	10^{-2}–760	Initial pumpdown for oil-free systems of moderate size
Roots pump	Displacement of gas by counter-rotating rotors	10^{-3}–1	For medium to high loads at intermediate pressures
Turbomolecular pump	Gas transfer by high-speed turbine blades	10^{-9}–10^{-1}	Low compression ratio for hydrogen and helium
Diffusion pump	Gas transfer by high-speed oil vapor emanating from jets	10^{-10}–10^{-2}	Low compression ratio for hydrogen—oil vapor has to be trapped
Getter pump	Gas sorbed on evaporated titanium	10^{-10}–10^{-3}	Does not pump noble gases and methane
Sputter-ion pump	Metal bombarded with ions	10^{-10}–10^{-3}	Memory effect—small speed for noble gases
Cryogenic pump	Sorption and condensation on cold surfaces	10^{-11}–10^{-3}	Excessive throughput causes temperature rise of cold surfaces

Pumps



Name	Category	Approx. $/(L/s)	Backing pump req'd?	Oil present? Inlet	Oil present? Outlet	Problematic gases and vapors	Other comments
Dry rotary	Displacement	1000	No	No	Yes	Condensables require gas ballasting; see text	
Oil-sealed rotary		300	No	Yes	Yes		Common for roughing/backing
Roots blower		70	Yes	No	Yes		Oil contam. unless foreline purged
Molecular drag		35	Yes	No	Yes*	Low compression ratio for H_2 and He	
Turbo-molecular		40	Yes	No	Yes*		
Oil diffusion		5	Yes	Yes	Yes		Greatest risk of oil contam.
Cryosorption	Trapping	450	No	No	(No outlet)	Explosion danger with flammables	For dry roughing
He-cycle cryopump		7	No	No	No†		Low capacity for He, H_2
Sputter-ion		25	No	No	(No outlet)	Poor for inerts	

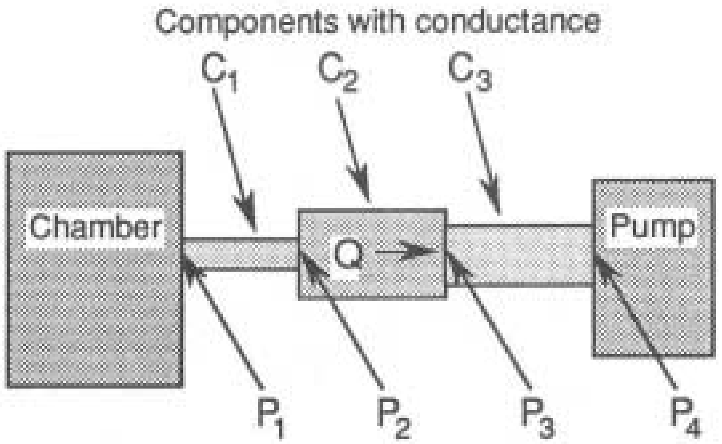
Flow regime for 5 cm diameter tube

log of pump inlet pressure

*except magnetically levitated bearing types, which use no lubrication

†Purge roughing pump line to avoid oil contamination during warmup regeneration cycle.

Conductance



$$P_1 - P_2 = \frac{Q}{C_1} \quad P_2 - P_3 = \frac{Q}{C_2} \quad P_3 - P_4 = \frac{Q}{C_3}$$

$$P_1 - P_4 = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)Q = \frac{Q}{C_t}$$

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$ components connected in series

- A connecting passage such as a tube, elbow, constriction or expansion impedes the gas flow (induces ΔP) and said to have resistance to flow.

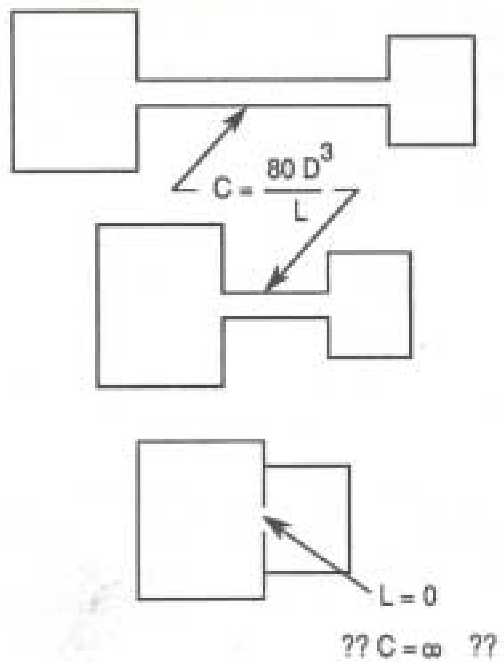
$$P_1 - P_2 = ZQ$$

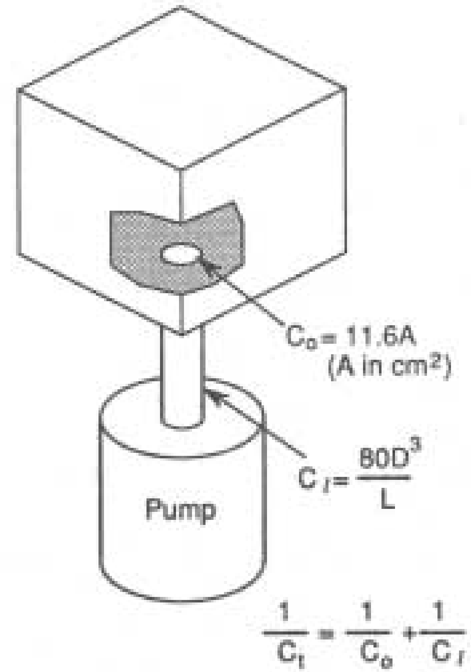
- Analogous to Ohm's law in electronics: ΔV=IR
- Frequently conductance is used to characterize the ΔP where C=1/Z

$$C = \frac{Q}{P_1 - P_2}$$

- Has same units of pumping speed but it is not the same thing

Conductance

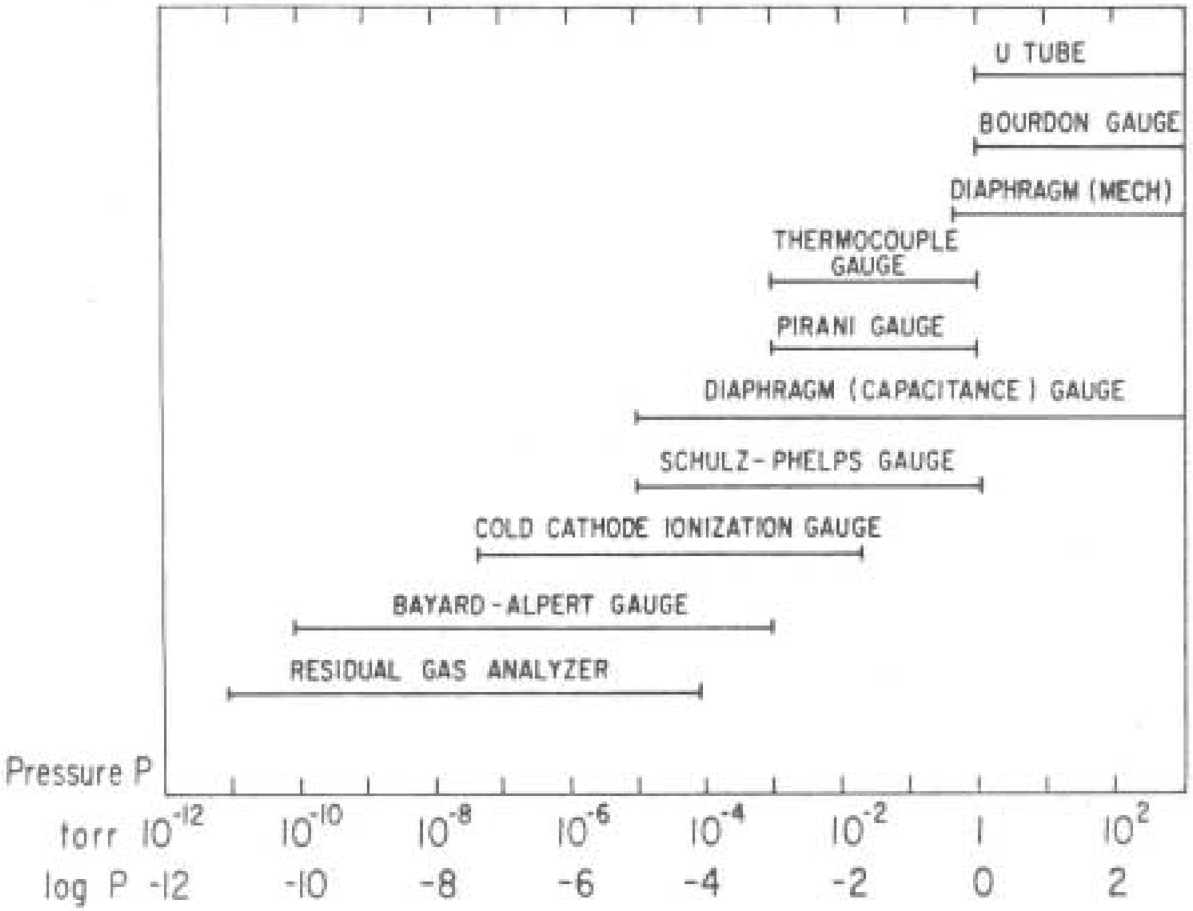




$$C_{\substack{tube\\viscous}}(\ell/s) = 3000\frac{\overline{P}(torr)D^4(inches)}{L(inches)}$$

$$C_{\substack{tube\\molecular}}(\ell/s) = 80\frac{D^3(inches)}{L(inches)}$$

Pressure Gauges



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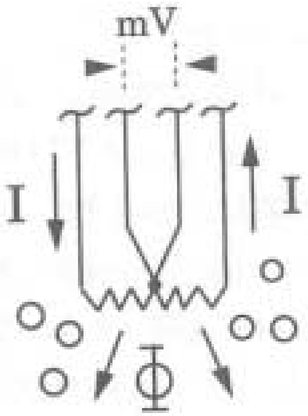

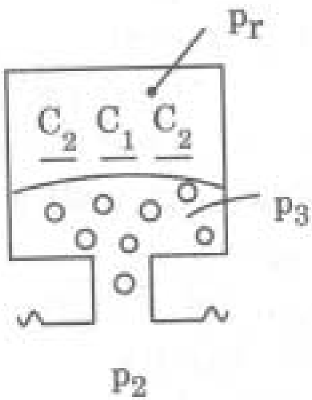

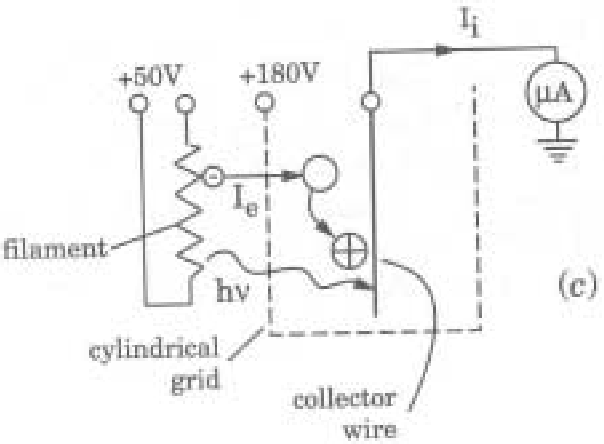

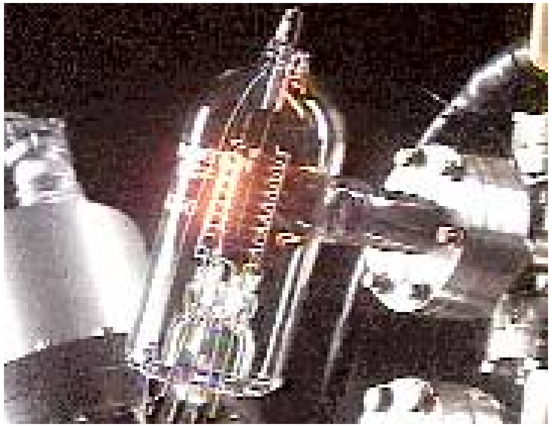

Thermocouple gauge capacitance manometer Ion Gauge

Flow Control Devices

- Mass flow controllers – senses mass flow via exchanging small amounts of heat with the gas stream.

$$\dot{Q} = \dot{m} C_p \Delta T$$

- Active feedback control. Automatic.
- Needle (or metering) valve – slow turning valve adjusts flow by changing the conductance over many turns. No feedback control. All manual