Surface and Interface Science
Physics 627; Chemistry 541

Lectures 12
Oct. 11 2010

Ultrahigh Vacuum Science and Technology

References:

1) A. Roth, Vacuum Technology, second revised edition (North Holland, Amsterdam, 1982)
2) P.A. Redhead, U. P. Hobson, E.V. Kornelson, The Physical Basis of Ultrahigh Vacuum (Chapman and Hall, Ltd., London, 1968); reprinted by the Am. Institute of Physics as an Am. Vac. Society Classic (1993).
3) D. Lichtman, The Physics Teacher, March 1975, P143.
4) Leybold Product and Vacuum Technology Reference Book
5) Woodruff and Delchar, Pp. 4 – 11.

Introduction: Why do we need UHV?

1 Atmosphere = 760 torr;   1 torr = 133 Pa

n ~ 2.5 x 10^{19} molecules/cm^3

υ= incident flux = (¼)nv_{av} = 2.9 x 10^{23} $cm^{-1}s^{-1}$

~ 10^9 Monolayers/s

At 1 x 10^{-6} torr, υ ~ 3.8 x 10^{14} molecules/$cm^{2}\cdot s$ (for CO, N_2)

υ ~ 1 ML/s   (1 ML ~ 10^{15} atoms/cm^2)

τ_{ML} ~ 1 s (assuming sticking probability S = 1)

So, for reasonable measurement times:

υ ~ 10^{-4} ML/s → τ_{ML} > 10^4 s

<u>P ~ 10^{-10} torr</u>

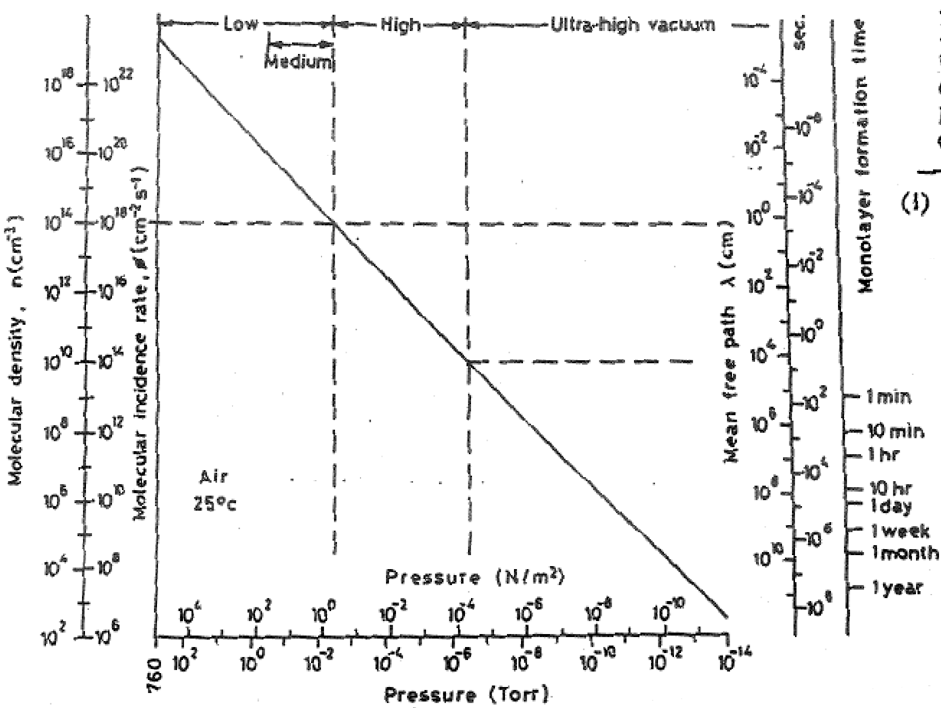
Basic Principles of UHV

Use three interrelated concepts
to define vacuum (all related to pressure):

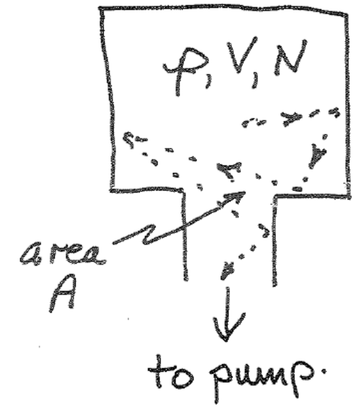
- Molecular Density
  (average number of
  molecules/unit volume)
- Mean Free Path
  (average distance
  between molecular collisions)
- Time to monolayer formation, τ_{ML}

Component	Atmosphere(1)		Ultra-high vacuum	
	Percent by volume	Partial pressure Torr	Partial pressure Torr (2)	(3)
N_2	78.08	5.95×10^{2}	2×10^{-11}	—
O_2	20.95	1.59×10^{2}	—	3×10^{-13}
Ar	0.93	7.05	6×10^{-12}	—
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}	—
He	5.24×10^{-4}	4×10^{-3}	3.6×10^{-10}	—
Kr	1.1×10^{-4}	8.4×10^{-4}	—	—
H_2	5.0×10^{-5}	3.8×10^{-4}	1.79×10^{-9}	2×10^{-11}
Xe	8.7×10^{-6}	6.6×10^{-5}	—	—
H_2O	1.57	1.19×10^{1}	1.25×10^{-10}	9×10^{-13}
CH_4	2×10^{-4}	1.5×10^{-3}	7.1×10^{-11}	3×10^{-13}
O_3	7×10^{-6}	5.3×10^{-5}	—	—
N_2O	5×10^{-5}	3.8×10^{-4}	—	—
CO	—	—	1.4×10^{-10}	9×10^{-12}

(1) Norton (1962) p. 11, (2) Dennis and Heppel (1968) p. 105, (3) Singleton (1966) p. 355.



Basic Principles of UHV

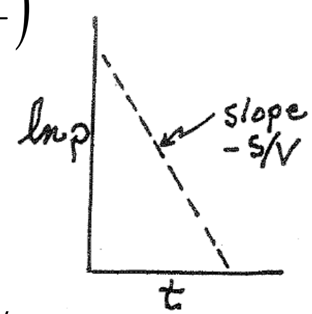


Function of a pump: Molecules strike or pass through an orifice of area A and enter the pump, which attempts to keep them from returning to the volume V.

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

From Eqn 8 of A-I, for an ideal system (no leaks or outgassing): $$\frac{dp}{dt} = -\frac{S}{V}p$$

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

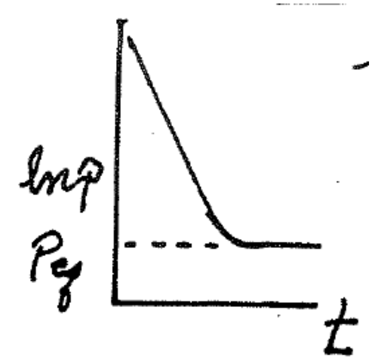


Max pumping speed for 1 cm^2 orifice: $$S = \frac{v_a A K}{4} \quad \left(v_a = \sqrt{\frac{8}{\pi}\frac{kT}{m}}\right)$$

$$v_a = 1.46\times10^4\sqrt{\frac{T}{m}}\ \text{cm/s} \quad \cong 4.64\times10^4\ \text{cm/s}$$

K= 1 (statistical capture coefficient [related to conductance])

Which gives: $$S = \frac{4.64\times10^4 \times 1\text{cm}^2 \times 1}{4} = 11.5\times10^3\text{cm}^3/\text{s} = 11.5\ \text{l/s}$$

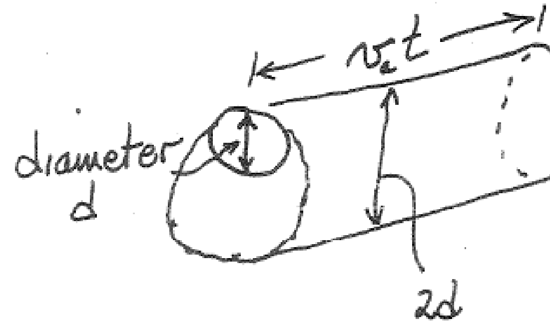


Note: in real system, pressure is limited by leaks, outgassing, etc, limiting the ultimate base pressure. For constant leak L (torr l/s)

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

Basic Principles of UHV

<u>*Gas flow at low pressures:*</u>



Mean free path: λ

Volume swept out in time *t*: $\delta V = \pi d^2 v_a t$

Number of particles in δV: $\delta n = (\pi d^2 v_a t) n$

But: number of particles in δV
equals number of collisions in time *t*.

→Mean free path (mfp) $\lambda = \dfrac{v_a t}{(\pi d^2 v_a t) n} = \dfrac{1}{\pi d^2 n}$

→ for air at 300K: $\lambda = \dfrac{5 \times 10^{-3}}{p}$

with λ in cm and *p* in torr.

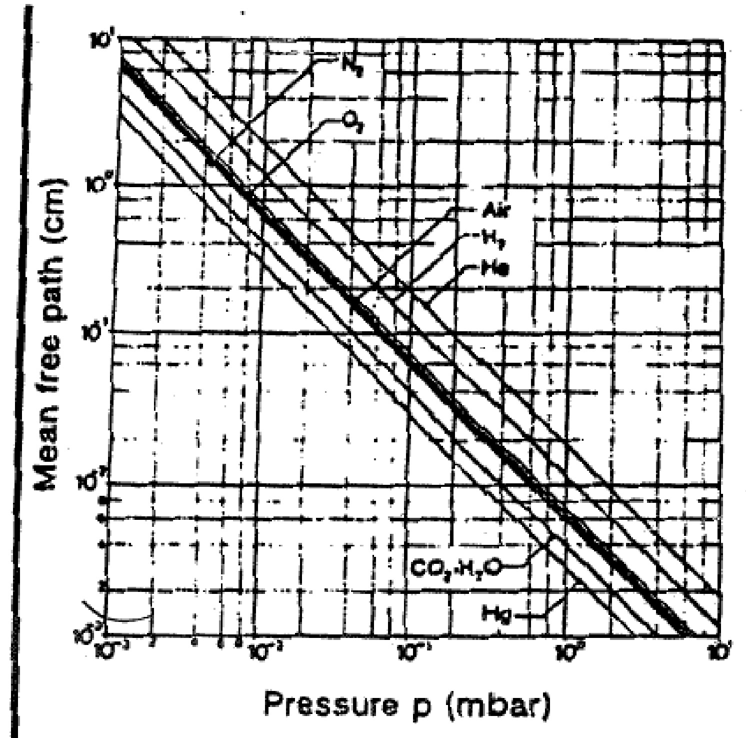


Fig. 82.1 Mean free path l as a function of pressure p for 20 °C (see also Table 3).

Basic Principles of UHV

ii) Flow Conditions:

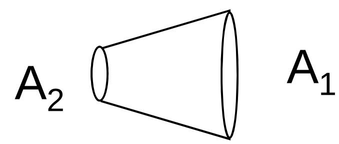
Viscous: (may be turbulent or laminar) $\lambda << D$ (typical diameter of vessel)

Molecular Flow $\lambda >> D$ (UHV) [limit discussion to this case]

Transition $\lambda \sim D$

iii) Throughput, Conductance:

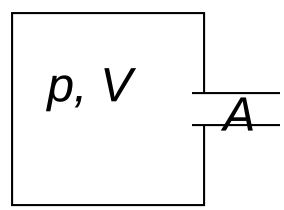
Pumping gas from volume, two main assumptions:



Ideal Gas law: $pV = NkT$

Continuity equation: $n_1 A_1 v_1 = n_2 A_2 v_2$ where: $Av = \frac{dV}{dt} = S$ 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 mass flow rate $Q = p\frac{dV}{dt} = pAv$

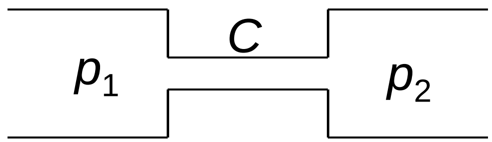


Also Q = pS [But $p \sim K(N/V) \rightarrow Q \sim (S/V)N$]

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.

Basic Principles of UHV

In real cases, we don't pump though 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 calculated: Long tube: $C \sim D^3/L$; orifice: $C \sim D^2$

At UHV, conductance is constant

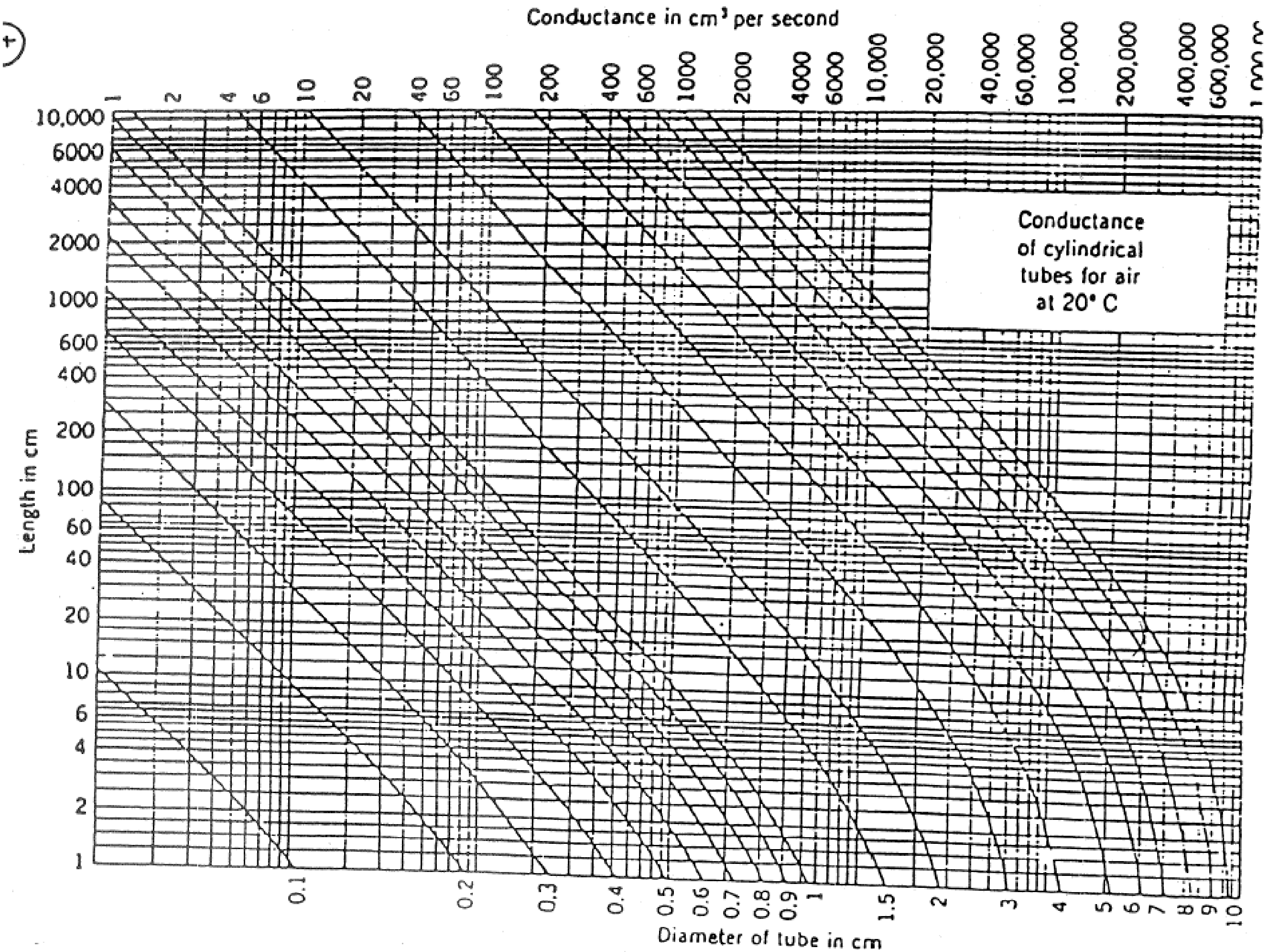
Ohm's law analog: Q ~ current; Δp ~ voltage; C ~ conductivity (flow resistance $R \sim 1/C$)

iv) <u>Relation of Pumping Speed and Conductance</u>

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

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

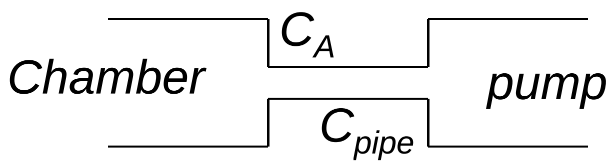
(so, for $S_P = C$, $S = 0.5\,S_P$) Effect of conductance is to reduce pumping speed.



Conductance in cm³ per second
1
2
4
6
10
20
40
60
100
200
400
600
1000
2000
4000
6000
10,000
20,000
40,000
60,000
100,000
200,000
400,000
600,000
Length in cm
10,000
6000
4000
2000
1000
600
400
200
100
60
40
20
10
6
4
2
1
Conductance of cylindrical tubes for air at 20° C
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.5
2
3
4
5
6
7
8
9
10
Diameter of tube in cm

Basic Principles of UHV

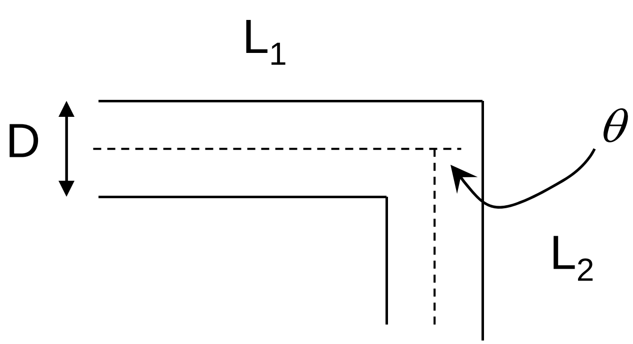
Example: Suppose a 60 l/s turbo pump is connected to a chamber via a straight pipe 3 cm in diameter and 30 cm long. What is S?



From chart, C_{pipe} = 9 l/s.
Opening has conductance C_A where $C_A = 11.5\ l s^{-1} cm^{-2} \times (\pi D^2/4) = 81.3\ l/s$

So $1/C = 1/C_A + 1/C_{pipe}$ → C = 8.1 l/s ; so: $S = (8.1)\left[\dfrac{1}{1+{}^{8.1}\!/_{60}}\right] = 7\ \text{l/s}$

Conductance of Elbow: $C = (12.5)\left[\dfrac{D^3}{L_1 + L_2 + \alpha D}\right]$ where $\alpha = 1.33\left({}^{\theta^\circ}\!/_{180^\circ}\right)$



Basic Principles of UHV

v) Outgassing; Bakeout

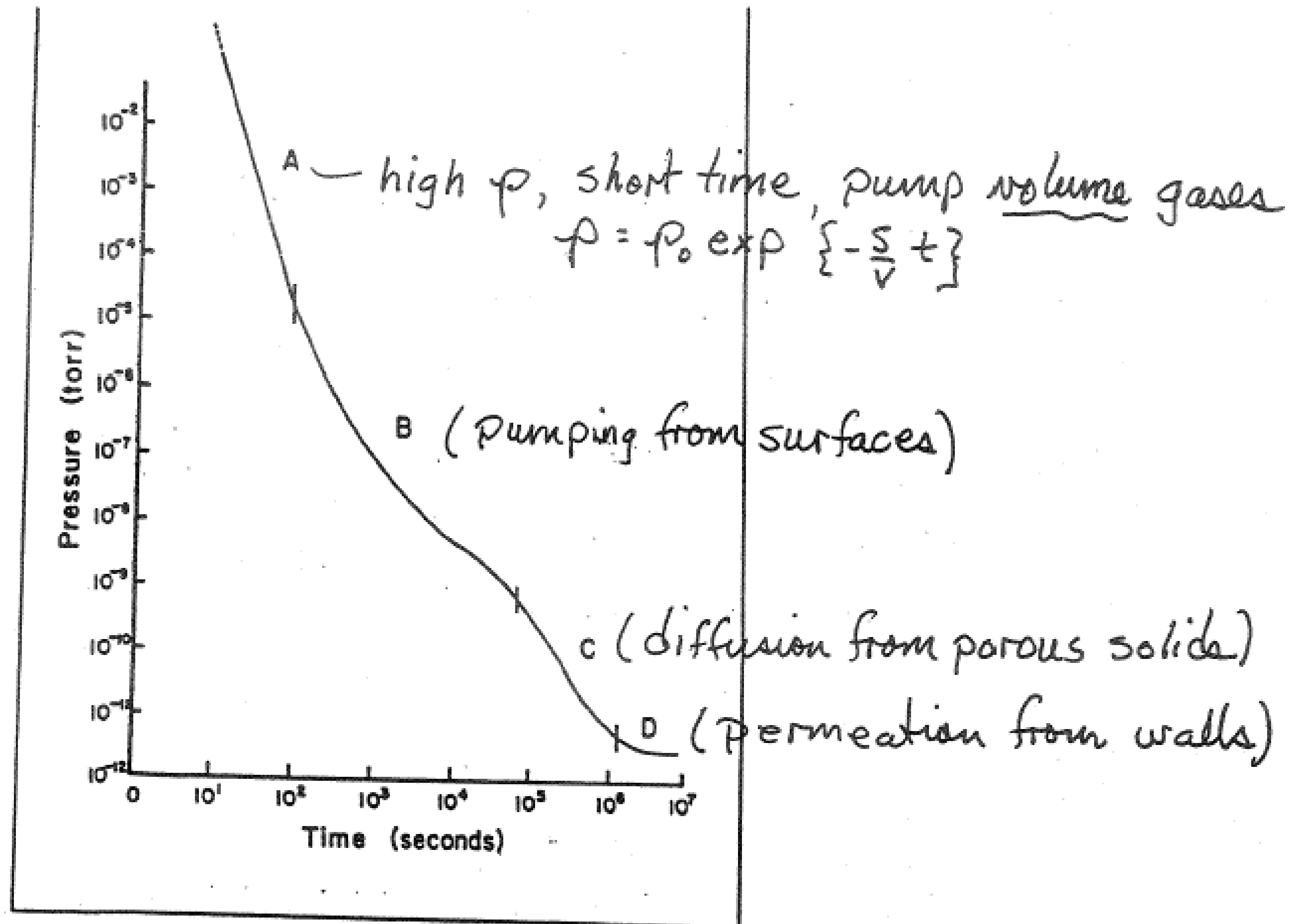


Fig. 1. Typical pump-down curve showing four major regions. (A) volume gas removal (B) limitation due to gas removal from inside surfaces (C) limitation due to gas evolving from the bulk materials of the chamber and components, and (D) limitation due to permeation through the vacuum chamber walls.

Basic Principles of UHV

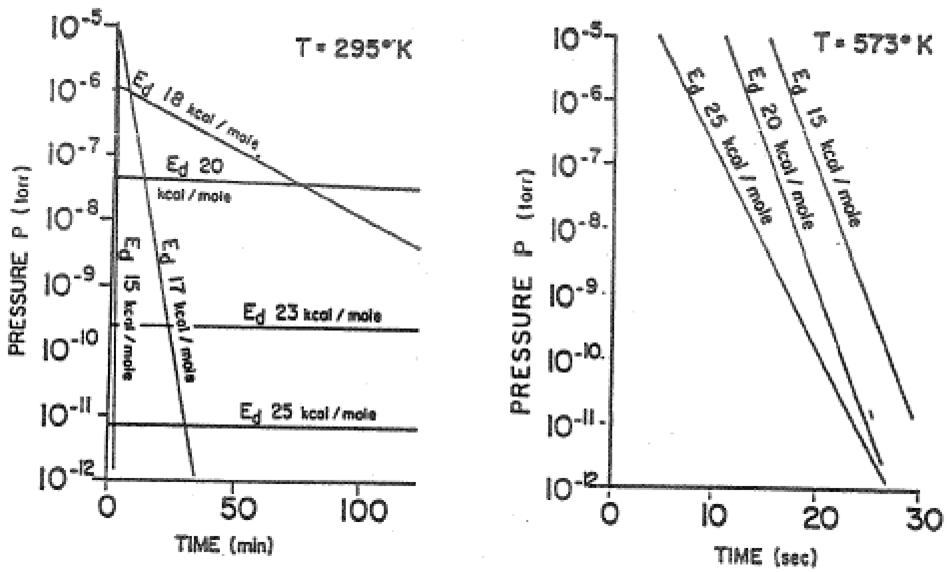
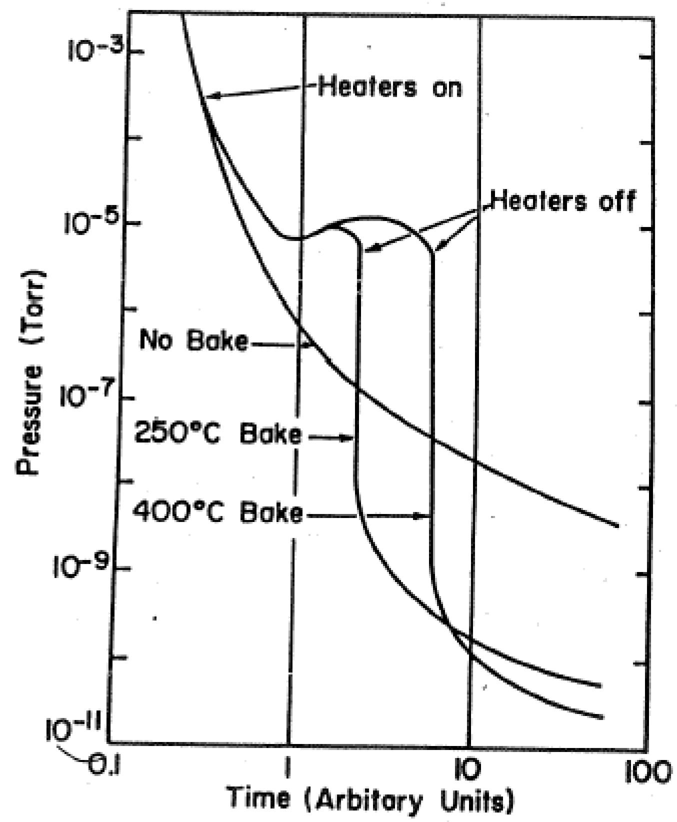


Fig. 10.1 Pressure vs time with $V = 1$ litre, $S = 1$ litre sec^{-1}, $A = 100$ cm^2 covered with a monolayer at $t = 0$.
(a) $T = 295°K$
(b) $T = 573°K$



Pumping of an Ideal Gas

From the Kinetic Theory of ideal gases,

$$pV = NkT \tag{1}$$

Take the derivative with respect to time, yielding,

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

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

$$M = \frac{nv_a A}{4} \tag{3}$$

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

$$\frac{dN}{dt} = \frac{nv_a A}{4} \times K \tag{4}$$

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

$$\frac{dp}{dt} = -\frac{kT}{V}\frac{nv_a AK}{4} \tag{5}$$

from (1)

$$n = \frac{N}{V} = \frac{p}{kT} \tag{6}$$

and,

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

then, let $\frac{v_a AK}{4} \equiv S$

$$\frac{dp}{dt} = -\frac{S}{V}p \tag{8}$$

where S is called the pumping speed with units of volume/time.

Now, for gas leakage alone,

$$\frac{dp}{dt} = \frac{L}{V} \tag{9}$$

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

$$\frac{dp}{dt} = -\frac{S}{V}p + \frac{L}{V} \tag{10}$$

then, at equilibrium $\left(\text{i.e. } \frac{dp}{dt} = 0\right)$

$$p_{eq} = \frac{L}{S} \tag{11}$$

(10) can also be written as,

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

Finally, integrating (12) leads to

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

for $p_i >> p_{eq}$

$$p = p_i e^{-\frac{S}{V}t} \tag{14}$$

NOTE: The maximum possible pumping speed, S, is ~ 10 liters/sec/cm^2.

Numerical values of R for various systems of units.
(universal gas consant)

P	V	T	R_0
dyne/cm^2	cm^3	°K	8.314×10^7 erg/°K mole
Newton/m^2	m^3	°K	8.314 Joule/°K mole
Torr	cm^3	°K	6.236×10^4 Torr·cm^3/°K mole
Torr	liter	°K	62.364 Torr·liter/°K mole
atm	cm^3	°K	82.057 atm·cm^3/°K mole