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Vacuum Technology

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大綱

- 真空氣壓與氣流 (Pressure, Gas Flow)
- 真空抽氣與氣導限制 (Pump Down, Conductance)
- 真空系統組成 (Vacuum Systems)
- 真空腔的釋氣 (Outgas)

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- 真空幫浦抽氣原理 (Pumps)
 - 真空計測量氣壓原理 (Gauges, RGA)
 - 真空系統的維護 (Vacuum Maintenance)
 - 結論 (Conclusion)

真空氣壓與氣流

- 真空氣壓的單位與範圍
- 真空中氣體分子運動速率
- 平均自由徑與氣流範圍

真空概論

- 有”空無一物”的”絕對真空”嗎？
 - 目前沒有！因為：
 - 開放空間(宇宙)－難求證(找不到)。
 - 密閉空間(腔室)－難達到(做不到)。
- 真空腔為何達不到”絕對真空”？
 - 因為腔體材料不斷釋放出氣體(Outgas)。
 - 因為幫浦無法完全抽除腔內的氣體(Pumping)。
 - 所達到的真空計測程度為氣體壓力(Pressure)。

真空氣壓的單位

Pressure: 每單位面積受的力 ($1 \text{ atm} \sim 1 \text{ kg/cm}^2$)

Pa: Newton/m² (SI unit), 1 Newton = 1 kg-m-sec⁻²

bar: (kg/cm²), 10⁶ dyne/cm², 1 dyne = 1 g-cm-sec⁻²

mb: milli-bar, 10⁻³ bar, 10³ dyne/cm²

Torr: mm-Hg (at 0 °C)

$$1 \text{ Torr} = 1.333 \text{ mb} = 133.3 \text{ Pa} \doteq 1.316 \times 10^{-3} \text{ atm}$$

$$1 \text{ Pa} = 10^{-2} \text{ mb} \doteq 7.5 \times 10^{-3} \text{ torr} \doteq 9.869 \times 10^{-6} \text{ atm}$$

$$1 \text{ atm} \doteq 760 \text{ Torr} \doteq 1013 \text{ mb} \doteq 1.013 \times 10^5 \text{ Pa}$$

一大氣壓的單位表示

Atmospheric Pressure (Standard) =

0	gauge pressure (psig)
14.7	pounds per square inch (psia)
29.9	inches of mercury
760	millimeter of mercury (毫米汞柱)
760	Torr (托耳)
760,000	milliTorr or microns
101,325	Pascal (Pa)
1.013	bar (巴)
1013	millibar (mb) (毫巴)

真空氣壓範圍

Vacuum: an environment with a pressure of < 1 atm

低真空 Low Vacuum: 760 – 25 Torr

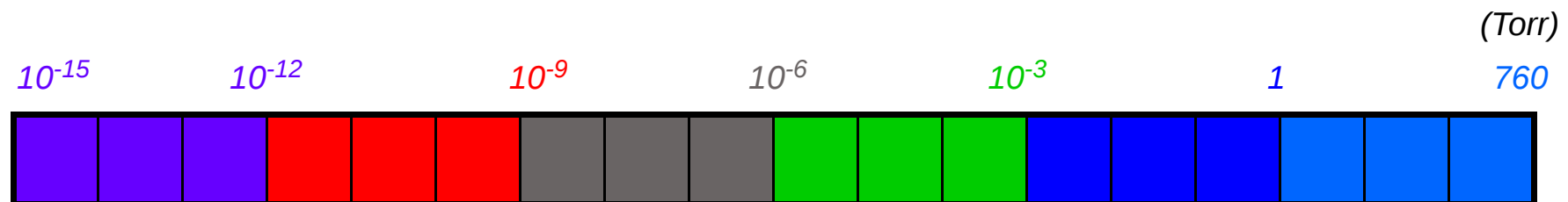
中真空 Medium Vacuum: 25 – 10^{-3} Torr

高真空 High Vacuum (HV): 10^{-3} – 10^{-6} Torr

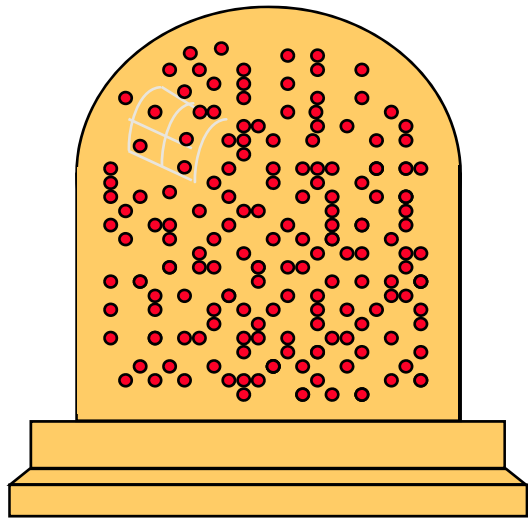
很高真空 Very High Vacuum: 10^{-6} – 10^{-9} Torr

超高真空 Ultra High Vacuum (UHV): 10^{-9} – 10^{-12} Torr

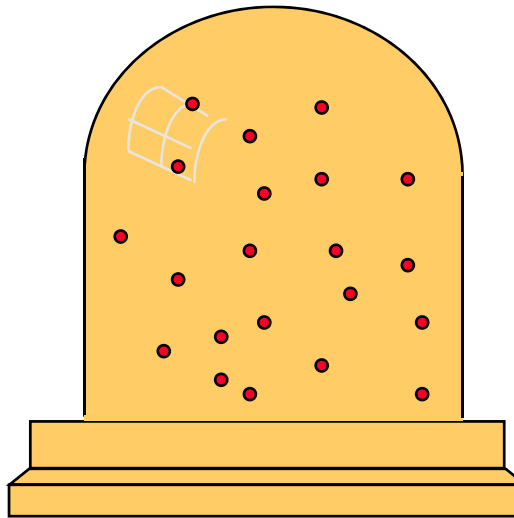
極高真空 Extreme High Vacuum (XHV): $< 10^{-12}$ Torr



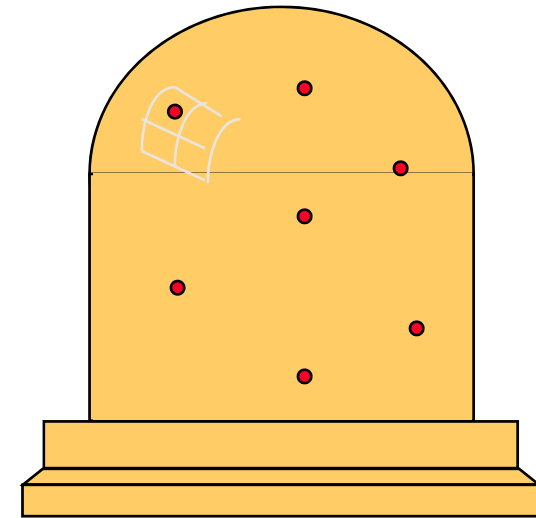
真空系統概略的壓力範圍



ROUGH
ATM to 10^{-3}
Torr



HIGH
 10^{-3} to 10^{-9}
Torr



ULTRAHIGH
 10^{-9} to 10^{-12}
Torr

波義耳定律(Boyle's Law)

$$P \cdot V = N \cdot K_B \cdot T \rightarrow N = \frac{P \cdot V}{K_B \cdot T}$$

$$\frac{d}{dt}(P \cdot V) = \frac{d}{dt}(N K_B T) = Q$$

$$V \frac{dP}{dt} + P \frac{dV}{dt} = Q = V \frac{dP}{dt} + P \cdot S$$

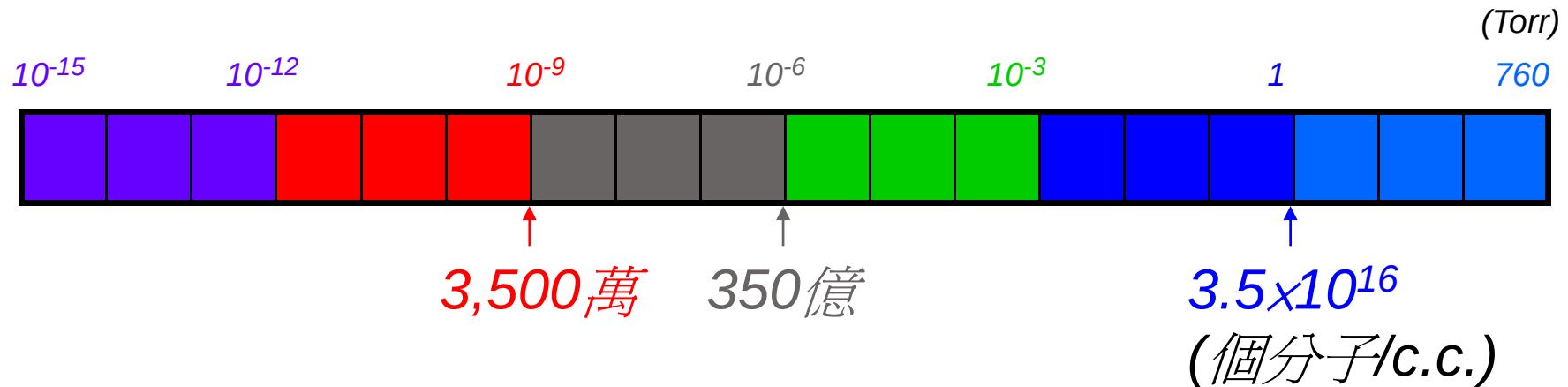
$$k_B = 1.38 \cdot 10^{-23} \left[\frac{N \cdot m}{K} = \frac{Pa \cdot m^3}{K} \right]$$

$$k_B = 1.38 \cdot 10^{-23} \left[\frac{Pa \cdot m^3}{K} \right] = 1.04 \cdot 10^{-22} \left[\frac{Torr \cdot \ell}{K} \right] = 1.38 \cdot 10^{-22} \left[\frac{mbar \cdot \ell}{K} \right]$$

$$\text{for } T = T_{RT} = 296 \text{ K}$$

$$\frac{1}{k_B T_{RT}} = 2.45 \cdot 10^{20} [Pa \cdot m^3]^{-1} = 3.3 \cdot 10^{19} [Torr \cdot \ell]^{-1} = 2.5 \cdot 10^{19} [mbar \cdot \ell]^{-1}$$

1 c.c. 體積中有多少氣體分子?



$$N = P \cdot V / K_B \cdot T = 3.3 \times 10^{19} \text{ Molecules} / \text{Torr} \cdot l (296 \text{ K})$$

$$1 \text{ Torr} \sim 3.3 \times 10^{16} \text{ Molecules} / \text{cm}^3$$

$$1 \times 10^{-6} \text{ Torr} \sim 3.3 \times 10^{10} (330 \text{ 億}) \text{ Molecules} / \text{cm}^3$$

$$1 \times 10^{-9} \text{ Torr} \sim 33,000,000 \text{ Molecules} / \text{cm}^3$$

氣體分子速率 – v (cm/s)

Maxwell-Boltzmann distribution of velocity

$$f(v) = (4/\pi^{1/2}) (m/2kT)^{3/2} v^2 \exp(-mv^2/2kT)$$

v_p : maximum value of velocity ($df(v)/dv = 0$)

$$v_p = (2kT/m)^{1/2} = (2RT/M)^{1/2}$$

v_{av} : average velocity ($\int v f(v) dv / \int f(v) dv$)

$$v_{av} = (2/\pi^{1/2}) (2kT/m)^{1/2} = 1.128 v_p$$

$$v_{av} = 1.45 \times 10^4 (T/M)^{1/2} \text{ cm/s}$$

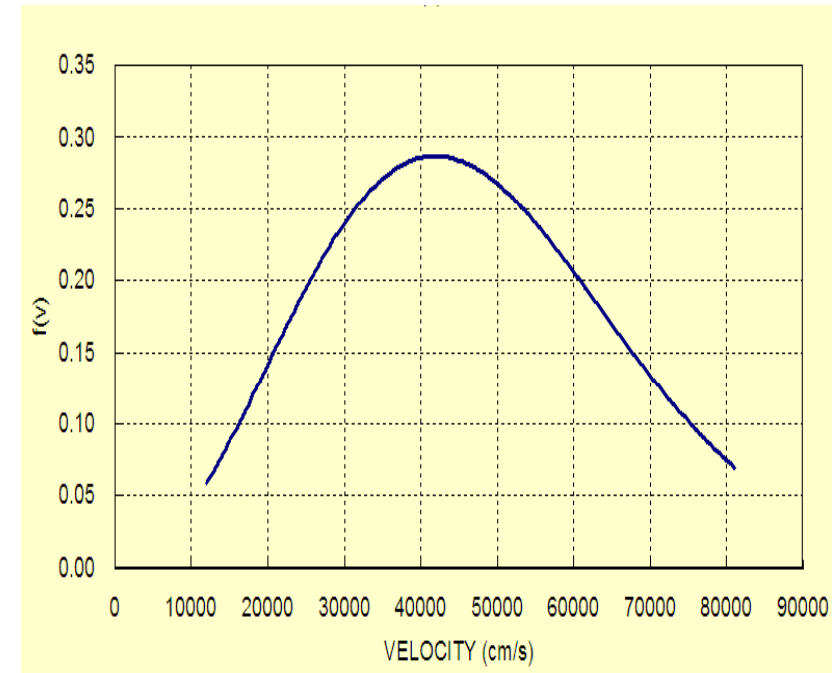
$$k = 1.38 \times 10^{-16} \text{ erg/K}$$

$$R = 8.314 \times 10^7 \text{ ergs/K}\cdot\text{mole} = k \cdot N_A$$

$$N_A = 6.02 \times 10^{23} \text{ molecules/mole}$$

$$M = m \cdot N_A$$

Maxwell-Boltzmann distribution curve



(EX) For N₂ at 296 K,

$$v_p \sim 41900 \text{ cm/s}$$

$$v_{av} \sim 47200 \text{ cm/s}$$

氣體分子平均速率 – v_{av} (cm/s)

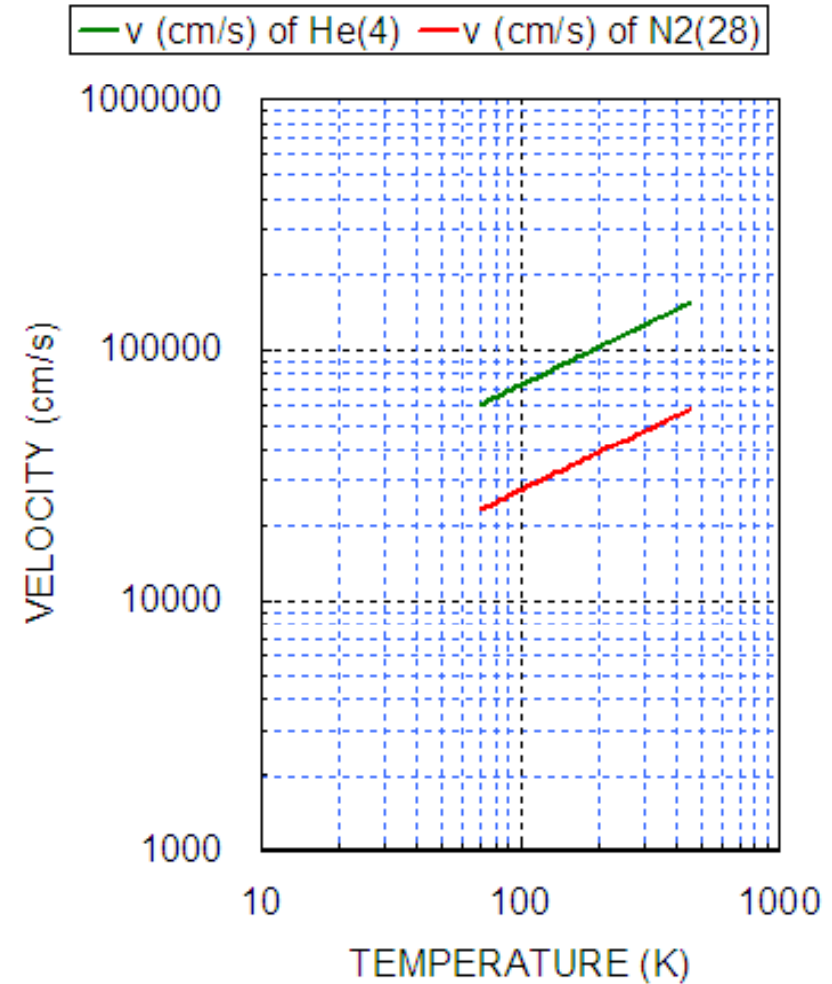
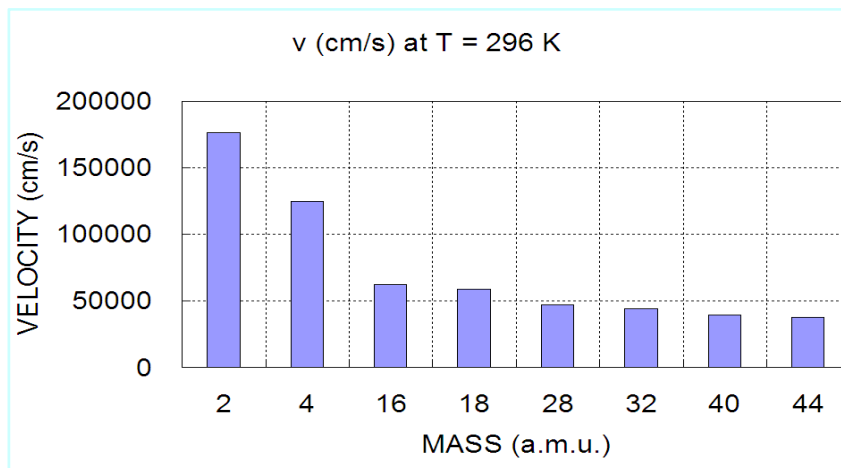
Velocity of molecule : v (cm/s)

$$v = 1.45 \times 10^4 (T/M)^{1/2} \text{ cm/s}$$

T (K) : Temperature

M (a.m.u.) : Mass of molecule

$$v \sim (T)^{1/2} \sim 1/(M)^{1/2}$$



單位面積氣體入射平均速率 – ϕ (molecules/cm²·s)

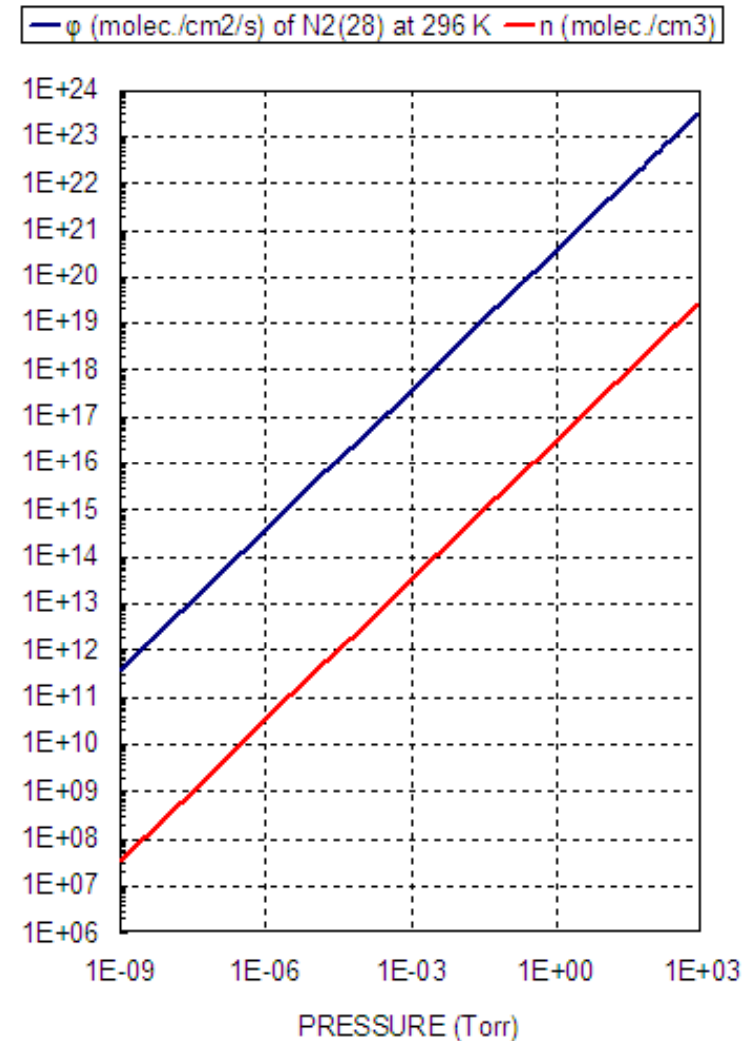
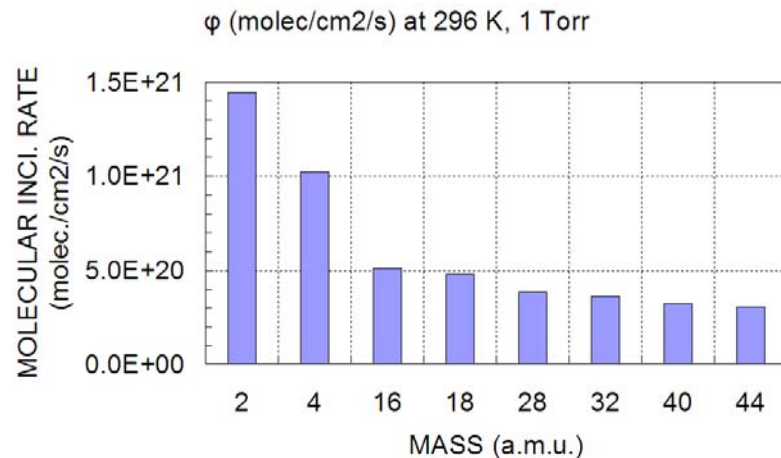
Molecular incident rate : ϕ (molec./cm²/s)

$$\phi = nv/4 = 3.5 \times 10^{22} [P/(MT)^{1/2}]$$

P (Torr) : Pressure

n (molec./cm³) : Molecular density

$$\phi \sim 1/(M)^{1/2} \sim P$$



平均自由徑: Mean Free Path (MFP, λ)

Average distance traveled between collisions (average mean free path) depends on the size of the molecule and the number of molecules present (density or pressure).

氣體分子移動要碰到
下一個分子的距離。

$$\lambda = \frac{1}{\sqrt{2} \pi d^2 n} = \frac{kT}{\sqrt{2} \pi d^2 P} = 2.33 \times 10^{-20} \frac{T}{d^2 P}$$

where d is the molecular diameter in centimeters, and n is the number of molecules per cubic centimeter. For air at room temperature, the mean free path (MFP, λ) can be found from

$$\lambda (cm) = \frac{5 \times 10^{-3}}{P_{(Torr)}}$$

在 1×10^{-4} Torr 時，
MFP = 50公分。
(> 真空腔管路尺寸)

Flow Regimes (氣流範圍)

- **Reynold number (viscous flow) : R_e**

$$R_e = \rho v D / \eta$$

$$\rho = nm = MP / (RT) ; Q = P v (\pi D^2 / 4)$$

$$R_e = \frac{MP}{RT} \cdot \frac{4Q}{\pi D^2 P} \cdot \frac{D}{\eta} = \frac{4M}{\pi RT \eta} \cdot \frac{Q}{D}$$

$$Q_{air} = 9.06 \times 10^{-2} R_e D$$

- **Knudsen number (laminar ~ mole. flow)**

$$K_n = \lambda / D = (MFP) / (Diameter\ of\ pipe)$$

$$D / \lambda = D / (5 \times 10^{-3} / P) = D \cdot P / (5 \times 10^{-3})$$

State of the gas	Flow regime	Condition
viscous	turbulent	$Re > 2100$
		$Q > 200 D$ (air)
	laminar	$Re < 1100$
		$Q < 100 D$ (air)
		$D / \lambda > 110$
transition	intermediate	$1 < D / \lambda < 110$
rarefied	molecular	$D / \lambda < 1$

$$* \eta_{(air\ at\ 20\ ^\circ C)} = 1.829 \times 10^{-4} (g/cm \cdot s)$$

$$\lambda, D (cm) ; P (Torr) ; Q (Torr \cdot l/s)$$

-
- Viscous flow ($D / \lambda > 110$) : $D \cdot P > 0.5\ cm \cdot Torr$ or $P > 5 \times 10^{-1} / D$
 - Molecular flow ($D / \lambda < 1$) : $D \cdot P < 5 \times 10^{-3}\ cm \cdot Torr$ or $P < 5 \times 10^{-3} / D$

Flow Regimes (氣流範圍)

- Viscous Flow: (粘滯流) $D \cdot P > 0.5 \text{ (cm} \cdot \text{Torr)}$

Distance between molecules is small; collisions between molecules dominate; flow through momentum transfer.

[EX] $D = 50 \text{ cm}$, $P > 0.01 \text{ Torr (10 mTorr)}$.

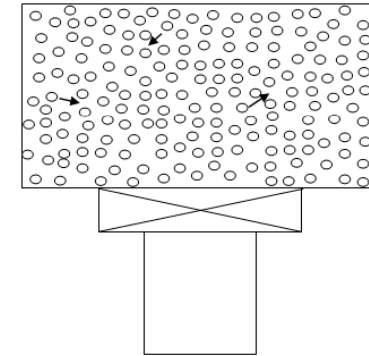
- Transition Flow: (過渡流) Region between viscous and molecular flow

- Molecular Flow: (分子流) $D \cdot P < 5 \text{ (cm} \cdot \text{mTorr)}$

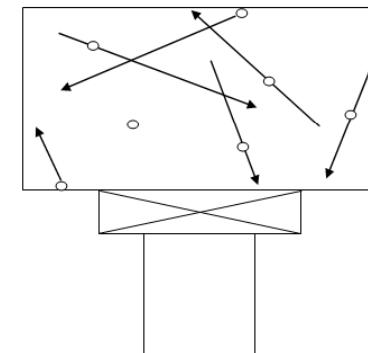
Distance between molecules is large; collisions between molecules and wall dominate; flow through random motion;

[EX] $D = 50 \text{ cm}$, $P < 0.1 \text{ mTorr}$.

- * **A system is in molecular flow when the mean free path is longer than the diameter of the tube or chamber. ($\lambda > D$)**



Viscous Flow
(momentum transfer
between molecules)



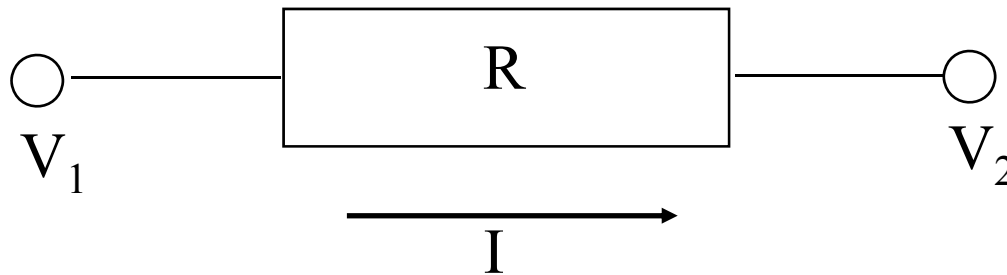
Molecular Flow
(molecules move
independently)

真空抽氣與氣導限制

- 氣導的計算
- 有效抽氣速率

氣導 (Conductance)

Ohm's Law: $(V_1 - V_2) = V = I \cdot R$



$$C \equiv \frac{1}{R}$$

電導 = 1 / 電阻

$$I = \frac{(V_1 - V_2)}{R} = C \cdot (V_1 - V_2)$$

電流 = 電導 × 電壓差

真空的歐姆定律 (Ohm's Law)

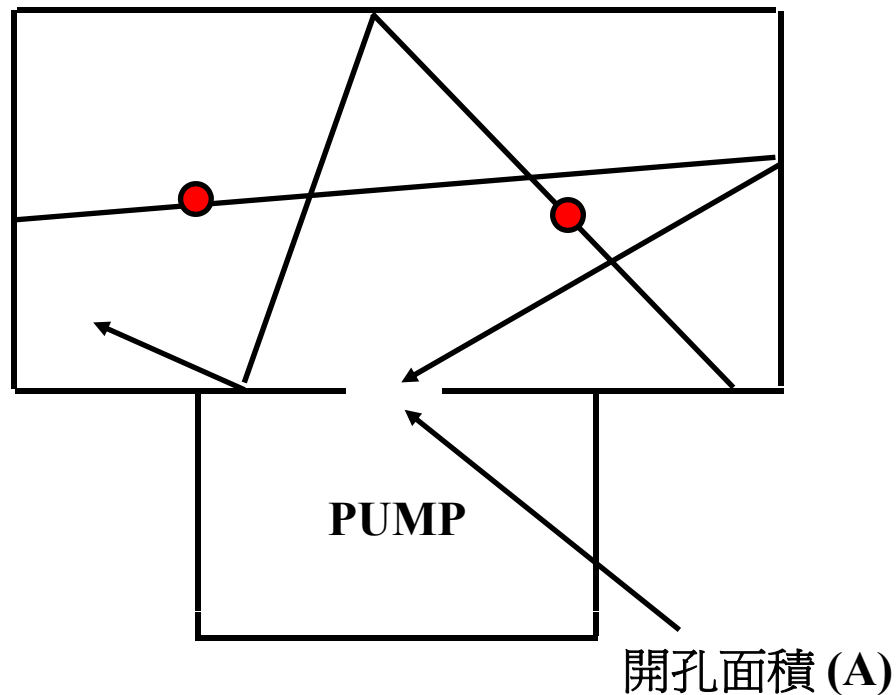
流量法(Throughput method)

真空系統: $Q = C \cdot (P_1 - P_2)$

氣流 = 氣導 × 氣壓差

氣導的定義

氣導：氣體分子到達單位面積表面(開孔)的機率



$$C \sim \frac{\bar{v}}{4} A$$

氣體平均速率 (cm/s)

面積 (cm²)

$$C = 3.64 \times 10^3 \cdot \sqrt{\frac{T}{M}} \cdot A \quad (\text{cm}^3 / \text{s})$$

[EX] Air at 20°C,

$$C = 11.6 \cdot A \quad (\text{liter/s})$$

氣導的計算(分子流)

- 抽氣孔(Orifice)的氣導：

$$C_A = 3.64 \cdot \sqrt{\frac{T}{M}} \cdot A \quad (l/s)$$

A = 抽氣孔面積 (cm²)

T = 系統溫度 (K)

M = 氣體分子質量 (a.m.u.)

- 抽氣管(Tube)的氣導：

$$C_T = \frac{3.44 \times 10^4}{\sqrt{\pi}} \cdot \sqrt{\frac{T}{M}} \cdot \frac{A^2}{B \cdot L} \quad (l/s)$$

A = 抽氣管截面積 (cm²)

B = 抽氣管截面週長 (cm)

L = 抽氣管長 (cm)

[例] 氮氣(N₂), 20°C : 孔的氣導: $C_A \sim 11.7 A \quad (l/s)$

M = 28 a.m.u.

T = 293 K

管的氣導: $C_T \sim 6.27 \times 10^4 A^2/(B \cdot L) \quad (l/s)$

短圓管、長圓管的氣導(分子流)

- 抽氣管(Tube)的氣導：
$$C_T = \frac{3.44 \times 10^4}{\sqrt{\pi}} \cdot \sqrt{\frac{T}{M}} \cdot \frac{A^2}{B \cdot L} \quad (l/s)$$

$A = \pi D^2 / 4 \text{ (cm}^2\text{)} ; B = \pi D \text{ (cm)} ; L = \text{管長 (cm)}$

- 長圓管的氣導 (C_L):
$$C_L = 3.81 \cdot \sqrt{\frac{T}{M}} \cdot \frac{D^3}{L} \quad (l/s)$$

- 短圓管的氣導 (C_S):
$$C_S = 3.81 \cdot \sqrt{\frac{T}{M}} \cdot \frac{D^3}{L + 1.33 \cdot D} \quad (l/s)$$

[例] 氮氣(N₂), 20°C :

$$C_L = 12.3 \frac{D^3}{L} (l/s)$$

$$C_S = 12.3 \frac{D^3}{L + 1.33D} = \frac{11.7 \cdot A}{1 + \frac{3L}{4D}} (l/s)$$

氣導的限制 (短管)

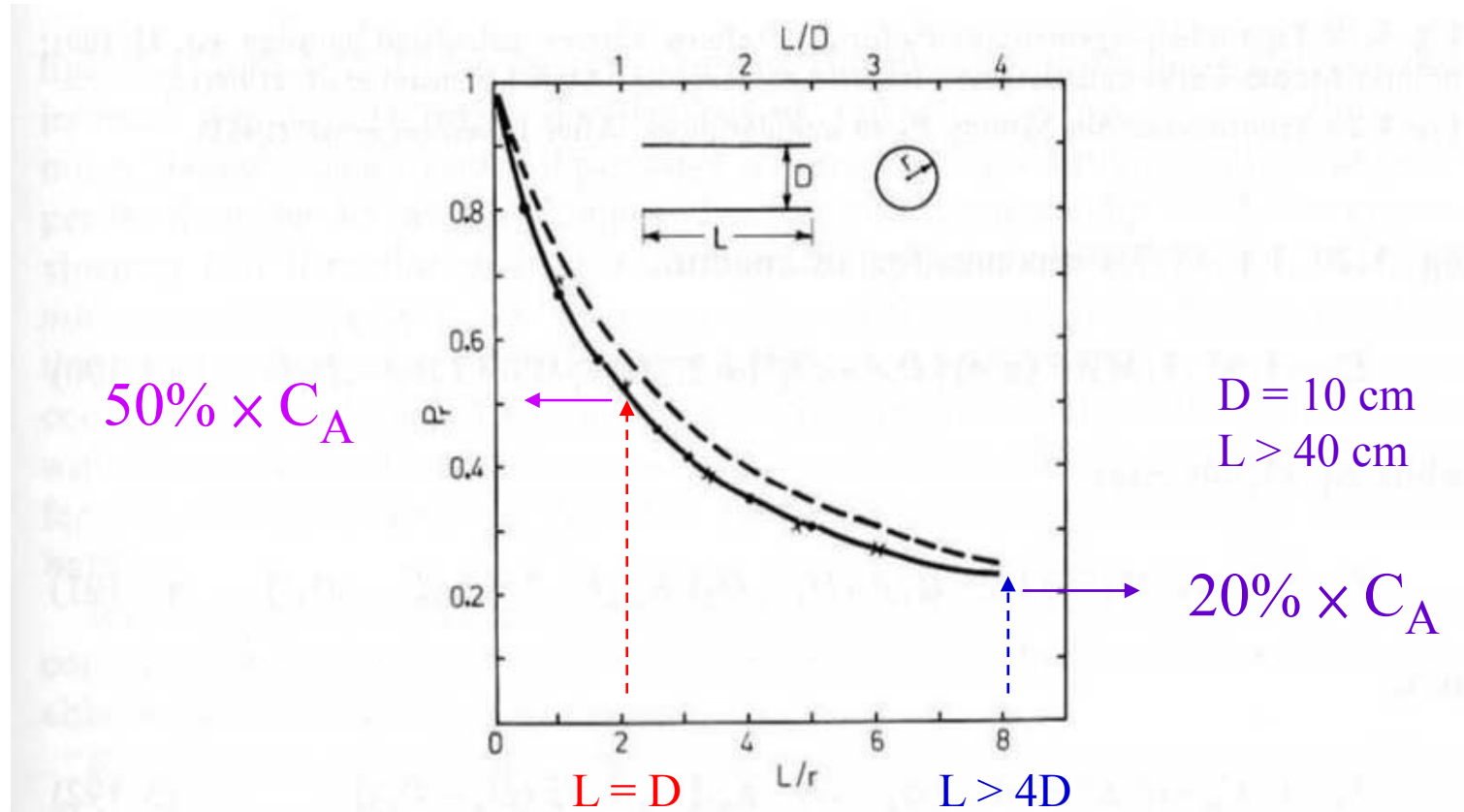


Fig. 3.18 Transmission probability P_T for tubes with circular cross section. Continuous curve: calculated by using eq. (3.109); dotted curve: calculated by using eq. (3.107), points: Monte-Carlo calculations; x-experimental values. After Levenson *et al.* (1960).

(A. Roth)

[Ref.] A. Roth, "Vacuum Technology", 3rd edition, Elsevier Science B.V., (1990).

氣導的限制 (彎管)

$$1/3 \times C_A$$

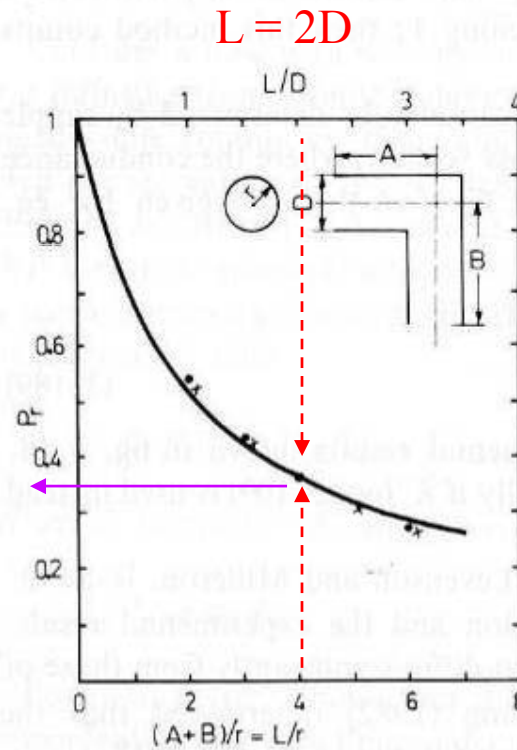


Fig. 3.19

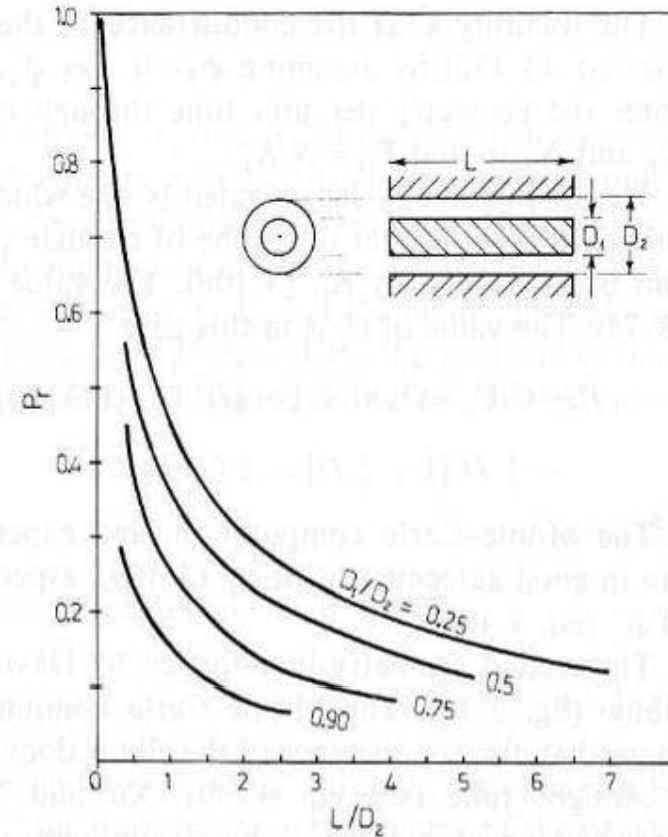


Fig. 3.20

Fig. 3.19 Transmission probability P_T for a 90° elbow. Curves: calculated by using eq. (3.109); points: Monte-Carlo calculation; x-experimental values. After Levenson *et al.* (1960).

Fig. 3.20 Transmission probability P_T of annular pipes. After Levenson *et al.* (1963).

(A. Roth)

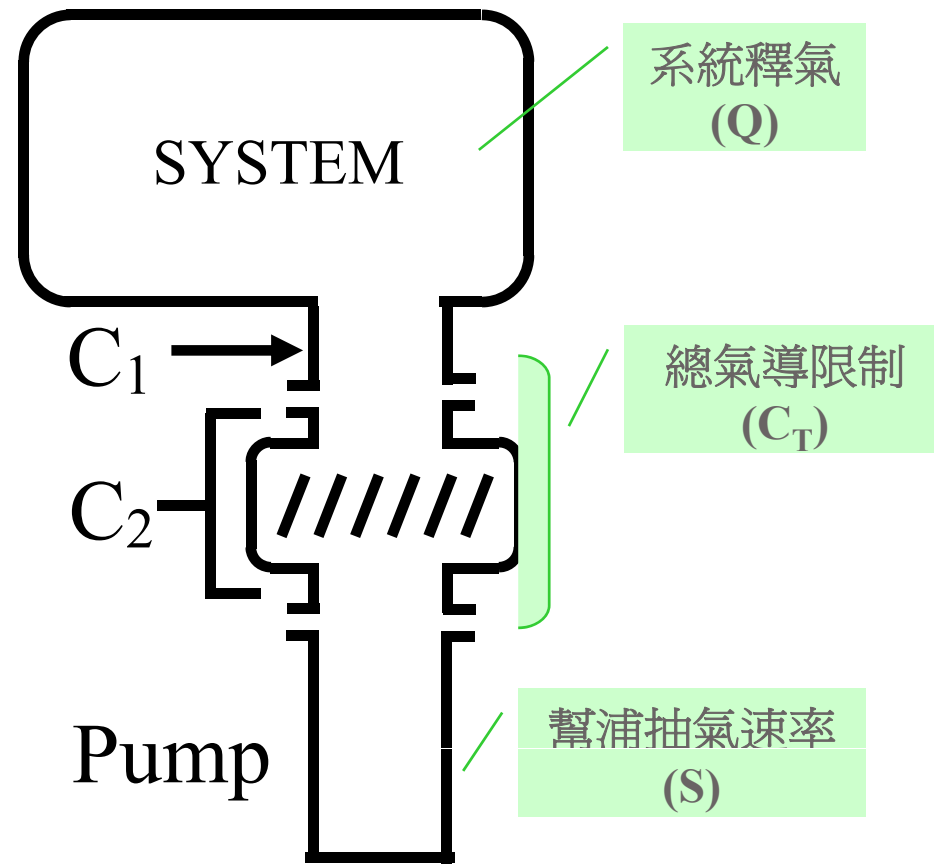
串聯的氣導

$$R_T = R_1 + R_2$$

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$= \frac{C_1 + C_2}{C_1 \times C_2}$$

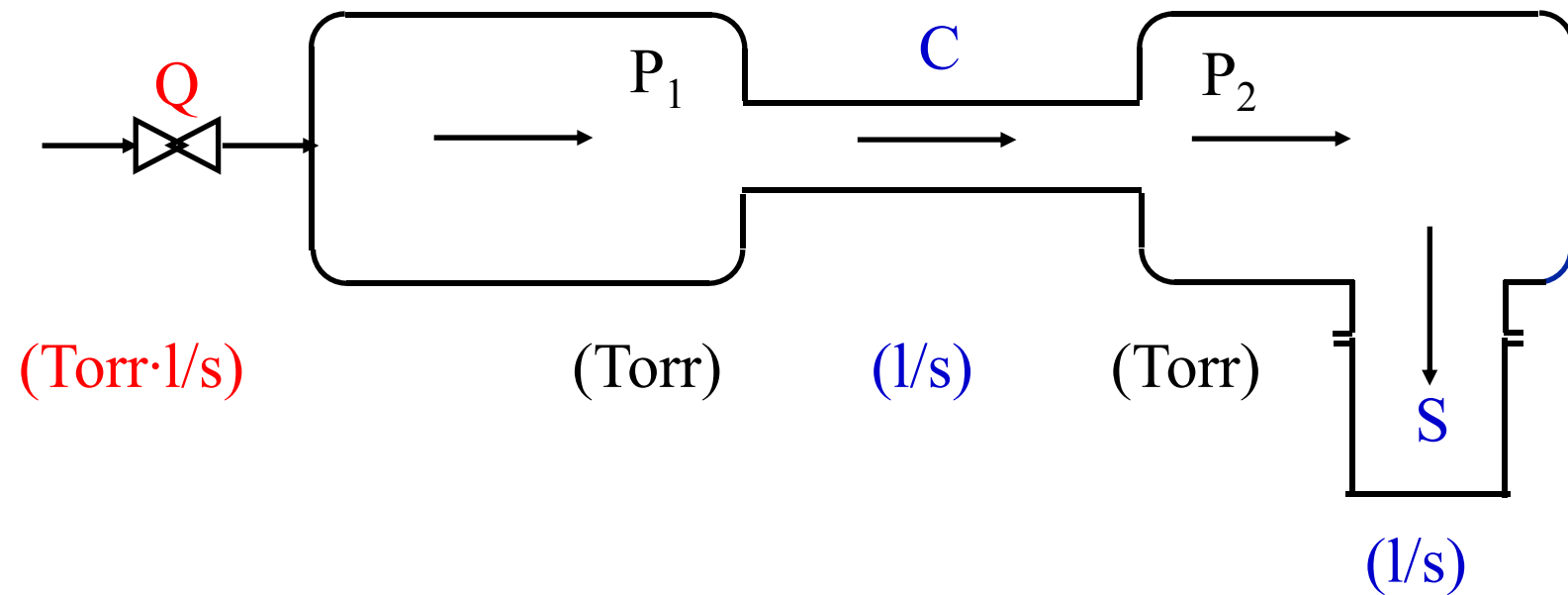
$$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$



流量 (Throughput) : Q

➤ 流量平衡公式

$$Q = C (P_1 - P_2) = P_2 S \quad (\text{單位: Torr} \cdot \text{liter/sec})$$



有效抽氣速率(S_{eff})

$$Q = C (P_1 - P_2) = P_1 \times S_{eff} = P_2 \times S$$

$$S = C (P_1/P_2 - 1)$$

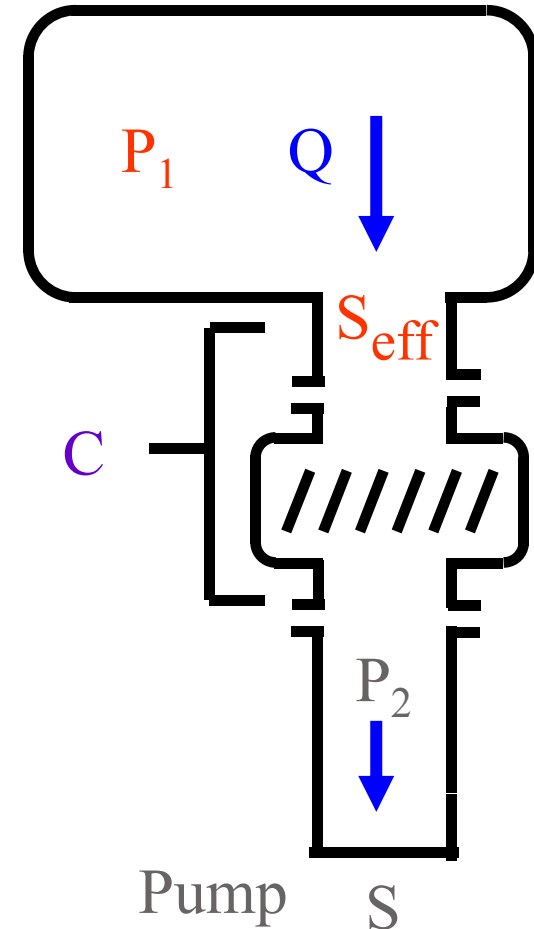
$$\frac{P_1}{P_2} = \frac{S}{S_{eff}} = \frac{S}{C} + 1 = \frac{S + C}{C}$$

$$S_{eff} = \frac{S \times C}{S + C} = \frac{S}{1 + \frac{S}{C}}$$

$$C \gg S, \quad S/C \sim 0, \quad S_{eff} = S$$

$$C = S, \quad S/C = 1, \quad S_{eff} = S / 2$$

$$C \ll S, \quad S/C \gg 1, \quad S_{eff} = C$$



Steady state with distributed gas load

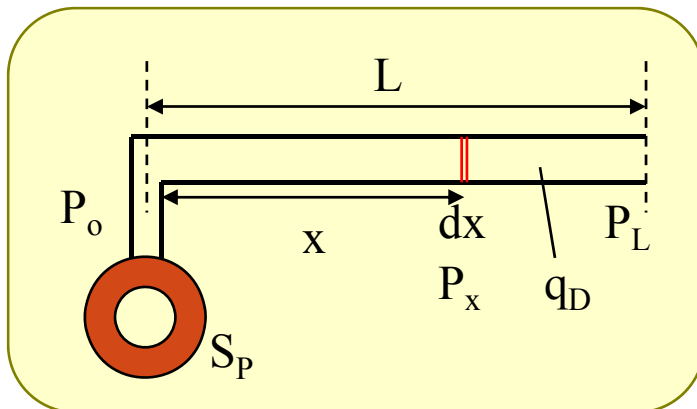
$$-dQ = q_D B dx \quad \text{The throughput through the length } dx \text{ is :} \quad Q = C \left(\frac{L}{dx} \right) dP$$

q_D : Thermal outgassing rate (Torr·l/s·cm²); C : Conductance of pipe; B : Perimeter of tube cross section

$$dQ = CL \frac{d^2 P}{dx^2} dx = -q_D B dx \Rightarrow \frac{d^2 P}{dx^2} = -\frac{q_D B}{CL} \Rightarrow \frac{dP}{dx} = -\frac{q_D B}{CL} x + \frac{q_D B}{C}$$

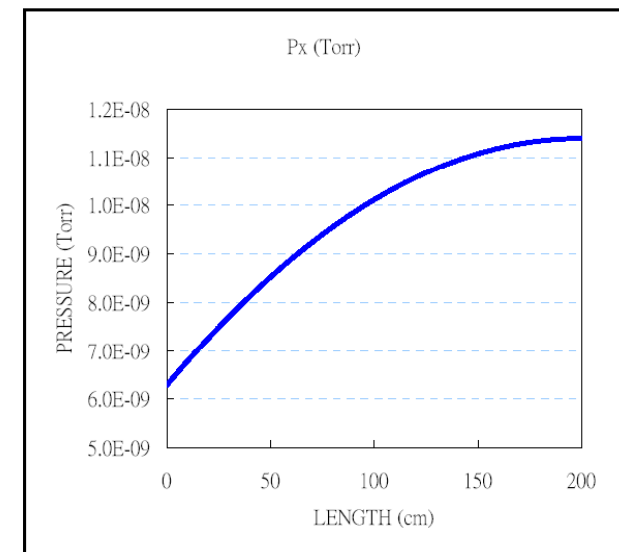
$$P_x = -\frac{q_D B}{2CL} x^2 + \frac{q_D B}{C} x + P_0 = q_D B \left[\frac{L}{S_p} + \frac{x}{C} - \frac{x^2}{2CL} \right] \quad \text{where} \quad P_0 = \frac{q_D BL}{S_p}$$

$$P_L = q_D BL \left(\frac{1}{S_p} + \frac{1}{2C} \right)$$



Circular Pipe

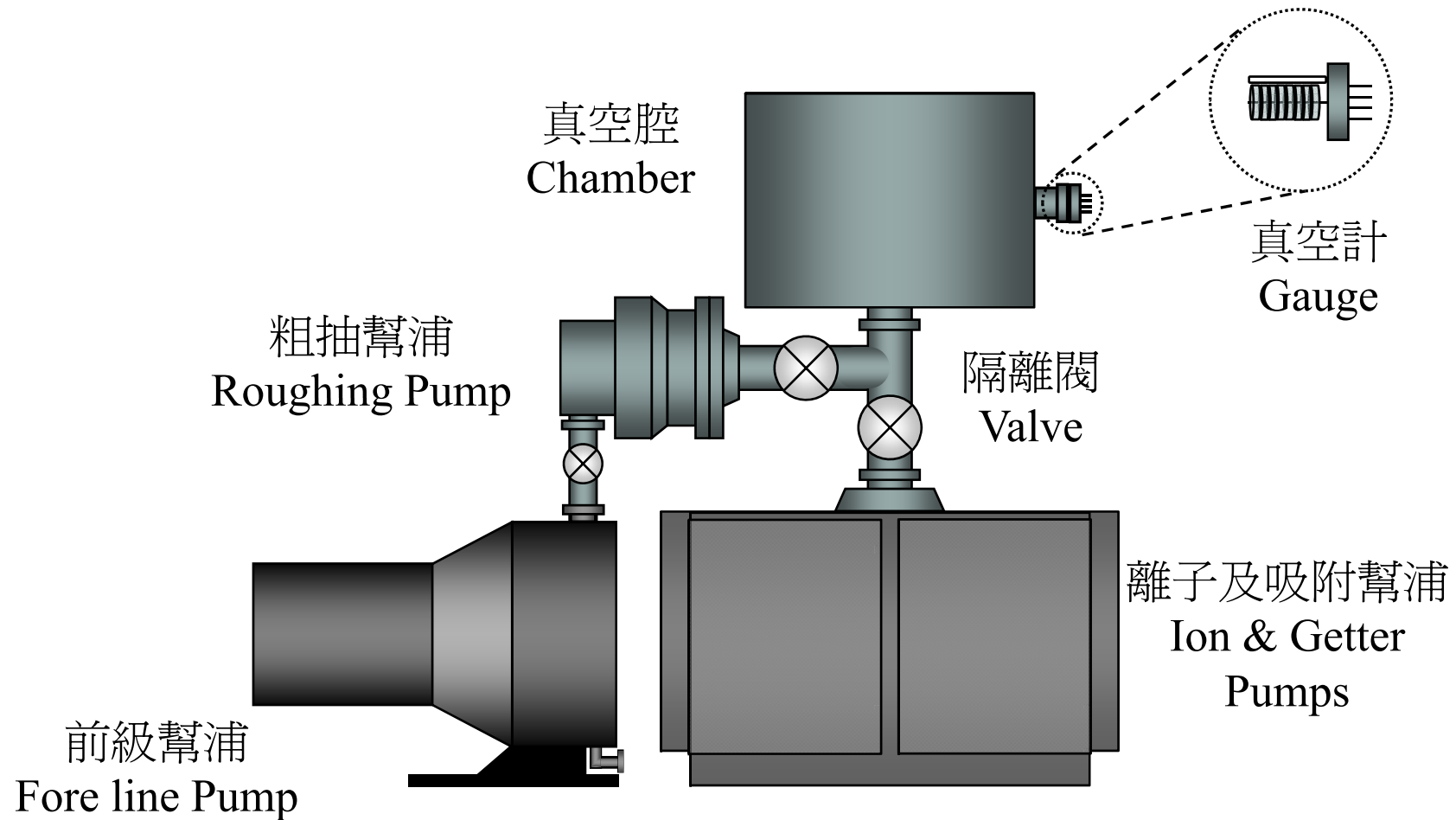
Diameter (cm) =	10
L (cm) =	200
B (cm) =	31.416
A (cm ²) =	78.54
C (l/s) =	61.5
S _p (l/s) =	100
q _D (Torr·l/s·cm ²) =	1.00E-10
P ₀ (Torr) =	6.28E-09
P _L (Torr) =	1.14E-08



真空系統組成

- 真空系統架構
- 真空腔的製程

基本真空系統組成



真空系統架構

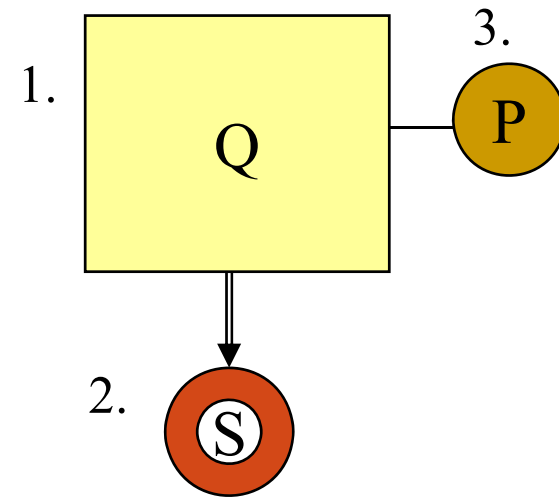
1. 真空腔 (chamber, vessel)
2. 真空幫浦 (pump)
3. 真空計 (gauge)

1. Q: 釋氣率 (outgassing rate, $\text{Pa}\cdot\text{m}^3/\text{s}$)
2. S: 抽氣速率 (pumping speed, m^3/s)
3. P: 氣壓 (pressure, Pa)

$$Q \sim S P$$

or

$$P \sim \frac{Q}{S}$$



$$1 \text{ atm} = 10^5 \text{ Pa} \sim 760 \text{ Torr}$$
$$1 \text{ Pa}\cdot\text{m}^3/\text{s} \sim 7.5 \text{ Torr}\cdot\text{l/s}$$

真空腔的製程

1. 材料選擇 —

(a)元素: AL, S.S., Cu, Ti, Ceramics, ...

(b)組成成份: 合金、純金、絕緣材料

(c)煉製方法: 鑄造(cast)、擠型(extrusion)、燒結(sinter)

2. 加工 — 車、銑、拋光、鑽、切、彎摺、壓

3. 銲接 — 氬銲(TIG)、硬銲(Brazing)、爆接(explosion)、

熱均溫壓接(HIP)、金屬氬銲(MIG)、

點銲(spot welding)、電子束銲接(EBW)

真空腔的製程

- 4. 表面清洗 — 化學清洗(鹼洗及酸洗)、EP (電解研磨)、
CP (化學研磨)、CMP (化學機械研磨)、
輝光放電(GDC) 、臭氧 (O_3) 、烘烤、
紫外光(VUV)
- 5. 組裝接合 — CF-Flange (metal gasket) 、O-ring 、Helicoflex

表面清洗 (Surface Cleaning)

1. Surface contamination usually contains machining oil, dust, salt, layers of oxide or hydroxide, etc..
2. Some dust, salt, or oil may be removed by acetone, ethanol, or vapor-degreasing, but the contaminated surface oxide layers can not be removed without chemical cleaning process.
3. In-situ baking, ion bombardment, electron bombardment, or VUV irradiation, etc., are useful to break the chemical bonding and remove the contaminants from the surface in vacuum.

表面清洗步驟

- Physical Wiping/Polishing
- Detergent Washing
- Chemical Cleaning (i.e. Acids, solvents/degreasers)
- Sand/Bead Blasting
- Ultrasonic Bath
- Electropolishing

Most manufactures and labs have devised their own proprietary methods, often combining these methods.

Avoid fingerprints and dust at all times!

化學清洗 (Chemical Cleaning)

1. Detergent in Alkaline solution to remove the oil contamination. (may assisted with ultrasonic treatment)
2. Rinsing in water. (may assisted with bubble treatment)
3. Pickling in an Acid to remove the oxide layers.
4. Rinsing in water. (may assisted with bubble treatment)
5. Ultrasonic bath in demineralized water ($R > 10 \text{ M}\Omega$) to remove all resident chemicals.
6. Drying to remove the water. (fast drying can shorten the oxidation on the fresh surface)

化學清洗 [以鋁合金為例]

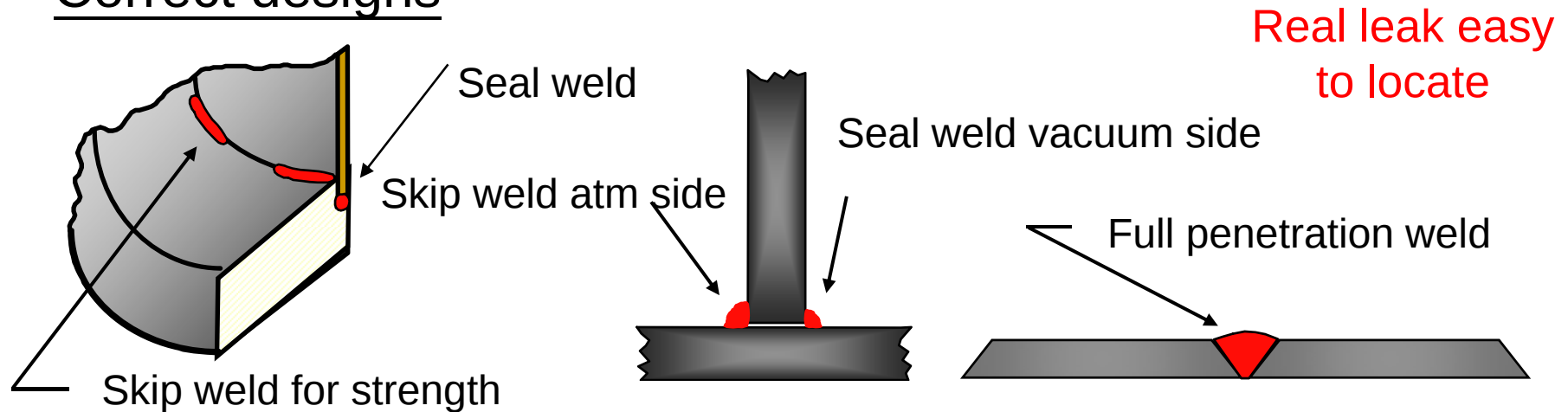
1. Immersion in NaOH (45 g/L) at 45 °C for 1~2 minutes.
2. Rinsing in demineralized water.
3. Immersion in an acid bath containing HNO₃ (50% by volume) and HF (3% by volume).
4. Rinsing in demineralized water.
5. Ultrasonic bath in demineralized water ($R > 10 \text{ M}\Omega$) for ~ 20 minutes.
6. Drying.

銲接 - 材料的永久接合

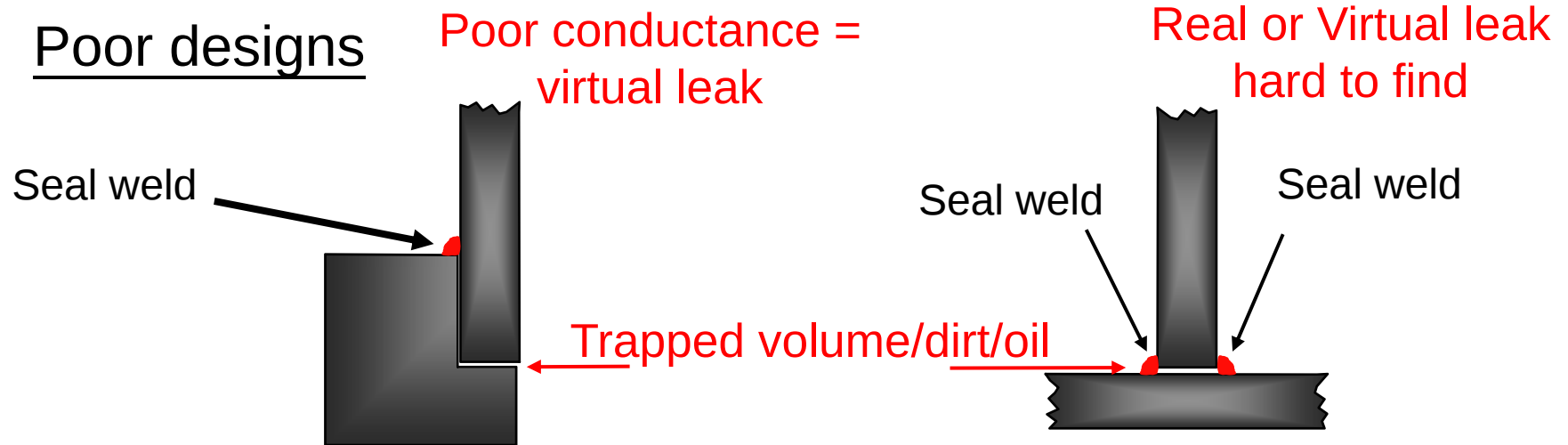
- Tungsten Inert Gas (TIG) 氬銲
- e-beam Welding (EBW) 電子束銲接
- Soldering and Brazing 真空硬銲
- Hot Isothermal Press (HIP) 熱均壓擴散接合
- Explosion Bonding 爆接

銲接應避免氣孔(導致假漏)

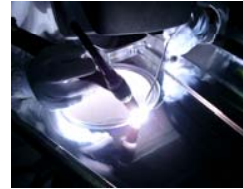
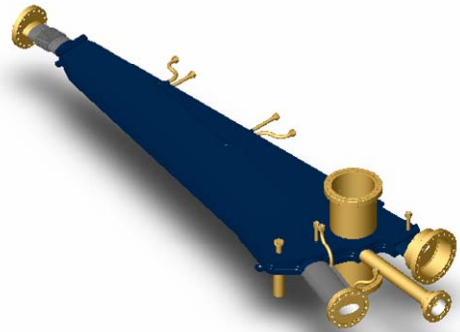
Correct designs



Poor designs

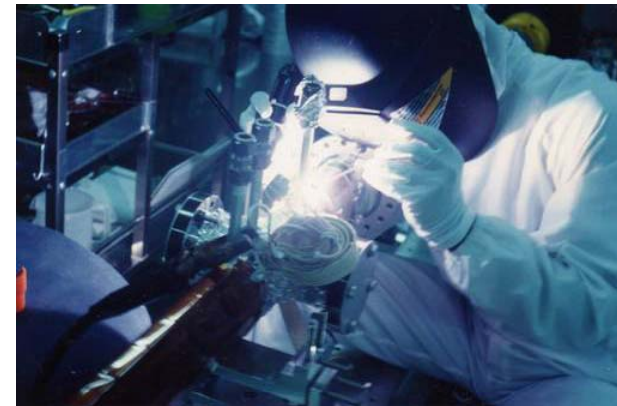


鋁合金超高真空腔銲接(TIG)



Chambers for Bending Magnets

*Tungsten Inert Gas (TIG)
Welding in Clean Room*



真空硬鐸 (Soldering and Brazing)

- Soldering and brazing of vacuum components is a common and cost effective method of joining.
- Both techniques use a flux to prepare the surface. It can be difficult to remove the flux completely.
- Soft soldering $< 300\text{ }^{\circ}\text{C}$ uses filler materials such as lead, tin, zinc, bismuth, which have high vapor pressures and are often not compatible with ultrahigh vacuum systems
- Silver soldering or torch brazing, accomplished at higher temperatures, generally uses copper and silver alloys. These require flux in most cases. Alloys not requiring a wet flux are available.
- In the case of silver soldering where strength is required, joint design is important.

真空腔密封的方式 - 法蘭(Flange)

- 刀口法蘭接合* – 金屬墊圈 (Gasket)
 - 不銹鋼法蘭 – 無氧銅 (OFHC) 墊圈
 - 鋁合金法蘭 – 純鋁合金 (A1050) 墊圈
- 平面(凹槽)法蘭接合 – 彈性墊圈
 - 金屬 – Helicoflex 或 金屬線圈(wire)
 - 非金屬 – O-Ring**
- 旋緊方式 –
 - 螺絲 (Bolt, Nut, and Washer)
 - 扣環 (Clamps)

* 法蘭接合面須平整 ($R_a < 1 \mu m$) 且無徑向可見紋路；潔淨無棉絮、髮毛等覆蓋物。

** 非金屬O-Ring有較高釋氣率及透氣率，於長時間測漏時氦氣會滲透進入真空腔。

真空元件

1. Vacuum Chambers 真空腔
2. Pumps 真空幫浦
3. Gauges 真空計
4. Sealing 密封 – Flanges 法蘭, Gasket 墊圈
5. Valves 真空閥
6. Bellows 軟管
7. Mechanical feedthroughs 機械導引|
8. Electrical feedthroughs 電導引|
9. Special components 特殊元件
 - Ceramic chambers 陶瓷真空腔
 - Glass viewports 玻璃透光視窗

抽氣幫浦

1. 機械式 (DP, TMP) — 初(粗)抽排氣 (全部氣體)
2. 離子式 (IP) — 放電吸附 (全部氣體)
3. 鈦昇華 (TSP) — 蒸鍍吸結 (活性氣體)
4. 非蒸發式 (NEG) — 內擴散吸結 (H_2 、 CO)
5. 冷凍式 (Cryo) — 低溫冷凍 (全部氣體)

真空計

1. 機械、電容式 — $1000 \text{ mb} \sim 1 \text{ mb}$
2. 熱導式 — $1 \text{ mb} \sim 1 \times 10^{-3} \text{ mb}$
3. 放電(冷陰極) — $1 \times 10^{-2} \text{ mb} \sim 1 \times 10^{-10} \text{ mb}$
4. 熱游離 — $1 \times 10^{-4} \text{ mb} \sim 1 \times 10^{-11} \text{ mb}$
5. 質譜儀 (分壓) — $1 \times 10^{-5} \text{ mb} \sim 1 \times 10^{-10} \text{ mb}$

真空腔的釋氣

- 表面吸附與表面釋氣
- 表面釋氣率
- 真空系統材料的選用
- 真空系統中釋氣的來源與水釋氣

真空腔的釋氣(Outgas)來源與分類

真空腔總釋氣率(Q_T) :
(Total outgassing rate)

$$Q_T = Q_o + Q_L + Q_p$$

單位面積釋氣率(q_o):

$$Q_o = q_o \times A$$

Unit:

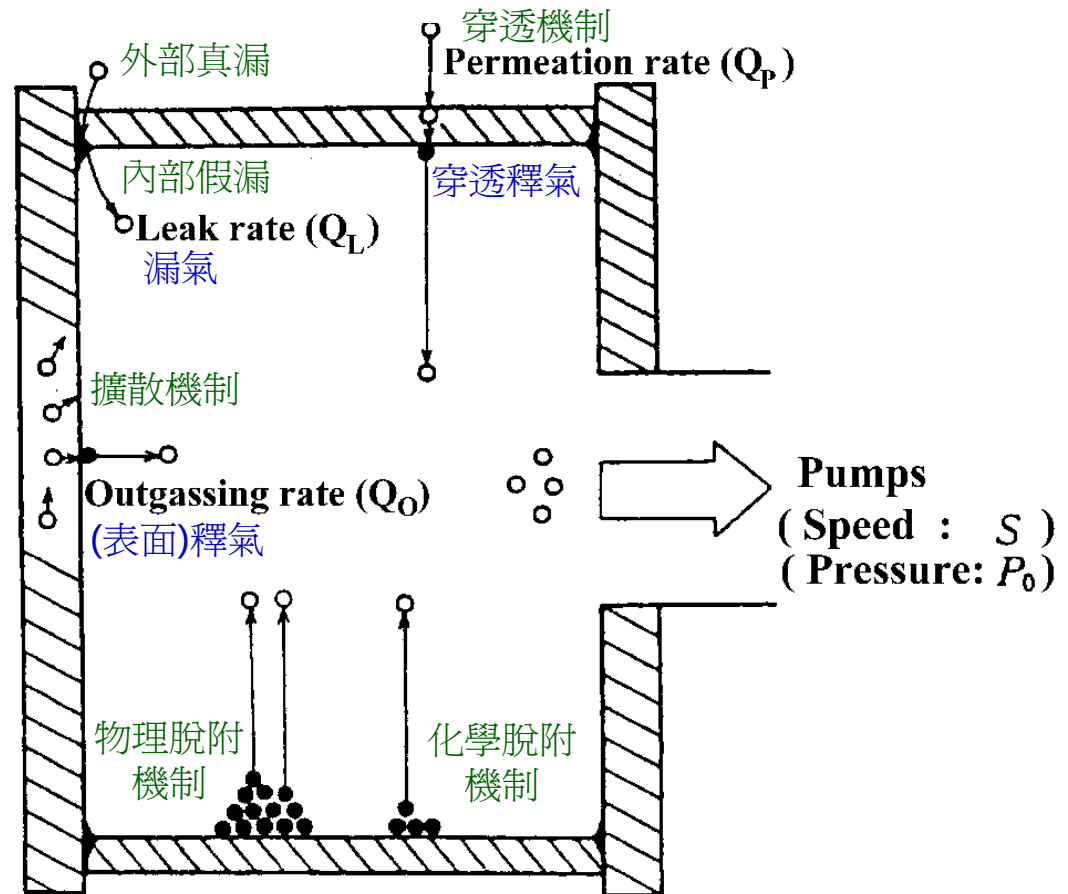
Q (Pa·m³/s) or Torr·l/s

S (m³/s) l/s

P_o (Pa) Torr

q (Pa·m³/s·m²) Torr·l/s·cm²

A (m²) cm²

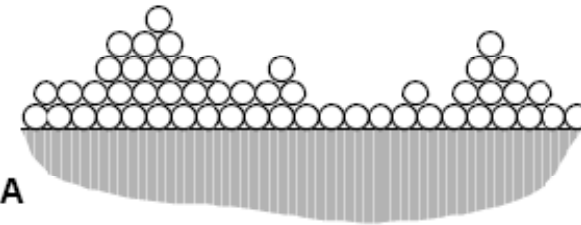


總釋氣率(Total Outgassing Rate)

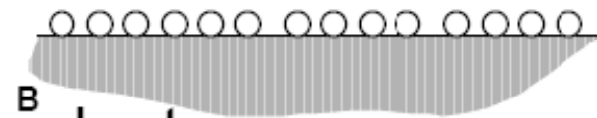
- Q_L ：漏氣率可以堵絕，一般測漏儀測量靈敏度($\sim 1 \times 10^{-9}$ Torr·l/s)。
- Q_P ：穿透釋氣須慎選腔體材料及控制腔體外部氣體種類而可減至最低($< 1 \times 10^{-14}$ Torr·l/s)。
- Q_o ：真空腔材料表面熱釋氣率可藉由表面洗淨、鍍膜阻絕、烘烤脫附等(減少 q_o)或加工研磨拋光(減少 A)等方法改善表面品質而減低表面釋氣率($< 1 \times 10^{-12}$ Torr·l/s)。腔內之真空元件需慎選低釋氣率材料。

表面吸附與表面釋氣 (Surface Absorption and Surface Outgas)

- **Physisorption** ($E < 0.1 \text{ eV}$)
 - dipole interaction
 - weaker bonding
 - non-selective
 - first stages of condensation^A



- **Chemisorption** ($E > 1 \text{ eV}$)
 - stronger interaction
 - chemical bonds, ionic or covalent
 - selective



q 的單位

q = 每單位面積(cm²)釋出氣體數量的速率(molecules/s)

✓ $\cdot \frac{\text{Pa} \cdot \text{m}^3}{\text{s} \cdot \text{m}^2} = \frac{\text{Pa} \cdot \text{m}}{\text{s}}$

✓ $\cdot \frac{\text{Torr} \cdot \ell}{\text{s} \cdot \text{cm}^2}$

✓ $\cdot \frac{\text{mbar} \cdot \ell}{\text{s} \cdot \text{cm}^2}$

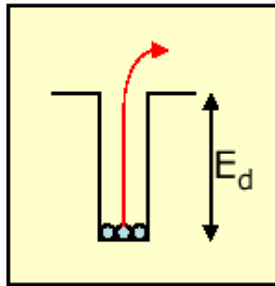
✓ $\cdot \frac{\text{molecules}}{\text{s} \cdot \text{cm}^2}$

✓ $\cdot \frac{\text{mol}}{\text{s} \cdot \text{cm}^2}$

	$\frac{\text{Pa m}}{\text{s}}$	$\frac{\text{Torr l}}{\text{s cm}^2}$	$\frac{\text{mbar l}}{\text{s cm}^2}$	$\frac{\text{molec}}{\text{s cm}^2}$	$\frac{\text{mol}}{\text{s cm}^2}$
$\frac{\text{Pa m}}{\text{s}}$		7.5×10^{-4}	10^{-3}	2.5×10^{16}	4.1×10^{-8}
$\frac{\text{Torr l}}{\text{s cm}^2}$	1330		1.33	3.3×10^{19}	5.5×10^{-5}
$\frac{\text{mbar l}}{\text{s cm}^2}$	10^{-3}	0.75		2.5×10^{19}	4.1×10^{-5}
$\frac{\text{molec}}{\text{s cm}^2}$	4×10^{-17}	3×10^{-20}	4×10^{-20}		1.7×10^{-24}
$\frac{\text{mol}}{\text{s cm}^2}$	2.4×10^7	1.8×10^4	2.4×10^4	6.02×10^{23}	

氣體分子在表面平均滯留時間

Single desorption energy: mean stay time



The mean stay time (sojourn time) is given by the Frenckel's law:

$$\tau_d = \tau_o e^{\frac{E_d}{k_B T}}$$

where the value of τ_o is usually assumed to be about 10^{-13} s ($\approx h/K_B T$).

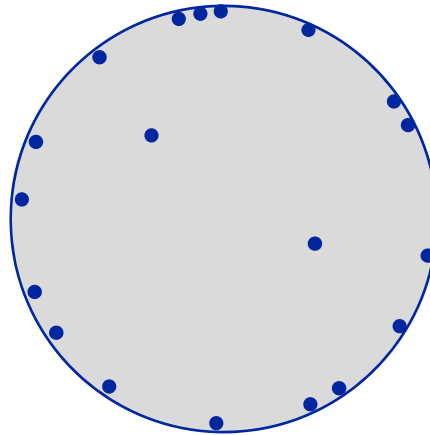
E_d [Kcal/mole]	Cases	τ_d [s]
0.1	Helium	1.2×10^{-13}
1.5	H ₂ physisorption	1.3×10^{-13}
3-4	Ar, CO, N ₂ , CO physisorption	1×10^{-11}
10-15	Weak chemisorption	3×10^{-6}
20	H ₂ chemisorption	100
25		6×10^5 one week
30	CO/Ni chemisorption	4×10^9 100 years
40		1×10^{17} age of Earth
150	O/W chemisorption	> age of universe

1 nTorr的真空特性

Pressure (Torr)	Molecular Density (molecules/cm ³)	Molecular Incidence (molecules/cm ² /sec.)	Mean Free Path (cm)	Monolayer Formation Time (sec)
760	2.49×10^{19}	2.87×10^{23}	3.9×10^{-6}	1.7×10^{-9}
1	3.25×10^{16}	3.78×10^{20}	5.1×10^{-3}	2.2×10^{-6}
10^{-3}	3.25×10^{13}	3.78×10^{17}	5.1	2.2×10^{-3}
10^{-6}	3.25×10^{10}	3.78×10^{14}	5.1×10^3	2.2
10^{-9}	3.25×10^7	3.78×10^{11}	5.1×10^6	2.2×10^3 (37 min)
10^{-12}	3.25×10^4	3.78×10^8	5.1×10^9	2.2×10^6 (25.5 days)

在 1×10^{-9} Torr氣壓時，表面覆蓋一層氣體只要半小時。

真空腔表面吸附氣體與空間可測量氣體量的比例



P (mbar)	<u>Molecules on Surface</u> Molecules in Volume	Time to Form Monolayer (sec)
10^{-3}	0.5	2.2×10^{-3}
10^{-6}	500	2.2
10^{-9}	500,000	2.2×10^3

表面釋氣率的影響因素

- ☞ Rate of outgassing is dependent upon the base material, temperature, and time.
- ☞ General outgassing rates are in Torr liters sec⁻¹ cm⁻² at a defined temperature.
- ☞ Detailed considerations require the knowledge of the rate for a specific gas species from an understood surface.
- ☞ Surface state is important
 - ◆ *Untreated (as received)*
 - ◆ *Machined (cutting oil used, etc...)*
 - ◆ *Degreased (method and solvents)*
 - ◆ *Post fabrication treatment (baking, degassing)*

熱釋氣 (Thermal desorption)

1. 熱釋氣的公式： $Q_{th} \sim \exp(-E_d/kT)$

E_d --- Surface binding energy of the desorbed gas (物理吸附)

k --- Boltzmann constant ($8.6 \times 10^{-5} \text{ eV K}^{-1}$)

T --- Temperature ($^{\circ}\text{K}$)

2. 超高真空腔熱釋氣的特性：

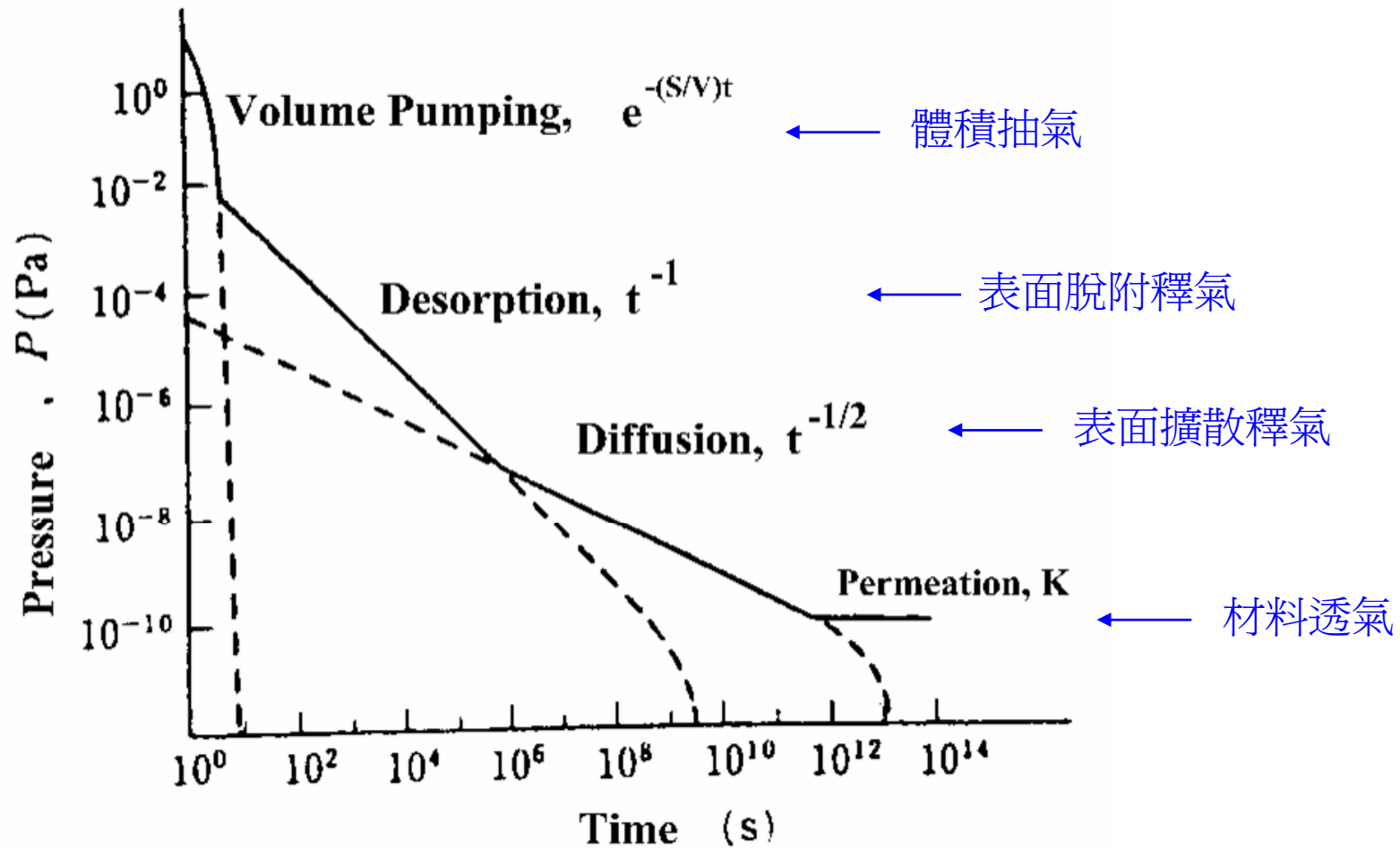
a) 釋氣機制：表面釋氣、表面擴散。

b) 有效降低釋氣率的方法：表面無油加工、化學清洗、真空烘烤。

c) 烘烤前水分子(H_2O)為主要釋氣；烘烤後氫氣(H_2)為的主要釋氣。

d) 超高真空系統以金屬材料為主，不採用高釋氣率或疏鬆軟質彈性材料為原則。

抽氣曲線(Pumping Down Curve)



最低氣壓(Ultimate Pressure)

1. Curve (a): *[Ideal case]*

$Q = 0$ (No outgas)

$$V (dP/dt) = -S P$$

2. Curve (b): *[Real case]*

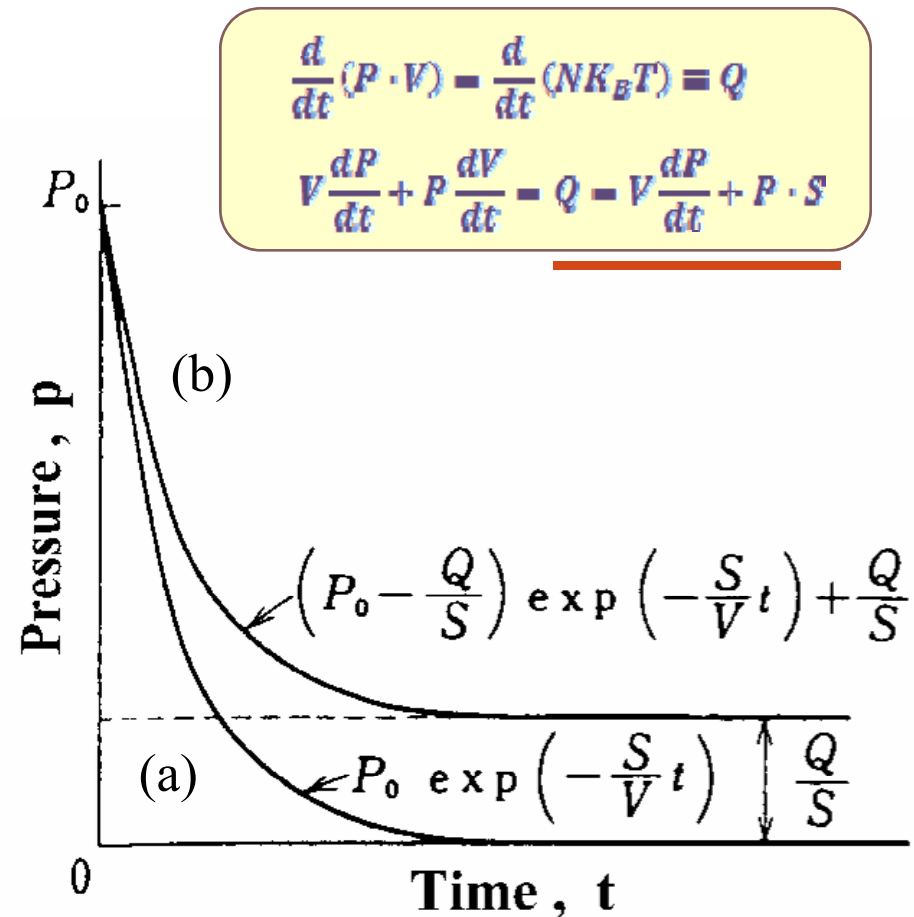
$Q \neq 0$

$$Q = S P + V (dP/dt)$$

(1) when $dP/dt \sim 0$,
 $P \sim Q / S$

*Q determines the ultimate P.

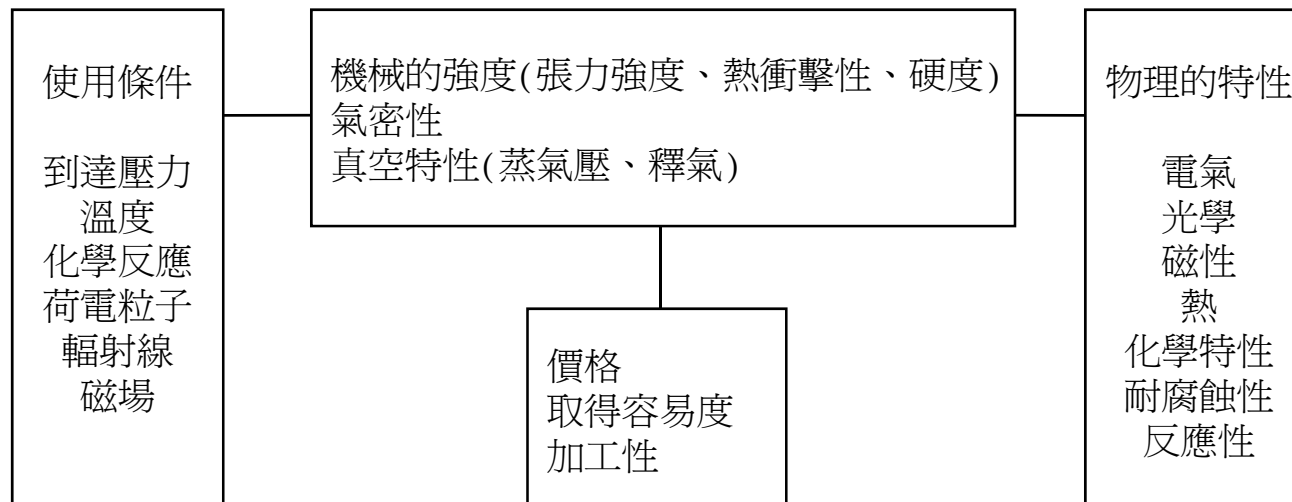
(2) when $S = 0$ (Build-up!),
 $Q \sim V (dP/dt)$



真空系統材料的選用

真空容器中的氣體主要來自於材料，因此選用材料需考慮的因素包括：

- (1) 材料在真空中所釋放出來的氣體(釋氣)。
- (2) 材料連接的銲接性，是否能夠達到真空密封不漏氣的要求。
- (3) 材料本身包括物理、化學、機械、電氣等的特性。



真空系統常用元件的材料

元件名稱	高真空用材料	超高真空用材料	功能
容器及內部元件	不銹鋼、鋁合金	不銹鋼、鋁合金、銅	高硬度
密封墊圈	橡皮(O-ring)、塑膠、銅、鈮	Viton、銅、金、鋁、鈮、Inconel	低硬度
視窗	玻璃	玻璃、藍寶石(Sapphire)、石英(Quartz)	高透光性
電氣用元件	銅、鎳、金	銅、鎳、金	高導電度
絕緣用元件	橡皮、鐵氟隆、玻璃、陶瓷	高密度陶瓷、Macor、PBN	高電阻
潤滑劑	低蒸氣壓油、油脂(Grease)	鉬、二硫化鎢、銀	低摩擦
加熱元件	鎳鉻合金(Nichrome)、鉬	鉬、鎢、鉭	高熔點
冷卻元件	銅、鋁	銅、鋁	高熱導性
機構元件	銅合金、不銹鋼	銅合金、Inconel、不銹鋼	高強度
幫浦元件	碳鋼、不銹鋼、鋁合金	不銹鋼、鋁合金、陶瓷、鈦、鈳合金	
測量元件	玻璃、白金、鉬、鎢	鎢、鉬	

蒸氣壓(常見氣體)

** Pressure Unit: Pa*

Temp. Gas	4 K (LHe)	20 K (LH ₂)	77 K (LN ₂)	195 K (乾冰)	273 K (冰)	300 K (常溫)
He	$\geq 10^5$					
H ₂	10^{-7}	$\geq 10^5$				
Ne	$< 10^{-11}$	10^4	$\geq 10^5$			
N ₂	$< 10^{-11}$	10^{-8}	$\geq 10^5$			
CO, Ar, O ₂	$< 10^{-11}$	10^{-10}	10^4	$\geq 10^5$		
CO ₂		$< 10^{-11}$	10^{-6}	$\geq 10^5$		
H ₂ O			$< 10^{-11}$	10^{-1}	10^3	10^4

水分子在常溫下會凝結吸附於材料表面上，在真空腔中不易抽除。

蒸氣壓(部分材料)

** Pressure Unit: Pa*

Materials	Temp. 300 K (27°C)	423 K (150°C)	573 K (300°C)	873 K (600°C)
鋅 (Zn)	10^{-9}	2×10^{-5}	2×10^{-1}	2000
鎂 (Mg)		10^{-7}	4×10^{-3}	133
鈣 (Ca)			4×10^{-6}	1

真空材料及元件應選用在室溫下低蒸氣壓(Vapour pressure)者。對於部分真空容器及元件須達到較高之操作溫度時，例如高溫烘烤(> 150 °C)，部分高蒸氣壓之材料更應避免選用。以表列幾個較高蒸氣壓之材料為例，鋅在150 °C時之蒸氣壓約 2×10^{-5} Pa，則不適合用於高真空或超高真空系統中。

釋氣率曲線(彈性材料)

Example:

q : outgassing rate per area

A : area of material

$Q \sim q A$: total outgassing rate

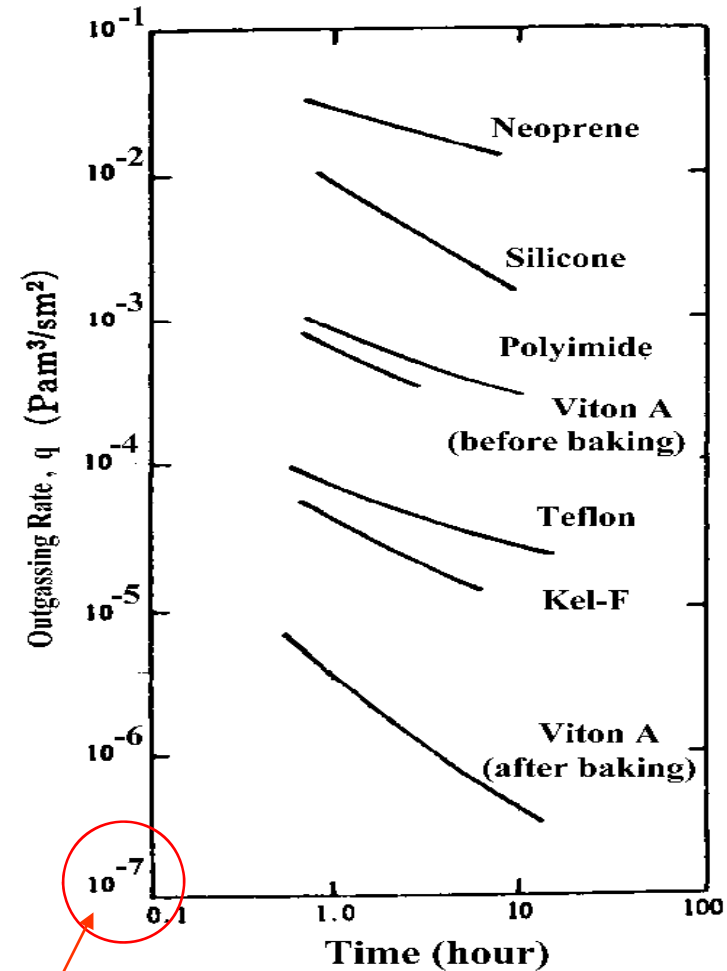
S : pumping speed

$P \sim Q / S$: Ultimate pressure

For a pump with $S \sim 1000 \text{ L/s}$,
or $S \sim 1 \text{ m}^3/\text{s}$,

$P \sim Q / S \sim q A / 1 \sim q A$

* $1 \text{ Pa} \cdot \text{m}^3/\text{s} \cdot \text{m}^2 = 1330 \text{ Torr} \cdot \text{l/s} \cdot \text{cm}^2$



($q \sim 1 \times 10^{-10} \text{ Torr} \cdot \text{l/s} \cdot \text{cm}^2$)

Average Outgassing Rates*

Outgassing rates in (Torr Liter/sec cm²)

	Evacuate to vacuum			Surface Condition			
	1 hour	10 hours	>24 hrs	untreated	degreased	polished	baked
Aluminum (anodized)	3x10 ⁻⁵	3x10 ⁻⁷	8x10 ⁻⁸	3x10 ⁻⁵	3x10 ⁻⁵	N/A	5x10 ⁻¹⁰
Aluminum	8x10 ⁻⁷	5x10 ⁻⁸	1x10 ⁻¹⁰	8x10 ⁻⁷	1x10 ⁻⁸	1x10 ⁻⁸	5x10 ⁻¹³
Brass	2x10 ⁻⁶	6x10 ⁻⁷	1x10 ⁻⁷	1x10 ⁻⁶	1x10 ⁻⁶	8x10 ⁻⁶	N/A
Beryllium	1x10 ⁻⁶	5x10 ⁻⁷	1x10 ⁻⁹	1x10 ⁻⁶	5x10 ⁻⁷	1x10 ⁻⁶	N/A
Copper	1x10 ⁻⁷	5x10 ⁻⁹	1x10 ⁻¹⁰	1x10 ⁻⁷	1x10 ⁻⁸	1x10 ⁻⁹	1x10 ⁻¹²
Copper (OFHC)	8x10 ⁻⁹	2x10 ⁻⁹	3x10 ⁻¹¹	8x10 ⁻⁹	8x10 ⁻⁹	5x10 ⁻⁷	1x10 ⁻¹²
Delrin	6x10 ⁻⁶	1x10 ⁻⁷	7x10 ⁻⁷	6x10 ⁻⁶	not available	not available	8x10 ⁻⁷
Lead	1x10 ⁻⁷	2x10 ⁻⁸	4x10 ⁻⁹	1x10 ⁻⁸	5x10 ⁻⁸	1x10 ⁻⁸	N/A
Mild Steel	2x10 ⁻⁶	2x10 ⁻⁷	3x10 ⁻⁸	2x10 ⁻⁶	5x10 ⁻⁷	5x10 ⁻⁸	5x10 ⁻¹⁰
1018 Steel (Ni plated)	2x10 ⁻⁶	5x10 ⁻⁷	1x10 ⁻⁸	not available	not available	not available	not available
Gold Sheet	8x10 ⁻⁸	not available	5x10 ⁻⁹	8x10 ⁻⁸	1x10 ⁻⁸	not available	not available
Titanium	1x10 ⁻⁹	not available	5x10 ⁻¹⁰	1x10 ⁻⁹	not available	not available	2x10 ⁻¹²
Stainless steel	5x10 ⁻⁸	1x10 ⁻⁸	1x10 ⁻¹⁰	7x10 ⁻⁸	1x10 ⁻⁹	5x10 ⁻⁹	3x10 ⁻¹³

*Rates can vary significantly, depending on pre-cleaning and preparation methods, and system history.

Average Outgassing Rates*

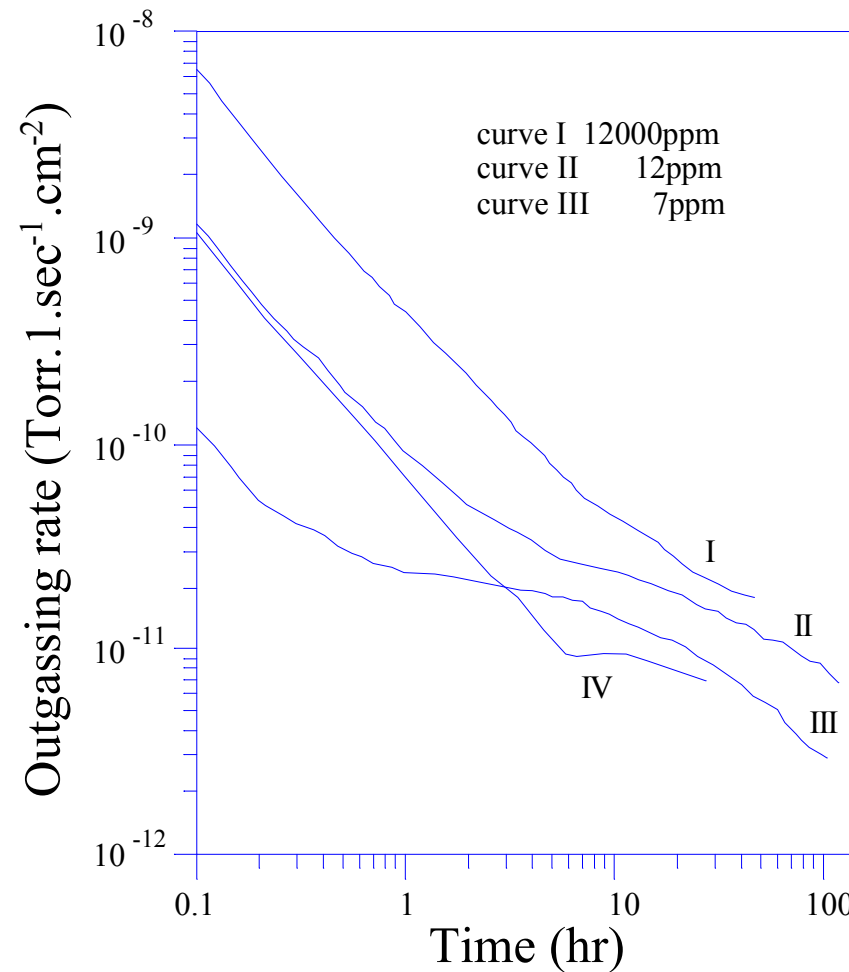
Outgassing rates in (Torr Liter/sec cm²)

	Evacuate to vacuum			Surface Condition			
	1 hour	10 hours	>24 hrs	untreated	degreased	polished	baked
Epoxy (Shell Epon)	2×10^{-5}	1×10^{-6}	not available	not available	not available	N/A	8×10^{-8}
Buna N	8×10^{-6}	2×10^{-6}	8×10^{-7}	8×10^{-6}	8×10^{-7}	N/A	4×10^{-8}
Neoprene	3×10^{-6}	8×10^{-7}	4×10^{-8}	3×10^{-6}	6×10^{-7}	N/A	2×10^{-9}
Mylar	8×10^{-7}	1×10^{-7}	7×10^{-9}	8×10^{-7}	N/A	N/A	2×10^{-9}
Acrylic	2×10^{-6}	1×10^{-6}	5×10^{-7}	2×10^{-6}	8×10^{-7}	N/A	1×10^{-8}
Teflon (poly'fluoro'lene)	2×10^{-7}	8×10^{-8}	2×10^{-8}	2×10^{-7}	N/A	N/A	8×10^{-9}
Nylon (polyamide)	5×10^{-6}	3×10^{-7}	4×10^{-8}	5×10^{-6}	N/A	N/A	6×10^{-9}
Lexan (polycarbonate)	7×10^{-7}	2×10^{-7}	6×10^{-8}	1×10^{-7}	N/A	N/A	8×10^{-9}
PVC	5×10^{-7}	3×10^{-7}	1×10^{-7}	5×10^{-7}	N/A	N/A	8×10^{-8}
Silicon rubber	7×10^{-6}	8×10^{-7}	6×10^{-8}	7×10^{-7}	2×10^{-7}	N/A	6×10^{-10}
Silastic (sealant)	5×10^{-5}	3×10^{-6}	6×10^{-7}	8×10^{-5}	N/A	N/A	5×10^{-8}
Viton	8×10^{-7}	5×10^{-8}	2×10^{-8}	8×10^{-7}	1×10^{-7}	N/A	5×10^{-10}
Steatite (ceramic)	5×10^{-8}	1×10^{-8}	7×10^{-9}	N/A	N/A	N/A	N/A
Pyrex (7740)	1×10^{-7}	2×10^{-8}	5×10^{-9}	not available	not available	N/A	2×10^{-9}

*Rates can vary significantly, depending on pre-cleaning and preparation methods, and system history.

釋氣率曲線(A6063鋁合金)

Diffusion phenomenon on the surface is more obvious for curve II & III with ≤ 12 ppm of H_2O contained N_2 purging.



J.R. Chen et al, J. Vac. Sci. Technol A12(4), 1750 (1994).

材料透氣率(Material Permeation)

- Permeation is the ability of a gas to pass through solid materials.
- Materials have permeation rates for different gases specific to that material.
 - Examples: steels have higher permeation rates with higher carbon content; copper has low permeation for all gases; aluminum has low permeation for hydrogen.
- Polymers are permeable to all gases.

透氣率 (Permeation)

A. Process of permeation: (→ small leak !)

Step.1 Gas adsorbs on the outer wall.

Step.2 Gas diffuses through the bulk.

Step.3 Gas desorbs from the interior wall.

B. Permeability:

$K_p = D$ (diffusion constant) * S' (solid solubility)

C. Steady state permeation rate, Q (Pa m/s or W/m²):

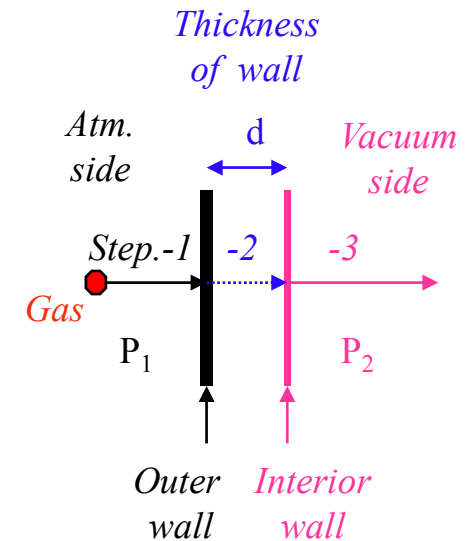
(a) Non-dissociating gas: (He ...)

$$Q_p = K_p (P_1 - P_2) / d ; \text{ where } K_p \text{ (m}^2/\text{s)}$$

(b) Diatomic gases: (H₂ ...)

$$Q_p = K_p (P_1^{1/2} - P_2^{1/2}) / d ; \text{ where } K_p \text{ (Pa}^{1/2} \text{ m}^2/\text{s)}$$

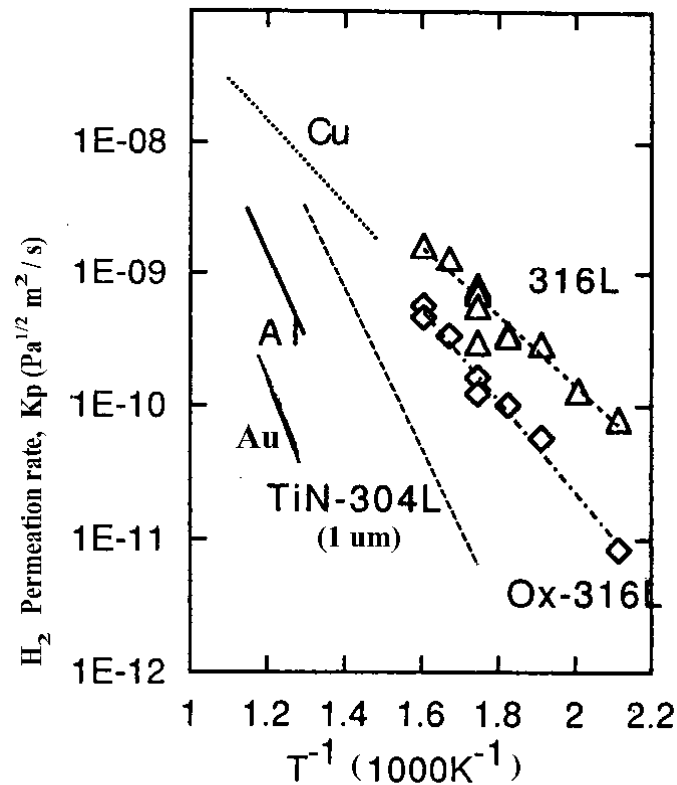
(* Gas dissociates at Step.1 and diffuses as atoms.)



透氣率 (Permeation) [例]

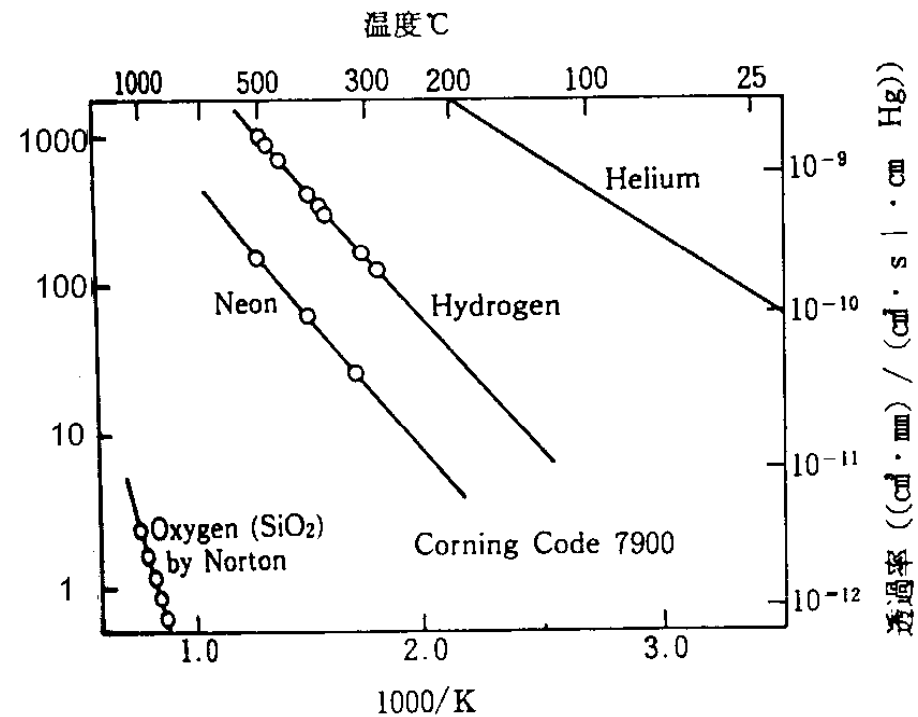
Permeation rate for H_2 :

$Cu \sim 316L \gg TiN-304L > Al$



Permeation rate for Glass:

$He \gg H_2 > Ne \gg O_2$



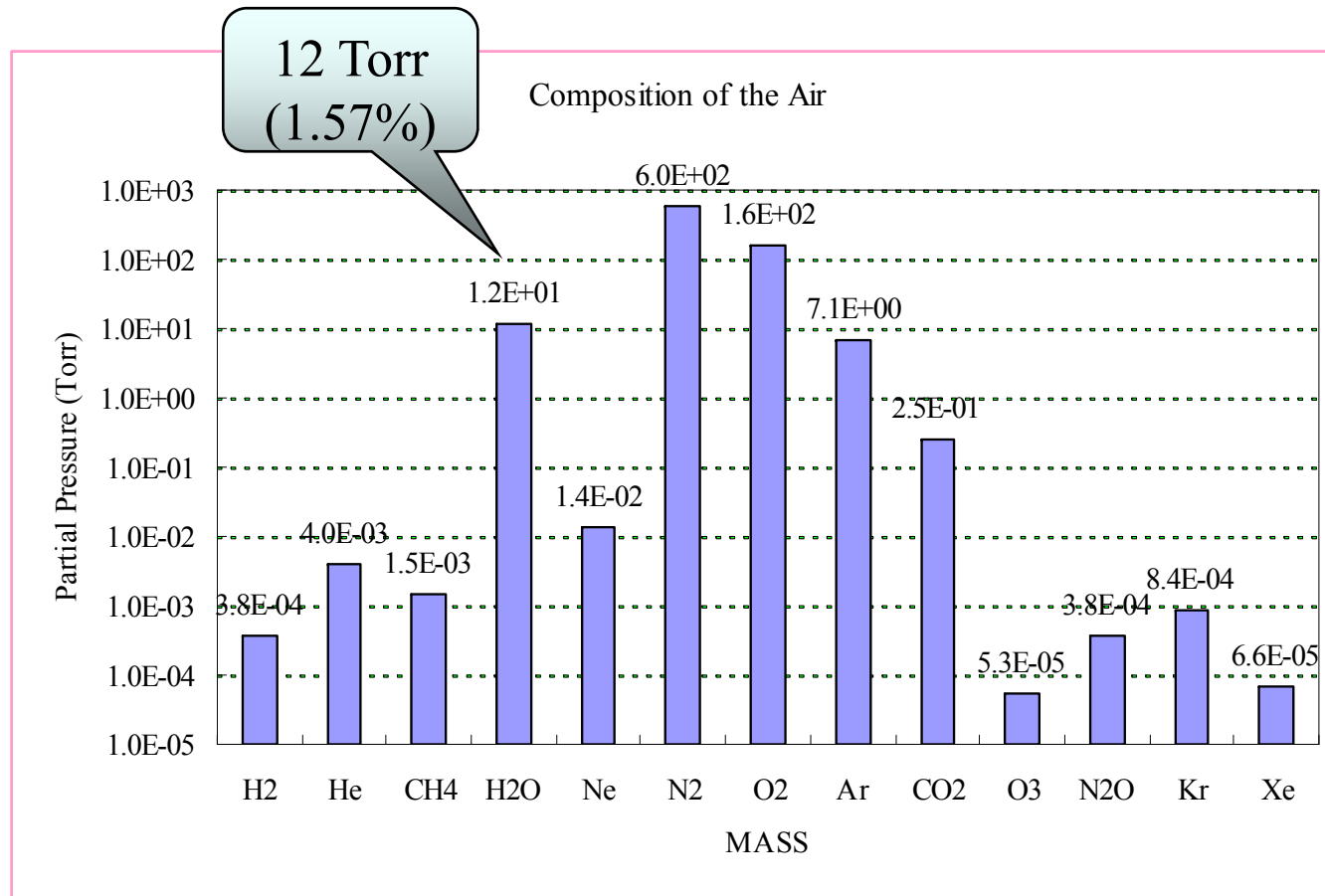
真空系統中釋氣的來源

釋氣率 $Q = \sum_i Q_i = \sum_i q_i a_i \sim q A$ ($A = \sum_i a_i$)

釋氣來源：

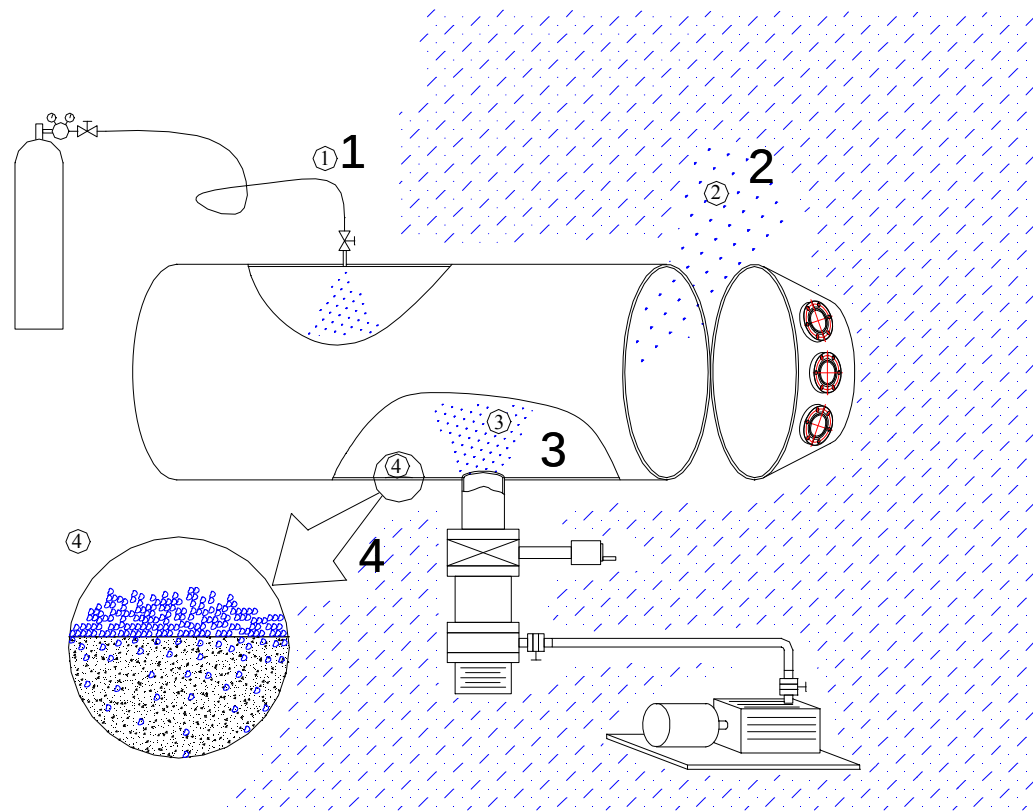
- 進氣污染 (破壞真空時)
- 曝露大氣 (打開真空腔或更換元件時)
- 幫浦回流 — 水氣、油氣 (抽氣中擴散回流)
- 表面釋氣 — 物理吸附、元件熱釋氣
化學吸附、表面層激發釋氣

空氣中有多少水?

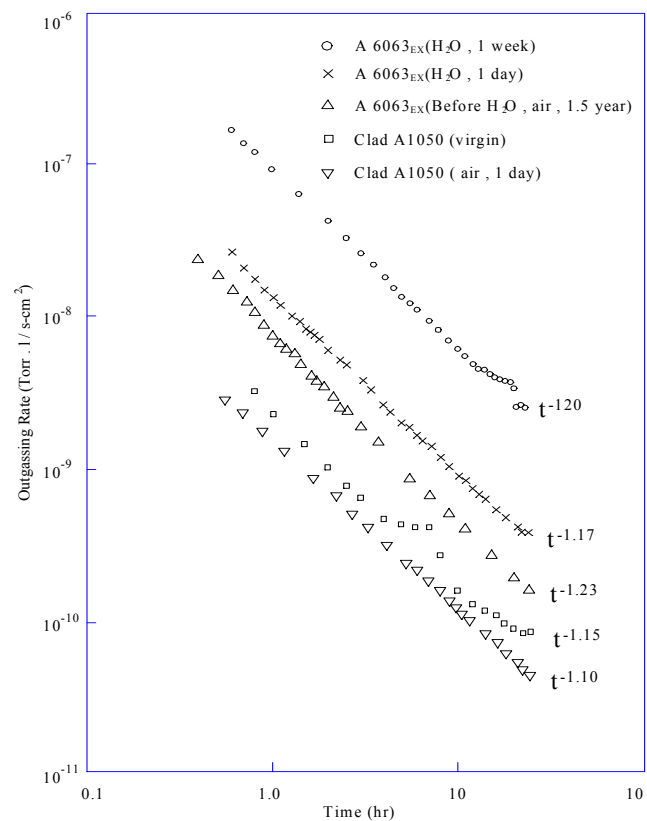


水氣如何進到真空腔內？

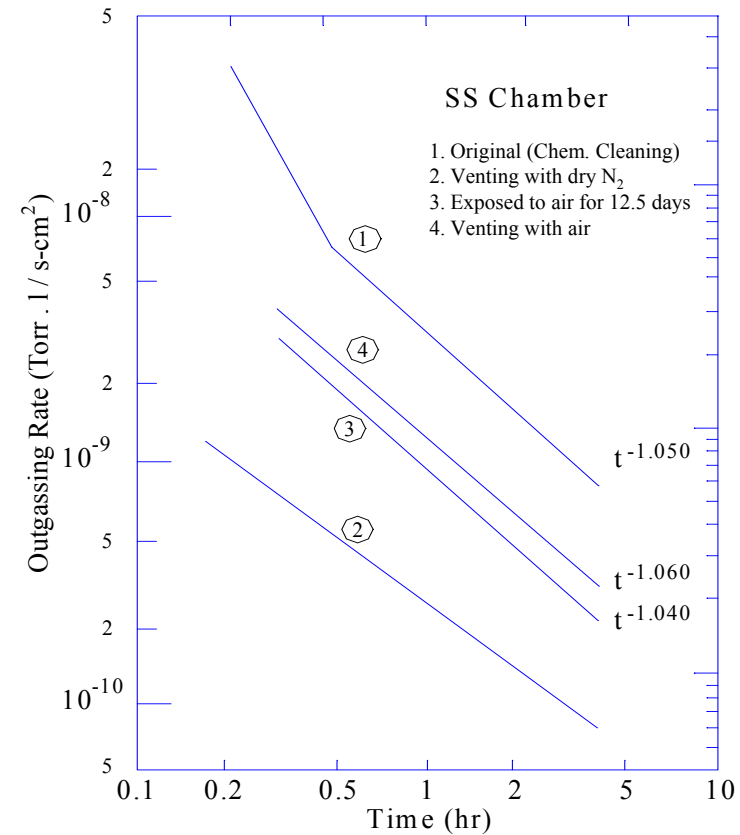
1. 進氣污染
2. 曝露大氣
3. 幫浦回流
4. 表面釋氣



真空腔的抽氣曲線很相似? → 表面水釋氣



鋁合金



不銹鋼

利用氣壓增建法測量系統釋氣率

真空系統隔離幫浦後氣壓上升

曲線斜率可估計 “Q”：

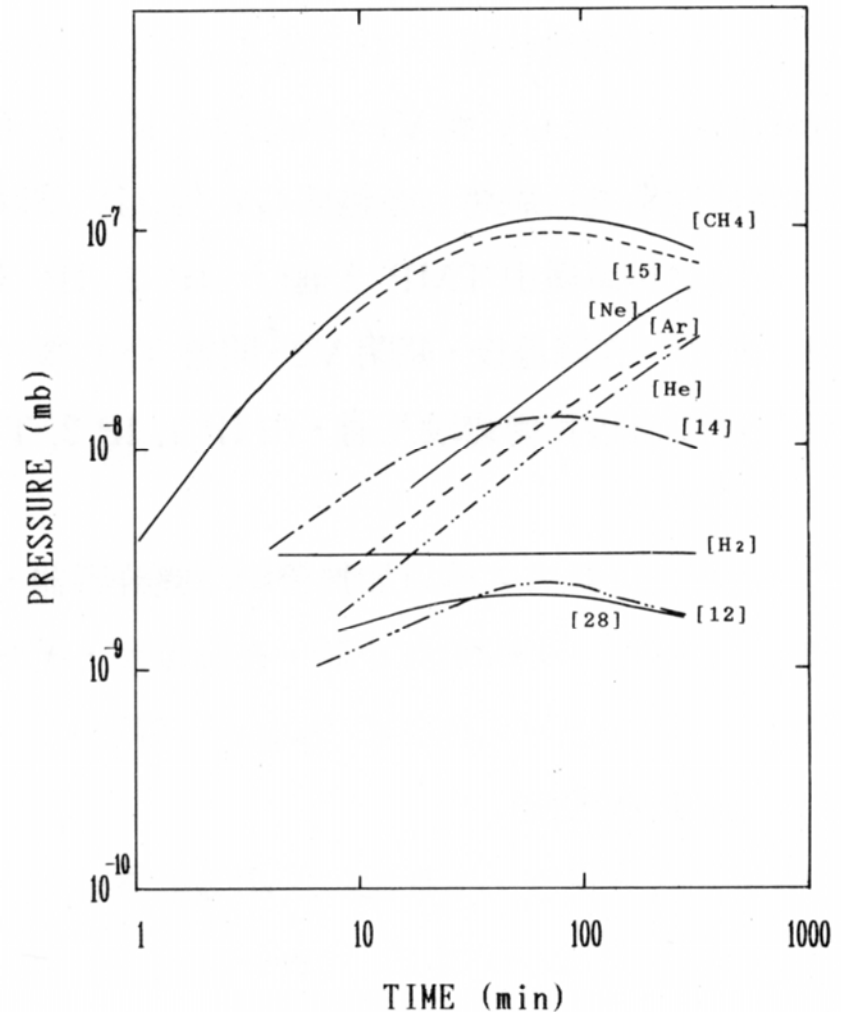
$$Q = S P + V (dP / dt)$$

$$Q \sim V (dP / dt), \text{ when } S \sim 0$$

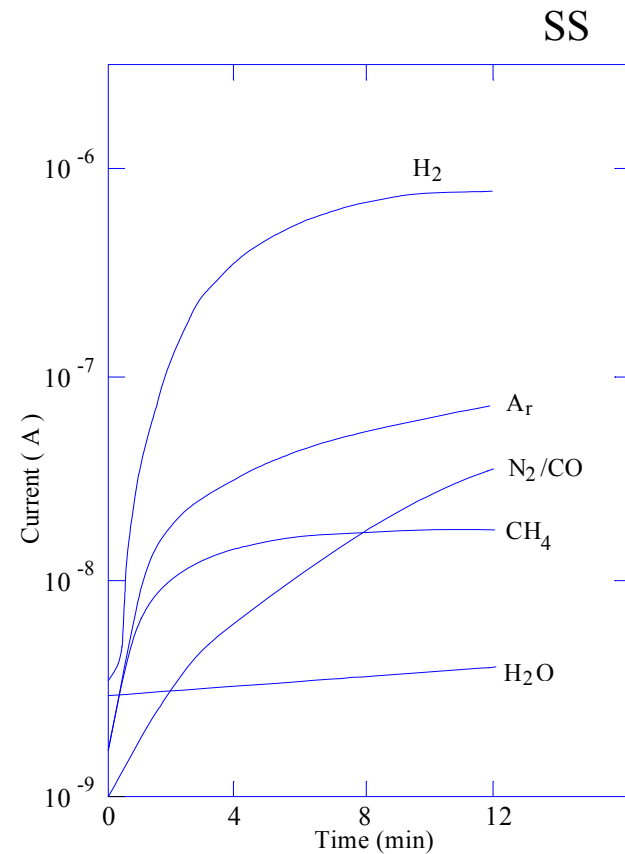
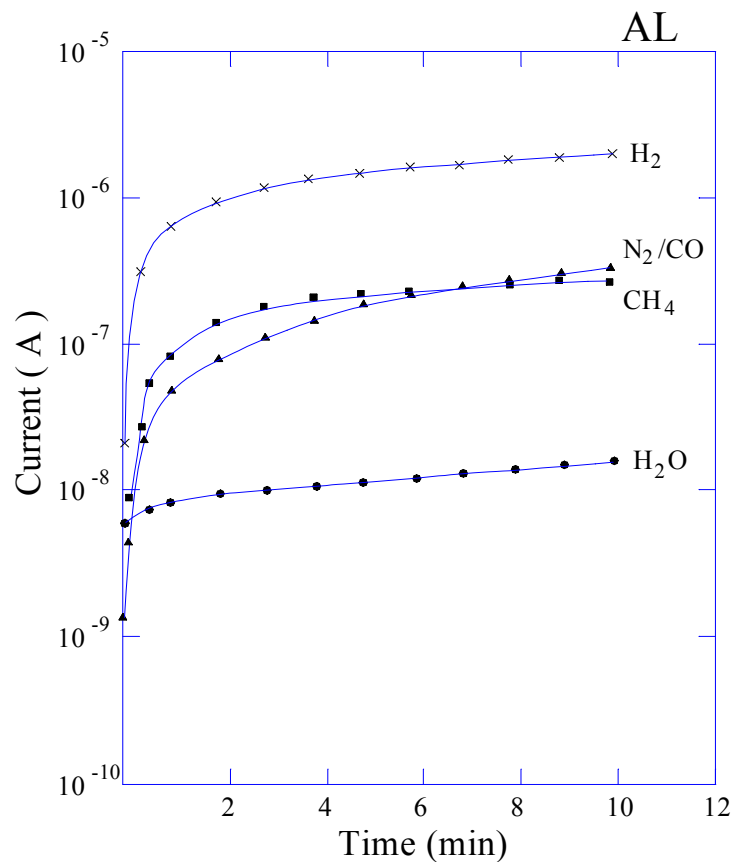
$$P(t) \sim (Q/V) t + P(t_0)$$

t_0 為真空系統隔離幫浦的時間。

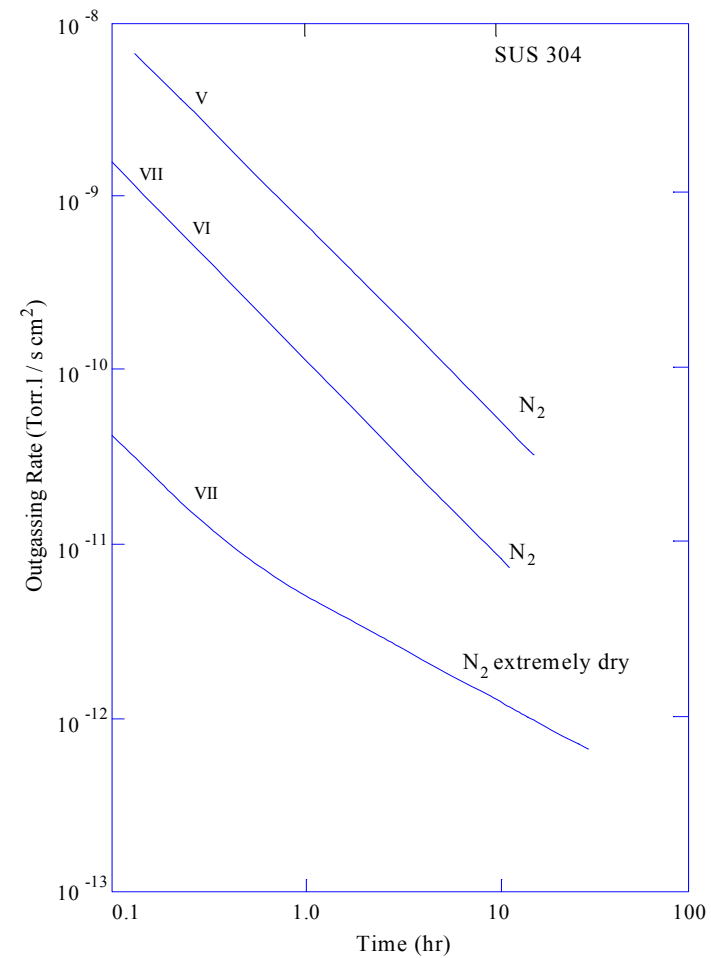
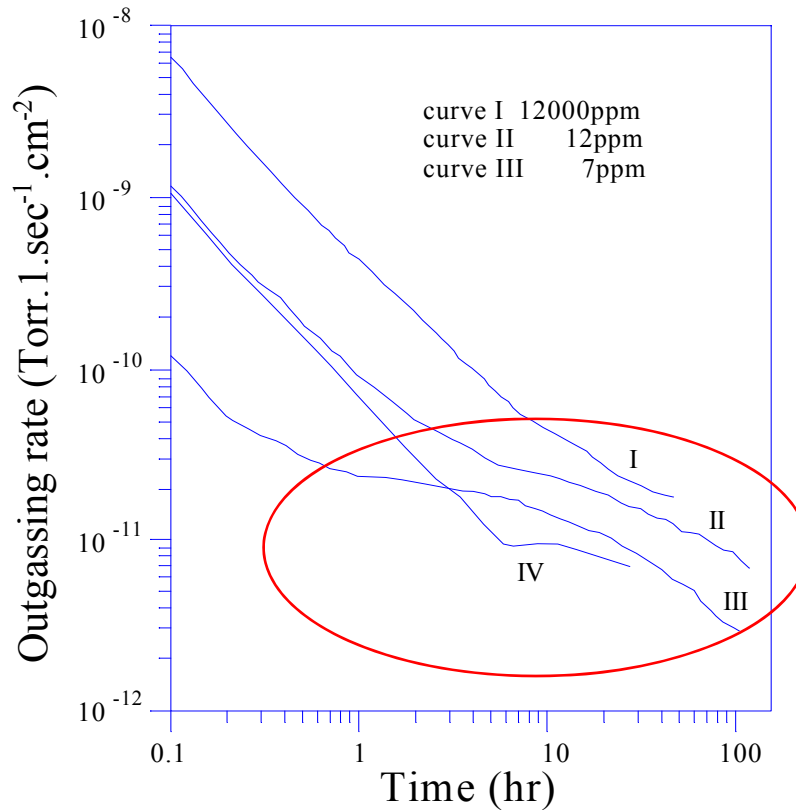
- 質譜圖可協助瞭解系統釋氣種類。
- 空氣含Ne, Ar等惰性氣體，在無抽氣作用時其分壓呈直線上升。



停止抽氣，看看氣壓上升趨勢：
→ 水上升的趨勢最平(留在表面上?)



鋁合金與不銹鋼的抽氣曲線也有不同處 → 鋁合金表面厚氧化層的擴散釋氣



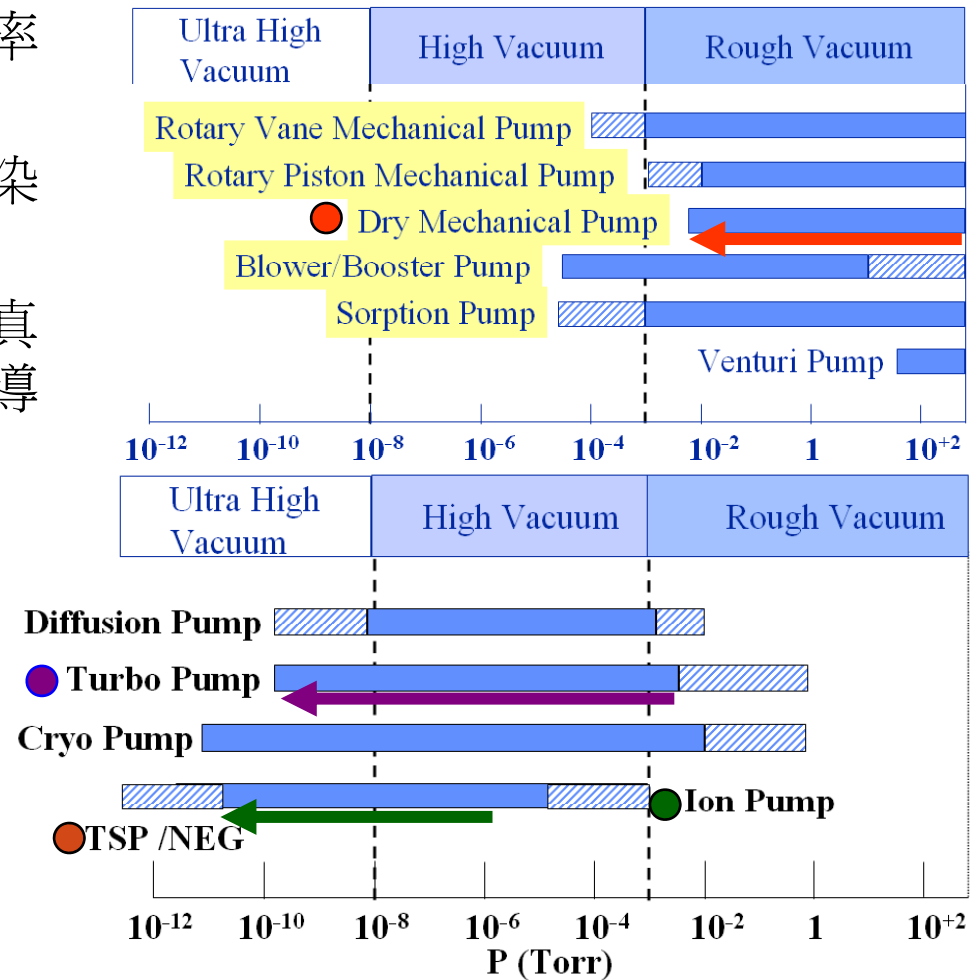
真空幫浦抽氣原理

- 粗抽幫浦
- 高真空與超高真空幫浦
- 真空幫浦的選用與組合運用

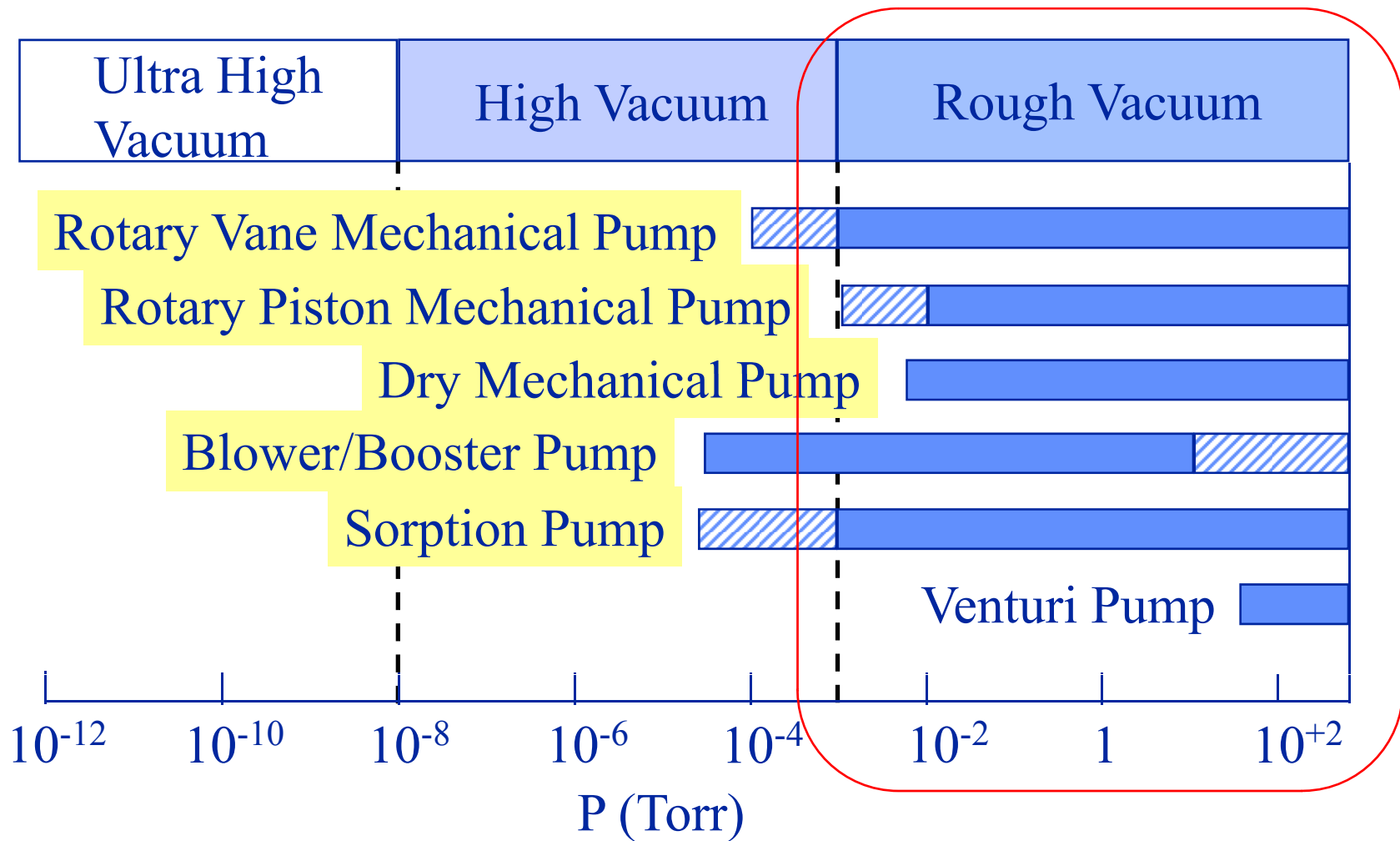
真空幫浦抽氣範圍與搭配

- 在不同氣壓範圍選用足夠抽氣速率的幫浦。
- 選用無油幫浦以減少油氣回流污染系統。
- 選用密閉式幫浦以維持系統長期真空條件避免停電或機械幫浦故障導致破壞真空。

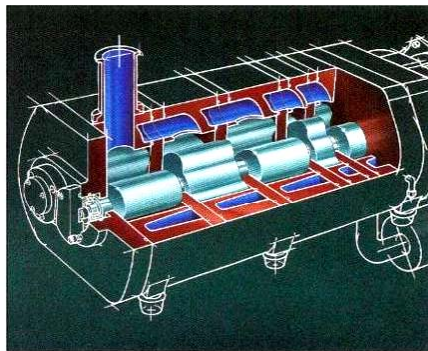
1. TMP and Dry pump (DP) for Roughing and Baking
2. Sputtering ion pump (SIP) for UHV
Pumping include noble gases (CH_4 , Ar)
3. Non-evaporable getter (NEG) pump for H_2 and CO Pumping
4. Titanium sublimation pump (TSP) for Chemical Getter Pumping



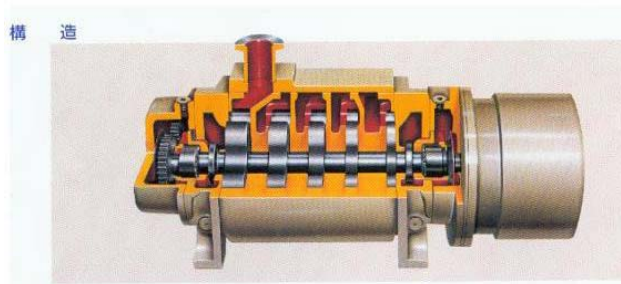
粗抽幫浦 (Roughing)



高通量乾式幫浦 (1 atm $\rightarrow$ 10^{-3} Torr)



Screw (螺旋式)

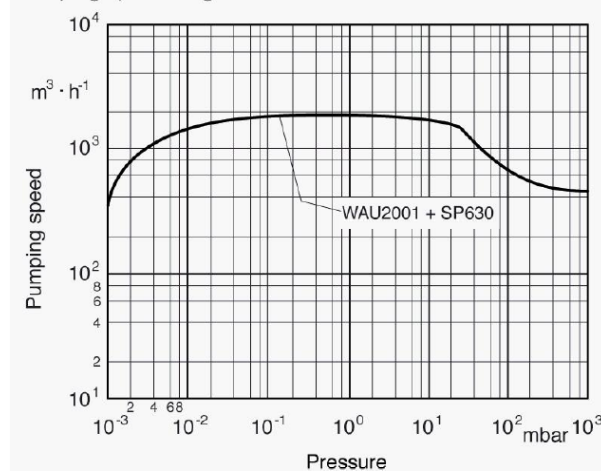


Roots (魯式)

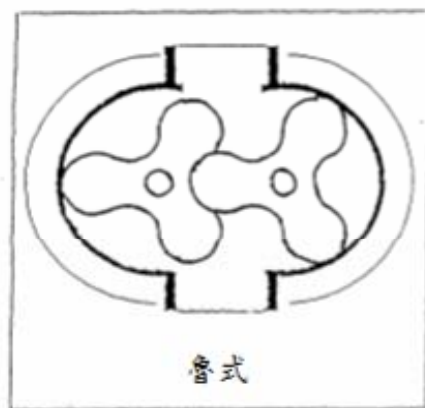


Scroll (渦卷式)

Pumping speed diagram at 50 Hz



乾式幫浦種類及排氣原理



滑式

(1)



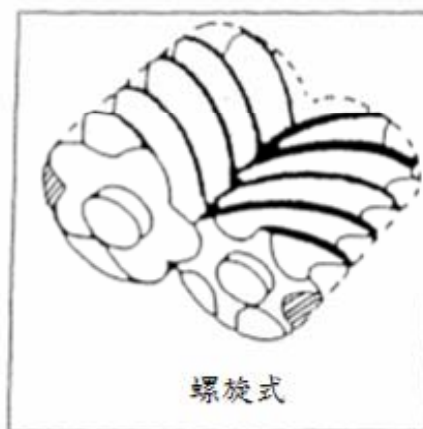
爪式

(2)



渦卷式

(3)

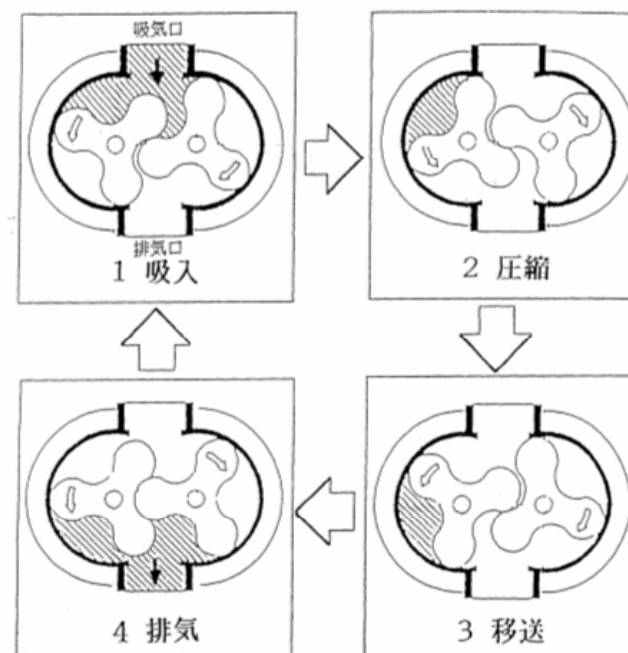


螺旋式

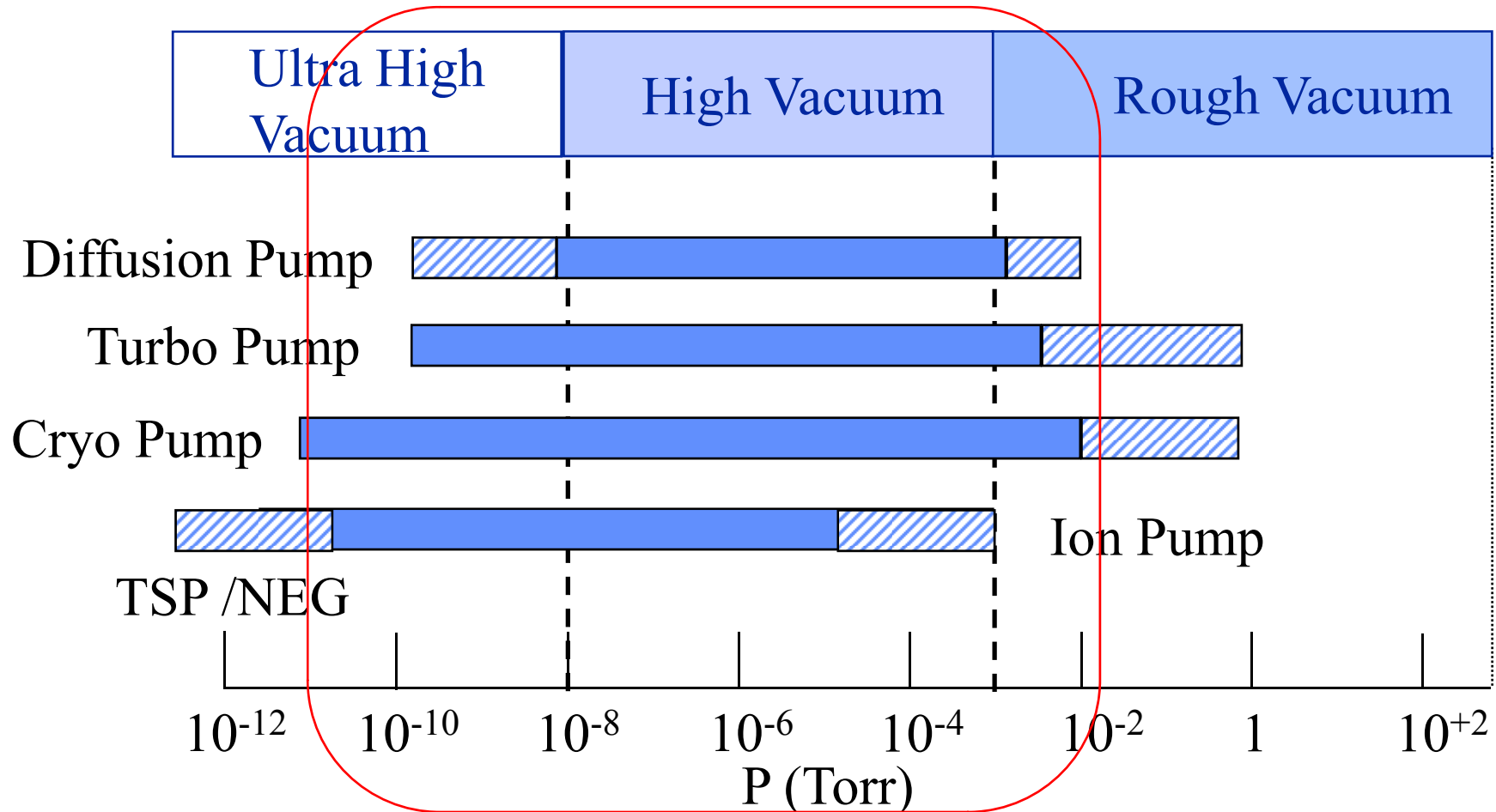
(4)

(體積挪移排氣)

排氣原理



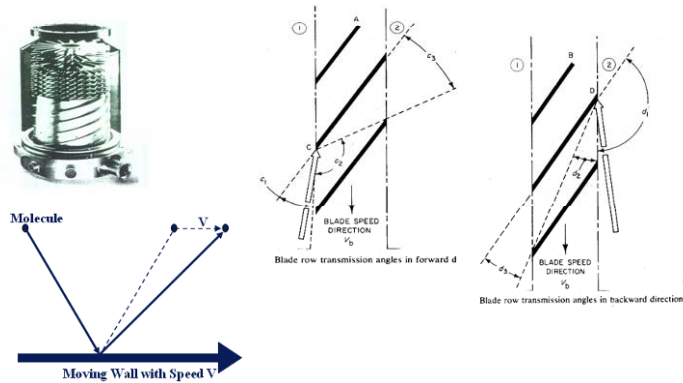
高真空與超高真空幫浦



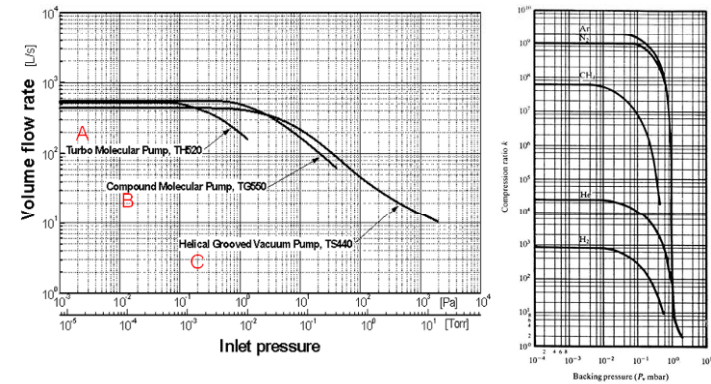
Turbo Molecular Pump (TMP)

渦輪分子幫浦

Turbo Molecular Pump (TMP)



渦輪分子幫浦抽氣速率與壓縮比



渦輪分子幫浦的轉子

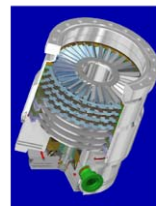
(A) 傳統渦輪葉片轉子



(B) 複合式轉子

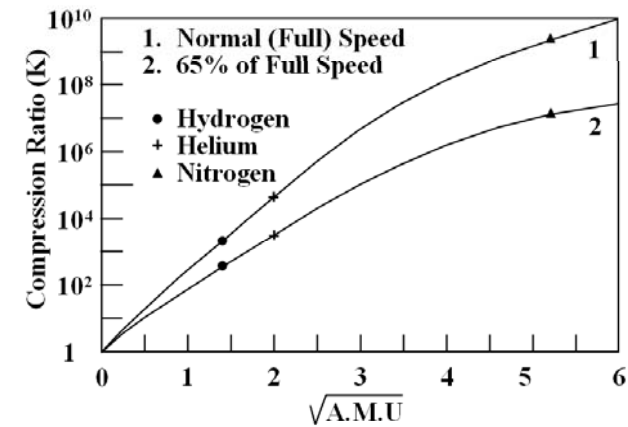


(C) 螺旋溝槽式轉子



提高抽氣通量

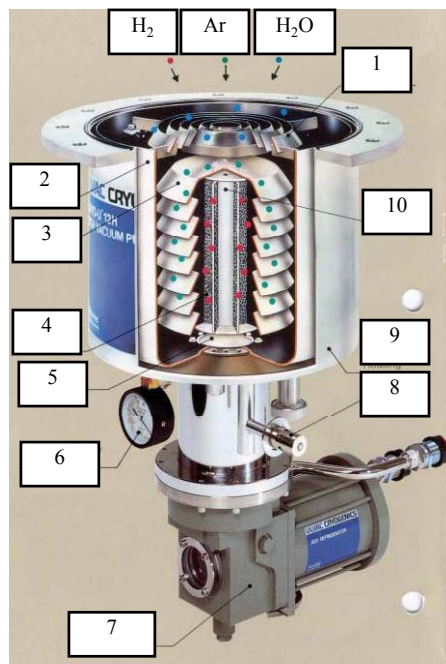
渦輪分子幫浦對不同氣體壓縮比比較



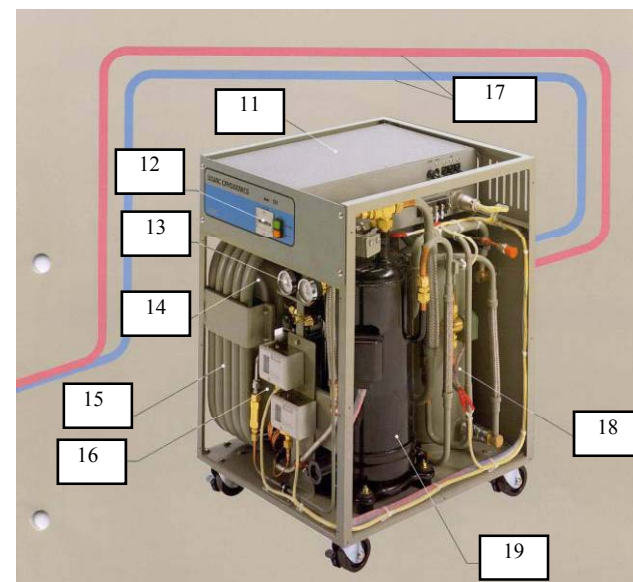
Cryogenic Pump

冷凍幫浦

(a) 真空幫浦本體



(b) 低溫冷凍系統

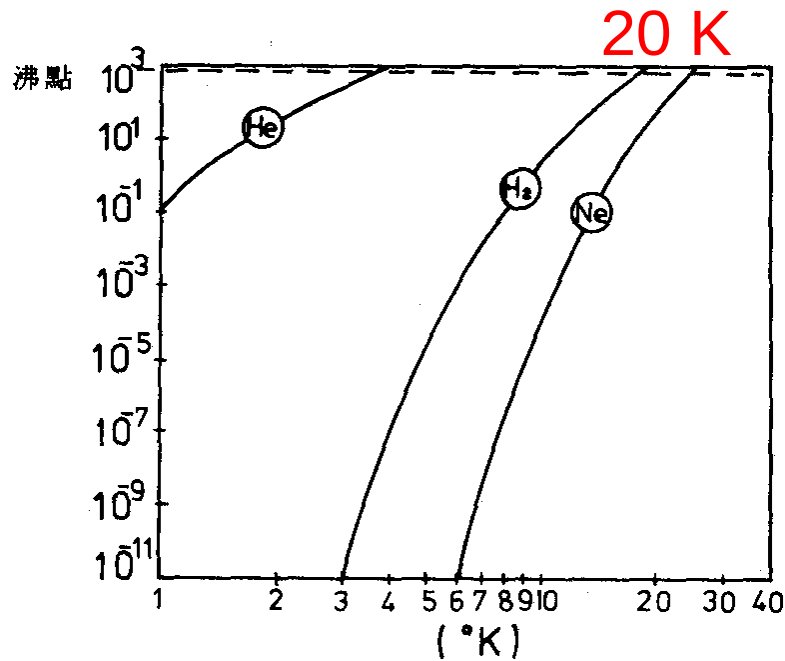


- 1: 80K檔板
- 2: 80K熱輻射外殼
- 3: 15K低溫板
- 4: 吸收器
- 5: 第一級冷頭
- 6: 氫氣蒸氣壓表
- 7: 冷凍單元及馬達

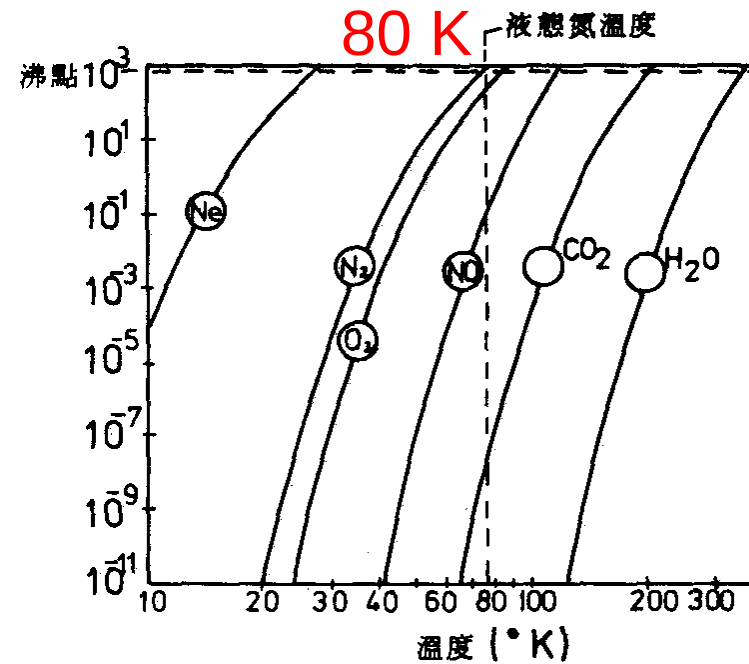
- 8: 洩壓閥
- 9: 不銹鋼外殼
- 10: 第二級冷頭
- 11: 控制模組
- 12: 使用時間記錄表
- 13: 氫氣壓力表
- 14: 油分離器

- 15: 熱交換器
- 16: 緩衝器
- 17: 氫氣管
- 18: 吸收器
- 19: 壓縮機

冷凍幫浦抽氣原理



(a)



(b)

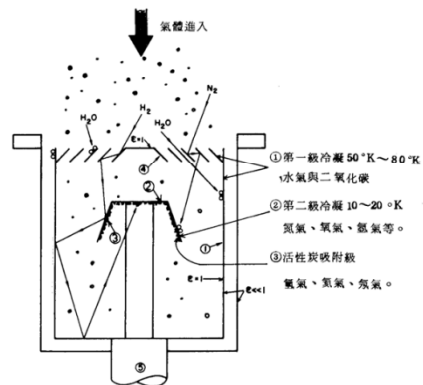
低溫冷凝 (Cryo-condensation)

低溫吸附 (Cryo-sorption)

低溫捕獲 (Cryo-trapping)

冷凍幫浦抽氣原理

冷凍幫浦抽氣原理



低溫冷凝

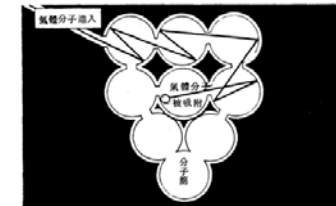
低溫冷凝是利用極低溫的表面將入射的氣體分子冷凝下來，並利用極小的氣體蒸氣壓力以保持其高真空的特性。

氣體種類	蒸氣壓約略值 (Torr)
水氣	10^{-22}
氮氣	500
二氧化碳	10^{-7}
一氧化碳	760
氫氣	>760
氬氣	>760
氧氣	350
氦氣	>760
氖氣	760

在溫度為-190°C時部分氣體的蒸氣壓力

低溫吸附

對於一些不易被低溫冷凝面冷凝下來的氣體(Non-Condensable Gas)，如 He、H₂及Ne等，利用多孔性的物質，使這些氣體進入後降低其動能，最後因為動能的喪失而停留在多孔性物質的內部，進而達到抽氣的效果。



活性炭(Charcoal) - 迷宮式多孔性分子篩結構之低溫吸附效果。

低溫捕獲

利用較易低溫冷凝的氣體(如氫氣)以吸附其他不易冷凝的氣體(如氬氣)，冷凝之氫分子具多孔性，使得氬分子容易被吸附而減低其蒸氣壓。

混合氣體種類	N_b/n_c
H ₂ /Ar	1.0
H ₂ /CO	0.5
H ₂ /D ₂	0.1
⁴ He/Ar	3×10^{-2}
⁴ He/D ₂	2×10^{-5}

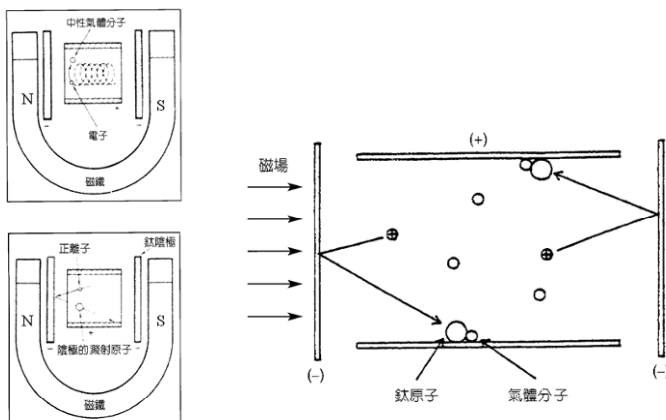
部分混合氣體在Tk=4.2K時的捕獲比率

Sputtering Ionization Pump (SIP)

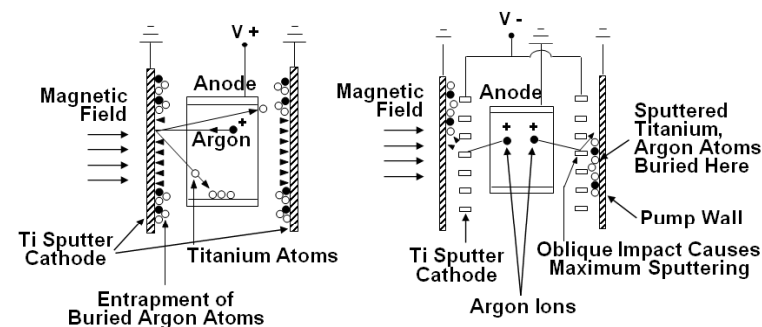
濺射式離子幫浦
Sputtering Ionization Pump (IP)



離子幫浦抽氣原理



二極式與三極式離子幫浦之比較

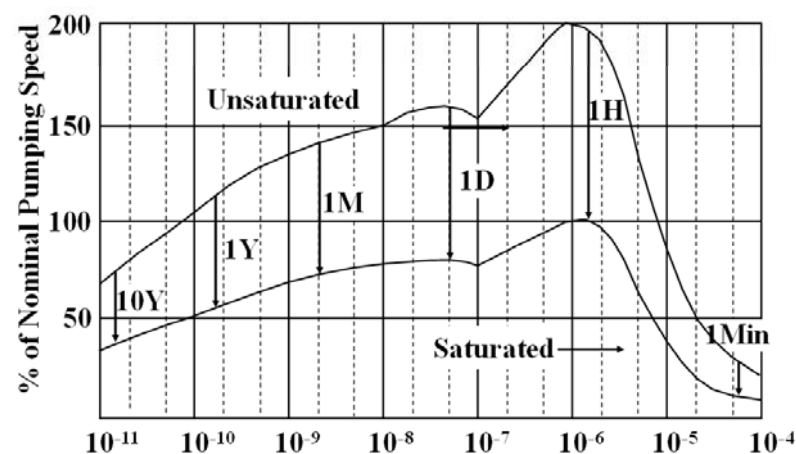


Pumping Mechanisms

(A) Diode Ion Pump

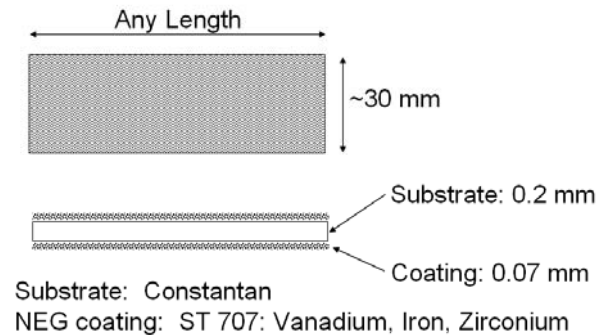
(B) Triode Ion Pump

離子幫浦飽和抽氣速率

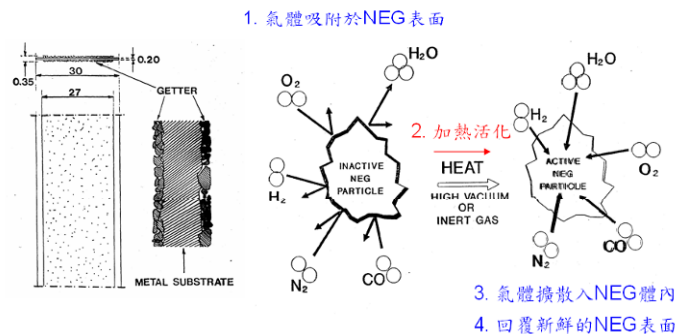


Non Evaporable Getter (NEG) Pump

非蒸發式結拖幫浦
Non Evaporable Getters (NEG)



NEG 抽氣原理



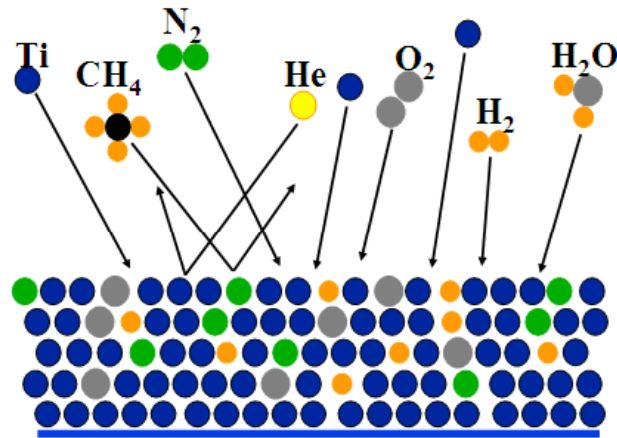
幫浦對不同氣體的抽氣能力比較

	TSP	NEG	TRIODE	STAR CELL	DIODE	NOBLE DIODE
HYDROGEN	3	4	1	2	3	1
HELIUM	0	0	3	4	1	3
WATER	3	3	2	2	3	2
METHANE	0	0	3	3	2	3
NITROGEN	3	3	2	2	3	3
O ₂ , CO, CO ₂	4	3	2	2	3	3
ARGON	0	0	3	4	1	3

NULL	0
POOR	1
GOOD	2
EXCELLENT	3
OUTSTANDING	4

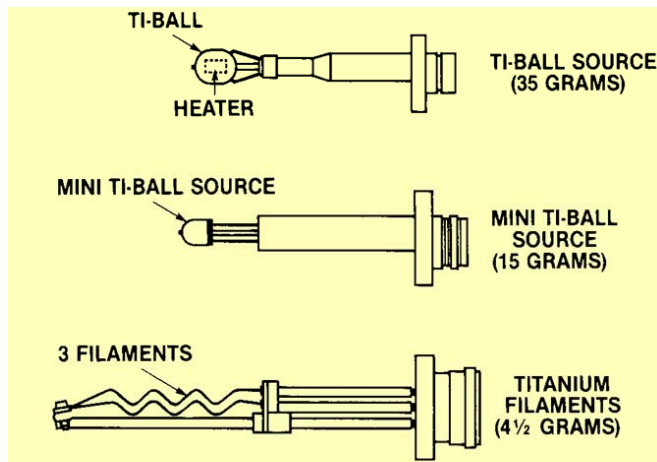
Titanium Sublimation Getter Pump (TSP)

鈦昇華幫浦



Typical pumping speed for various gases
on sublimed titanium surface
(liters per second per square cm)

Surface Temperature	H ₂	N ₂	O ₂	CO	CO ₂	H ₂ O
20°C	3.1	4.6	9.3	9.3	7.8	3.1
-196°C	10.1	10.1	10.8	10.8	9.3	14.0



TSP Designed To Reach Lower (UHV) Pressures
Provide Very High Speed At Low Pressures For All
Getterable Gases

Zero Pumping Speed For Noble Gases And Methane
Limited Use (Life) At Pressure Higher Than 10^{-7} Torr

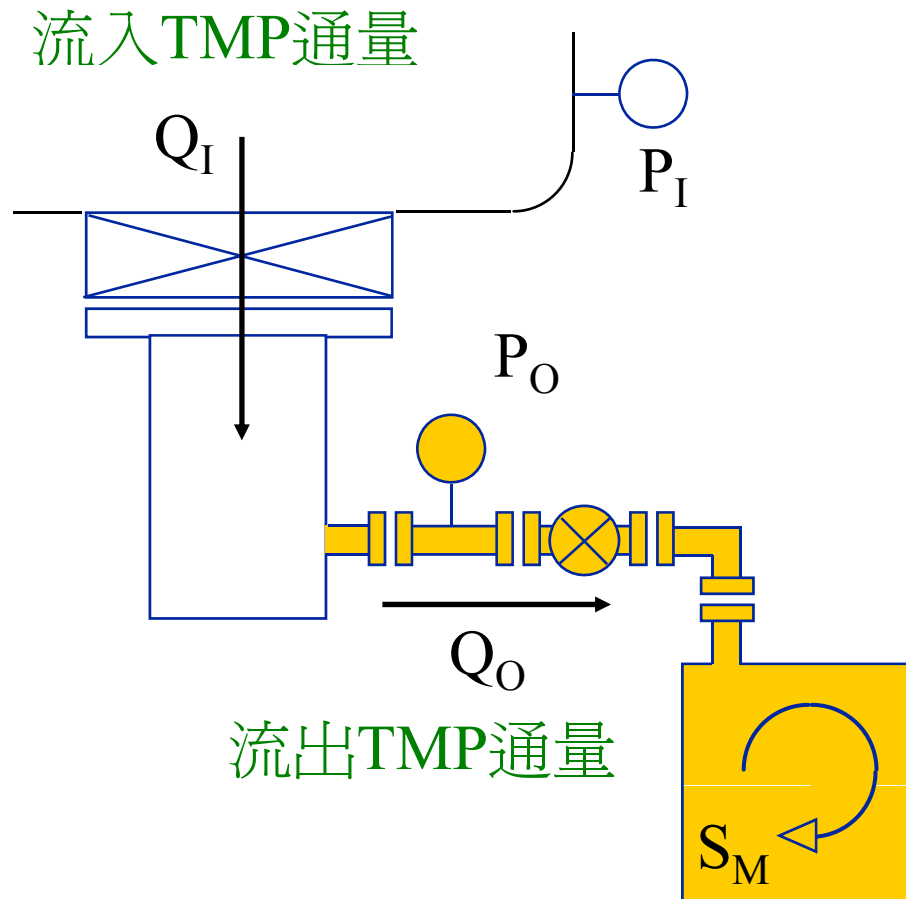
真空幫浦的選用

- DP – 1 atm 粗抽、高氣體流量抽氣
- TMP – 粗抽、烘烤排氣
- IP – 密閉高真空抽氣 (H_2 , CO, CO_2 , CH_4 , H_2O)
- NEG – 超高真空抽氣 (H_2 , CO)
- TSP – 超高真空抽氣 (活性氣體)
- Cryo-Pump – 高抽氣速率

粗抽前級幫浦的選用(自 1 atm抽氣)

優點	Type	缺點
Low ult pressure Low cost Long pump life	Rotary Vane	Backstreams oil Can produce hazardous waste Synthetic oil
High volume Low cost	Rotary Piston	Safety valve Noisy Vibration
Clean Low “dry” ultimate pressure	Scroll	Permeable to small gases Clean applications only
Quiet Easily serviced	Diaphragm	Low pumping speed High ultimate pressure Frequent service required
No backstreaming Low ultimate pressure	Hook & Claw Roots lobe	Expensive Frequent maintenance Requires purge gas
Low cost No moving parts Clean pumping	Sorption	Requires regeneration Limited pump capacity

TMP前級幫浦選用規格之考量



$$Q = S P$$

$$\text{通量: } Q_O > Q_I,$$

$$\text{即: } P_O \times S_M > P_I \times S_T$$

$$S_M > \frac{P_I \times S_T}{P_O}$$

高真空幫浦的選用

優點

TYPE

缺點

High H₂O pumping speed

CRYO

Regeneration required

Mounts any position

Affected by heat

Clean

Some vibration

Low cost

VAPOR JET
(DIFFUSION)

Backstreams

No moving parts

No pressure tolerance

Low maintenance

May require coldtrap

Clean

ION

Low throughput

No moving parts

No pressure tolerance

Needs no attention

Finite life

Continuous pumping

TURBO

Mechanical bearing

Clean

Vibration

High pressure

Cost

真空幫浦的組合運用

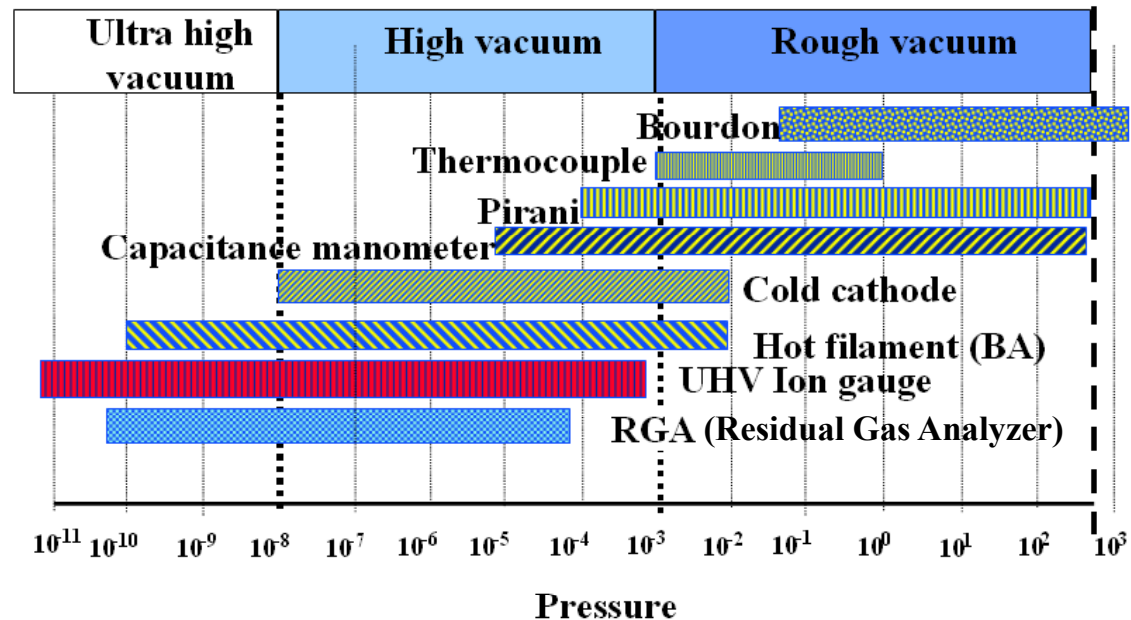
Roughing Systems	High Vacuum Systems	Ultra-High Vacuum Systems
a. Oil-Sealed Mechanical Pump	a. Mechanical Pump b. Baffle or Cryotrap c. Diffusion Pump	a. Dry Pump b. Ion Pump c. Titanium Sublimation Pump d. LN ₂ Trap
a. Dry Pump	a. Dry Pump b. Cryopump	a. Dry Pump b. Turbo Pump
a. Mechanical Pump b. Booster/Blower Pump	a. Dry Pump b. Turbo Pump	c. Ion Pump

真空計測量氣壓原理

- 機械、電容式真空計
- 熱導式真空計
- 放電(冷陰極)真空計
- 熱游離真空計
- 質譜儀 (測量分壓)

常用真空計與測量範圍

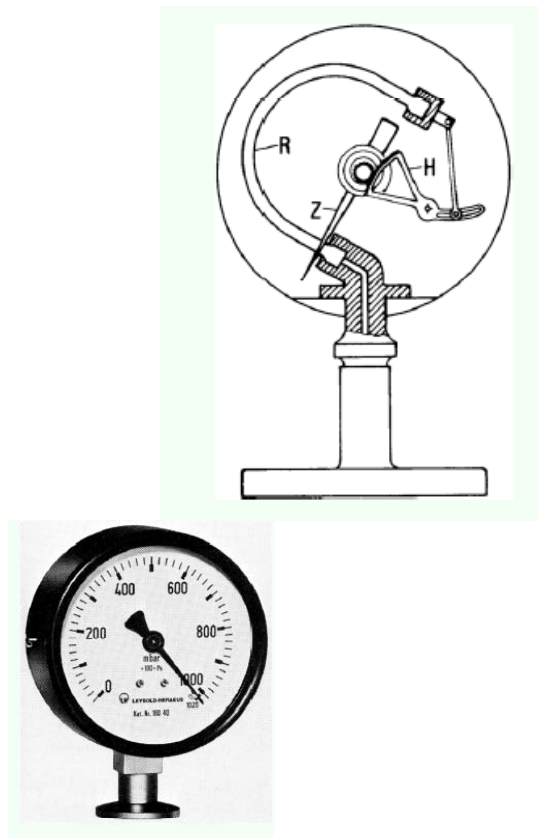
- 機械、電容式 — $1000 \sim 1$ mb
- 熱導式、電容式 — $1 \sim 1 \times 10^{-3}$ mb
- 放電式(冷陰極) — $1 \times 10^{-2} \sim 1 \times 10^{-10}$ mb
- 熱游離式 — $1 \times 10^{-4} \sim 1 \times 10^{-11}$ mb
- 質譜儀 (RGA測量分壓) — $1 \times 10^{-5} \sim 1 \times 10^{-10}$ mb



機械式 Bourdon Gauge

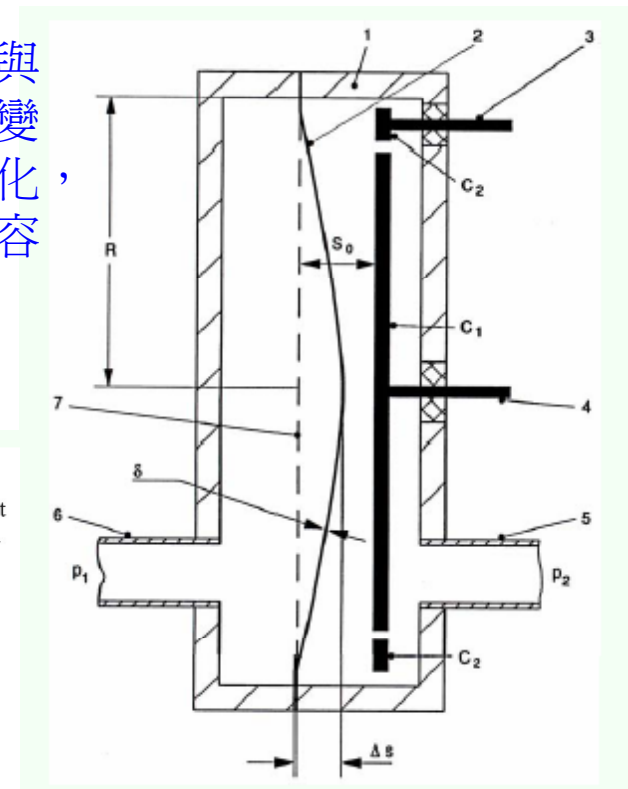
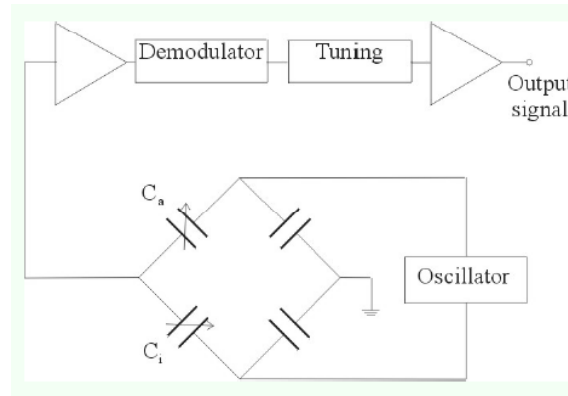
電容式 Capacitance diaphragm gauge

Bourdon Gauge



Capacitance diaphragm Gauge

此式真空計利用金屬薄膜與電極間的電容，當壓力改變時，二者間的距離發生變化，電容亦改變，因此測定電容即可轉換為壓力。
(電容 $C = \epsilon_0 \cdot A / D$)

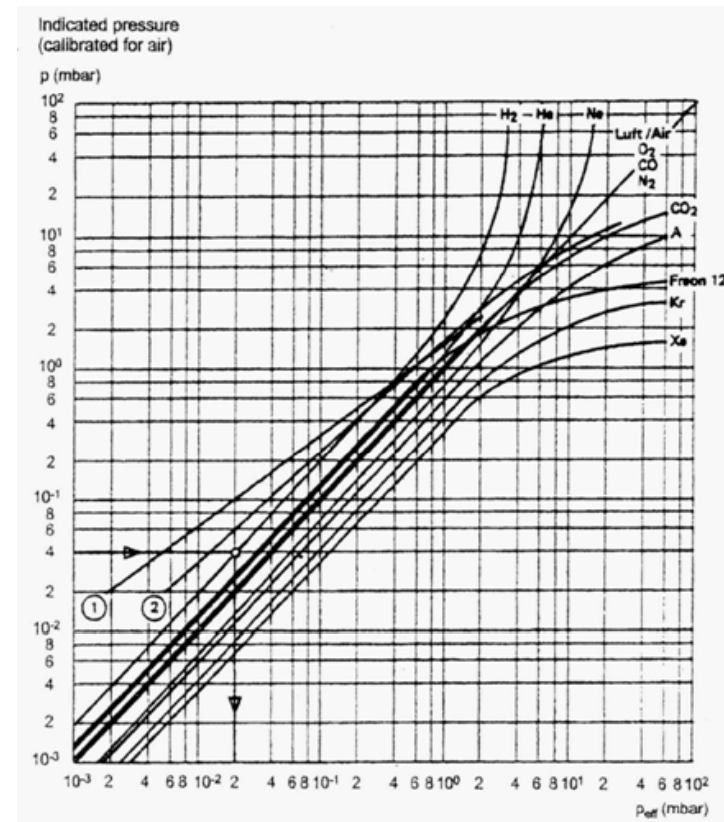


熱傳導式真空計 ($1 \text{ atm} \sim 10^{-3} \text{ mb}$)

由氣體分子碰撞發熱體而把熱能帶走，因此不同氣體分子的質量帶走的熱能不一樣。熱傳導與氣壓成線性關係。

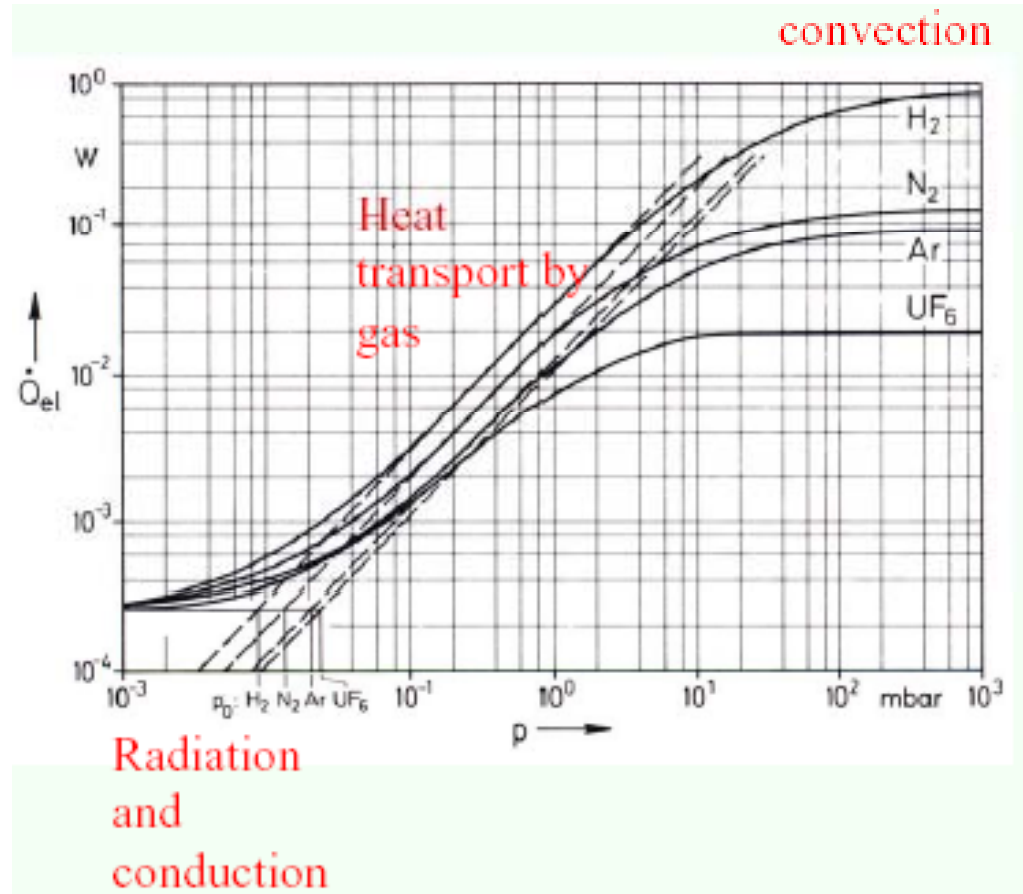
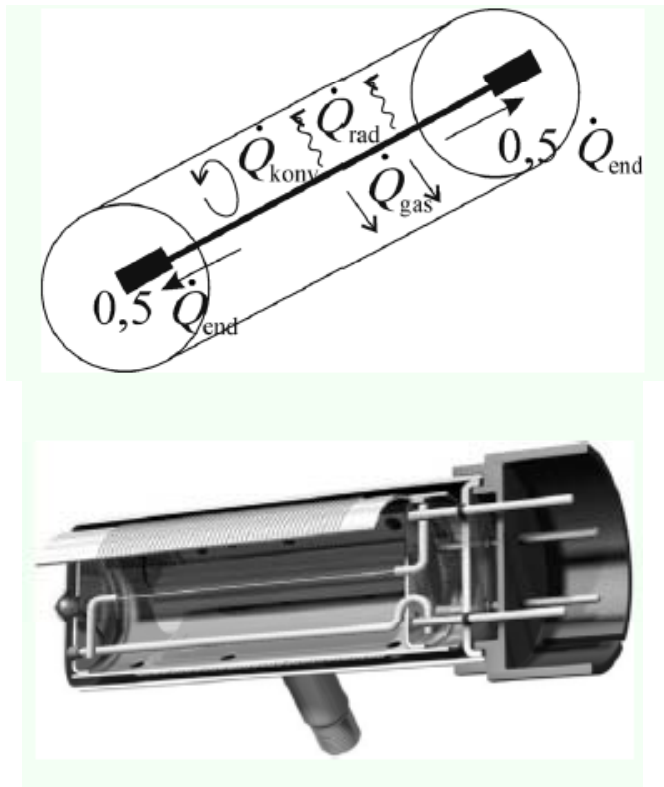
- Thermo-Couple Gauge
- Pirani Gauge
- Convectron Gauge

熱傳導式真空計對不同氣體測量靈敏度曲線 ($P < 1 \text{ mb}$ 呈線性)



熱傳導式 Convector Gauge

Heat conductivity through a gas

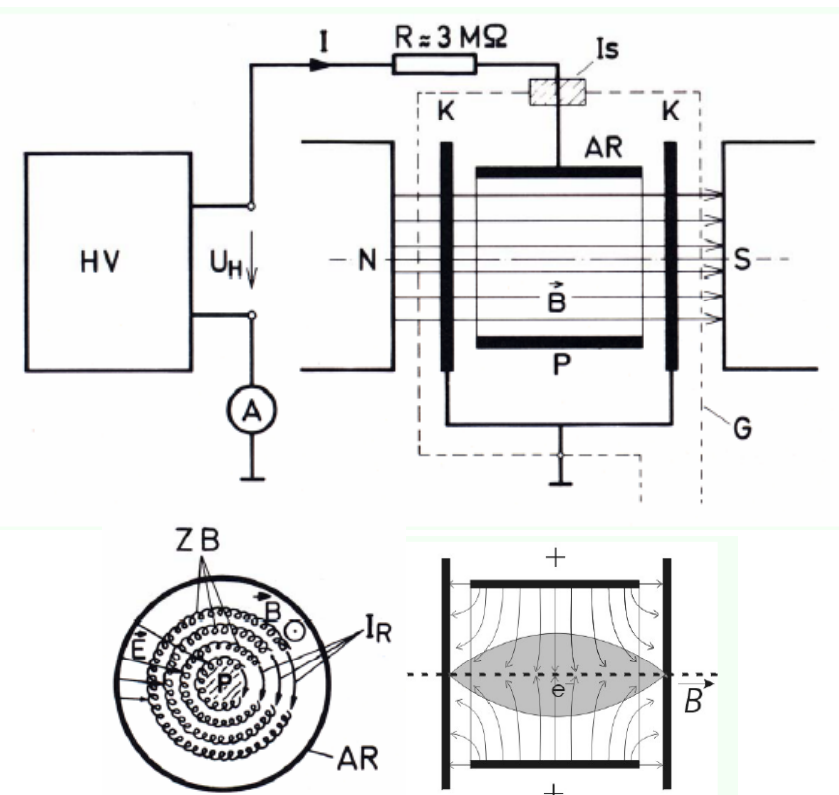


放電式冷陰極離子真空計

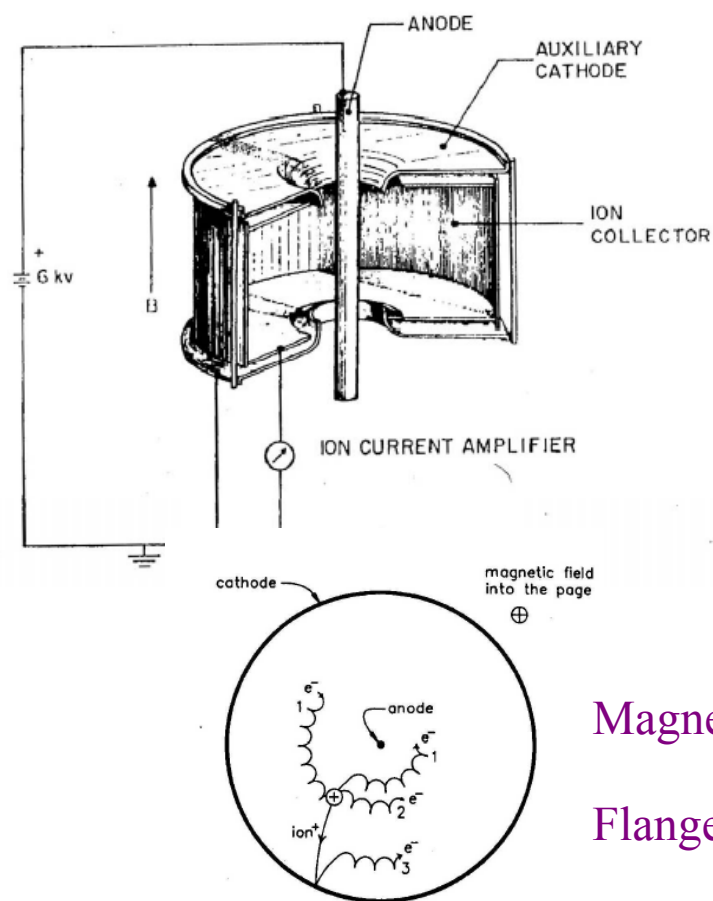
Cold-Cathode Gauge (Penning Gauge)

- 在中心之陽極與兩端之陰極板間供應2kV之電位差，使產生軸向電場。由於宇宙射線或兩極電場發射(field emission)效應之激發作用使陰極表面釋出電子被電場加速向陽極飛行，而外加的軸向磁場使電子在垂直於磁場的方向被加速而形成螺旋曲線式繞行，且因兩端陰極之排斥使電子在兩端陰極之間往復繞行運動，這種電磁場的作用延長電子在撞擊陽極之前的繞行軌跡並增加電子與氣體分子之間碰撞的機率，使較多氣體分子被游離成正離子並產生游離電子，而正離子因高壓電場之加速撞擊陰極並產生二次電子再度釋出，由以上連續發生不斷之衍生電子與游離作用形成放電，稱為彭寧放電(Penning Discharge)，測量陰極之放電電流可求得真空計中的氣壓。

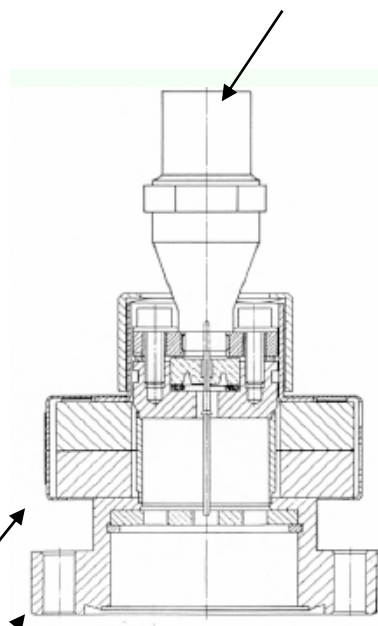
Penning Discharge



Inverted Magnetron Gauge (改良之 Cold Cathode Gauge)



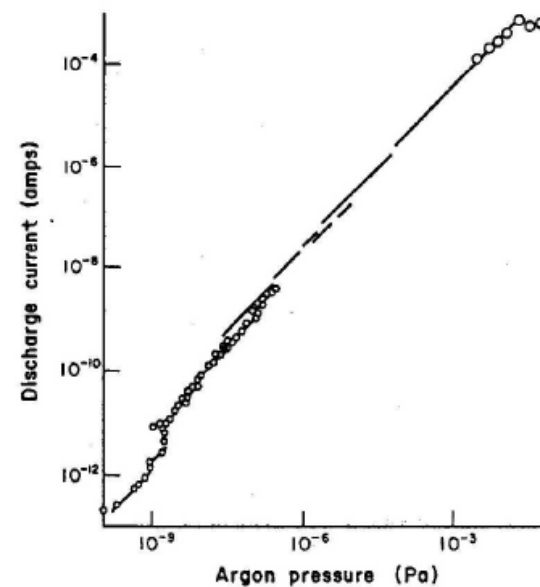
HV Feedthrough



Magnet
Flange

(Vacuum)

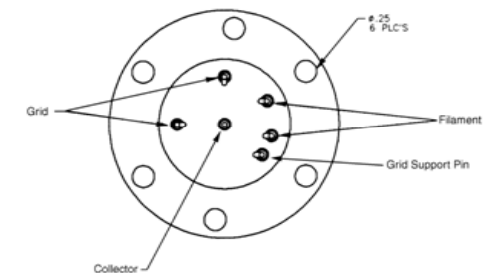
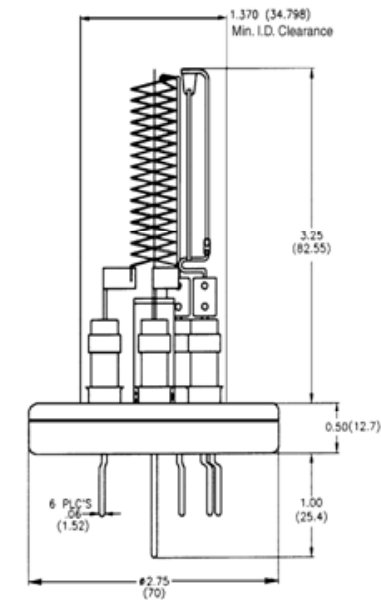
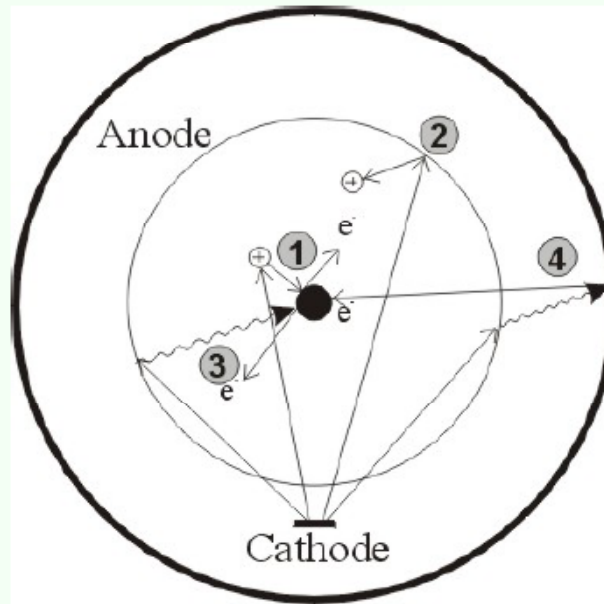
$$I^+ = K \cdot P^m$$



熱游離式真空計 (Ionization Gauge, IG)

Effects in Bayard-Alpert gauges

- 1: The desired ionisation
- 2: Electron stimulated desorption
- 3: X-ray effect
- 4: Inverse X-ray effect



熱游離式真空計 (Ionization Gauge, IG)

* 在真空系統中以帶有能量的電子撞擊氣體分子將氣體分子游離，再測量離子電流與系統氣壓成正比。所測定的壓力與氣體分子的種類有關。

Basic Principle:

$$I^+ = I_e P S$$

$$P = \frac{I^+}{I_e S}$$

I^+ : ion current

I_e : emission current (~mA)

P : pressure

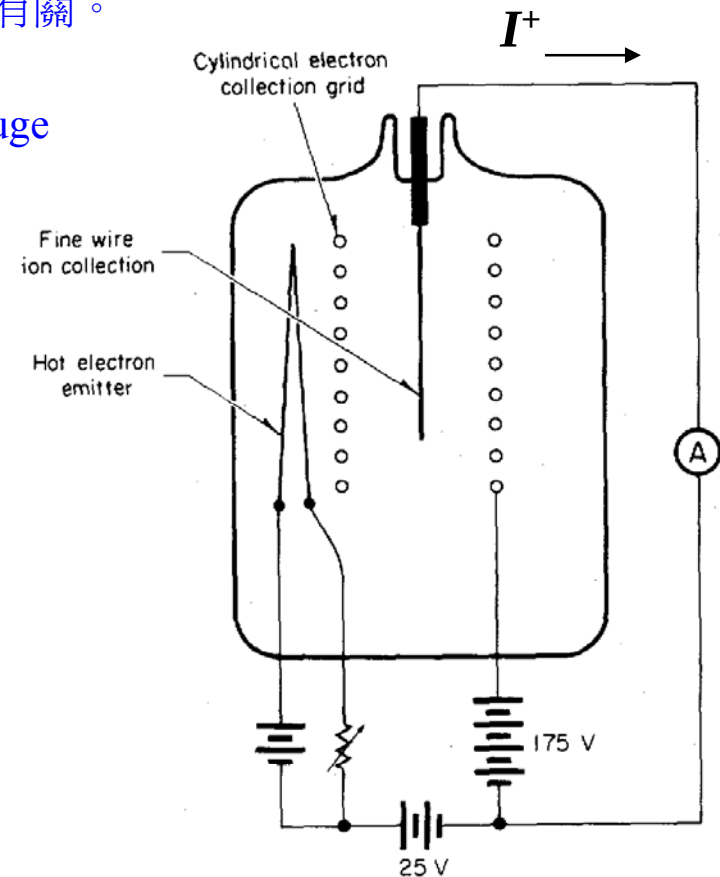
S : gauge sensitivity (~ 25 Torr⁻¹)

* X-ray Limit of BA Gauge ~ 2×10⁻¹¹ mb

* **Extractor Gauge** (hidden collector)
(e-field/ magnetic-field shielding)

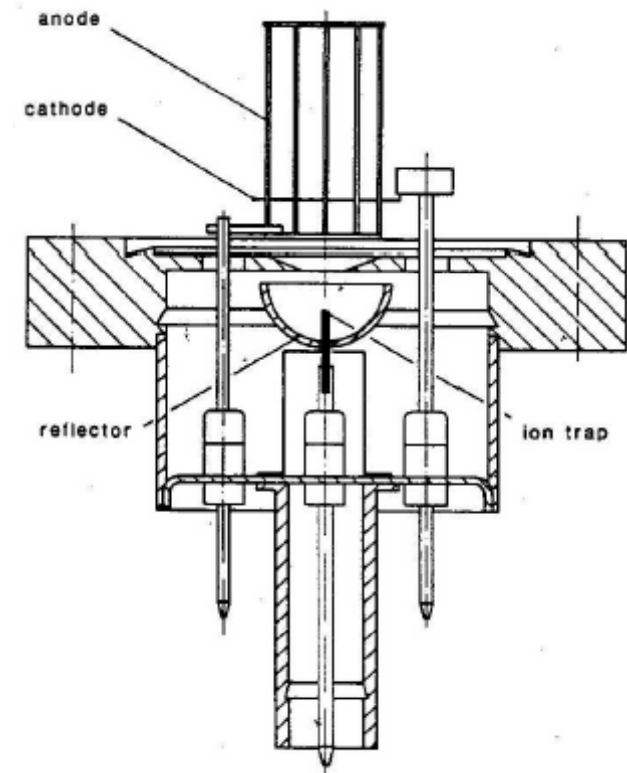
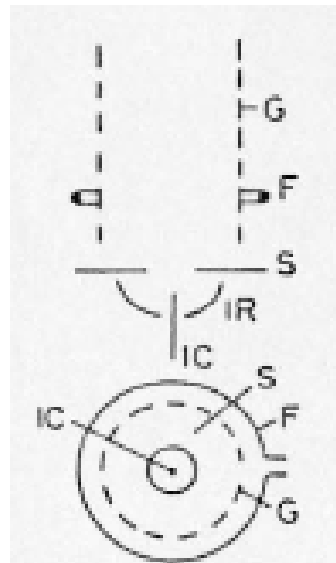
(Ex) Bayard-Alpert Gauge

Gas	Relative Sensitivity
Ar	1.2
CO	1.0 - 1.1
H ₂	0.40 - 0.55
He	0.16
H ₂ O	0.9 - 1.0
N ₂	1.00
Ne	0.25
O ₂	0.8 - 0.9
Solvents	>> 1



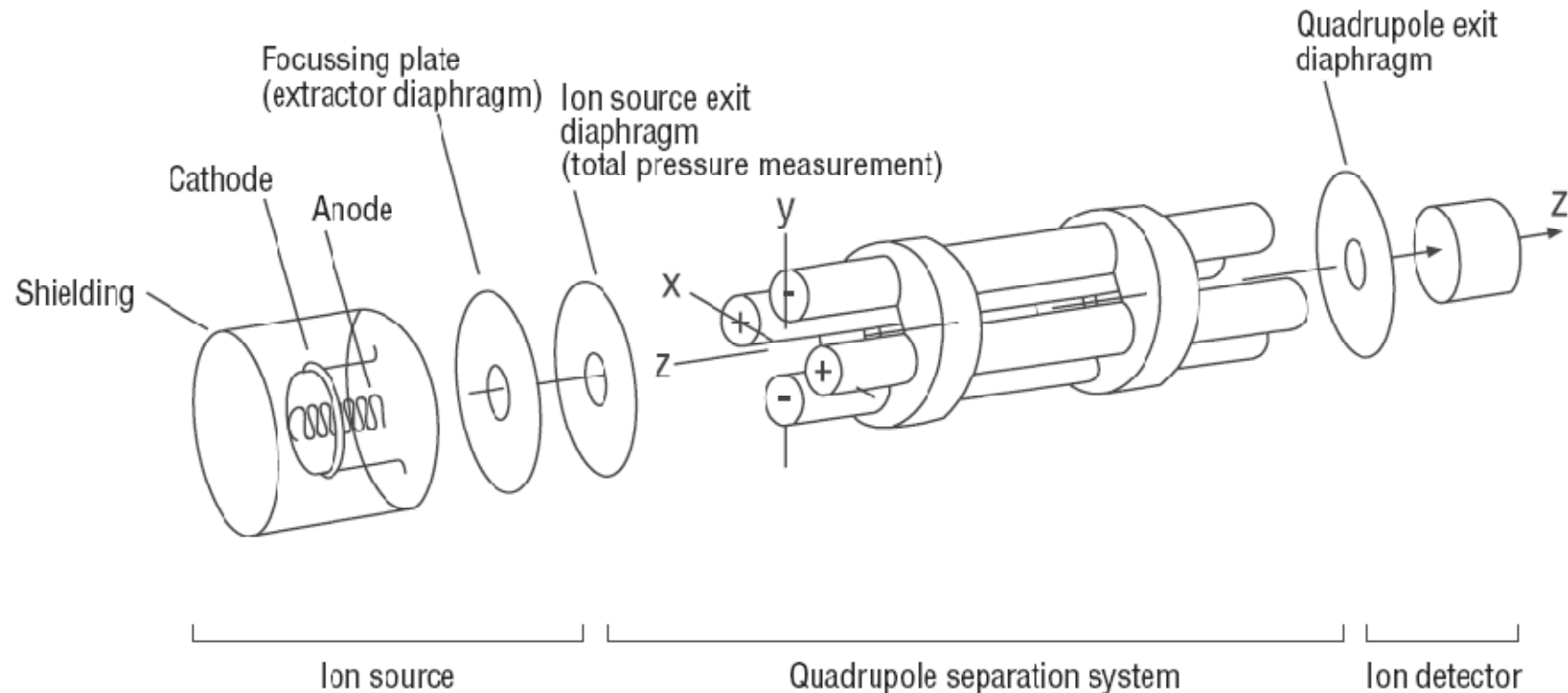
外收集式離子真空計(Extractor IG)

* 外收集式離子真空計將Ion Collector (IC)隱藏，並以Extractor負電極吸引被游離的正離子使撞擊至IC而測量離子電流(I^+)。Ion Reflector (IR)正極排斥離子具有將離子聚焦到IC的作用。



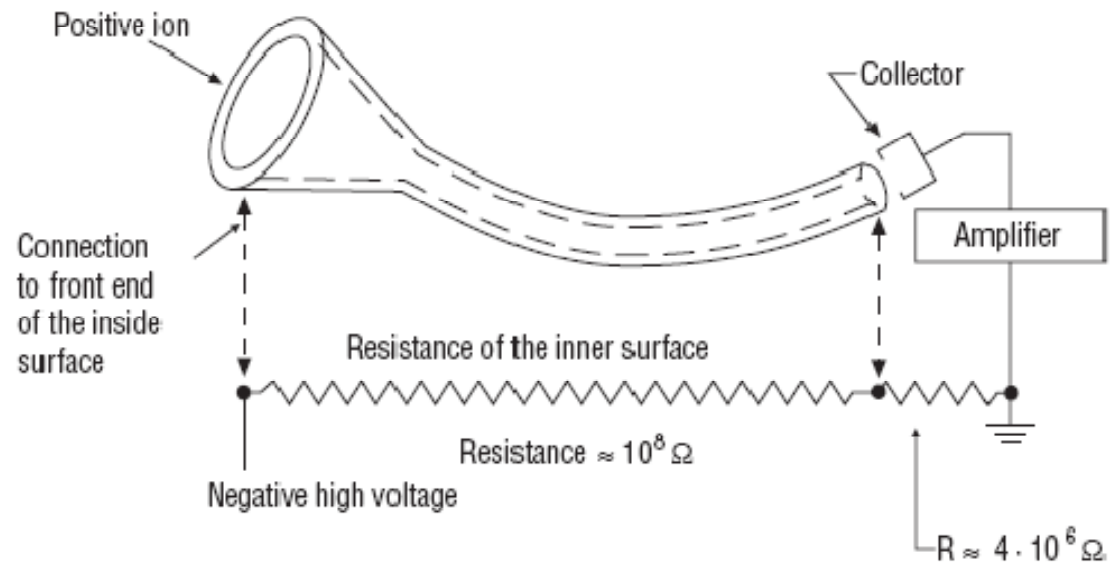
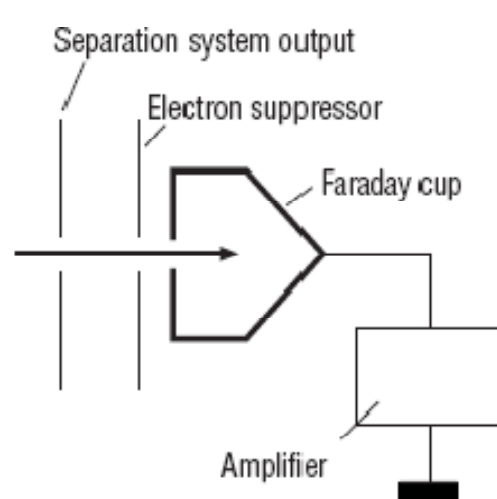
殘餘氣體分析(質譜)儀的利用 Residual Gas Analyzer, RGA

Sensor (Ion source, Mass filter)



RGA Detector

Channeltron Detector (Ion collector)



RGA 工作原理－四極Filter電場

$$\Phi = (U + V \cos \omega t) \cdot (x^2 - y^2) / r_0^2$$

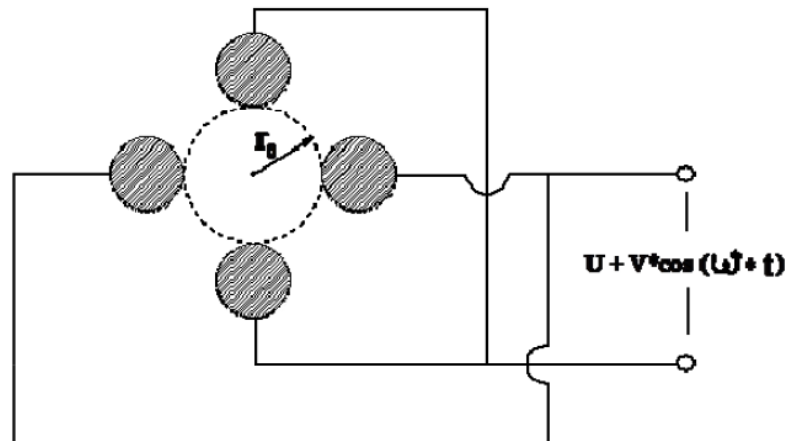
r_0 = radius of the cylinder which can be inscribed inside the system of rods

Exerting an effect on a single charged ion moving near and parallel to the center line inside the separation system and perpendicular to its movement are the forces

$$F_x = -\frac{2e}{r_0^2} \cdot x \cdot \cos(\omega \cdot t)$$

$$F_y = -\frac{2e}{r_0^2} \cdot y \cdot \cos(\omega \cdot t)$$

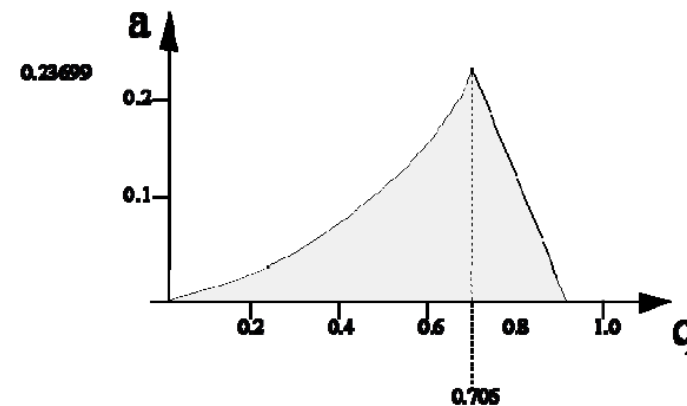
$$F_z = 0$$



RGA 工作原理－交直流電場調節解析度與零敏度 (a-q plot 直線斜率)

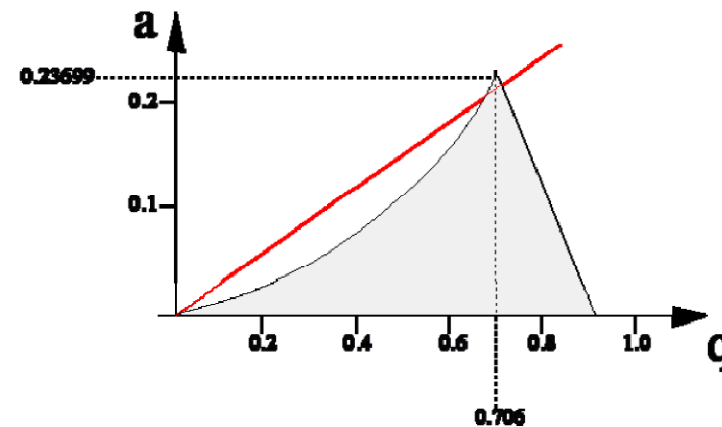
Only ions with a well defined m/e ratio can achieve stable trajectories in the RF-field

Mass separation in an electrical field:

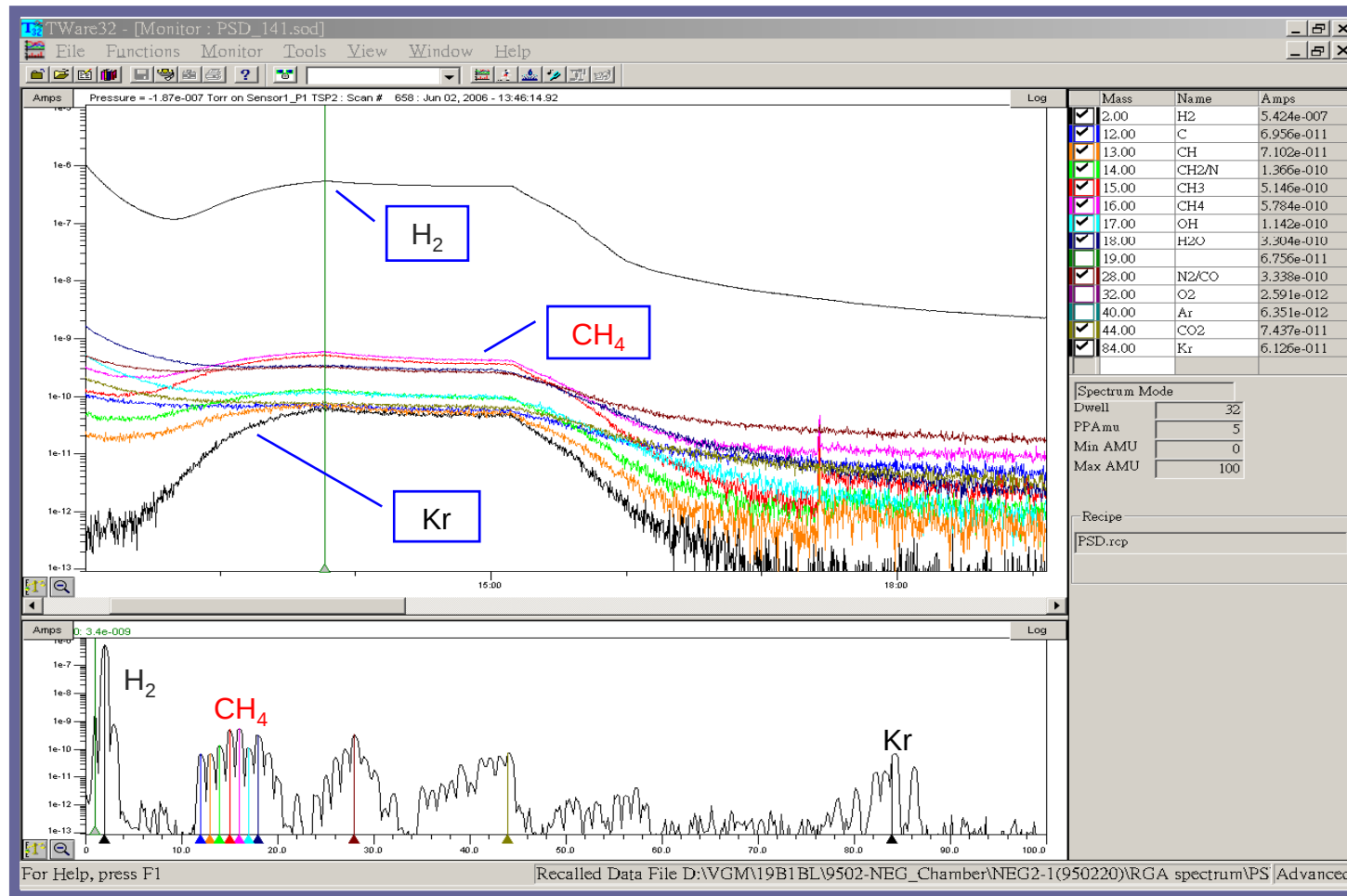


$$a = \frac{8 * e * U}{m * r_0^2 * \omega^2}$$

$$q = \frac{4 * e * V}{m * r_0^2 * \omega^2}$$



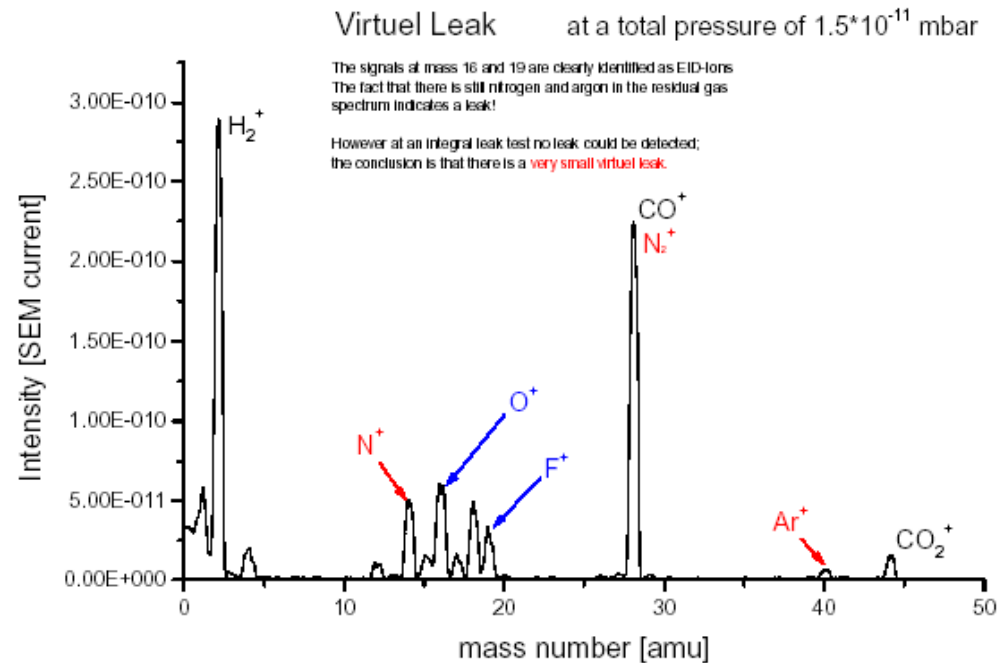
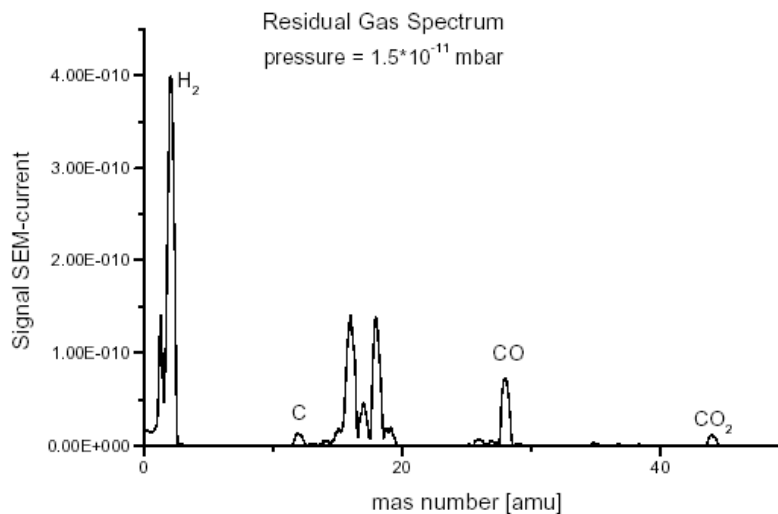
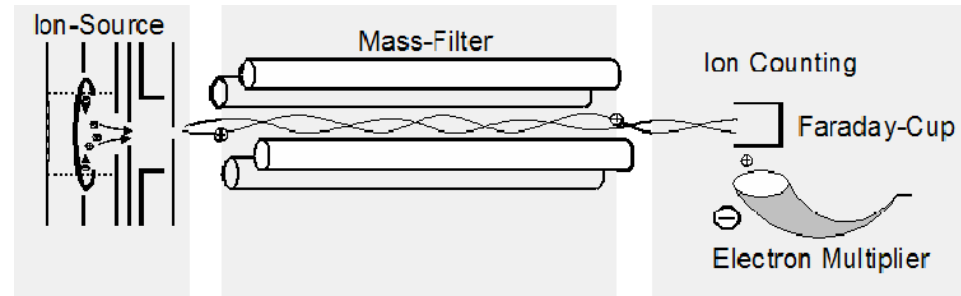
Kr and CH₄ Outgas (NEG鍍膜腔)



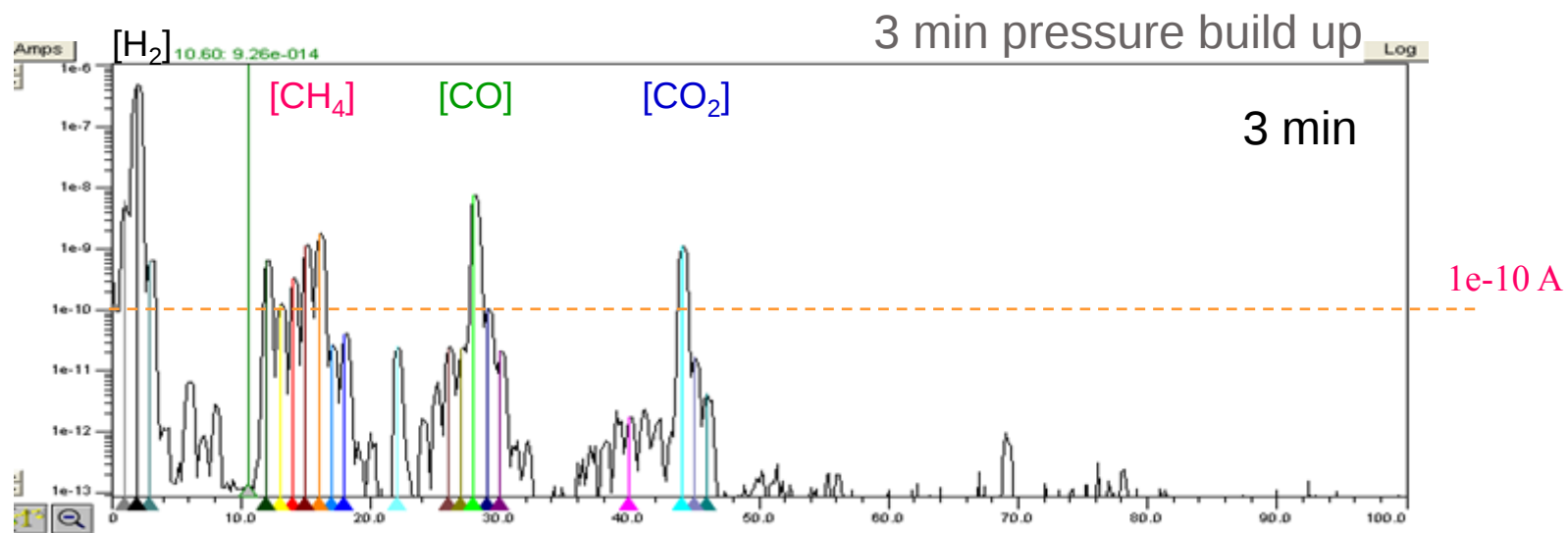
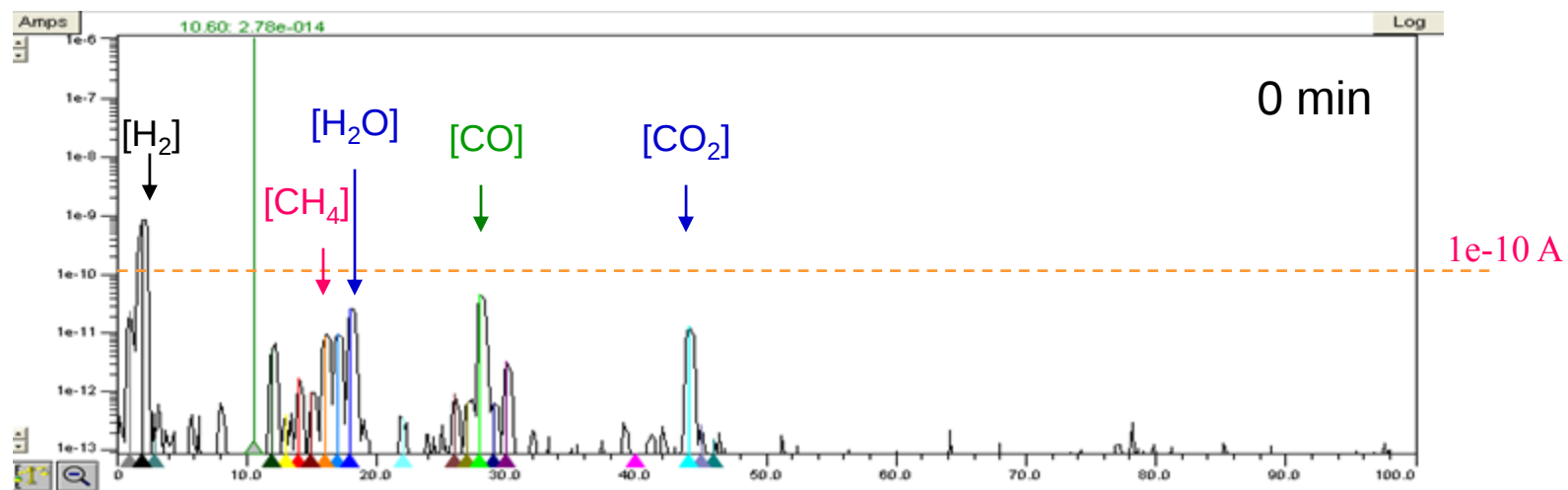
質譜儀 Residual Gas Analyzer (RGA)

Cracking pattern analysis (Peak identify)

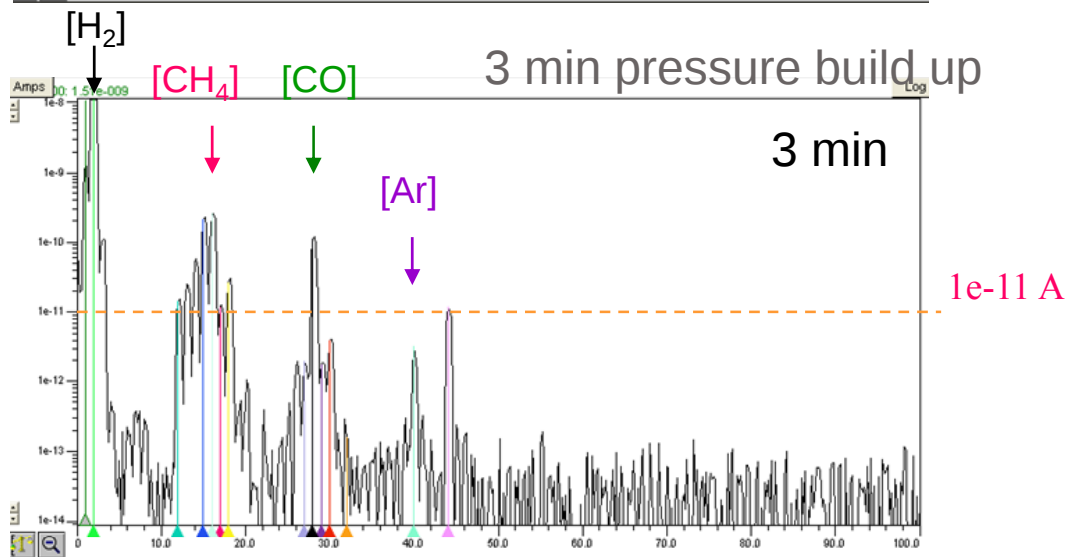
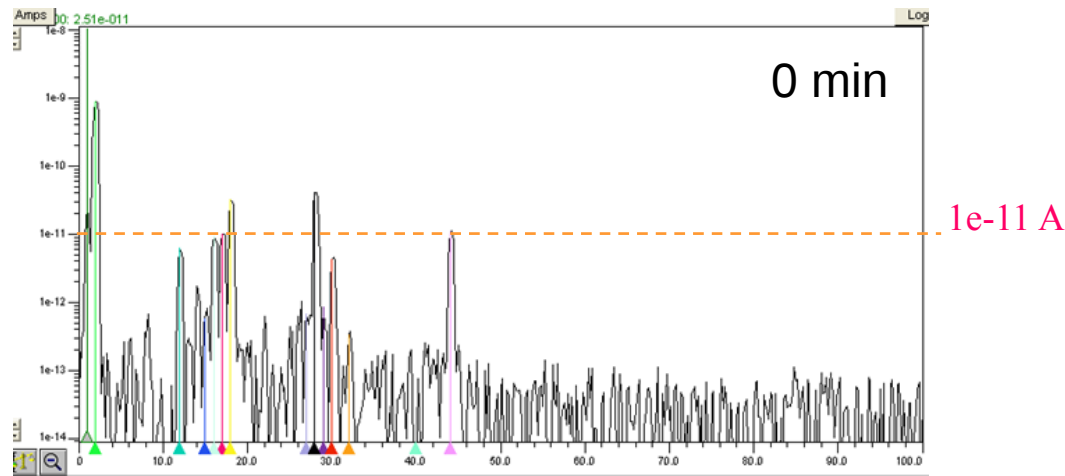
- H₂ [2]
- CH₄ [15] [16]
- H₂O [17] [18]
- N₂ [14] [28]
- CO [12] [28]
- Ar [20] [40]
- CO₂ [22] [44]



質譜儀本身的釋氣(關閉閥門隔離系統)



在0.1 nTorr時關閉離子幫浦後的釋氣



Assembly test for IP, RGA,
and Gauges

真空系統的維護

- 真空系統的診斷
- 真空測漏
- 破壞真空的注意事項

真空系統的診斷 (Diagnostics for the UHV Systems)

1. 氣壓高? (原因為何? 如何診斷?)

$$\begin{array}{ccccc} P & \sim & (a) & Q / S & (b) & Q / S \\ \uparrow & & \uparrow & & \downarrow & \\ \text{氣壓上升!} & & (a) \text{ 釋氣率增加?} & & (b) \text{ 抽氣速率減少?} & \end{array}$$

2. 診斷方法：

- (1) 氣壓增建法：利用真空計或質譜儀。
- (2) 測漏：利用測漏儀或質譜儀。

釋氣率(Q)增加的可能原因

- 真空系統中的實驗活動產生氣體分子，黏附在真空腔表面增加表面釋氣率。
 - 化學、鍍膜等反應產生氣體。
 - 進氣管路系統引入水氣或油氣等雜質氣體。
- 室溫增高使真空腔溫度升高，而增加釋氣率。
 - 天氣轉熱，且室內無冷氣調節室溫。
 - 真空腔及元件發熱或烘烤而升溫。
- 真空幫浦失常
 - 離子幫浦停止放電抽氣時，鈦陰極材料表面產生Ar、CH₄等氣體釋出。鈦昇華幫浦(TSP)之鈦膜表面亦不斷釋出CH₄氣體。
 - 機械幫浦停止運轉，導致幫浦內油氣及水氣回流。
- 系統元件脆弱破裂或老化失能而產生漏氣。

抽氣速率(S)減少的可能原因

- 真空幫浦故障而停止運轉。
 - 離子幫浦停止放電
 - 氣壓過高導致控制器保護關閉。
 - 氣壓太低($< 1 \times 10^{-10}$ Torr)導致Penning放電熄滅。
 - 台電或電力供應系統因停電或壓降而導致幫浦停止運轉。
 - 機械幫浦未定期保養、老舊或震動卡死而故障。
- 鈦昇華幫浦鈦膜表面已覆蓋滿，無吸氣作用。
- 抽氣幫浦前之閥門因停電或連鎖控制而關閉，導致隔離幫浦無抽氣。

真空腔的製程與可能漏氣原因

1. 材料選擇與成型 — (考慮材料透氣率、內部氣孔、缺陷)
 - (a)元素: AL, S.S., Cu, Ti, Ceramics, Viton, ...
 - (b)組成成份: 合金、純金屬、絕緣材料...
 - (c)煉製方法: 鑄造(cast)、擠型(extrusion)、壓延、燒結(sinter)...
2. 加工 — 車、銑、拋光、鑽、切、彎摺、壓 (考慮加工裂縫、缺陷)
3. 銲接 — 氬銲(TIG)、硬銲(Brazing)、爆接(explosion)、熱均溫壓接(HIP)、金屬氬銲(MIG)、電子束銲接(EBW)、雷射銲接(LBW)
(考慮銲道熔池週邊內部氣孔與裂縫、接合部位氣孔)

真空腔的製程與可能漏氣原因

4. 表面清洗 — 化學清洗(鹼洗及酸洗)、EP (電解研磨)、CP (化學研磨)、CMP (化學機械研磨)、輝光放電(GDC)、臭氧 (O_3)、丙酮、酒精、烘烤、紫外光(VUV)

(考慮酸洗腐蝕產生氣孔裂縫)

5. 組裝接合 — 接合法蘭(Flange)密封元件：Metal Gasket、Helicoflex、Metal Wire、O-ring (Viton, Kalrez, Elastomer,...)

(考慮鎖螺絲扭力不夠或不對稱均勻施力、法蘭刀口與密封表面的缺陷、密封材料的透氣率、法蘭密封部位的尺寸與精度不正確或不配合)

真空測漏

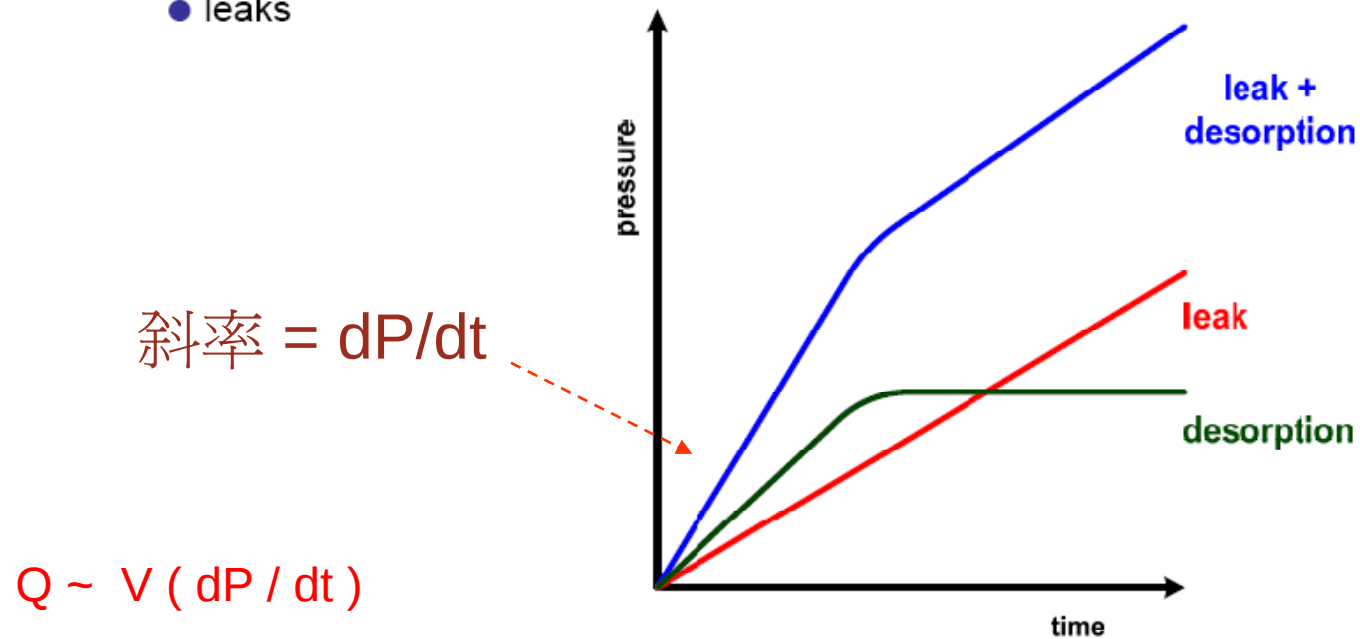
- **Ideal vacuum chamber**

- ➡ maintain vacuum pressure forever after switching off pumps

- **Real vacuum chamber** ➡ pressure increase without pumps

- outgassing and desorption

- leaks



漏氣率

- No vacuum system completely leak tight → even not necessary

specify acceptable leak rate in order
to reach required pressure

$$Q_l = V \frac{\Delta p}{\Delta t}$$

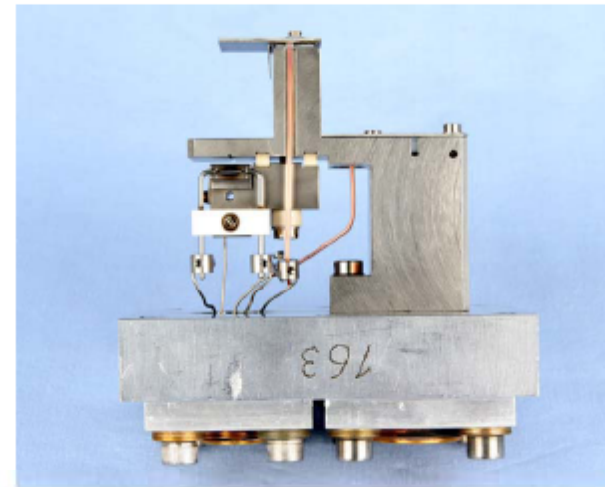
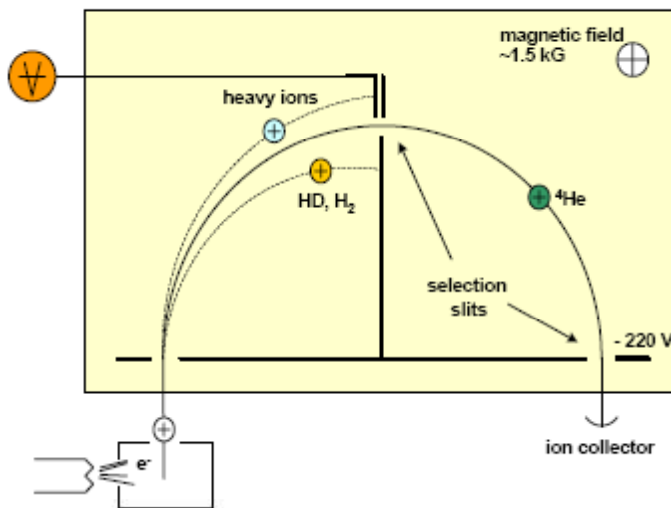
	mbar·l/s	Torr·l/s	Pa·m ³ /s	cm ³ /s
mbar·l/s	1	0.75	0.1	0.99
Torr·l/s	1.33	1	0.133	1.32
Pa·m ³ /s	10	$7.5 \cdot 10^{-3}$	1	$\sim 10^{-2}$
cm ³ /s	1.01	0.76	0.101	1

測漏儀



測漏儀離子源

- Operating pressure $p < 10^{-4}$ mbar
- In principle any type of RGA possible
- Most sensitive/safe → mass spectrometer with 180° magnetic sector field
 - optimized for mass 4 (3,2)



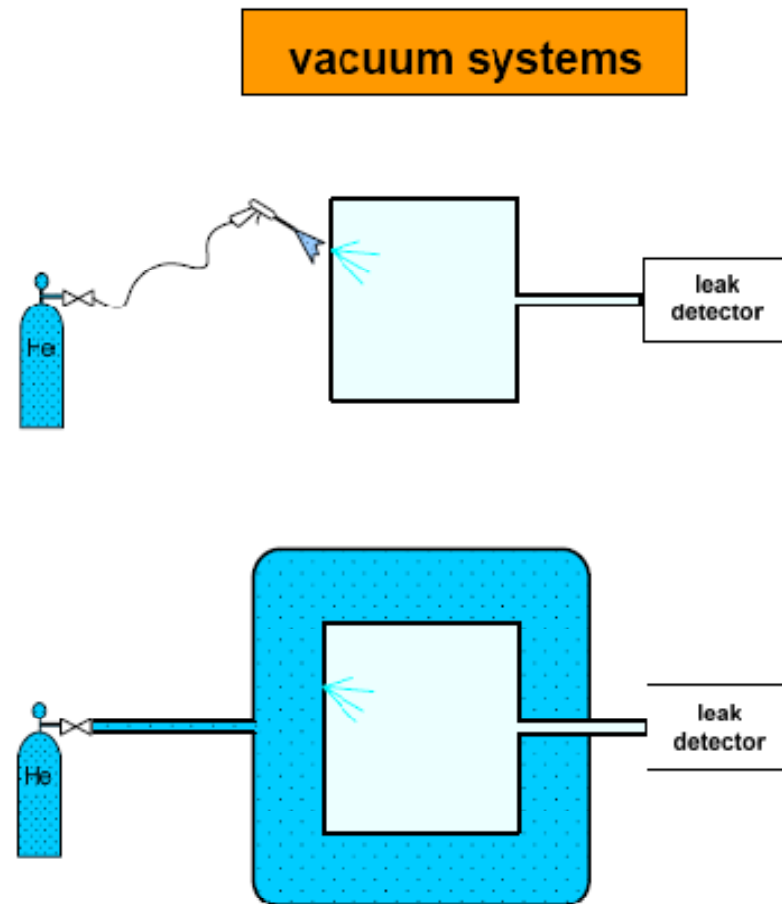
氦氣測漏

● Tracer probe

- gas penetrating into the system
- pumped via detector

leak location

total leakage measurement

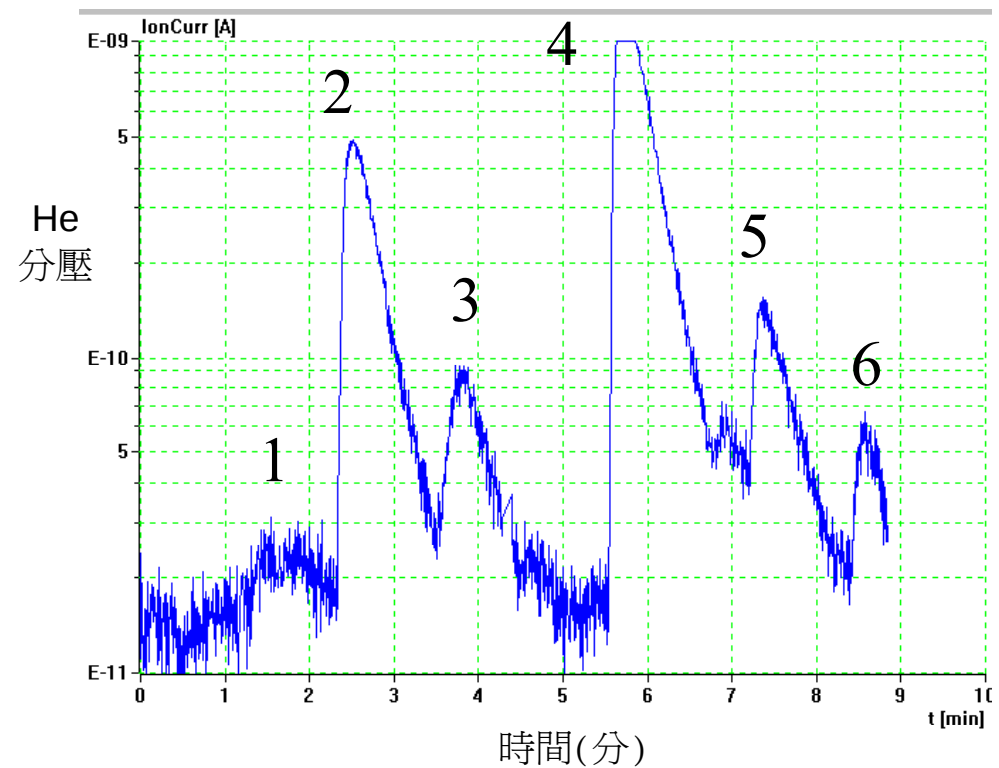
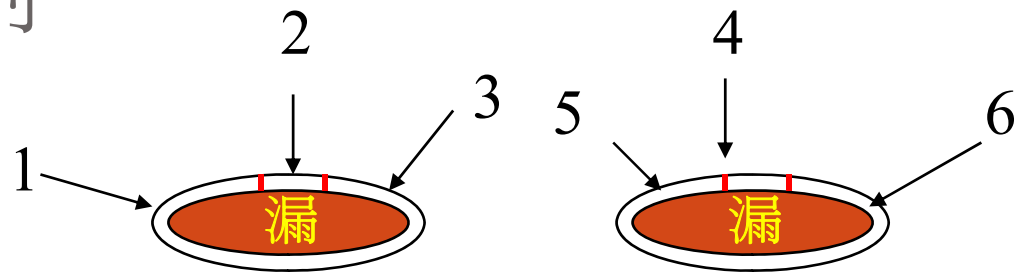


真空測漏

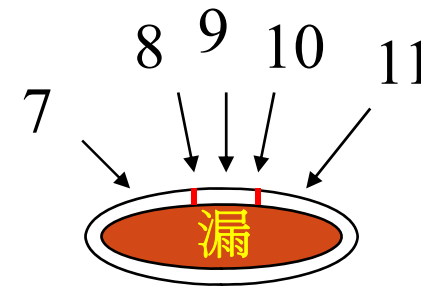
- 真空系統接測漏儀或質譜儀－用以量測氦氣分子 (**He**)
- 在真空腔外部噴氦氣，當氦氣靠近漏氣部位時則測量到 **He** 分子
- 一般常見之漏氣部位：
 - (a) 密封元件界面：密封墊圈(接合法蘭、閥門)；管路接合元件
 - (b) 銲接部位：真空銲接 (腔體、分支管)
 - (c) 不同材料界面：銲接部位 (真空導引、玻璃視窗等)
 - (d) 缺陷：材料裂縫；薄壁穿透；腐蝕

真空測漏實例

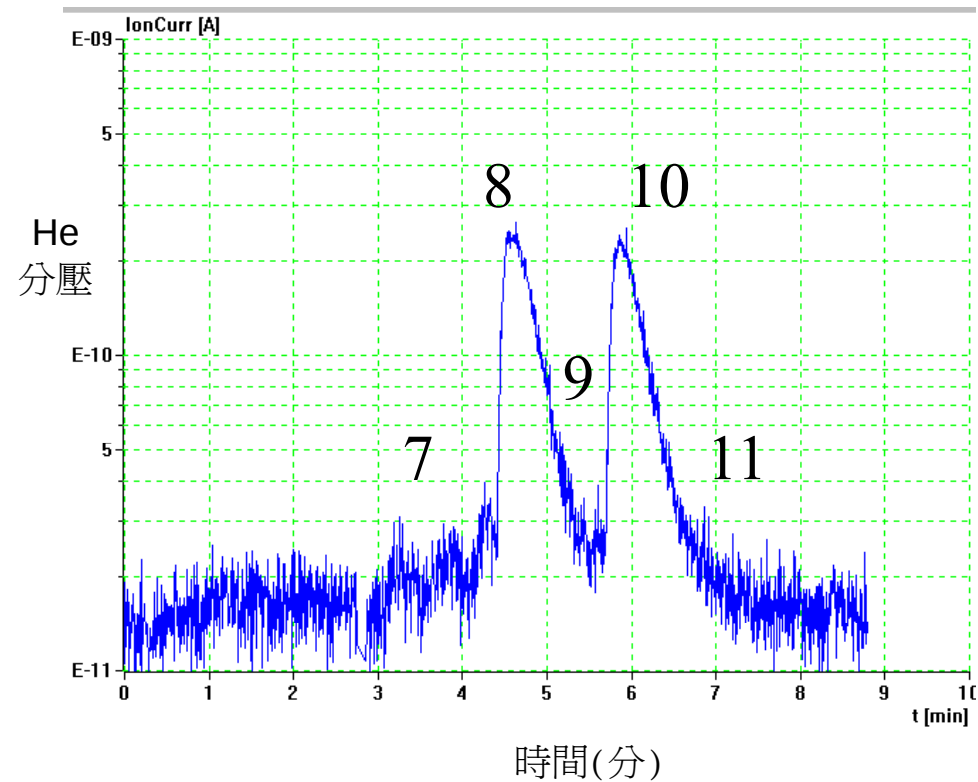
1. 真空系統以質譜儀測漏，質譜儀距離測漏部位約10米，橢圓截面高38mm寬80mm。測漏部位附近幫浦停止抽氣以提高測漏零敏度。
2. 在真空腔某Brazing銲道外部1~6等處噴氦氣(He)，測得He分壓如右圖。越靠近漏氣部位之He分壓越高，以第4處最高。



真空測漏實例

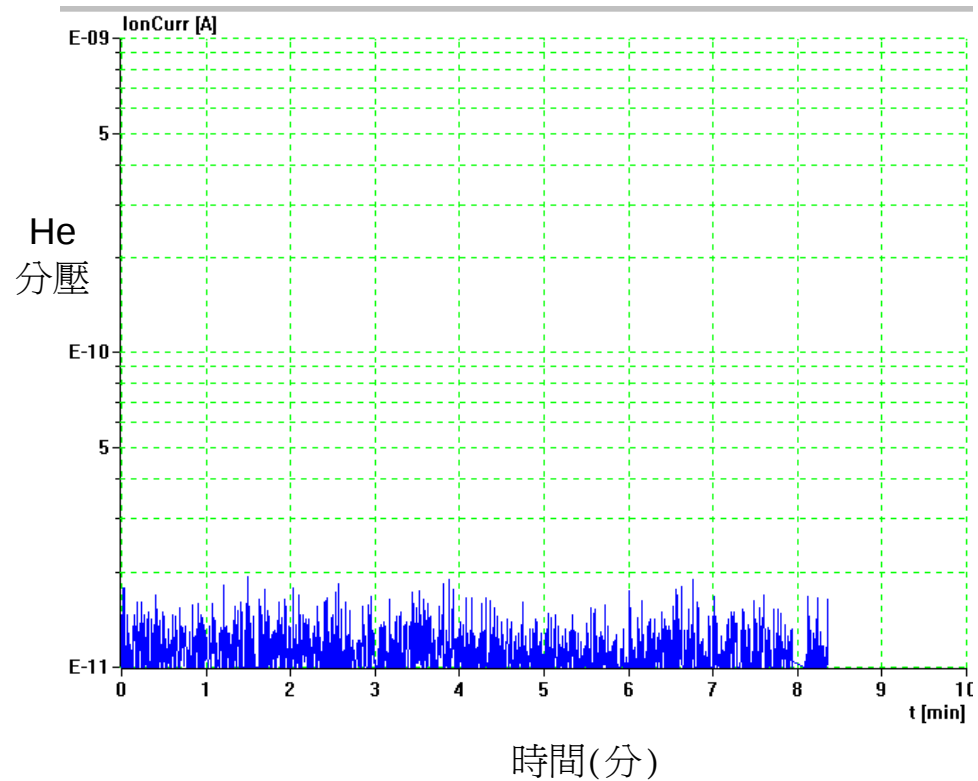


1. 將氦氣噴嘴靠近漏氣部位由7朝11移動(不噴氣)，以較小流量之He氣測試。
2. He分壓如右圖。可測得兩處漏氣部位，即第8處與第10處最高。



真空測漏實例

1. 以“Vac Seal”真空膠塗於漏氣部位，以阻絕漏氣。
2. 再噴以大量之He氣於漏氣部位附近。由右圖之He分壓起顯示無漏氣。真空氣壓由 2.6×10^{-7} Torr 降至 6×10^{-9} Torr (尚未開啓幫浦抽氣)。



破壞真空的注意事項

(Notes for Breaking the Vacuum)

- 關閉真空計(含RGA)及離子幫浦，以避免燒斷燈絲或大電流放電燒壞控制器。
- 關緊與其他系統連接的閥門以隔離真空。
- 系統中「可調漏氣閥」連接乾燥超高純度氮氣及進氣管路，管路宜加裝過壓洩氣閥以避免進氣壓力過高導致系統中玻璃視窗爆裂或軟管(Bellows)變形損毀。
- 進氣管路於靠近系統進氣端加裝液態氮或乾冰等低溫冷阱(cold trap)以冷凝方式過濾水氣與其他雜質氣體。進氣管路可先抽真空烘烤以減低管路本身釋氣。(注意：冷阱溫度需高於高壓進氣之沸點！)
- 系統於進氣到一大氣壓時可打開法蘭以安裝更換元件。建議系統內持續進氣外流以減少環境外氣擴散到腔內，安裝環境之濕度宜低於50%。

結論

- 真空系統之最低氣壓(P_{ult})決定於腔體內表面釋氣率(Q)之高低，其也決定於表面清洗方式與是否維持潔淨。
- 真空系統選用抽氣幫浦時，需針對系統內殘餘氣體分子之種類選擇，安裝時亦須考慮幫浦與腔體連接之間的氣導(C)限制及估算系統之有效抽氣速率(S')。
- 當真空腔內氣壓低於1 mTorr時，通常已達到分子流狀態(平均自由徑>腔體尺寸)，則腔內氣體互不碰撞而持續往復運行黏附於腔內表面後再釋放出來，導致氣體不易流向幫浦內被抽除，此為氣導之限制。
- 真空系統抽氣過程中，可利用隔離幫浦停止抽氣，記錄氣壓上升速率(dP/dt)，乘以系統體積(V)，可估算系統總釋氣率($Q \sim V \cdot dP/dt$)，此為氣壓增建法(Buildup)。

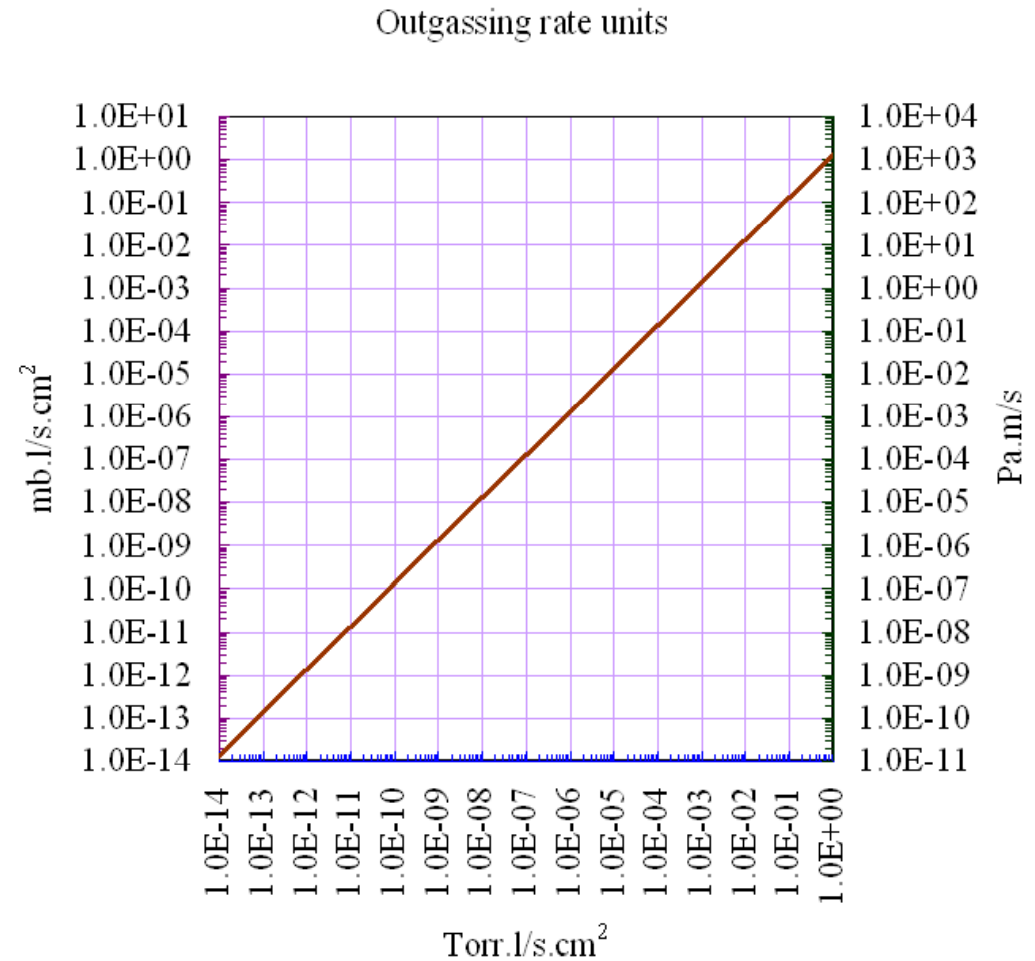
真空系統主要估計參數 (您了解您的真空系統嗎?)

- 求系統體積 – V (l)
- 求腔體表面積 – A (cm^2)
- 計算真空腔到幫浦之間的總氣導 – C (l/s)
- 查出幫浦的抽氣速率 – S (l/s)
- 計算有效抽氣速率 – $S' \text{ (l/s)} = (S \cdot C)/(S + C)$
- 計算總釋氣率 – $Q \text{ (Torr} \cdot \text{l/s)} = S' \cdot P$
- 若為真空腔大面積的材料表面釋氣率 –
 $q \text{ (Torr} \cdot \text{l/s} \cdot \text{cm}^2) = Q/A$

單位換算圖表

Outgassing rate units

Torr.l/s.cm ²	mb.l/s.cm ²	Pa.m/s	molecules/s.cm ²
1.00E+00	1.33E+00	1.33E+03	3.28E+19
1.00E-01	1.33E-01	1.33E+02	3.28E+18
1.00E-02	1.33E-02	1.33E+01	3.28E+17
1.00E-03	1.33E-03	1.33E+00	3.28E+16
1.00E-04	1.33E-04	1.33E-01	3.28E+15
1.00E-05	1.33E-05	1.33E-02	3.28E+14
1.00E-06	1.33E-06	1.33E-03	3.28E+13
1.00E-07	1.33E-07	1.33E-04	3.28E+12
1.00E-08	1.33E-08	1.33E-05	3.28E+11
1.00E-09	1.33E-09	1.33E-06	3.28E+10
1.00E-10	1.33E-10	1.33E-07	3.28E+09
1.00E-11	1.33E-11	1.33E-08	3.28E+08
1.00E-12	1.33E-12	1.33E-09	3.28E+07
1.00E-13	1.33E-13	1.33E-10	3.28E+06
1.00E-14	1.33E-14	1.33E-11	3.28E+05

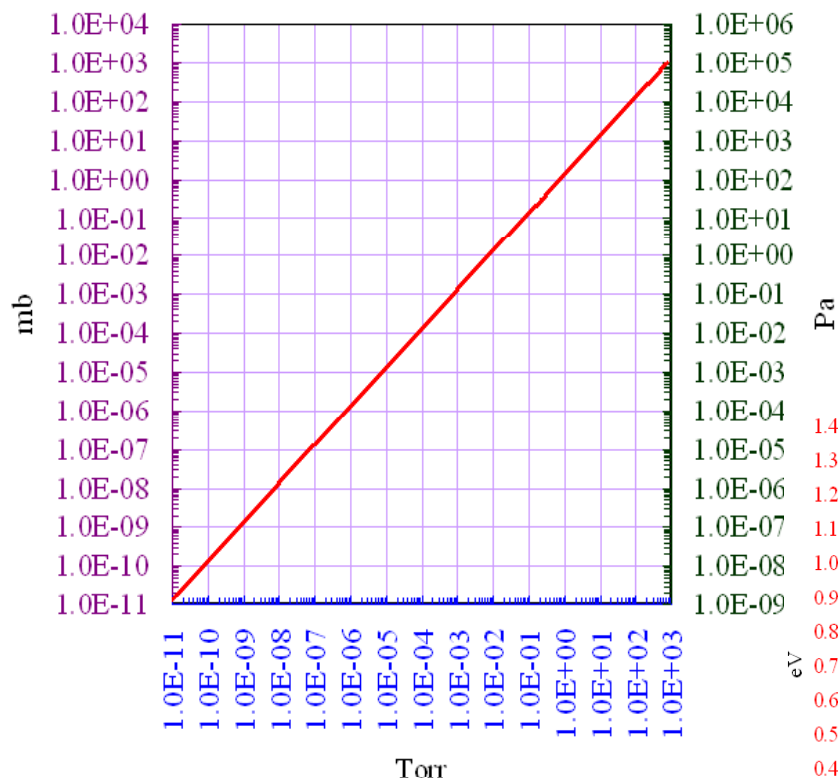


單位換算圖表

Pressure units

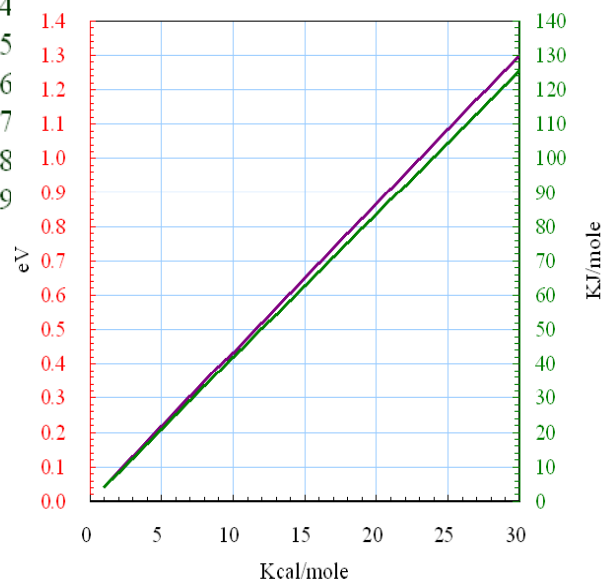
Adsorption energy units

Pressure units



Torr	mb	Pa
7.60E+02	1.01E+03	1.01E+05
1.00E+00	1.33E+00	1.33E+02
1.00E-01	1.33E-01	1.33E+01
1.00E-02	1.33E-02	1.33E+00
1.00E-03	1.33E-03	1.33E-01
1.00E-04	1.33E-04	1.33E-02
1.00E-05	1.33E-05	1.33E-03
1.00E-06	1.33E-06	1.33E-04
1.00E-07	1.33E-07	1.33E-05
1.00E-08	1.33E-08	1.33E-06
1.00E-09	1.33E-09	1.33E-07
1.00E-10	1.33E-10	1.33E-08
1.00E-11	1.33E-11	1.33E-09

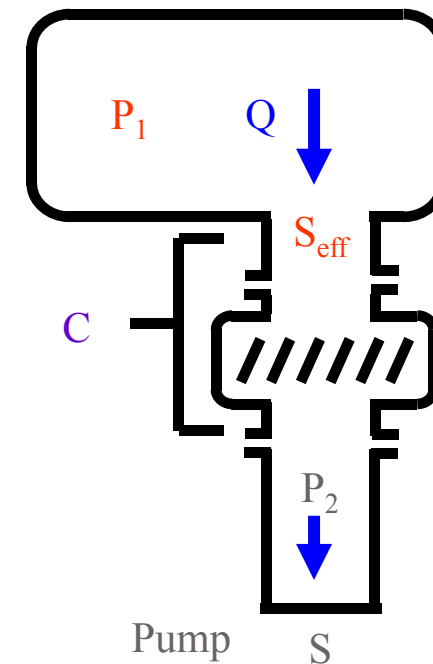
Adsorption energy units



Kcal/mole	eV	KJ/mole	Torr-l/mole
1	0.04	4.18	31380
2	0.09	8.37	62760
3	0.13	12.55	94140
4	0.17	16.74	125520
5	0.22	20.92	156900
6	0.26	25.10	188280
7	0.30	29.29	219660
8	0.35	33.47	251040
9	0.39	37.66	282420
10	0.43	41.84	313800
11	0.48	46.02	345180
12	0.52	50.21	376560
13	0.56	54.39	407940
14	0.61	58.58	439320
15	0.65	62.76	470700
16	0.69	66.94	502080
17	0.74	71.13	533460
18	0.78	75.31	564840
19	0.82	79.50	596220
20	0.87	83.68	627600
21	0.91	87.86	658980
22	0.95	92.05	690360
23	1.00	96.23	721740
24	1.04	100.42	753120
25	1.08	104.60	784500
26	1.13	108.78	815880
27	1.17	112.97	847260
28	1.21	117.15	878640
29	1.26	121.34	910020
30	1.30	125.52	941400

Question 1

- A vacuum chamber, as shown in Fig. 1, contains the mixed gases of 80% H_2 and 20% CO. A pump with speed of 100 l/s for H_2 and 500 l/s for CO is attached for evacuation the vacuum chamber through the connecting tube of conductance (N_2 -equivalent) $C = 5$ l/s. The ultimate pressure P_2 near the pump side is 1×10^{-8} Pa (10 nPa). (a) Please calculate the effective pumping speed (S_{eff}) of H_2 and CO inside the chamber, respectively. (b) Please calculate the partial pressure of H_2 and CO inside the chamber, respectively. (Assume the pressure gauges are not sensitive to the various gas molecules.)



[Hints]

1. Assume the mixed gases are not scattered each other in the vacuum system.
2. Total outgassing rate, $Q = Q_{H_2} + Q_{CO}$
3. $Q_{H_2} = 80\% (Q)$, $Q_{CO} = 20\% (Q)$; i.e. $Q_{H_2} = 4 Q_{CO}$
4. Total pressure = Sum of Partial Pressure

$$P_1 = P_1^{H_2} + P_1^{CO}$$

$$P_2 = P_2^{H_2} + P_2^{CO} = 10 \text{ nPa}$$

Question 2

- 一支長直段不銹鋼圓管，長 $L = 2\text{ m}$ 、內徑 $D = 5\text{ cm}$ ，(a)端接一個抽氣速率(S_p) = 300 l/s 抽氣幫浦，於抽氣平衡時幫浦端氣壓讀值(P_0) = 10 nTorr ；另一(b)端密封，氣壓讀值(P_L)，參考圖2。系統中僅有管內表面釋氣之殘餘氣體 H_2 。
- (一)求不銹鋼真空腔之單位面積表面釋氣率(q_D)。
- (二)求(b)端之氣壓值(P_L)。

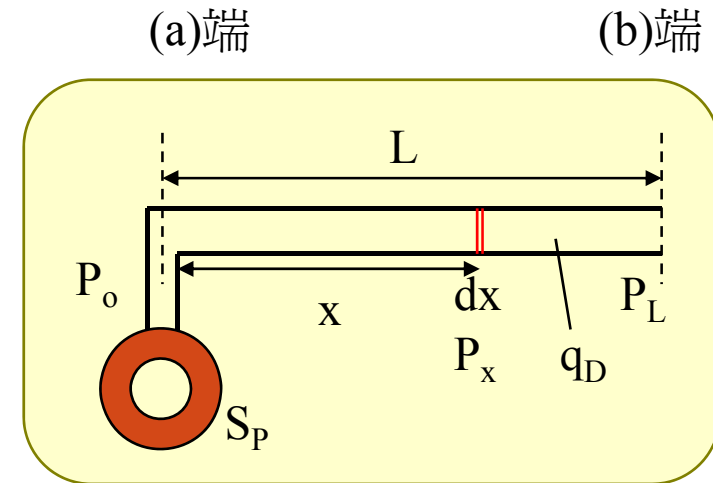


圖2

Question 3

- 前一題之(b)端突然發生漏氣(N_2)，使(a)端氣壓由10 nTorr上升至100 nTorr。
- (一)求(b)端之 N_2 漏氣率(Q_L)。
- (二)考慮 H_2 釋氣與 N_2 漏氣，求(b)端氣壓(P_L)。

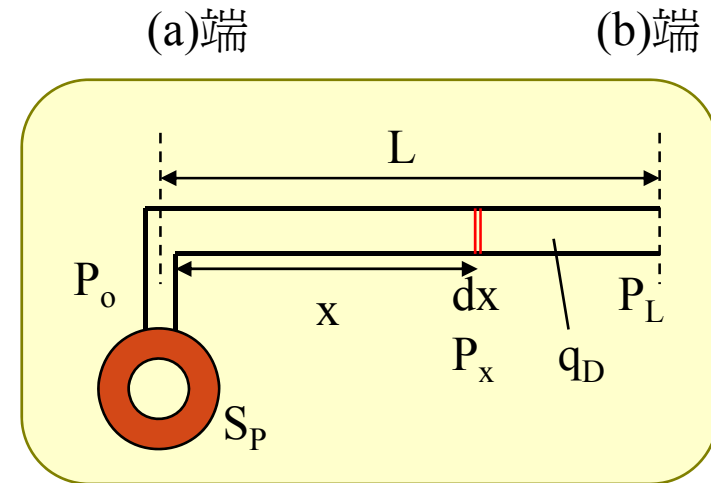
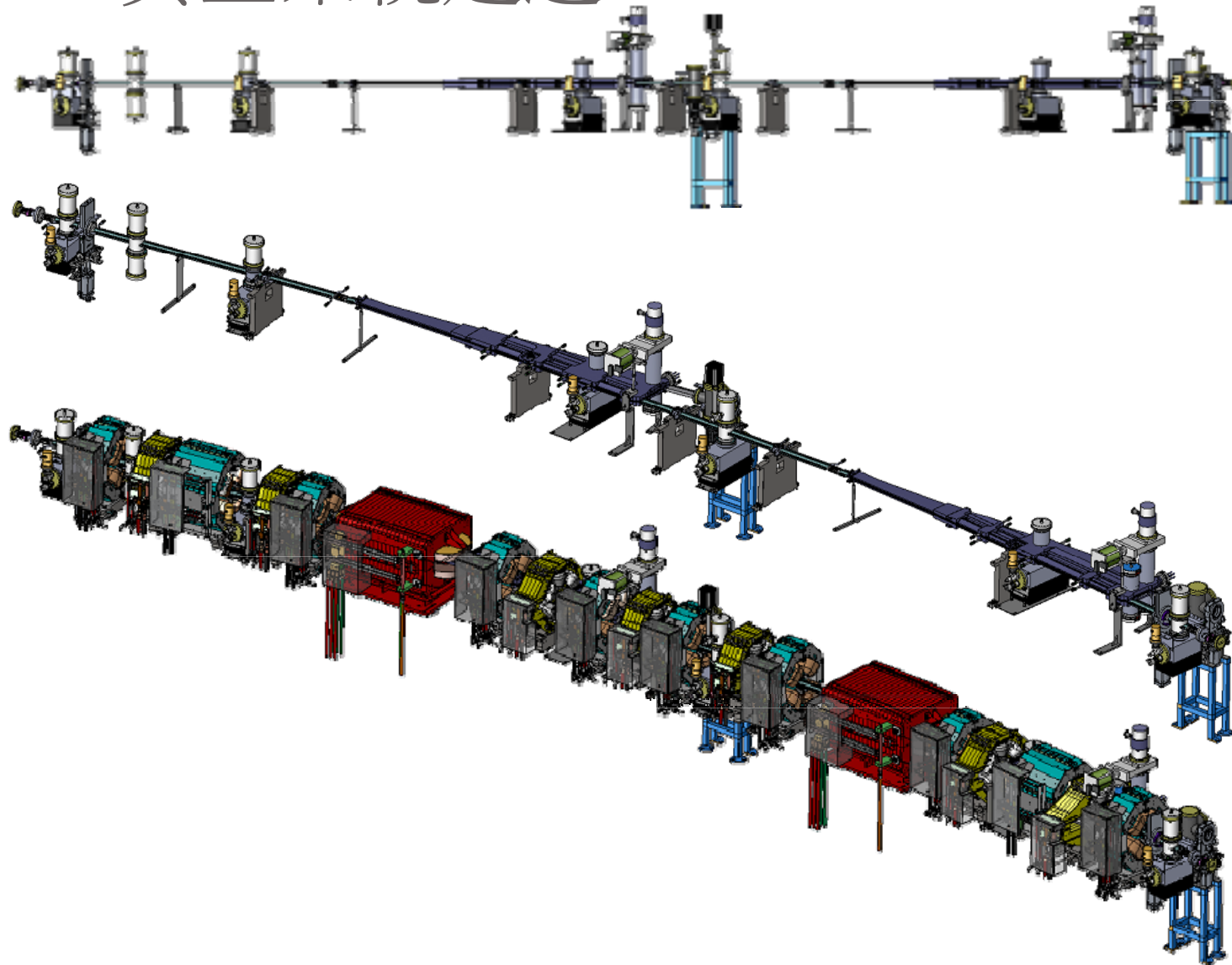
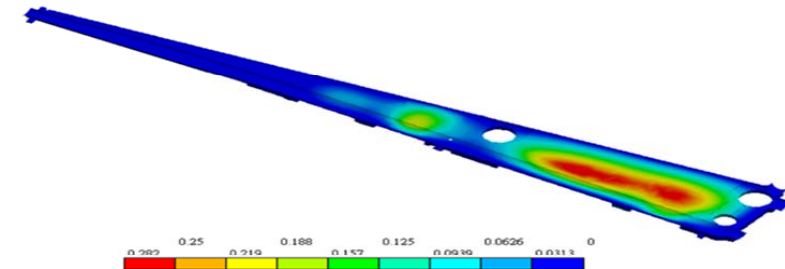
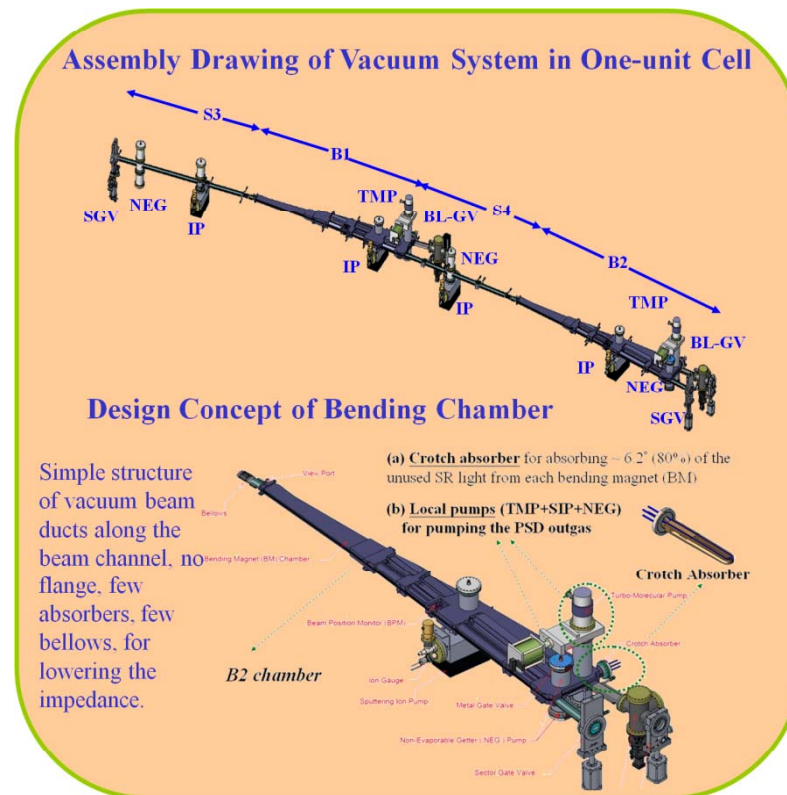


圖2

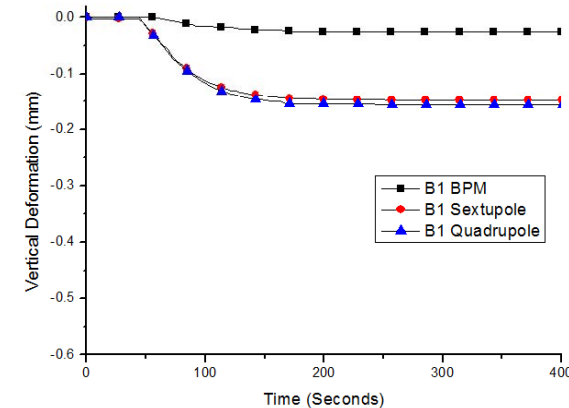
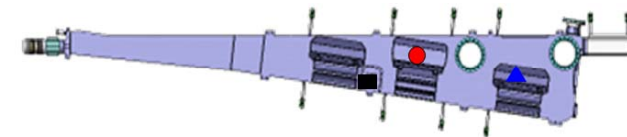
[範例] TPS電子儲存環1/24段14 m彎段 Cell真空系統建造



1. 真空設計：物理、工程、系統
2. 模擬分析：抽氣變形、氣壓分布



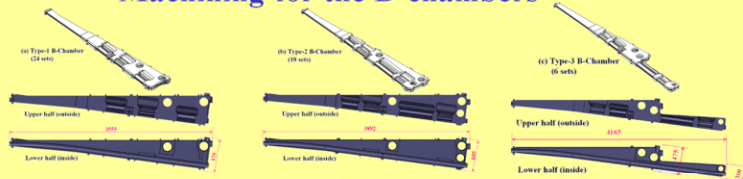
Deformation of a bending chamber due to evacuation (ANSYS)



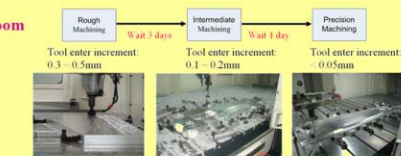
Deformation curve of a bending chamber due to evacuation

[在無塵室中] 鋁合金彎段真空腔精密加工、清洗、銲接、尺寸檢驗、測漏

Machining for the B-chambers

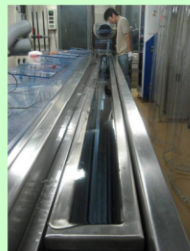


Oil-free CNC Machining in Clean Room



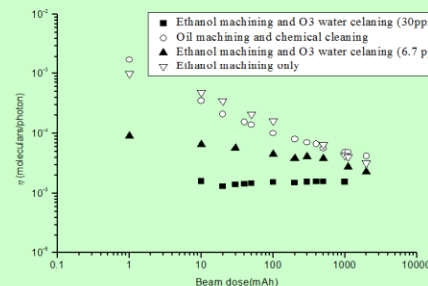
CNC Machining Processes (sprayed with pure alcohol)

Ozonated Water Cleaning for the B-Chamber



Ozonated Water Cleaning Bath
(> 20 ppm)

Photon-stimulated desorption (PSD) results with various surface treatments ^{a,b}



^a Chan, et al., "Design of the TPS Bending Chamber", APAC'07, THPMA056, p.703 (2007)
^b T. Momose, et al., J. Vac. Sci. Technol. A13(3) (1995) 515

Sequence of Bending Chamber Welding



Upper and Lower Halves



Pumping Port Welding



B-Chamber Alignment



Auto-Welding System



Beam Duct Welding



Straight Chamber Welding



Dimension Check for Straight Chamber

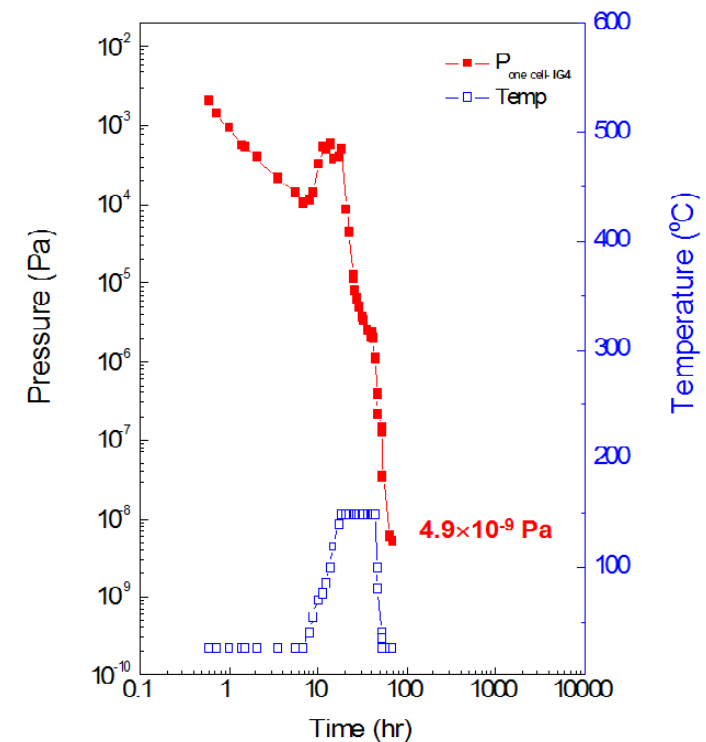


Vacuum Leakage Test



Dimension Check for Bending Chamber

1/24段14 m真空系統組裝、準直、抽氣、測漏、真空烘烤到超高真空



Pumping curve corresponding to the baking temperature

在無塵室中進行真空系統組裝、檢驗等工作以確保真空腔內表面的潔淨度



2010.10.30台灣真空學會真空測漏訓練班