

Lecture 4

Ultrahigh Vacuum Science and Technology

Why do we need UHV?

1 Atmosphere = 760 torr; 1 torr = 133 Pa; $N \sim 2.5 \times 10^{19}$ molecules/cm³

Hertz-Knudsen equation

$$Z_w = \frac{p}{(2\pi m k_b T)^{1/2}}$$

At $p = 10^{-6}$ Torr it takes ~ 1 s to one molecule thick layer (1 ML)

So, for reasonable measurement times:

at $p = 10^{-10}$ Torr it takes $\sim 10^4$ s = 2.75 hrs for 1 ML

References:

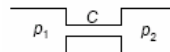
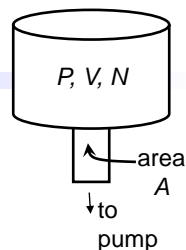
- 1) Leybold Product and Vacuum Technology Reference Book
- 2) Woodruff & Delchar, pp. 4 – 11
- 3) Luth, pp.6-17
- 4) Kolasinski, Chapter 2, pp. 57 -61,
- 5) Yates, Chapter 1

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Outline

1. Basic Principles of UHV
2. How to attain UHV?
3. Pumping through conducting elements
4. UHV Setups
5. Pumps
6. Material Considerations



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Universal density scale

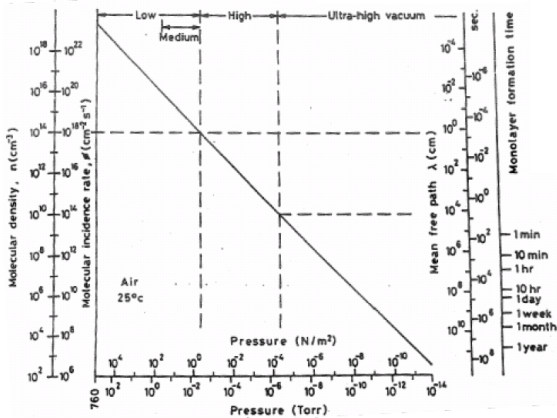
Universal density scale	g/cm ³
Big Bang	∞
Black hole	10^{27}
Neutron Star	10^{14}
White Dwarf	10^6
Solar Center	158
Sun (average density)	1.4
Water on Earth	1
Air	10^{-3}
Vacuum in Laboratory	10^{-18}
Interstellar Space	10^{-24}
Universe	10^{-30}
Empty Regions in Space	10^{-33}

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4.1 Basic Principles of UHV

Use 3 interrelated concepts to define vacuum (all related to pressure)

- **Molecular Density** (average number of molecules/unit volume)
- **Mean Free Path** (average distance between molecular collisions)
- **Time to monolayer formation**, τ_{ML}



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Mean Free Path

- **Mean free path** (average distance traveled between collisions)
 - depends on the size of the molecule and molecular density (pressure)

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n}$$

where d is the molecular diameter, in cm , and
 n is the number of molecules per cm^3 .

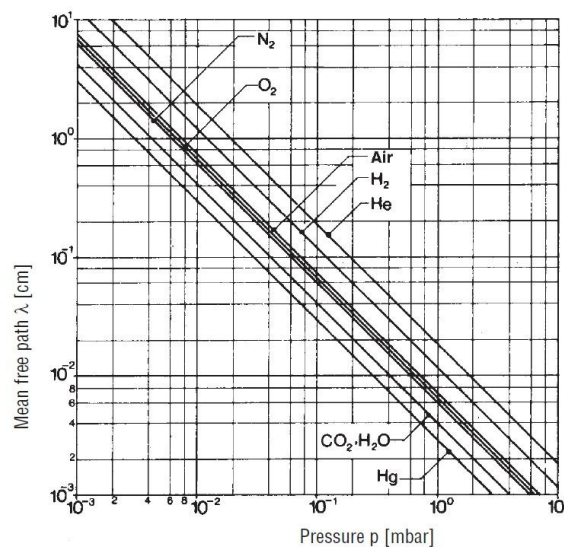
- For air at room temperature, the mean free path (in cm) can be found from

$$\lambda = \frac{0.005}{p_{Torr}}$$

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Mean Free Path correction for different gasses



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Typical contaminants are different...

Component	Atmosphere		Ultra-high vacuum	
	Percent by volume	Partial pressure, Torr	Partial pressure, Torr	Partial pressure, Torr
N ₂	78.1	5.9×10 ²	2×10 ⁻¹¹	-
O ₂	20.9	1.6×10 ²	-	3×10 ⁻¹³
H ₂ O	1.57	1.2×10 ¹	1.3×10 ⁻¹⁰	9×10 ⁻¹³
Ar	0.93	7.05	6×10 ⁻¹³	-
CO ₂	0.033	2.5×10 ⁻¹	6.5×10 ⁻¹¹	6×10 ⁻¹²
Ne	1.8×10 ⁻³	1.4×10 ⁻²	5.2×10 ⁻¹¹	-
CH ₄	2.0×10 ⁻⁴	1.5×10 ⁻³	7.1×10 ⁻¹¹	3×10 ⁻¹³
H ₂	5.0×10 ⁻⁵	3.8×10 ⁻⁴	1.8×10 ⁻⁹	2×10 ⁻¹¹
CO	-	-	1.4×10 ⁻¹⁰	9×10 ⁻¹²

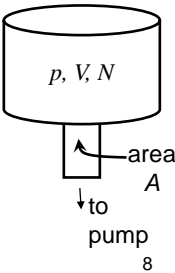
Leybold Product and Vacuum Technology Reference Book

4.2 What determines vacuum system performance?

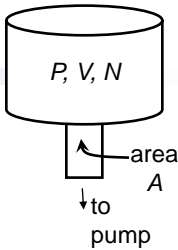
- Vacuum system performance is determined by:
- System design (volume, conductance, surface, materials)
 - Gas load, Q
 - Surface condition (outgassing and contaminations)
 - System materials (diffusion and permeation)
 - Leaks (external and internal leaks)
 - Pumping speed, S

$$p \propto \frac{Q}{S}$$

Function of a pump: molecules strike or pass through an orifice of area A and enter the pump, which attempts to keep them from returning to the volume V .



How to attain UHV?



For an ideal gas, using kinetic theory of ideal gases, one can calculate the rate of pumping, S , and p_{eq} : (see Appendix A-II for details)

From Eq.8 of A-II, for an ideal system (no leaks or outgassing):

$$\frac{dp}{dt} = -\frac{S}{V} p; \quad S - \text{pumping speed (l/s)}; \quad p = p_i \exp\left[-\frac{S}{V} t\right] \quad p = 0 \text{ at } t = \infty;$$

$$S = \frac{v_a AK}{4} = \frac{\sqrt{\frac{8}{\pi}} kT}{4} AK; \quad K - \text{statistical capture coeff. } (0 \leq K \leq 1)$$

Max pumping speed for 1 cm² orifice: $S(1\text{cm}^2) = \frac{4.64 \times 10^4 \times 1\text{cm}^2 \times 1}{4} = 11.5\text{l/s}$

Note: in real system, pressure is limited by leaks, outgassing, etc., limiting the ultimate base pressure. For constant leak L (Torr l/s), we have eq. 12:

$$\frac{dp}{dt} = -\frac{S}{V} (p - p_{eq}), \quad \text{where } p_{eq} = \frac{L}{S}$$

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Gas flow at low pressures

Flow Conditions:

Viscous: (may be turbulent or laminar) $\lambda \ll D$ (typical diameter of vessel)

Transition: $\lambda \sim D$

Molecular Flow (HV, $p < 10^{-3}$ Torr): $\lambda \gg D$ (limit discussion to this case)

D: diameter of the pipe

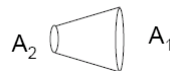
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Gas flow at low pressures: throughput

Throughput, Q :

Pumping gas from volume, two main assumptions:



1) Ideal gas law: $pV = N k T$

2) Continuity equation: $n_1 A_1 v_1 = n_2 A_2 v_2$, where $Av = S$, so $n_1 S_1 = n_2 S_2$

(# molecules/s crossing cross section is constant)

Important quantity is throughput, Q , which is proportional to the mass flow rate:

$$Q = p \frac{dV}{dt} = pAv$$

!!! Don't confuse throughput and pumping speed:

- Q depends on p while S does not.
- S is defined as the volume of gas/unit time which the pump removes from the system with pressure p at the inlet of the pump.

4.3 Pumping through conducting elements

In real cases, we don't pump through ideal orifices: consider throughput through any conducting element (tube, elbow, etc.)



Define **conductance** as: $Q = C (p_1 - p_2)$

The conductance is determined by the geometry of the element, and is approximated by:

$C \sim D^3/L$ – for long tube,

$C \sim D^2$ (for orifice)

See Appendix III for more details

Pumping through conducting elements

At UHV conductance is constant

Ohm's law analog: $Q \sim$ current, $\Delta p \sim$ voltage; $C \sim$ conductivity

Relation of Pumping Speed and Conductance

Effective pumping speed S in a chamber connected by conductance C to a pump having speed S_p is given by:

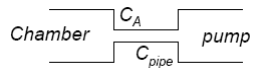
$$\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C} \Rightarrow S = C \left[\frac{1}{1 + \frac{C}{S_p}} \right]$$

Effectively conductance is reducing pumping speed

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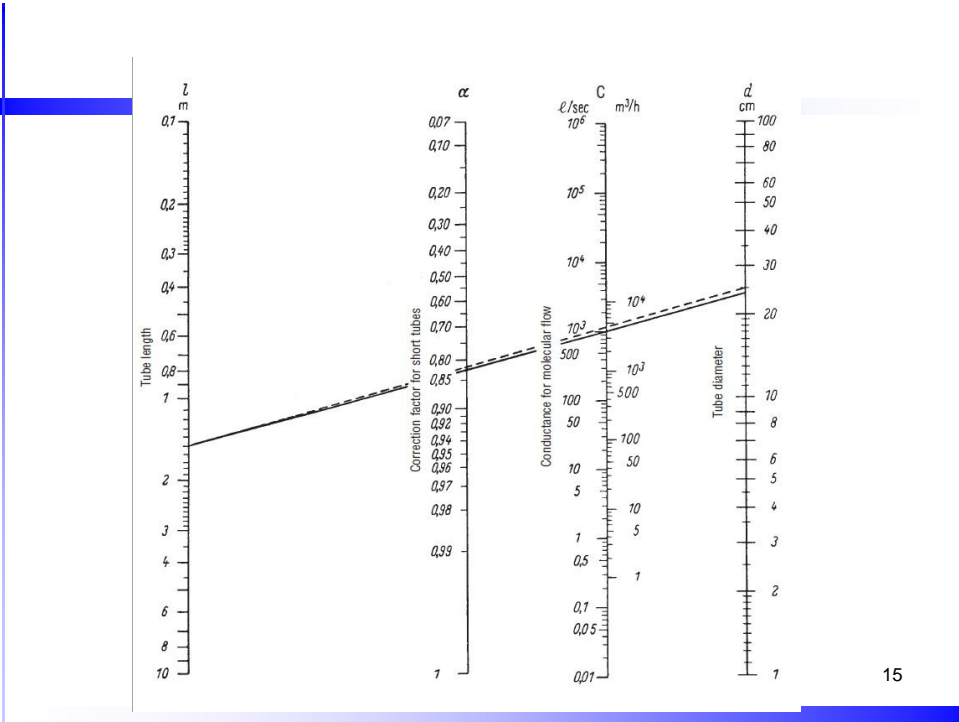
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Example: Suppose a 60 l/s turbo pump is connected to a chamber via a straight pipe 3 cm in diameter and 30 cm long. What is S ?



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4.4 UHV Setups

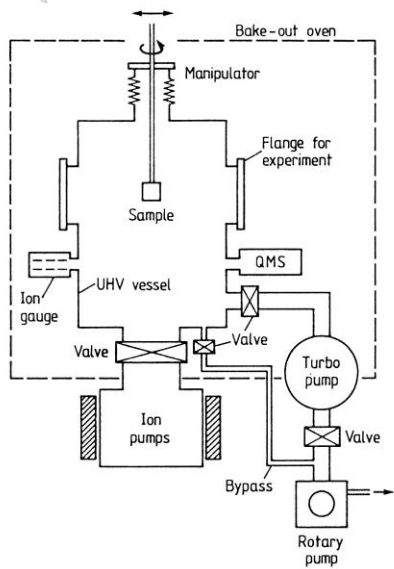


Fig.I.1. Schematic view of an Ultrahigh High Vacuum (UHV) system: stainless steel UHV vessel pumped by different pumps; the rotary backing pump can be connected to the main chamber in order to establish an initial vacuum before starting the ion pumps. Quadrupole mass spectrometer (QMS) and ion gauge are used for monitoring the residual gas. All parts enclosed by the dashed line (bake-out oven) must be baked in order to achieve UHV conditions

- Typically includes:
- Pumping stations
 - Pressure gauges
 - Quadrupole Mass Spectrometer (QMS)
 - Sample manipulation and preparation tools
 - Bakeout

Outgassing: bakeout

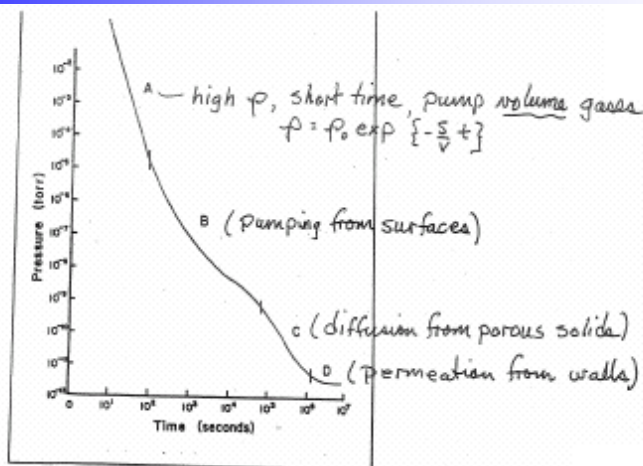


Fig. 1. Typical pump-down curve showing four major regions. (A) volume gas removal (B) limitation due to gas removal from inside surfaces (C) limitation due to gas evolving from the bulk materials of the chamber and components, and (D) limitation due to permeation through the vacuum chamber walls.

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4.5 Pumps

760 Torr – 10^{-3} Torr:

rotary, dry, sorption, membrane

HV: 10^{-2} – 10^{-6} Torr:

turbomolecular, diffusion, cryo

UHV: 10^{-6} – 10^{-12} Torr:

ion, turbomolecular, diffusion, cryo

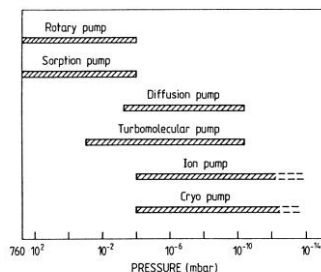


Fig.1.2. Pressure ranges in which different types of pumps can be employed

- **Positive displacement** pumps: expansion of a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere
- **Momentum transfer** pumps: high speed jets of dense fluid or high speed rotating blades to knock gaseous molecules out of the chamber
- **Entrapment** pumps capture gases in a solid or absorbed state (cryo, getter, ion pumps)

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Roughing pumps

- Rotary vane (a.k.a. mechanical, roughing) – positive displacement
- Sorption (e.g., contains zeolite cooled with LN_2)
- Diaphragm dry and membrane pumps – zero oil contamination
- Scroll pumps (the highest speed dry pump)

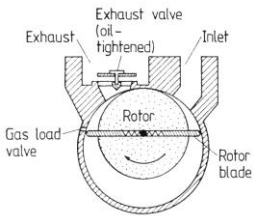


Fig.I.4. Schematic cross section through a rotary roughing pump. During the gas inlet phase the inlet volume expands. Further rotation of the eccentric rotor causes compression of this volume until the outlet phase is reached

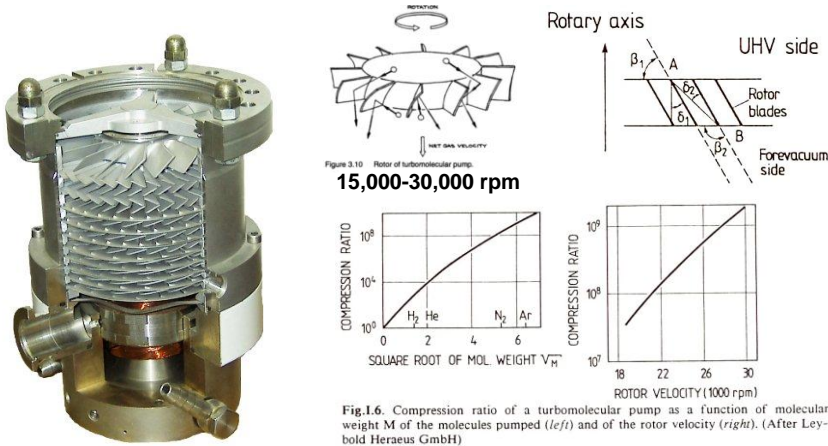


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Turbomolecular Pumps

Gas molecules are accelerated from the vacuum side to the exhaust side
 Depends on impact processes between the pumped molecules: molecular mass of the gas and rotor velocity (not as good for He and H_2)



Getter UHV pumps

- Ti sublimation getter pump
- Ion getter pump
- Cryo pump (need regeneration)
- + Effective for H_2 , H_2O and CO
- need HV to start

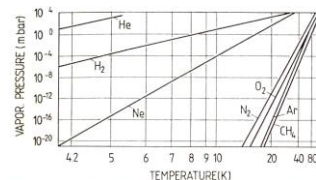
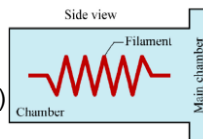


Fig. 1.10. Saturation vapor pressures of various coolant materials

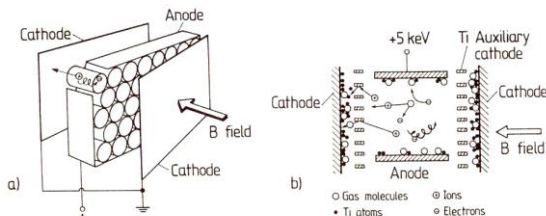


Fig. 1.7a,b. Schematic view of an ion-getter pump: (a) The basic multicell arrangement. Each cell consists essentially of a tube-like anode. The cells are sandwiched between two common cathode plates of Ti, possibly together with auxiliary cathodes of Ti. (b) Detailed representation of the processes occurring within a single cell. Residual gas molecules are hit by electrons spiralling around the magnetic field B and are ionized. The ions are accelerated to the cathode and/or auxiliary cathode; they are trapped on the active cathode surface or they sputter Ti atoms from the auxiliary cathode, which in turn help to trap further residual gas ions



4.6 Material Considerations:

- Vapor pressure – function of temperature (watch for alloys containing materials with high vapor pressure at working temperature)
- Mechanical strength – shape, temperature
- Electrical properties – insulators, non magnetic
- Optical properties
- Gas solubility, permeability
- Cost
- Fabrication capability

Metals:

Stainless Steels – 304, etc; general steels

Ni, Cu, Al – problem of bonding (Al); strength (Cu) OFHC copper

Rare metals – Zr, Ti

Refractory metals – W, Mo, Ta, Nb, Re

Precious metals – gold, Pt, AG

Soft metals – In, Ga

Materials

Glasses

Quartz (>96% SiO2): permeation primarily He through open structure
Good electrical properties; optical – different for different glasses
Borosilicate – mostly silica + alumina
Other window material:
Sapphire, LiF, CaF₂, mica (not easy to machine)

Ceramics

Many different types – most preferred for UHV high purity alumina
Macor – machinable ceramics

Elastomers and Plastomers:

HV: rubber, tygon,
UHV: nylon, teflon, silver epoxy neoprene, viton

Appendix I

1 ↓ = →	mbar	Pa (N/m ²)	dyn · cm ⁻² (μbar)	atm (phys.)	Torr (mm Hg)	inch Hg	Micron (μ)	cm H ₂ O	kp · cm ⁻² (at tech.)	lb · in ⁻² (psi)	lb · ft ⁻²
mbar	1	10 ²	10 ³	9.87 · 10 ⁻⁴	0.75	2.953 · 10 ⁻²	7.5 · 10 ²	1.0 ²	1.02 · 10 ⁻³	1.45 · 10 ⁻²	2.089
Pa	10 ⁻²	1	10	9.87 · 10 ⁻⁶	7.5 · 10 ⁻³	2.953 · 10 ⁻⁴	7.5	1.02 · 10 ⁻²	1.02 · 10 ⁻⁵	1.45 · 10 ⁻⁴	2.089 · 10 ⁻²
μbar	10 ⁻³	0.1	1	9.87 · 10 ⁻⁷	7.5 · 10 ⁻⁴	2.953 · 10 ⁻⁵	7.5 · 10 ⁻¹	1.02 · 10 ⁻³	1.02 · 10 ⁻⁶	1.45 · 10 ⁻⁵	2.089 · 10 ⁻³
atm	1013	1.01 · 10 ⁵	1.01 · 10 ⁶	1	760	29.92	7.6 · 10 ⁵	1.03 · 10 ³	1.033	14.697	2116.4
Torr	1.33	1.33 · 10 ²	1.33 · 10 ³	1.316 · 10 ⁻³	1	3.937 · 10 ⁻²	10 ³	1.3595	1.36 · 10 ⁻³	1.934 · 10 ⁻²	2.7847
in Hg	33.86	33.9 · 10 ²	33.9 · 10 ³	3.342 · 10 ⁻²	25.4	1	2.54 · 10 ⁴	34.53	3.453 · 10 ⁻²	0.48115	70.731
μ	1.33 · 10 ⁻³	1.33 · 10 ⁻¹	1.333	1.316 · 10 ⁻⁶	10 ⁻³	3.937 · 10 ⁻⁵	1	1.36 · 10 ⁻³	1.36 · 10 ⁻⁶	1.934 · 10 ⁻⁵	2.785 · 10 ⁻³
cm H ₂ O	0.9807	98.07	980.7	9.678 · 10 ⁻⁴	0.7356	2.896 · 10 ⁻²	7.36 · 10 ²	1	10 ⁻³	1.422 · 10 ⁻²	2.0483
at	9.81 · 10 ²	9.81 · 10 ⁴	9.81 · 10 ⁵	0.968	7.36 · 10 ²	28.96	7.36 · 10 ⁵	10 ³	1	14.22	2048.3
psi	68.95	68.95 · 10 ²	68.95 · 10 ³	6.804 · 10 ⁻²	51.71	2.036	51.71 · 10 ³	70.31	7.03 · 10 ⁻²	1	1.44 · 10 ²
lb · ft ⁻²	0.4788	47.88	478.8	4.725 · 10 ⁻⁴	0.3591	1.414 · 10 ⁻²	359.1	0.488	4.88 · 10 ⁻⁴	6.94 · 10 ⁻³	1

Normal conditions: 0 °C and sea level, i.e. p = 1013 mbar = 760 mm Hg = 760 torr = 1 atm
in Hg = inches of mercury; 1 mtorr (millitorr) = 10⁻³ torr = 1 μ (micron ... μm Hg column)
Pounds per square inch = lb · in⁻² = lb / sqin = psi (psig = psi gauge ... pressure above atmospheric, pressure gauge reading; psia = psi absolute ... absolute pressure)
Pounds per square foot = lb / sqft = lb / ft²; kgf/sqcm² = kg force per square cm = kp / cm² = at; analogously also: lbf / squin = psi
1 dyn · cm⁻² (cgs) = 1 μbar (microbar) = 1 barye; 1 bar = 0.1 Mpa; 1 cm water column (cm water column = g / cm² at 4 °C) = 1 Ger (Geryk)
atm ... physical atmosphere – at ... technical atmosphere; 100 - (x mbar / 10.13) = y % vacuum

Table II: Conversion of pressure units

Appendix II

Pumping of an Ideal Gas

From the kinetic theory of ideal gases,

$$pV = N k T \quad (1)$$

Take the derivative with respect to time, yielding,

$$\frac{dp}{dt} = -\frac{kT}{V} \left(\frac{dN}{dt} \right) \quad (2)$$

assuming T and V constant (usually a good assumption). Now,

$$M = \frac{nv_a A}{4} \quad (3)$$

number of molecules striking surface area A per unit time. Then,

$$\frac{dN}{dt} = K \frac{nv_a AK}{4} \quad (4)$$

number of molecules removed per unit time with K as statistical capture coefficient ($0 < K < 1$), and

$$\frac{dp}{dt} = -\frac{kT}{V} \frac{nv_a AK}{4} \quad (5)$$

from (1)

$$n = \frac{N}{V} = \frac{p}{kT} \quad (6)$$

and

$$\frac{dp}{dt} = -\frac{kT}{V} \frac{v_a AK}{4} \frac{p}{kT} = \frac{v_a AK}{4V} p \quad (7)$$

then, let $\frac{v_a AK}{4} \equiv S$, pumping speed with units of volume/time

$$\frac{dp}{dt} = -\frac{S}{V} p \quad (8)$$

Now, for gas leakage alone:

$$\frac{dp}{dt} = \frac{L}{V} \quad (9)$$

where L is leakage rate into the system and for both leakage and pumping,

$$\frac{dp}{dt} = -\frac{S}{V}p + \frac{L}{V} \quad (10)$$

At equilibrium $\frac{dp}{dt} = 0$

$$\frac{S}{V}p_{eq} = \frac{L}{V} \text{ and } p_{eq} = \frac{L}{S} \quad (11)$$

Eq. (10) can be written as:

$$\frac{dp}{dt} = -\frac{S}{V}(p - p_{eq}) \quad (12)$$

Finally, integrating (12) leads to

$$p = p_{eq} + (p_i - p_{eq})\exp\left(-\frac{S}{V}t\right) \quad (13)$$

For $p_i \gg p_{eq}$

$$p = p_i \exp\left(-\frac{S}{V}t\right) \quad (14)$$

CONDUCTANCE

Define the conductance "C" of a piece of vacuum hardware
as: $C = Q/\Delta P$ gas flow/pressure difference

The units of conductance are therefore 'volume/time', usually given in liters/sec.

For parallel connections $C_T = C_1 + C_2 + \dots$

For series connections $1/C_T = 1/C_1 + 1/C_2 + \dots$

In the molecular flow region (i.e. where the mean free path is greater than the dimensions of the system)

1. Conductance of an orifice

$$C = 3.64(T/M)^{1/2} \text{ liters/sec/cm}^2 \times A \text{ (cm}^2\text{)}$$

T is temperature in degrees K; M is molecular number of the molecule.

2. Conductance of a pipe

$$C = 3.8(T/M)^{1/2}(D^3/L) \text{ liters/sec}$$

D and L are in centimeters

for comparison, in the viscous flow region(for nitrogen):

$$C \sim 188 (D^4/L) p_{av} \text{ liters/sec}$$

where D & L are in centimeters and p(average) is in torr