진공 기술 기초 및 응용

2020.11.05

하태균
(hatae@postech.ac.kr)

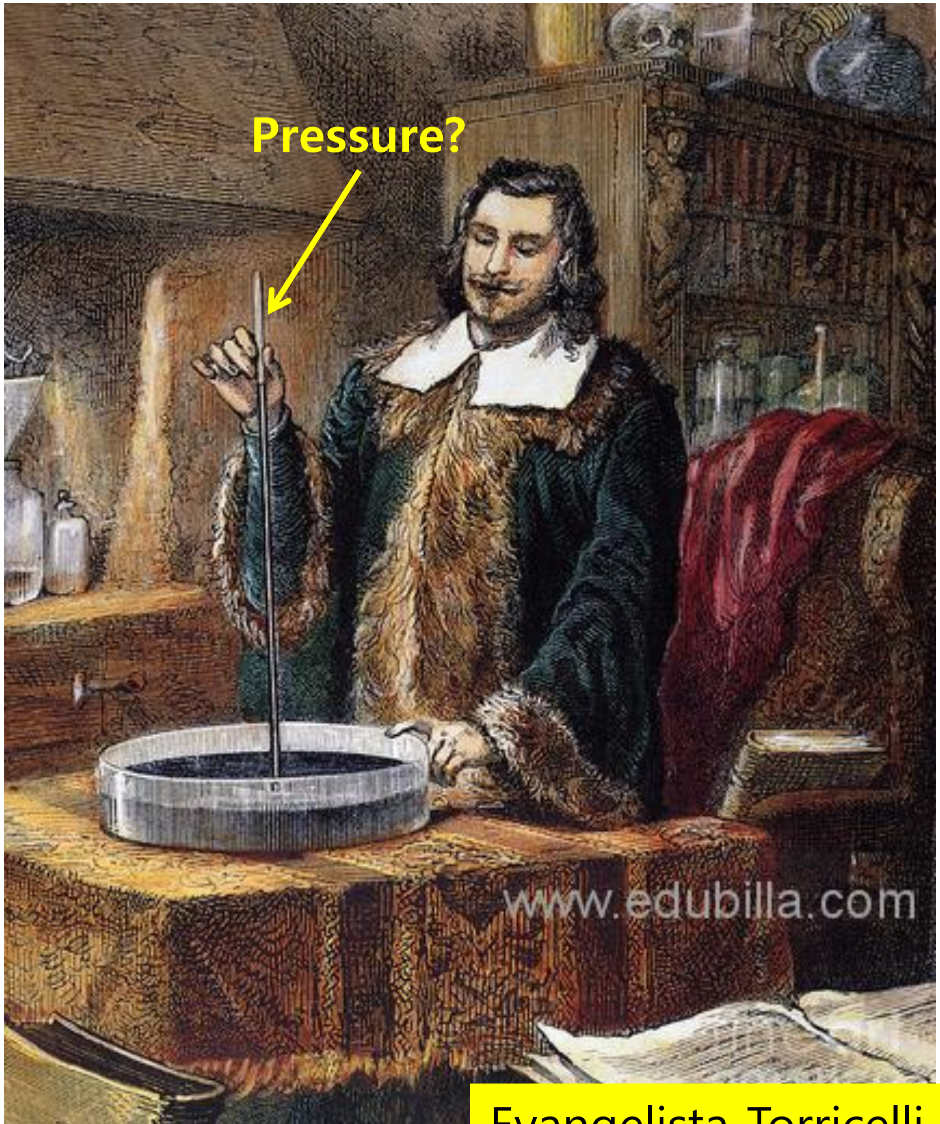
포항가속기연구소

Objectives of This Lecture

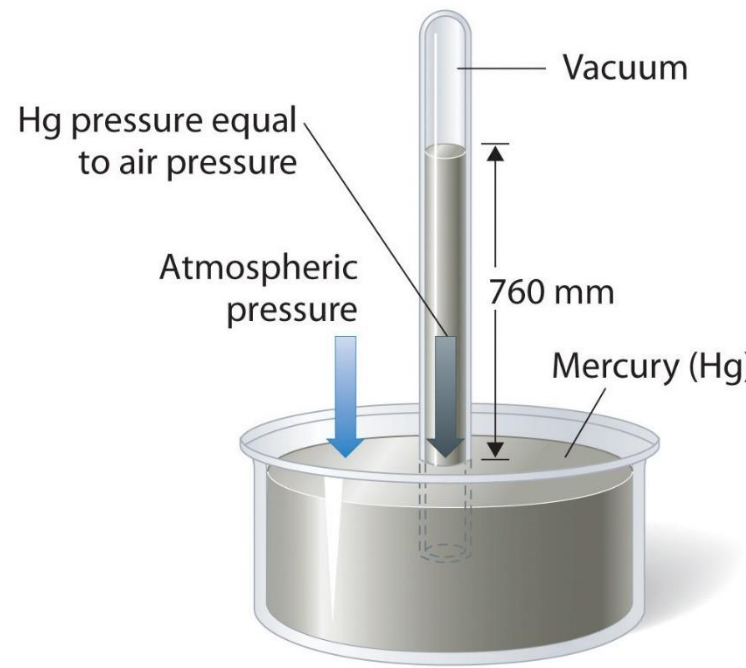
- To understand:
  - Key concept in vacuum technology
    - Vapor pressure
    - Maxwell Boltzmann distribution
    - Mean free path, impingement rate, monolayer time
    - Behavior of gas in different flow regime (viscous vs. molecular flow)
    - Conductance, throughput, volume flow rate, pumping speed
  - How to generate vacuum
  - How to measure pressure
  - Outgassing mechanism
  - Vacuum materials

What is vacuum?

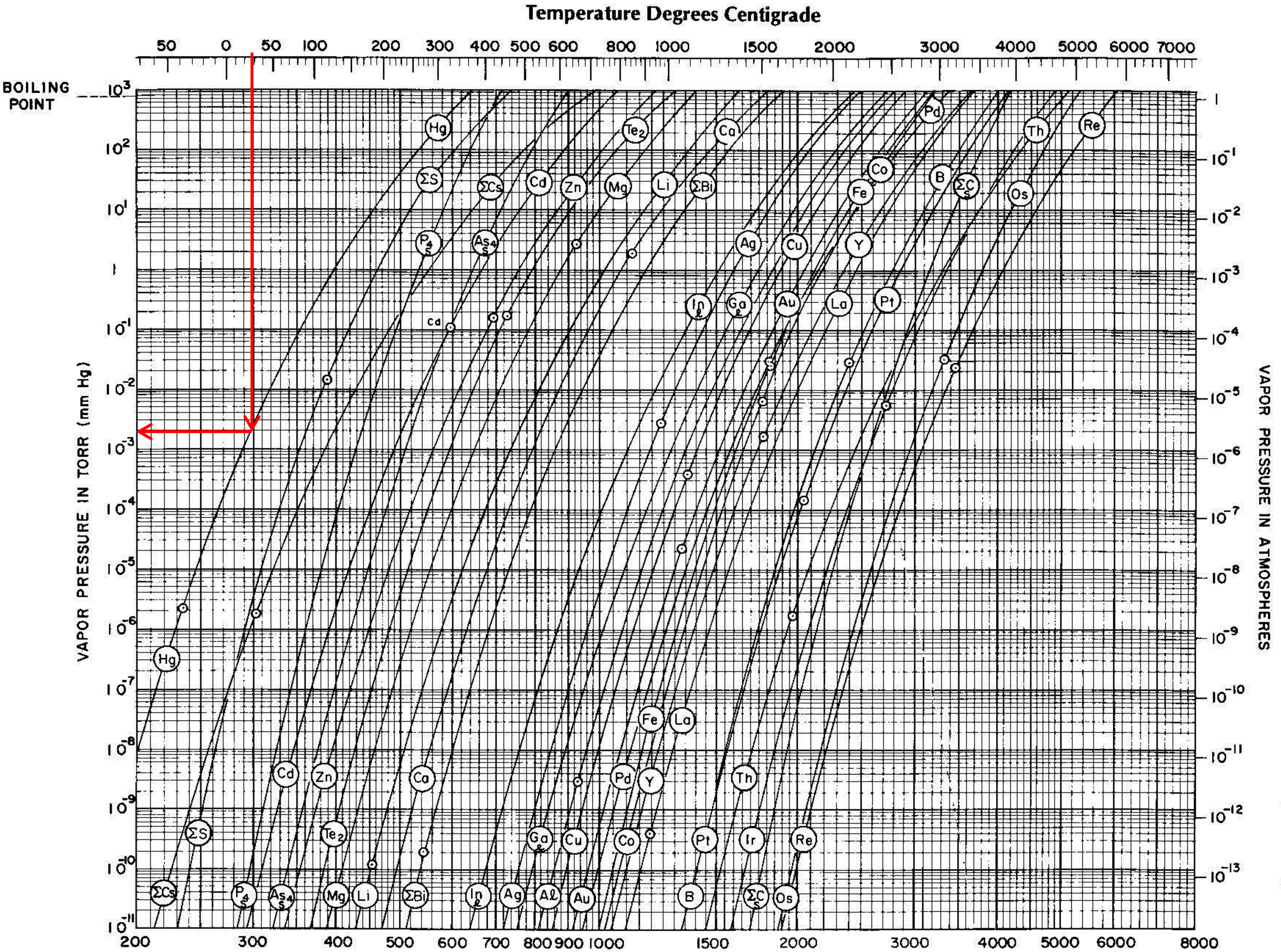
First Demonstration of Vacuum



Evangelista Torricelli (1644)

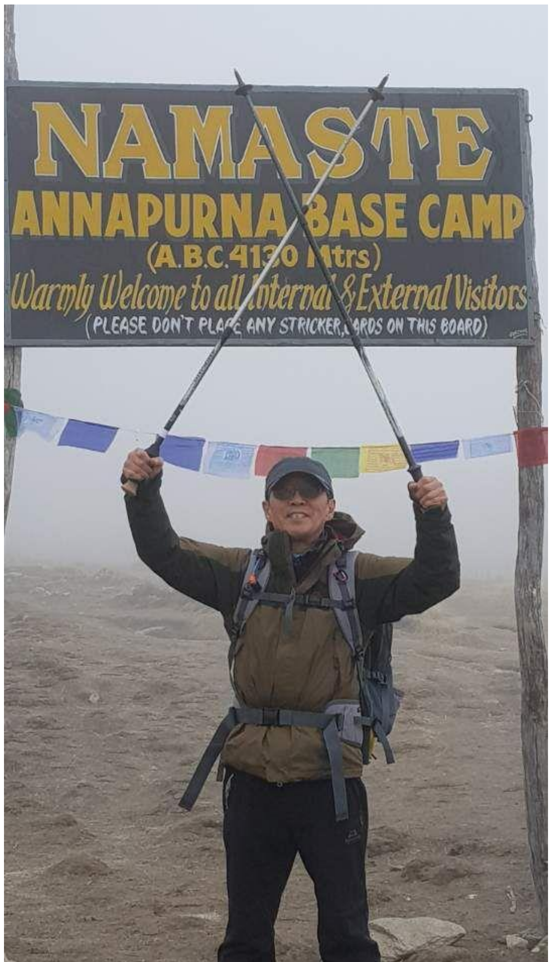


VAPOR PRESSURE CURVES OF THE ELEMENTS



Law of Atmosphere

" The only source of knowledge is experience."
– Albert Einstein



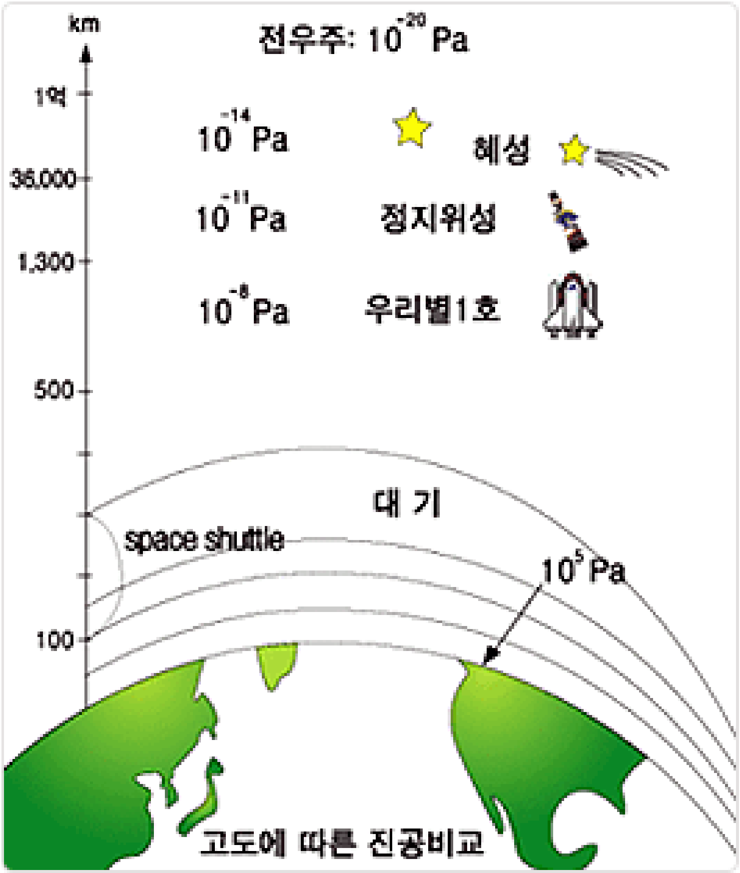
$$P = P_0 \exp(-Mgh / RT)$$

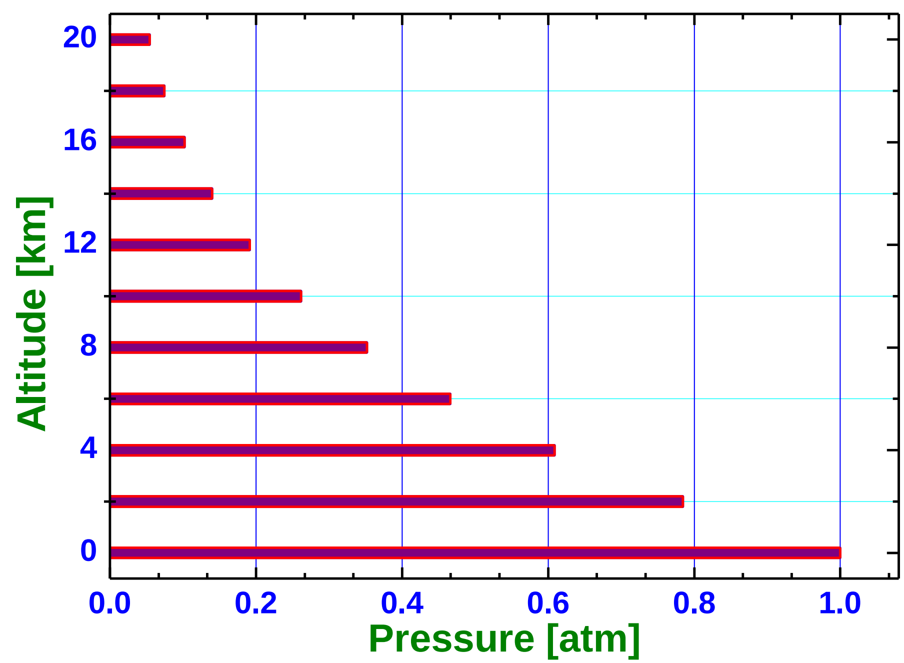
✓ Mount Everest: 250 Torr

✓ $T(h) = T_0 + \alpha \cdot h$
(α = -0.6° / 100 m)

M : molar mass of Earth's air
g : gravitational acceleration
h : height above sea level
R : gas constant (8.3 J/mol·K)

Vacuum & Altitude





Vacuum Regimes

	Pressure	Pump	Gauge	Residual Gas	Note
Low Vacuum	→1 Torr	Rotary Vane Dry pump Absorption	Manometer Bourdon CDG Pirani	Air (N_2, O_2, Ar)	Packing Vacuum cleaner Freeze drying
Middle Vacuum	→10^{-3} Torr	Booster Ejection Dry pump	McLeod CDG SRG Ionization	H_2O Air	CVD
High Vacuum	→10^{-7} Torr	Diffusion pump TMP Cryo-pump	SRG Ionization	H_2O	Evaporation Implantation Vacuum melting
Ultra High Vacuum	→10^{-11} Torr	TMP TSP, NEG, SIP Cryo-pump	Ionization (BA type)	H_2 CO H_2O	Surface analy. Accelerator
Extreme High Vacuum	< 10^{-11} Torr	TSP, NEG, SIP Cryo-pump	Ionization (Filter)	H_2 CO	Quantum device New material

Kinetic Theory Data

	Pressure					
	10^{3}	10^{0}	10^{-3}	10^{-7}	10^{-11}	mbar
	7.5×10^{2}	7.5×10^{-1}	7.5×10^{-4}	7.5×10^{-8}	7.5×10^{-12}	Torr
	10^{5}	10^{2}	10^{-1}	10^{-5}	10^{-9}	Pa
Particle density, n (cm^{-3})	10^{19}	10^{16}	10^{13}	10^{9}	10^{5}	
Mean free path, λ (cm)	10^{-6}	10^{-3}	10	10^{3}	10^{6}	
Impingement rate, J ($s^{-1} \cdot cm^{-2}$)	3×10^{23}	3×10^{20}	3×10^{17}	3×10^{13}	3×10^{9}	
Collision rate, Γ_V ($s^{-1} \cdot cm^{-3}$)	10^{29}	10^{23}	10^{17}	10^{9}	10	
Monolayer time, τ	3 ns	3 μs	3 ms	30 s	80 h	
Type of gas flow	◄—— Viscous—||–Knudsen–||———molecular——————————►					

❖ 1 atm = 760 Torr = 14.7 psi = 1013 mbar = 1013 hPa

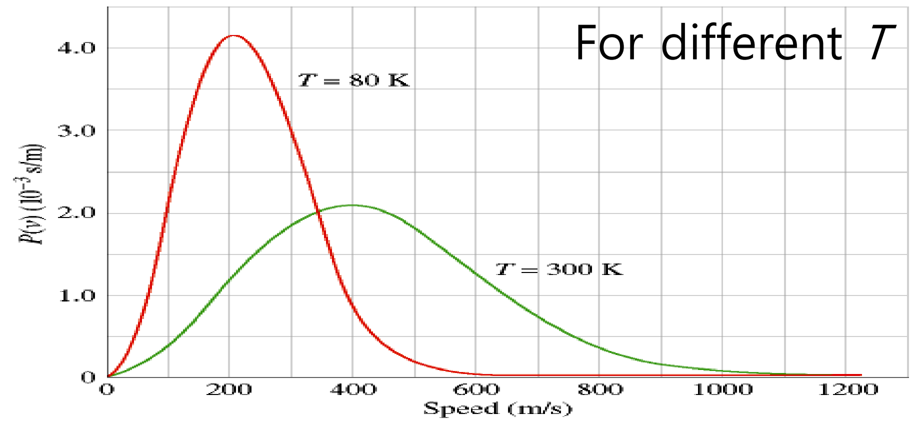
Maxwell Boltzmann Distribution

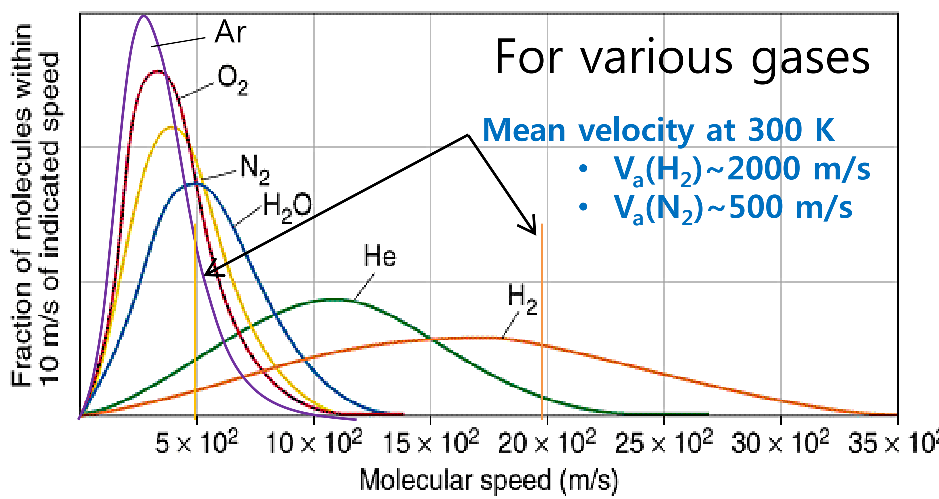
1. The distribution function is independent of direction of motion
   → $f(v_x, v_y, v_z) = f(v_x)f(v_y)f(v_z)$

2. The distribution function only depends on magnitude of velocity
   → $f(v_x, v_y, v_z) = f(v_x^2 + v_y^2 + v_z^2)$

3. Only exponential function satisfy the above conditions
   → $f(v) = A\exp(-\alpha v^2)$

$$f(v)dv = 4\pi v^2\left(\frac{m}{2\pi kT}\right)^{3/2} e^{\frac{-mv^2}{2kT}}\,dv$$





$$v_a = \int_0^\infty v f(v)dv = \sqrt{\frac{8kT}{\pi m}} = 146\sqrt{\frac{T}{M}} \qquad (\mathrm{m/s})$$

Particle Density & Pressure

- Ideal gas law

$$PV = N\,k_B T$$

or

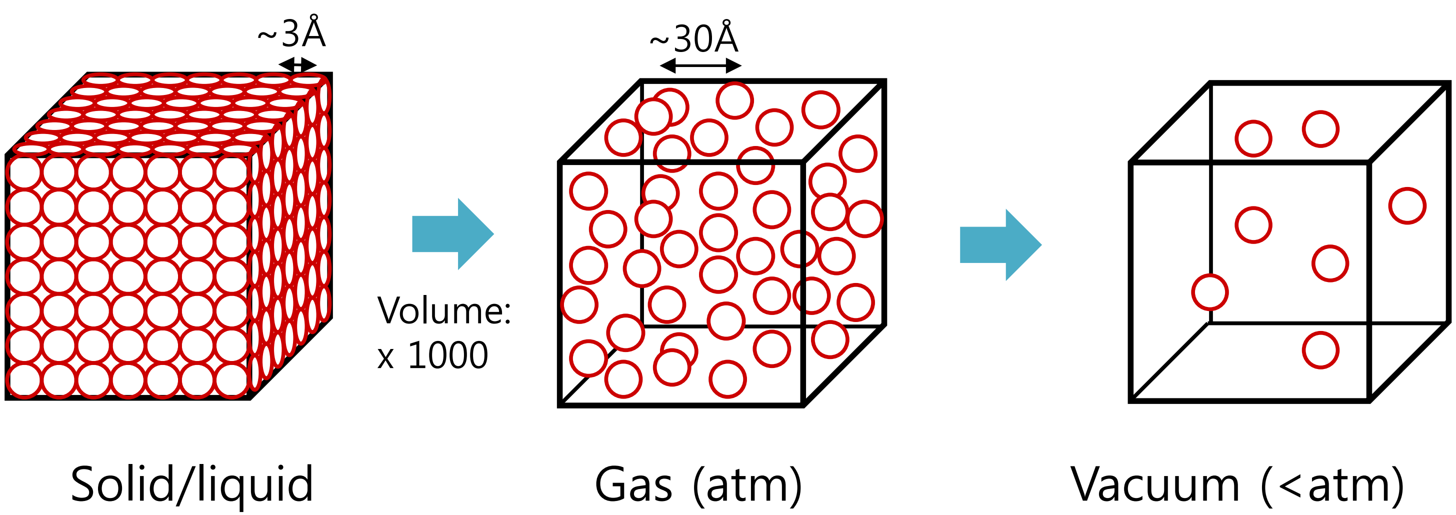
$$P = n\,k_B T = n_M\,R T$$

energy unit

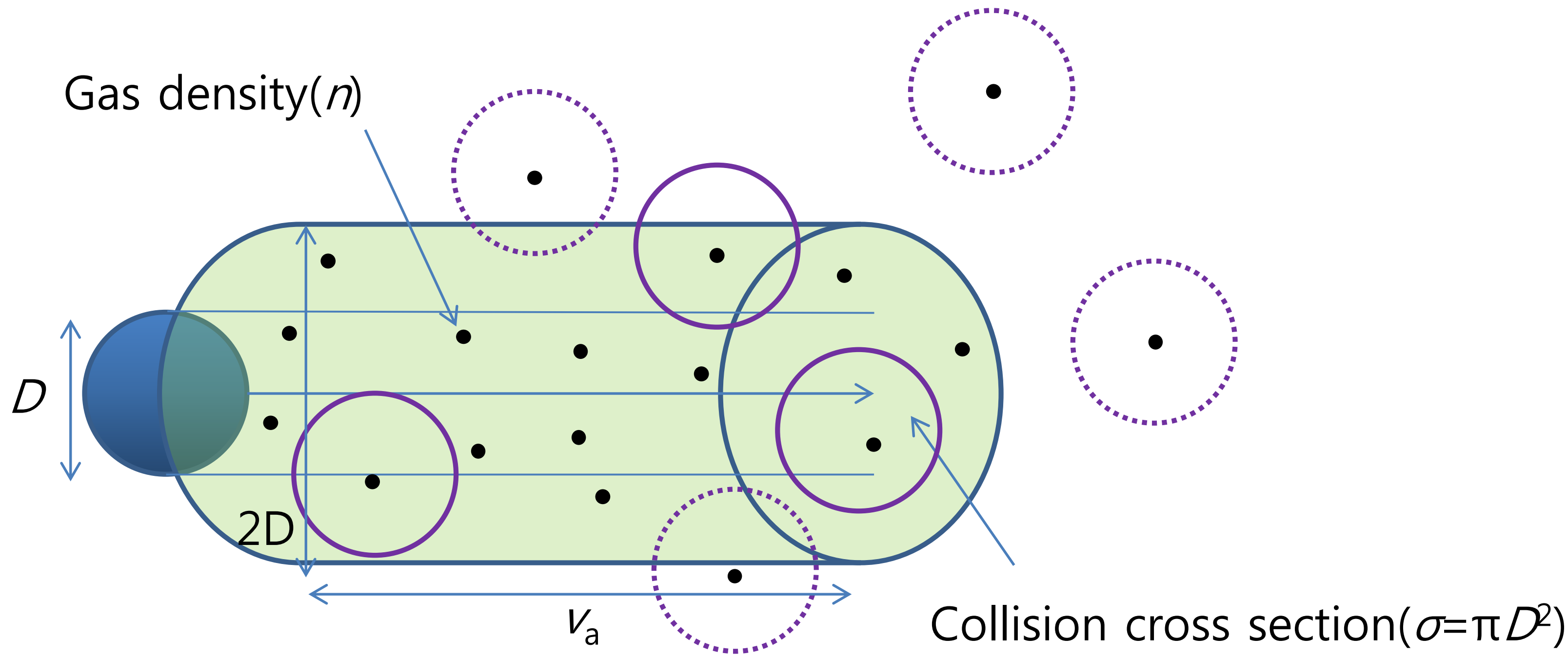
P : pressure
V : volume
N : number of particles
n : density of particles
n_M: Mole
T : temperature [K]
k_B: Boltzmann const.
R: gas constant

- Particle density

$n ≒ 3.3\text{x}10^{16} P$ (ea/cm^{-3}) at 23°C, air



Mean Free Path

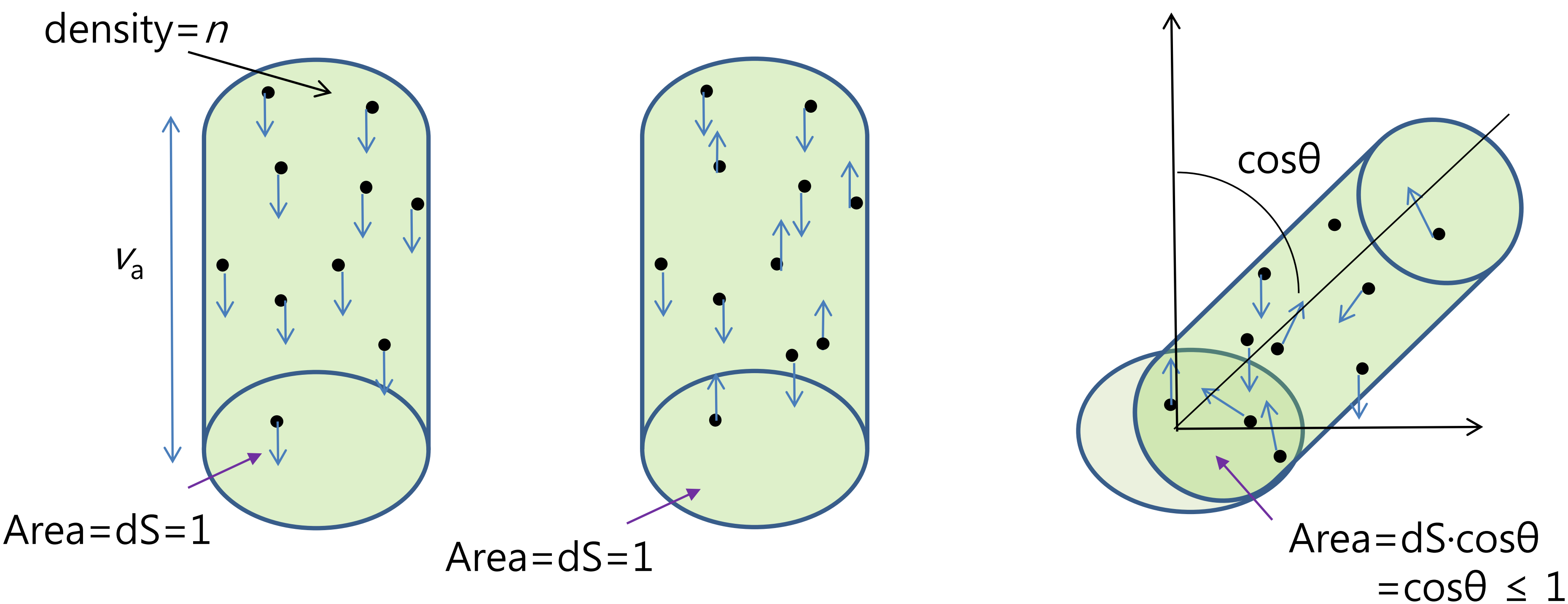


- Number of collision per second $z = n v_a \pi D^2$
- Mean free path $\lambda = v_a / z = 1/n \pi D^2$

  $\boldsymbol{\lambda \fallingdotseq 5 \times 10^{-3}/P}$ (cm) at 23°C, air

Impingement Rate (J)

- Def.) # of particles incident on unit surface per unit time



$J = nv_a$

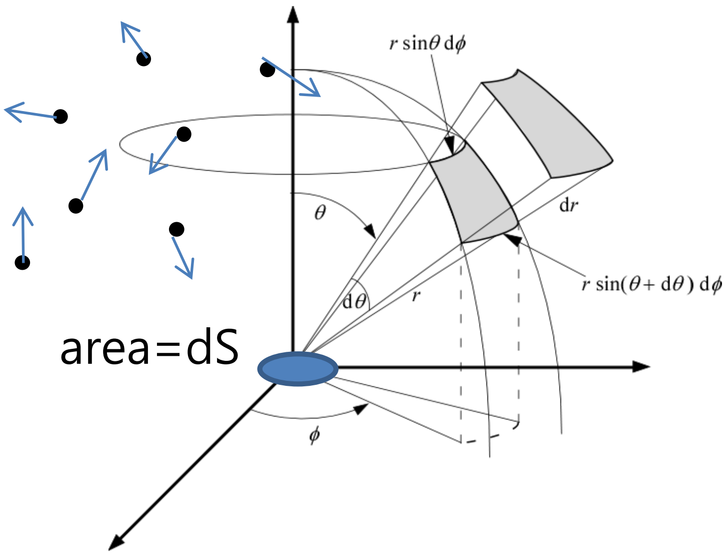
(1-directional case)

$J = \frac{1}{2} \cdot nv_a$

(1-dimensional case)

$J = \frac{1}{4} \cdot nv_a$

(3-dimensional case)



$$N_i = \left[\frac{n}{4\pi} \int_0^\infty v f(v) dv \int_0^{\pi/2} 2\pi \sin\Theta \cos\Theta d\Theta \right] dt dS$$

$$J = \frac{N_i}{dt dS} = \frac{n}{4} \int_0^\infty v f(v) dv = \frac{1}{4} n v_a$$

$$J = \frac{P}{\sqrt{2\pi m k T}} = 3.5\times10^{22} \frac{P}{\sqrt{MT}}$$ (ea cm^{-2} s^{-1})

- Impingement rate

  $J \fallingdotseq 3.3\text{x}10^{20} P$ (cm^{-2} s^{-1}) at 23^{o}C, air

- Monolayer time $\tau = 10^{15}/J = 4\text{x}10^{15}/nv_a$

  (Approximately 10^{15} surface sites per cm^2)

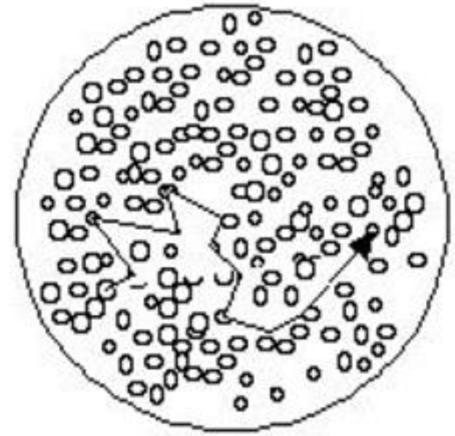
  $\tau \fallingdotseq 3\text{x}10^{-6}/P$ (s) at 23^{o}C, air

Flow Regime

1. **Viscous flow**

   $\lambda / d < 0.01$

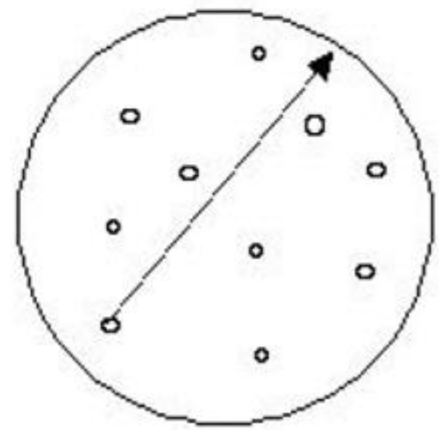
   $P \cdot d$ (Torr, cm) > 0.5



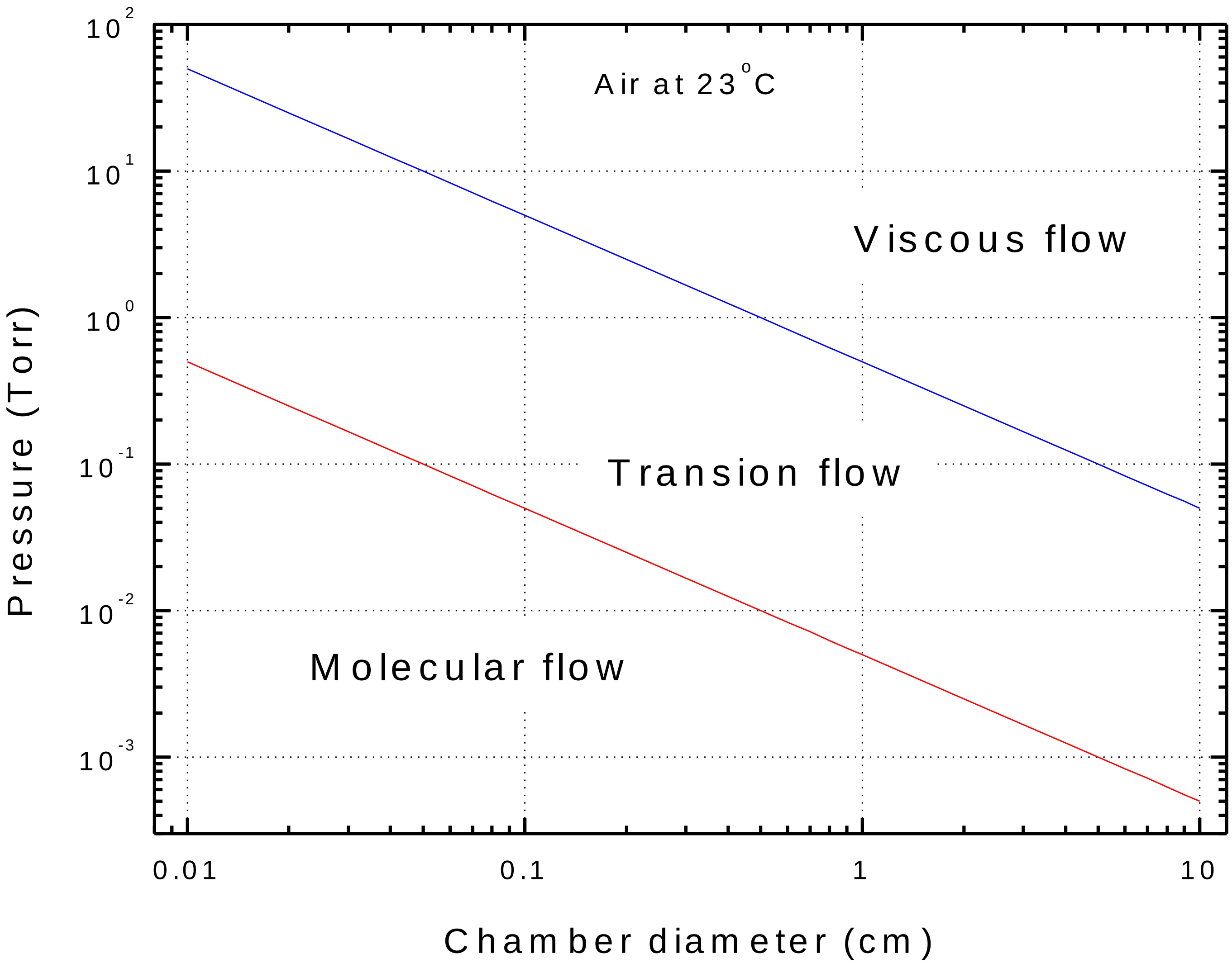
2. **Molecular flow**

   $\lambda / d > 1$

   $P \cdot d$ (Torr, cm) < 0.005



*) $\lambda \sim 5 \times 10^{-3} / P$ (Torr, cm) at 23°C, air



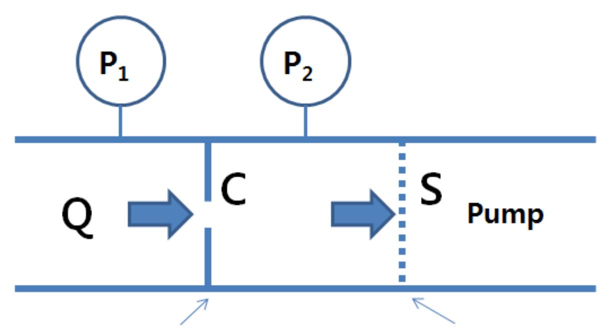
Air at 23 °C
Viscous flow
Transion flow
Molecular flow
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Pressure (Torr)
0.01
0.1
1
10
Chamber diameter (cm)

Conductance(C), Pumping speed(S), Throughput(Q)

C = ratio of throughput under steady state conservative conditions to the pressure differential between two specified cross sections inside a pumping system (l/s)

S = ratio of the throughput of a given gas to the partial pressure of that gas at the cross section of the inlet port of the pump (l/s)

Q = amount of gas in pressure-volume units flowing per unit time across a specified cross section at a specified temperature (mbar l/s)



$Q_1 = C\Delta P = C \times (P_1 - P_2)$

$Q_2 = P_2 \times S$

$Q_1 = Q_2$

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

Conductance

[C. D. Park]

- **Definition**

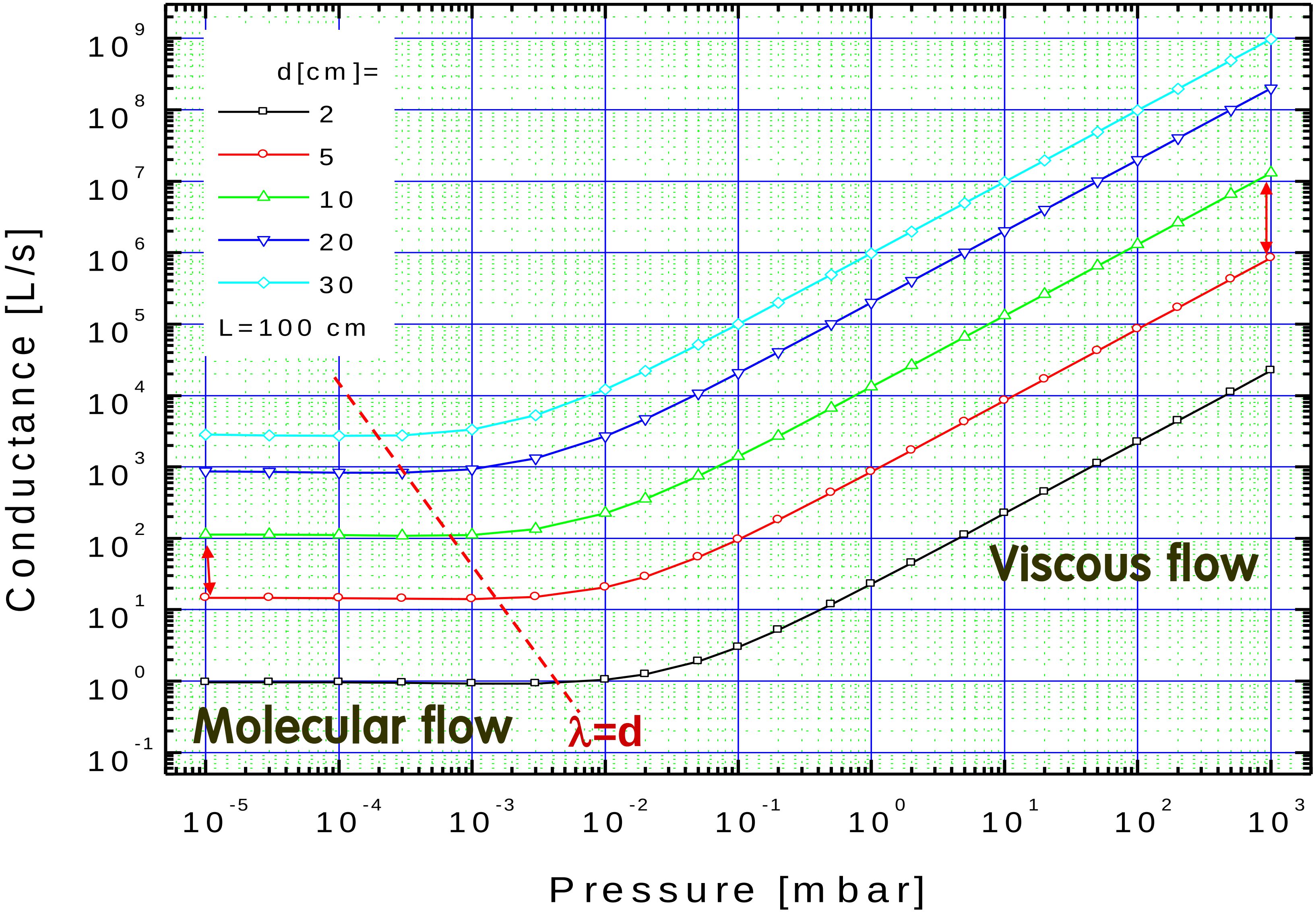
$$Q = C\,(P_1 - P_2)$$

$$\rightarrow\ C = Q\,/\,(P_1 - P_2)$$ (depends on geometry)

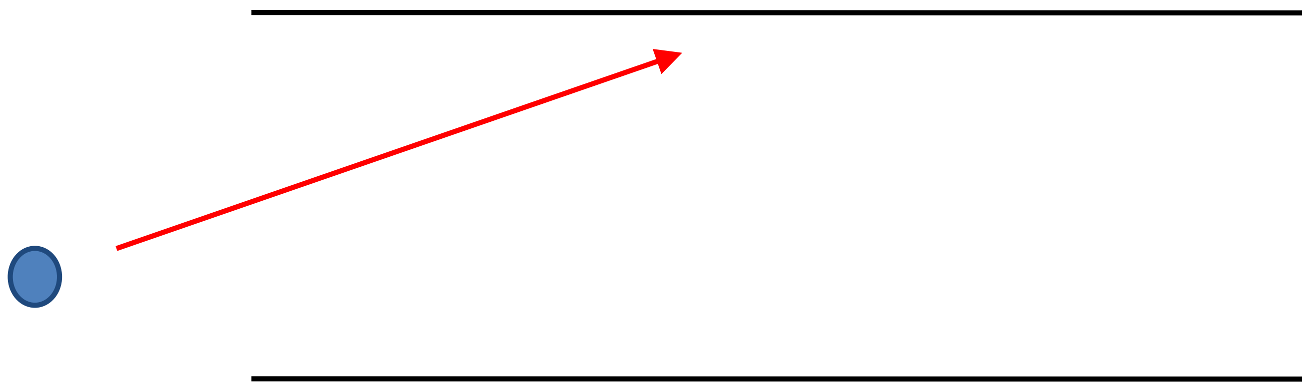
- Unit: l/s

Conductance of Circular Pipes

[S. R. In]

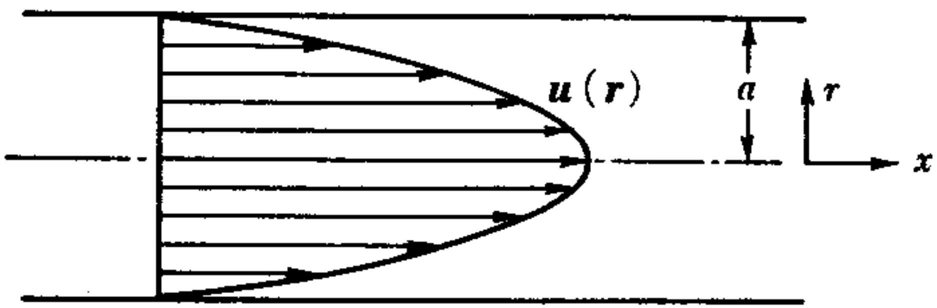


Where will this particle proceed towards after collision?



Conductance at Viscous Flow

✓ Long pipe

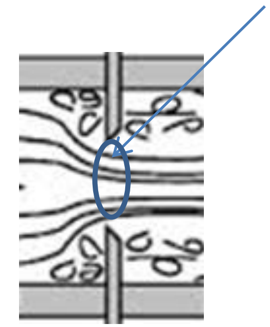


Poiseuille's law

$$Q = \frac{\pi d^4}{128 \eta L} \bar{P} (P_1 - P_2)$$

$$C = \frac{\pi d^4}{128 \eta L} \bar{P}$$

✓ Orifice

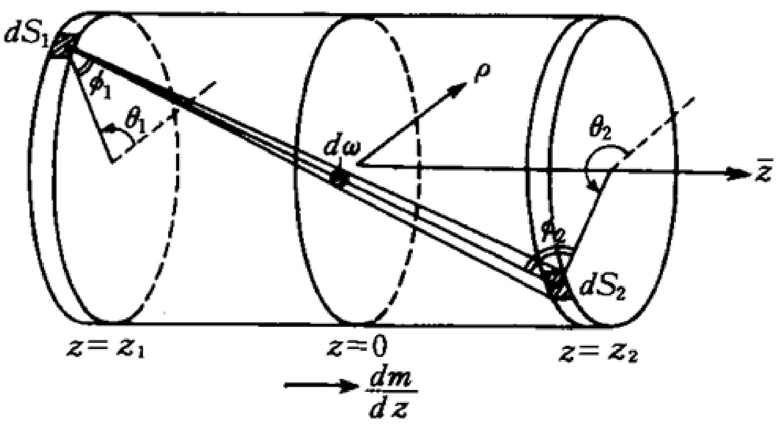


$$C_o = \frac{17.2 A}{(1 - \frac{P_{down}}{P_{up}})} \quad \ell/s$$

❖ **Approximation**
- **22°C, Diatomic gas. eg. Air(N_2+O_2)**
- **P_{up} > 1.92 P_{down}**

Conductance at Molecular Flow

✓ Long pipe

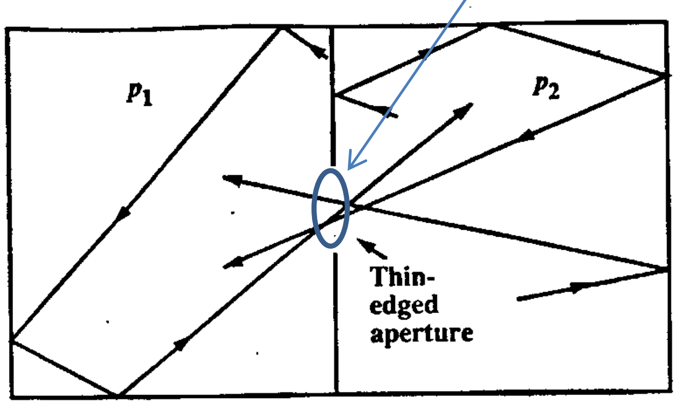


$$Q = \frac{2\pi}{3} d^3 v_a \frac{(P_2 - P_1)}{L}$$

$$C = \frac{2\pi}{3} \frac{d^3}{L} v_a$$

✓ Orifice

area=*A* [cm]

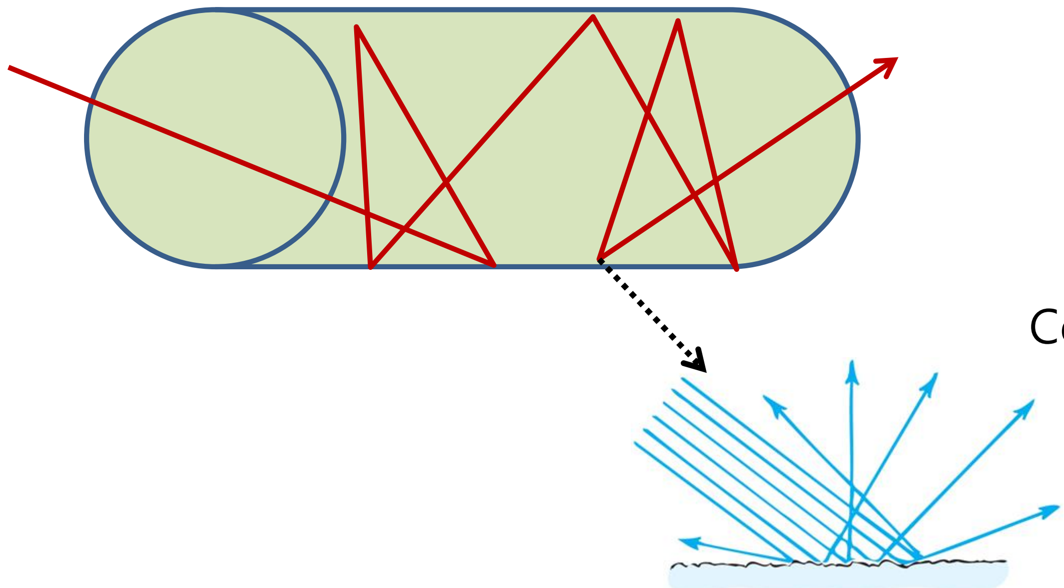


$$C_o = \frac{1}{4} \bar{v}_a A = 3.64 \sqrt{\frac{T}{M}} A \quad l/s$$

C_o = 11.6 A (l/s, cm²) at 23°C, air

Transmission Probability and Cosine Law

[C. D. Park]



Conductance of a pipe
= Conductance of inlet (orifice) x transmission probability (a)

$$C = aC_o$$

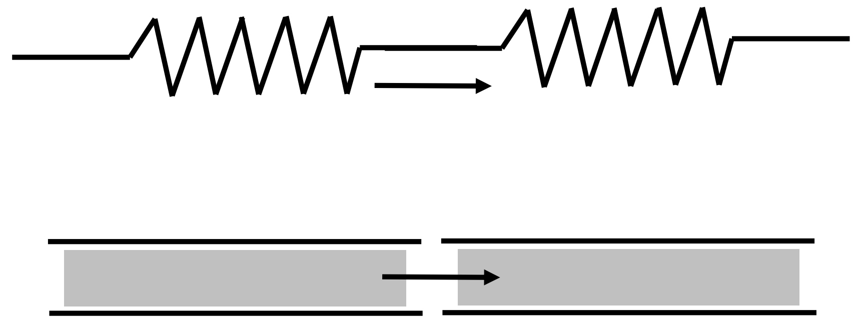
Transmission Probability (Clausing coeff.)

L/d	a	L/d	a	L/d	a	L/d	a
0.1	0.90922	3.7	0.23824	7.4	0.1404	14.6	0.07885
0.2	0.83408	3.8	0.23376	7.6	0.13739	14.8	0.07791
0.3	0.77115	3.9	0.22945	7.8	0.13451	15	0.07699
0.4	0.71779	4	0.2253	8	0.13175	15.2	0.07609
0.5	0.67198	4.1	0.2213	8.2	0.1291	15.4	0.07521
0.6	0.63223	4.2	0.21745	8.4	0.12656	15.6	0.07436
0.7	0.59736	4.3	0.21374	8.6	0.12412	15.8	0.07352
0.8	0.56651	4.4	0.21015	8.8	0.12177	16	0.0727
0.9	0.53898	4.5	0.20669	9	0.11951	16.2	0.0719
1	0.51423	4.6	0.20334	9.2	0.11733	16.4	0.07112
1.1	0.49185	4.7	0.2001	9.4	0.11524	16.6	0.07036
1.2	0.4715	4.8	0.19697	9.6	0.11322	16.8	0.06961
1.3	0.45289	4.9	0.19393	9.8	0.11127	17	0.06887
1.4	0.43581	5	0.19099	10	0.10938	17.2	0.06816
1.5	0.42006	5.1	0.18814	10.2	0.10756	17.4	0.06745
1.6	0.40548	5.2	0.18538	10.4	0.10581	17.6	0.06677
1.7	0.39195	5.3	0.1827	10.6	0.1041	17.8	0.06609
1.8	0.37935	5.4	0.1801	10.8	0.10246	18	0.06543
1.9	0.36759	5.5	0.17757	11	0.10086	18.2	0.06478
2	0.35658	5.6	0.17512	11.2	0.09932	18.4	0.06415
2.1	0.34624	5.7	0.17273	11.4	0.09782	18.6	0.06353
2.2	0.33652	5.8	0.17041	11.6	0.09637	18.8	0.06292
2.3	0.32736	5.9	0.16815	11.8	0.09496	19	0.06232
2.4	0.31871	6	0.16596	12	0.09359	19.2	0.06173
2.5	0.31053	6.1	0.16382	12.2	0.09226	19.4	0.06116
2.6	0.30279	6.2	0.16174	12.4	0.09097	19.6	0.06059
2.7	0.29543	6.3	0.15971	12.6	0.08971	19.8	0.06004
2.8	0.28844	6.4	0.15773	12.8	0.08849	20	0.05949
2.9	0.28179	6.5	0.1558	13	0.0873	20.5	0.05817
3	0.27546	6.6	0.15392	13.2	0.08615	21	0.05691
3.1	0.26941	6.7	0.15209	13.4	0.08502	21.5	0.0557
3.2	0.26364	6.8	0.1503	13.6	0.08393	22	0.05455
3.3	0.25812	6.9	0.14855	13.8	0.08286	22.5	0.05344
3.4	0.25283	7	0.14684	14	0.08182	23	0.05237
3.5	0.24776	7.1	0.14517	14.2	0.0808	23.5	0.05135
3.6	0.24291	7.2	0.14355	14.4	0.07982	24	0.05037

Combination of Conductance

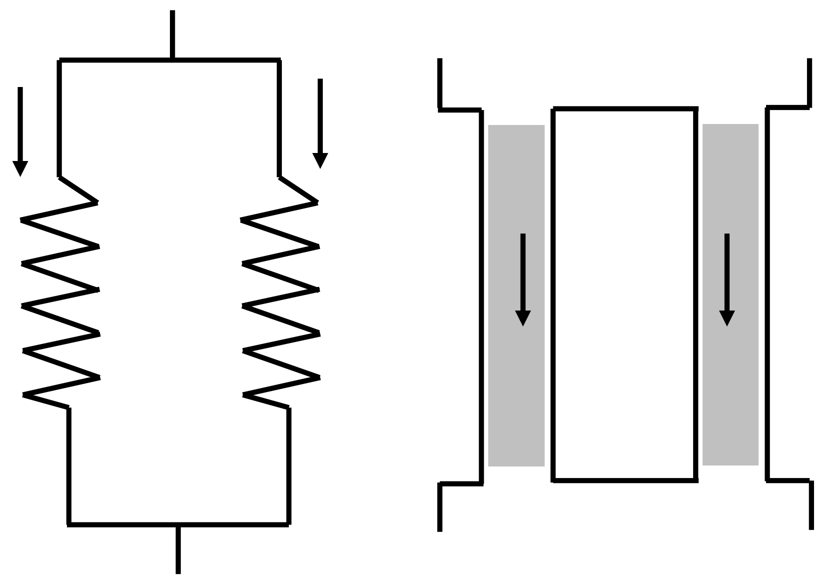
[C. D. Park]

For series connection



$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$$

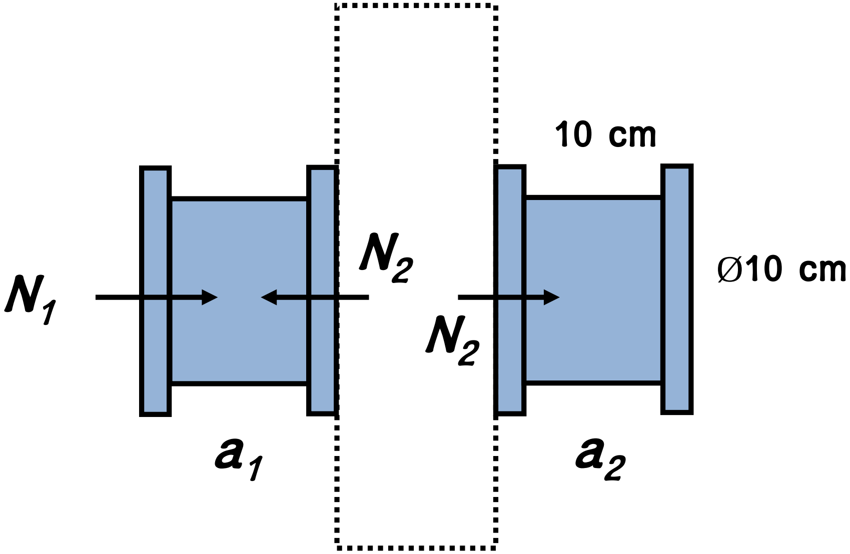
For parallel connection



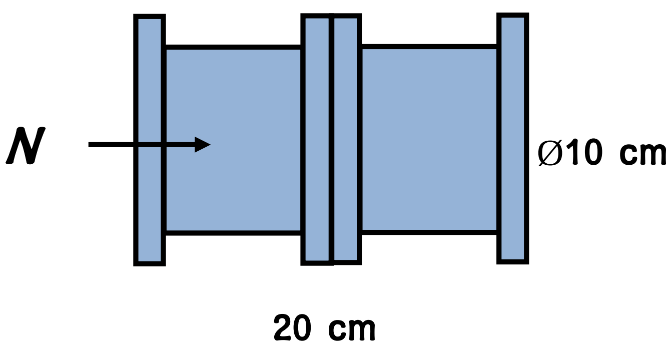
$$C = C_1 + C_2 + C_3 + \ldots$$

Combination of Conductance in Series

[C. D. Park]



$$\frac{1}{a} = \frac{1}{a_1} + \frac{1}{a_2}, \quad a = \frac{0.51423}{2}$$



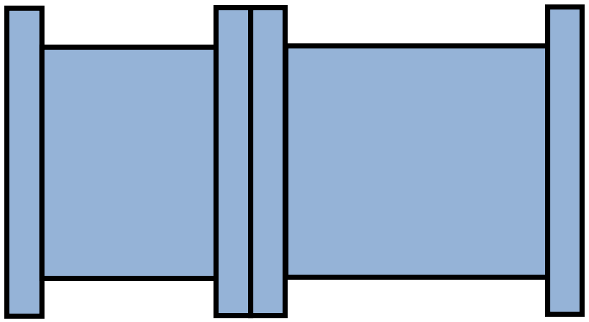
$$a_{clausing} = 0.35658 \quad (L/d = 2)$$

$$a_{combi} = 0.25711 \quad (27.9\%\ error)$$

Why?

❖ In case of the same cross section

[C. D. Park]



$$C = C_{(L_1+L_2)/d}$$

or

$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_o}\right)$$

$$\frac{1}{a} = \frac{1}{a_1} + \left(\frac{1}{a_2} - 1\right)$$

Oatley

(Subtract entrance effect once at a joint)

For $L_1 = L_2$:

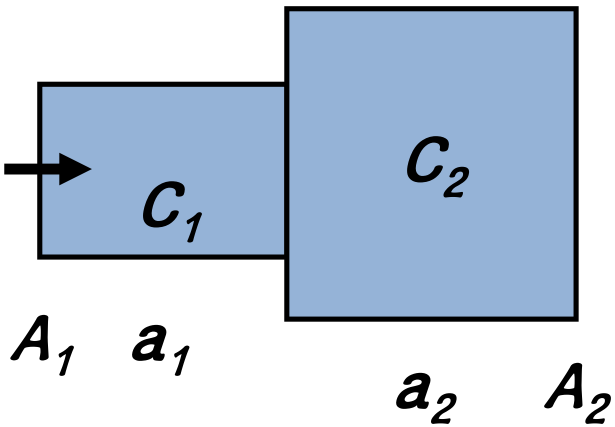
$a_{Clausing} = 0.35658 \quad (L/d = 2)$

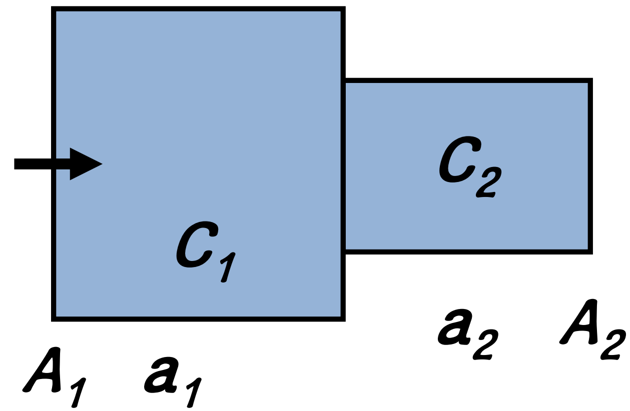
$a_{Combi} = 0.25711 \quad (27.9\%\ error)$

$a_{Oatley} = 0.3461 \quad (2.94\%\ error)$

❖ In case of different cross section

[C. D. Park]





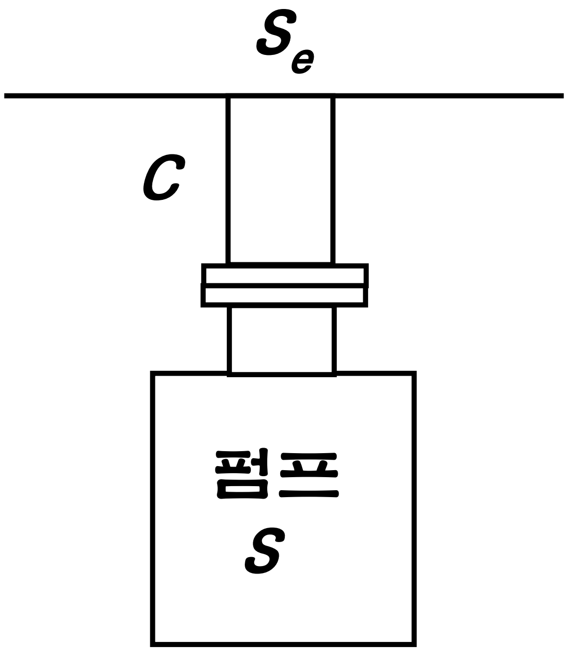
$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{2o}}\right) = \frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{1o}}\right)$$

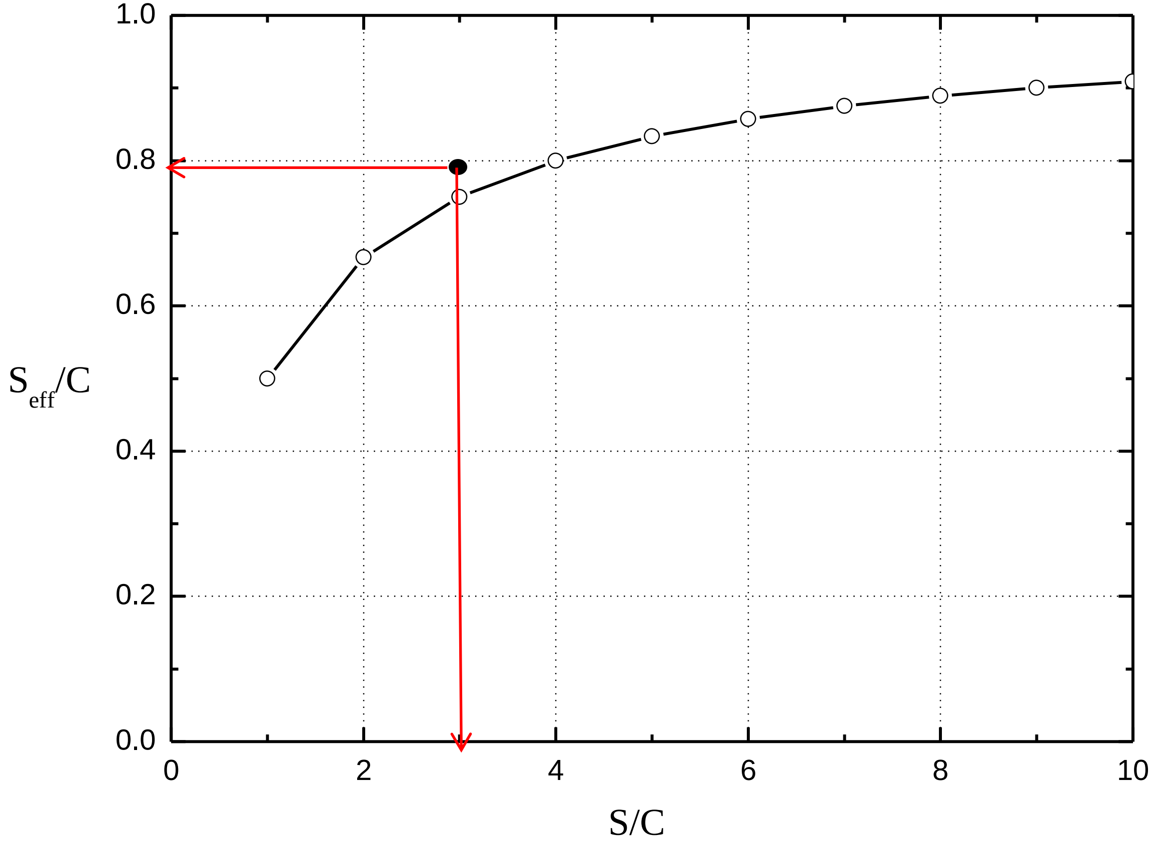
Generally,

$$\frac{1}{C} = \frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_{o(\max\ 1|2)}}\right) + \left(\frac{1}{C_3} - \frac{1}{C_{o(\max\ 2|3)}}\right) + \ldots,$$

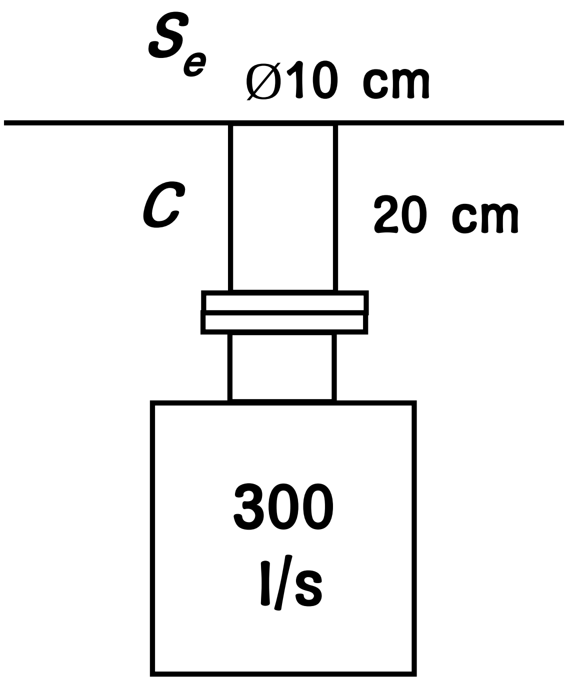
Effective Pumping Speed

[C. D. Park]





❖ S_{eff} (example) [C. D. Park]



*** 20ºC, air (cm)**

C =11.6 (0.35658)(3.14x5²)=325 l/s

C_o=11.6 (3.14x5²)=911 l/s

1. $$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S} \Rightarrow 155 \quad l/s$$

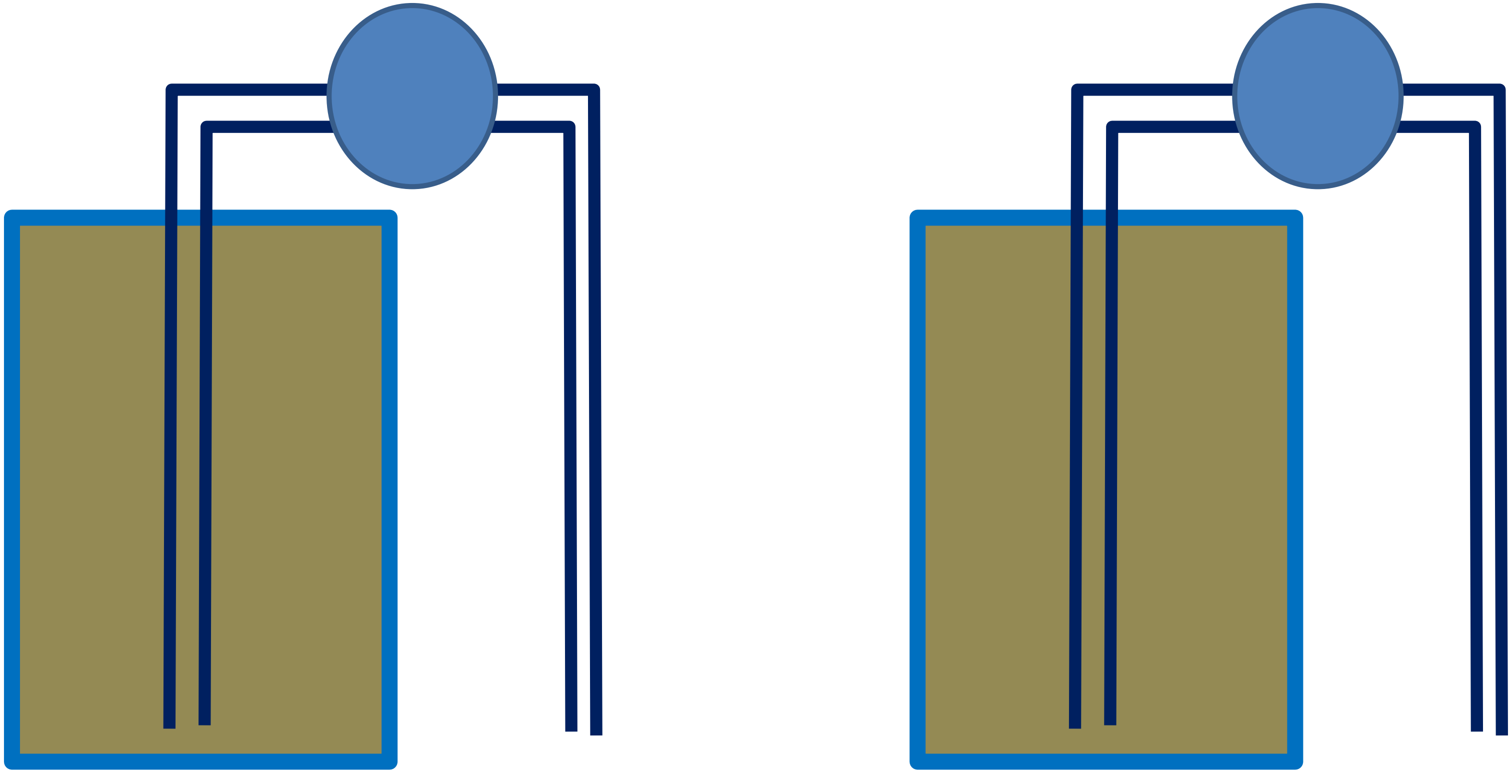
2. $$\frac{1}{S_{eff}} = \frac{1}{C} + \left(\frac{1}{S} - \frac{1}{C_o}\right) \Rightarrow 188 \quad l/s$$

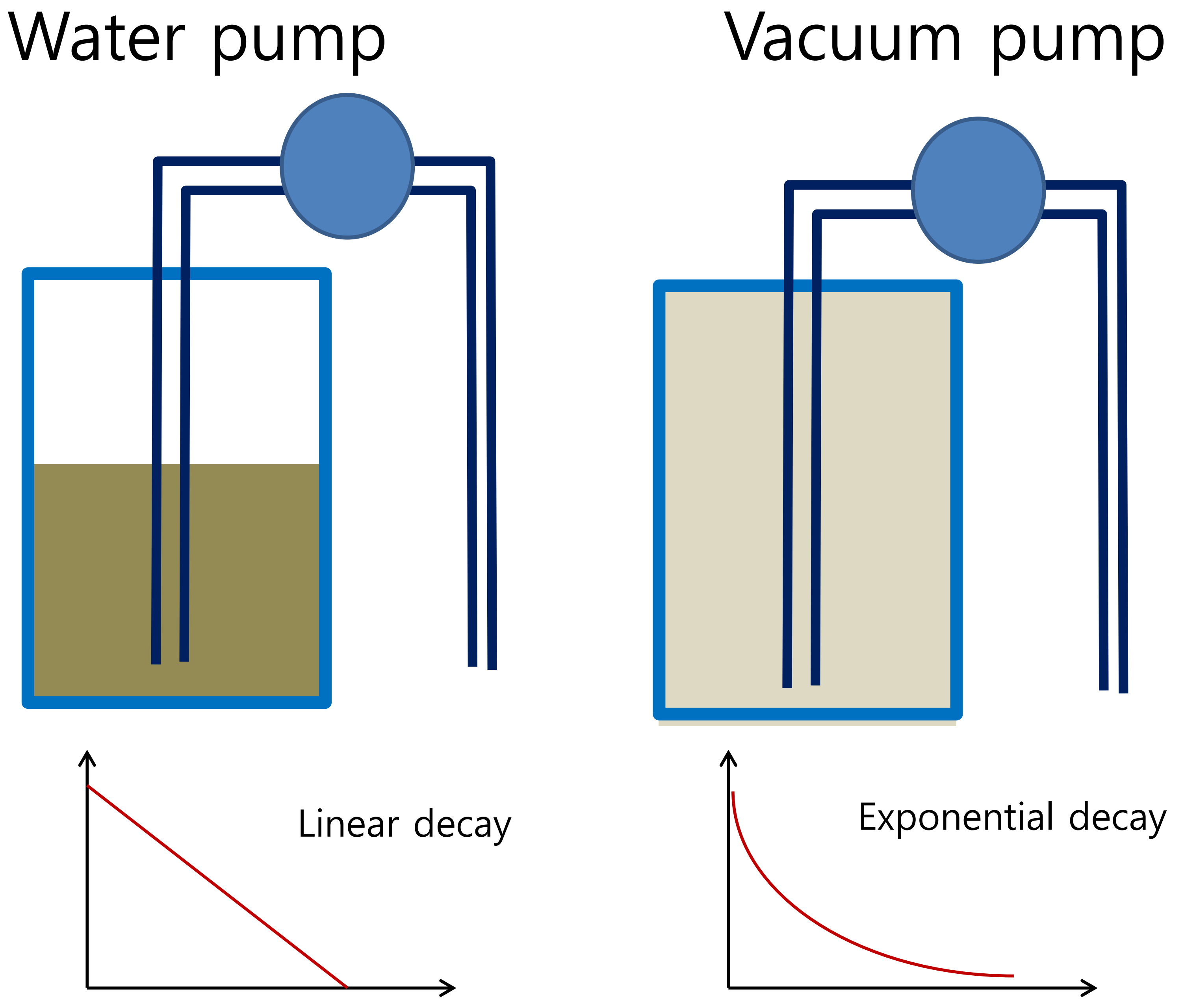
- **error ~18%**

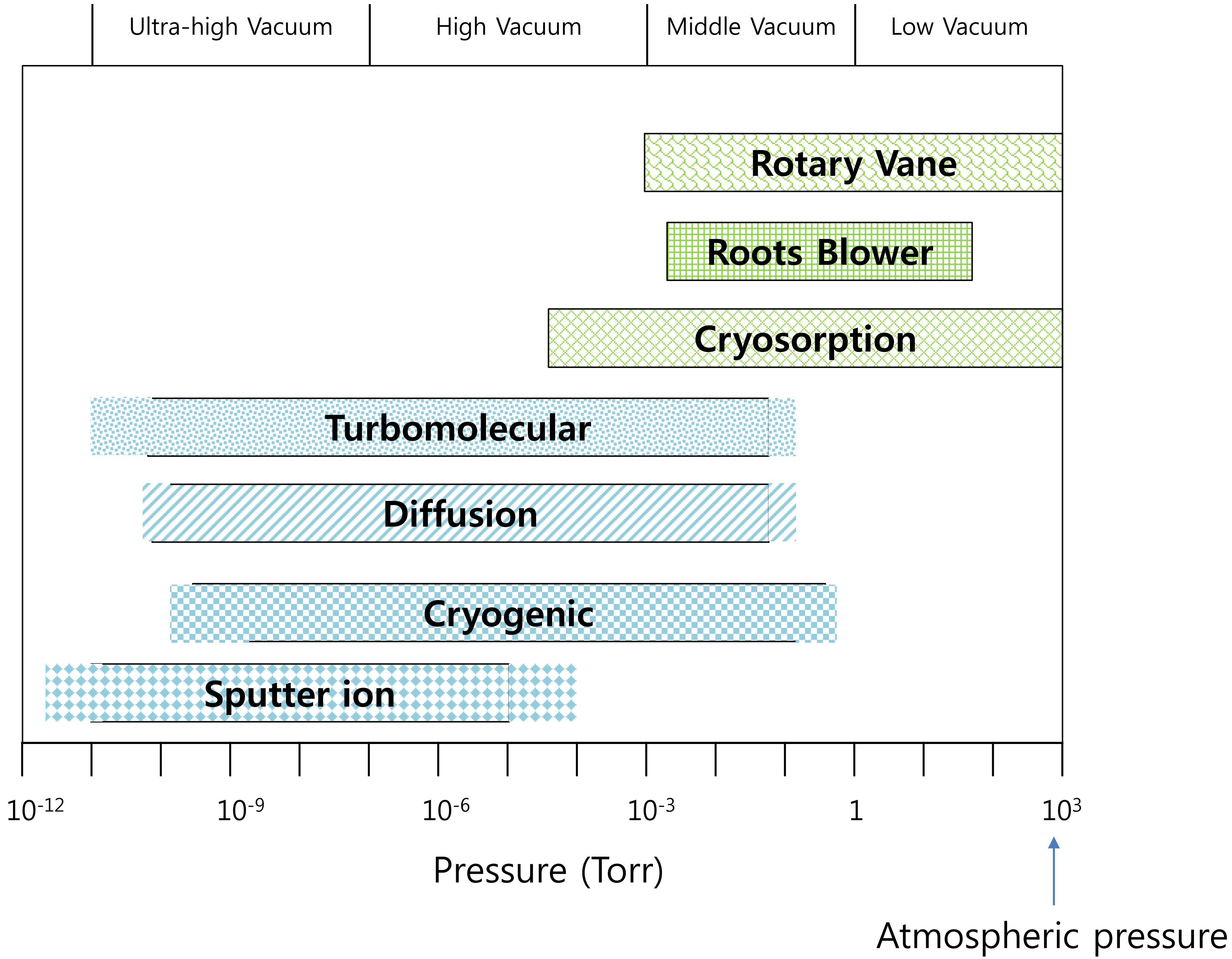
How to Generate Vacuum

- **Throughput mechanisms:**
  - **Positive displacement**: Molecules are compressed into a smaller volume, raising the pressure
  - **Momentum transfer**: Molecules are given a preferred direction by very fast moving surfaces or oil molecules
- **Capture mechanisms:**
  - **Chemical combination**: Molecules react with active metal surfaces and are converted to a solid
  - **Condensation**: Molecules land on a very cold surface and freeze into a solid
  - **Adsorption**: Molecules land on a surface and remain there
  - **Absorption**: Molecules land on a surface and dissolve into the bulk material
  - **Ionization & burial**: Molecules are ionized and accelerated into a surface with enough energy to burrow in

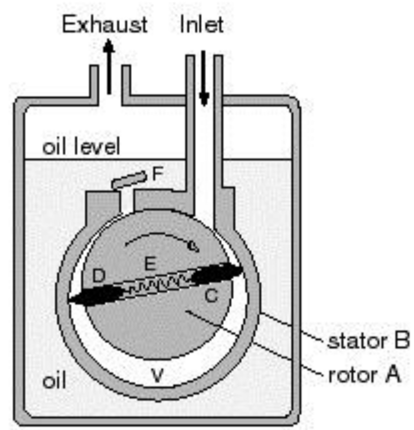
Water Pump & Vacuum Pump



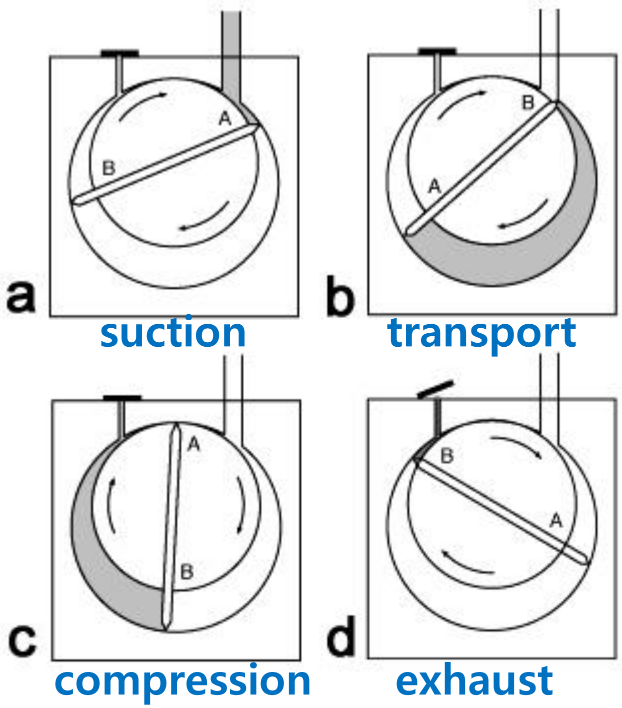

Water pump
Vacuum pump
Linear decay
Exponential decay


Ultra-high Vacuum
High Vacuum
Middle Vacuum
Low Vacuum
Rotary Vane
Roots Blower
Cryosorption
Turbomolecular
Diffusion
Cryogenic
Sputter ion
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
Pressure (Torr)
Atmospheric pressure

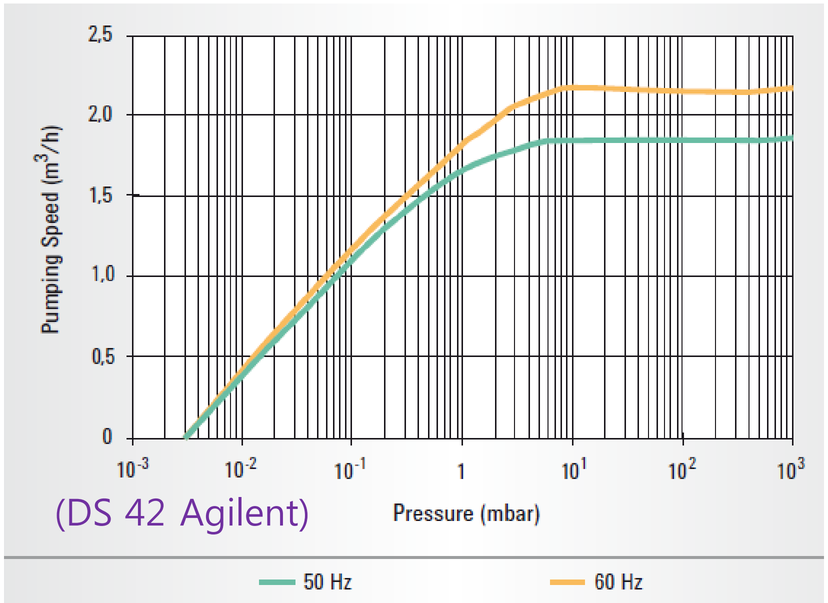
Rotary Vane Pump



Positive displacement

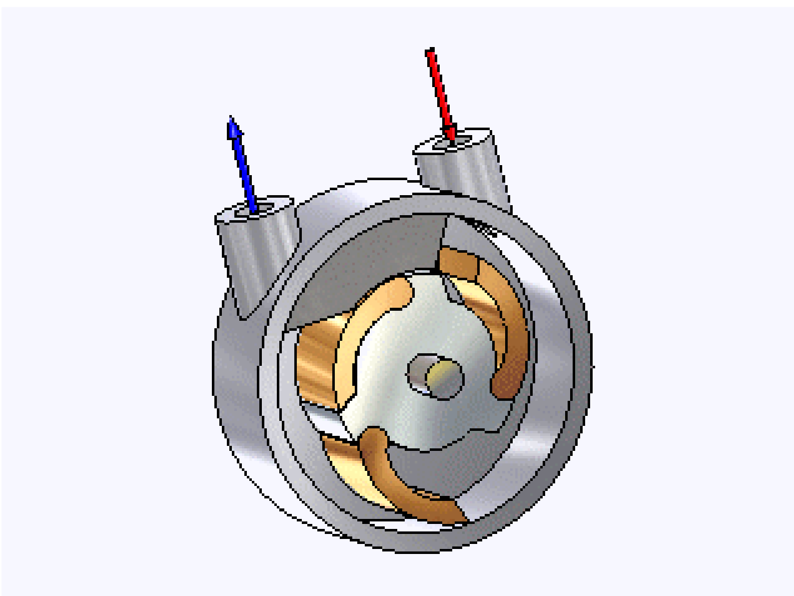


Typical pumping speed curve

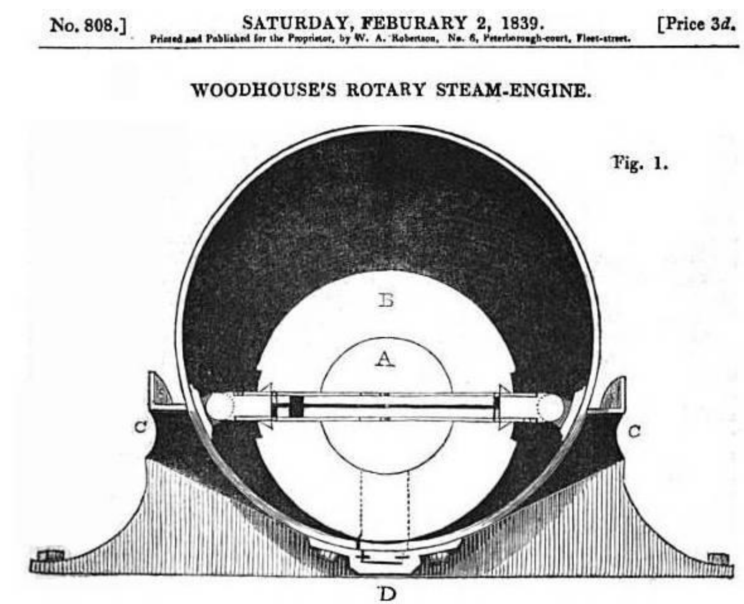


※ Rotary steam engines

Gas (steam) flow ➔ rotational energy



James Watt's three-vane rotary of 1782



No. 808.] SATURDAY, FEBURARY 2, 1839. [Price 3*d.*

Printed and Published for the Proprietor, by W. A. Robertson, No. 6, Peterborough-court, Fleet-street.

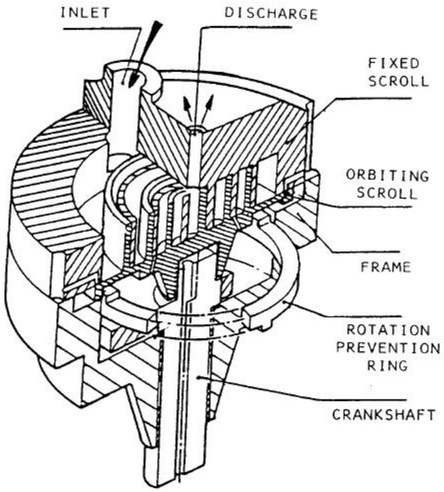
WOODHOUSE'S ROTARY STEAM-ENGINE.

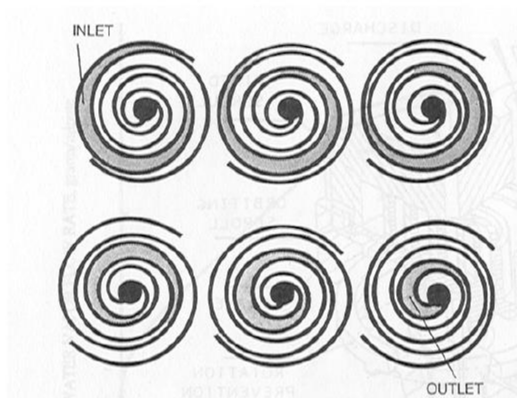
The Woodhouse rotary engine: 1839

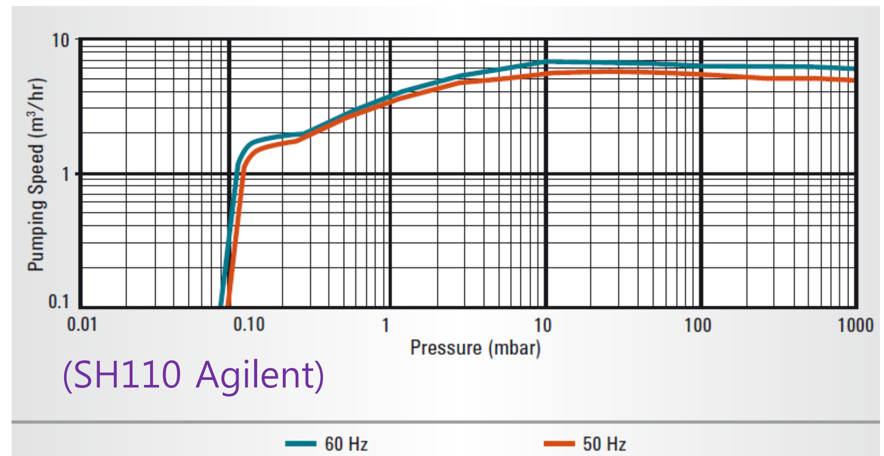
Scroll Pump (dry)

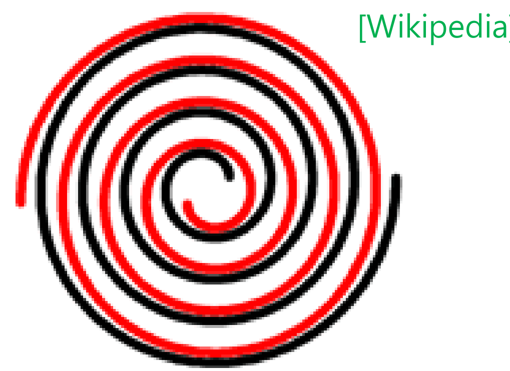
Positive displacement

Typical pumping speed curve

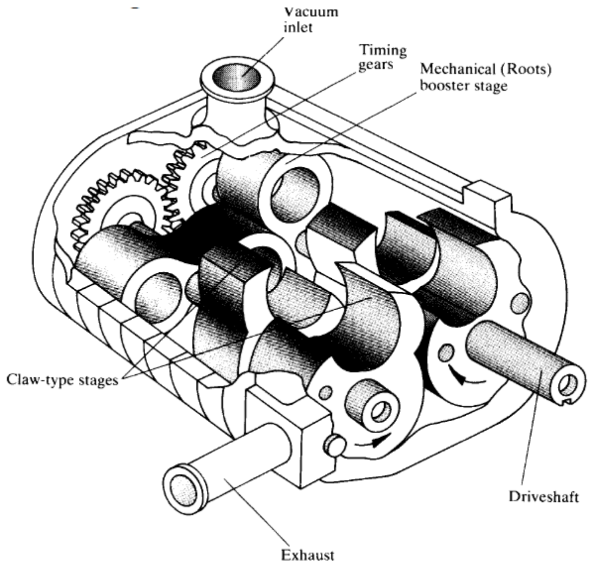




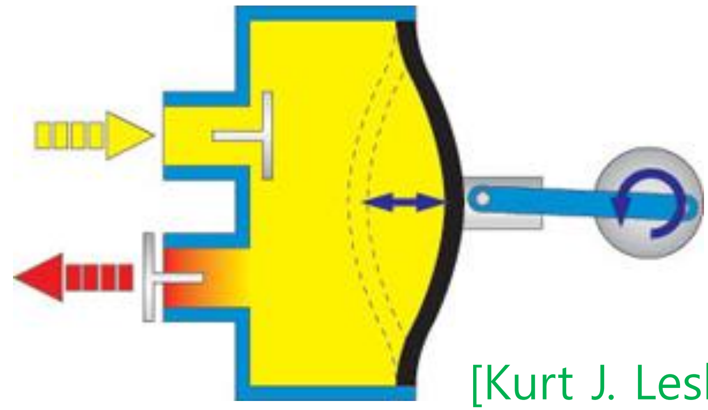




Claw Pump

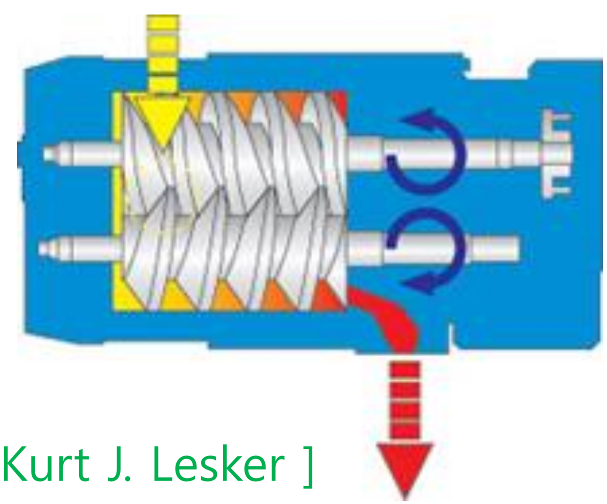


Diaphram Pump



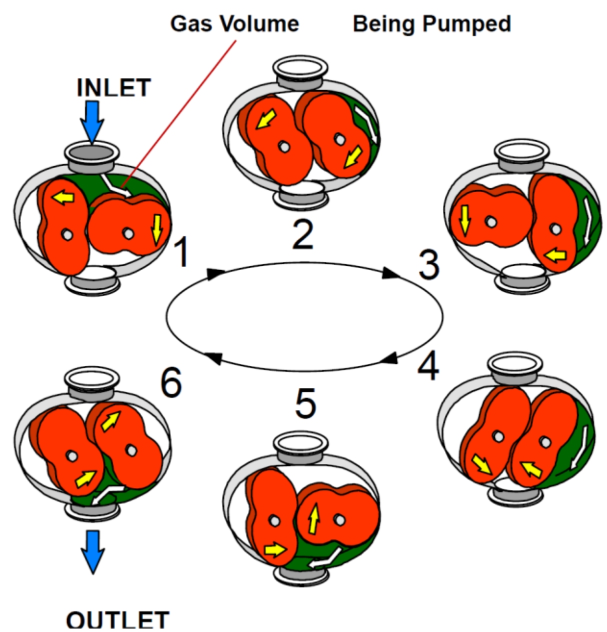
[Kurt J. Lesker]

Screw Pump



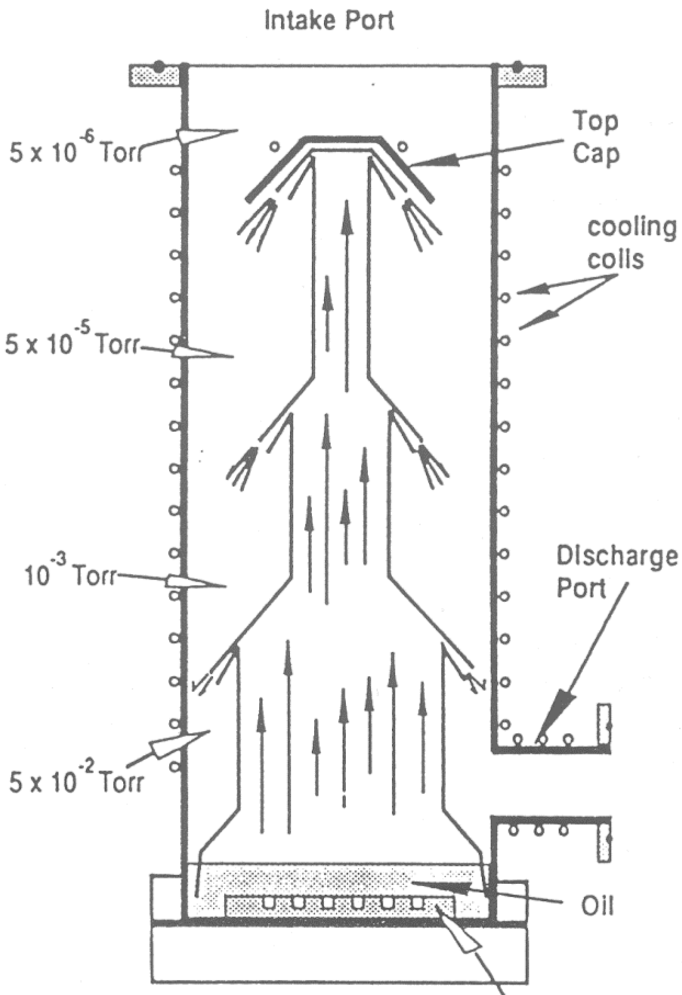
[Kurt J. Lesker]

Roots Pump

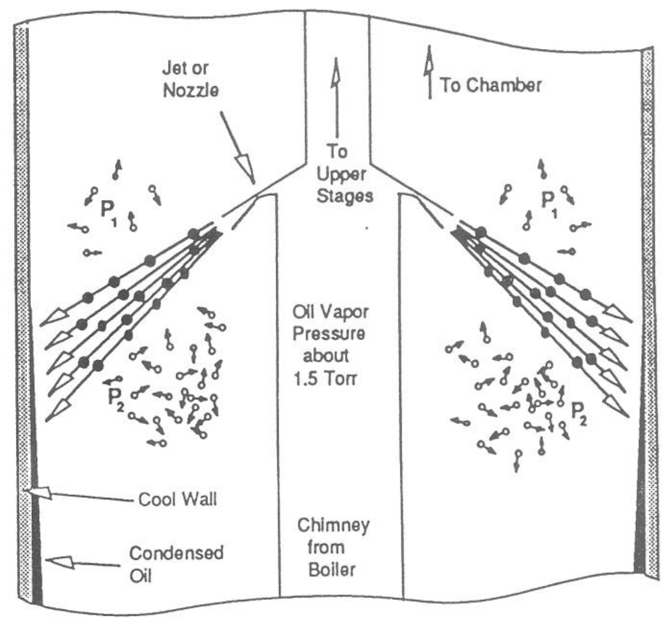


Diffusion Pump

Momentum transfer



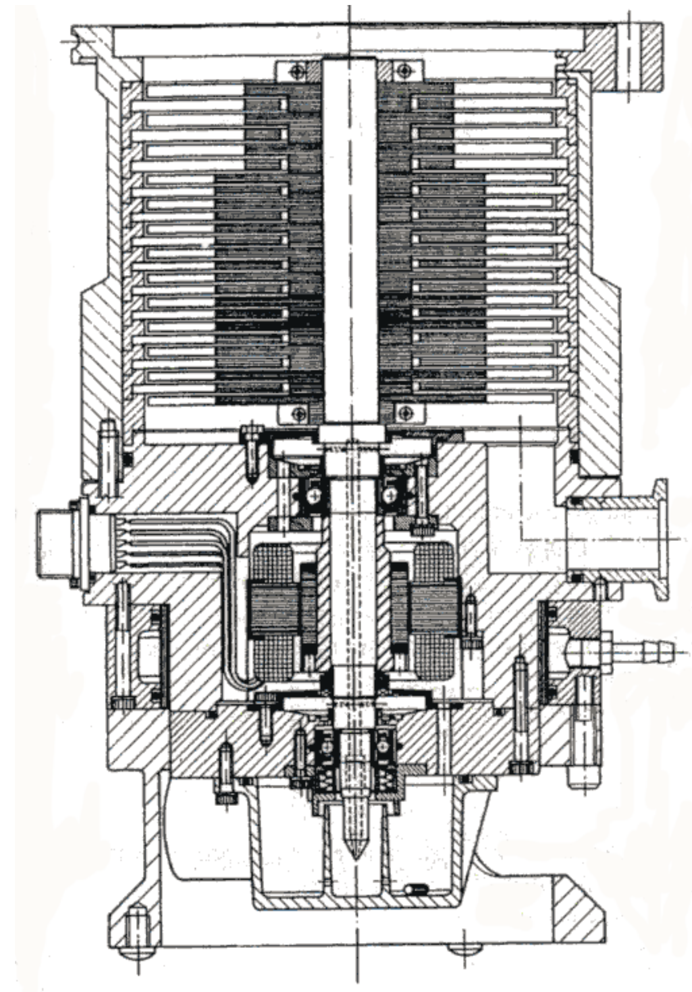
(A)



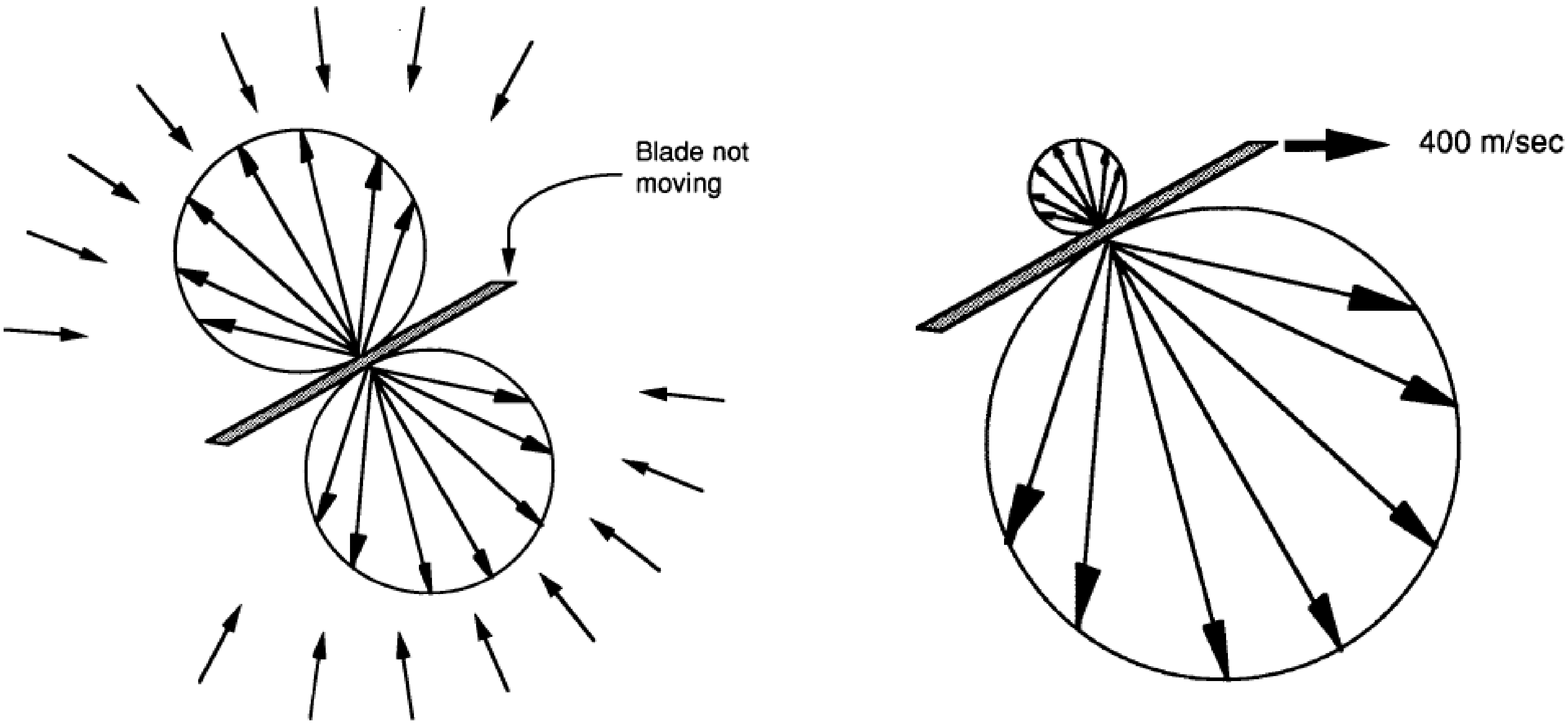
Turbo Molecular Pump (TMP)

Momentum transfer

- Operate in the molecular flow regime
- Operating range 10^{-2} to 10^{-10} Torr
- Pumping speed 10 to 10,000 l/s
- Infinite pumping capacity
- Blade rotation speed ranges from 14,000 to 90,000 rpm (mechanically vulnerable)



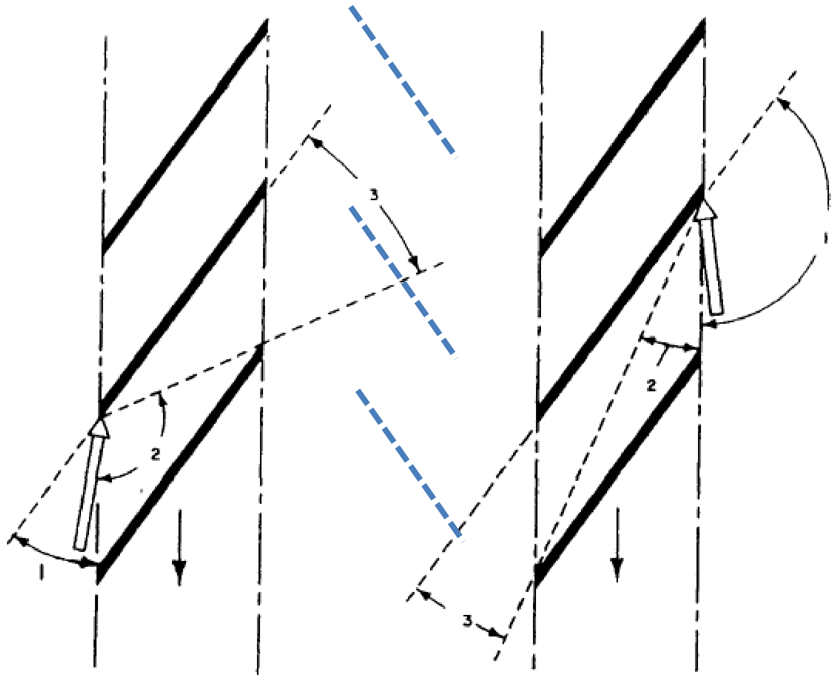
❖ Pumping mechanism of TMP



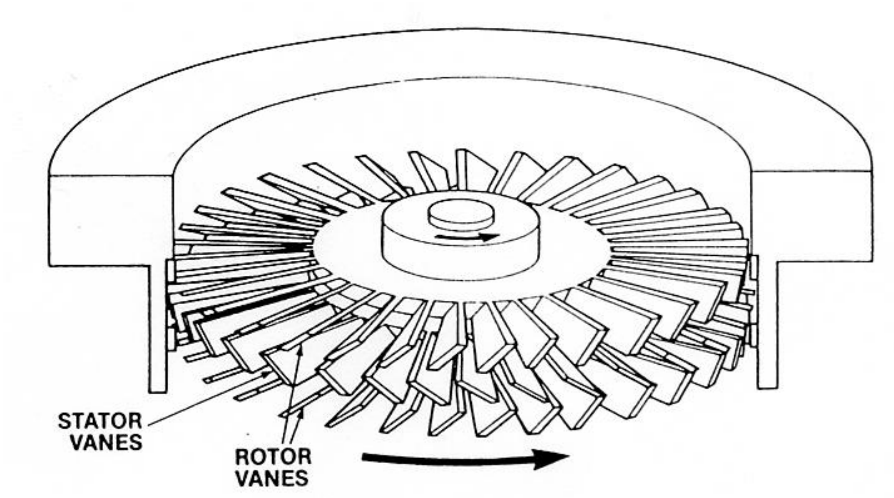
Velocity distribution from moving blades

❖ Pumping mechanism of TMP

Vacuum side

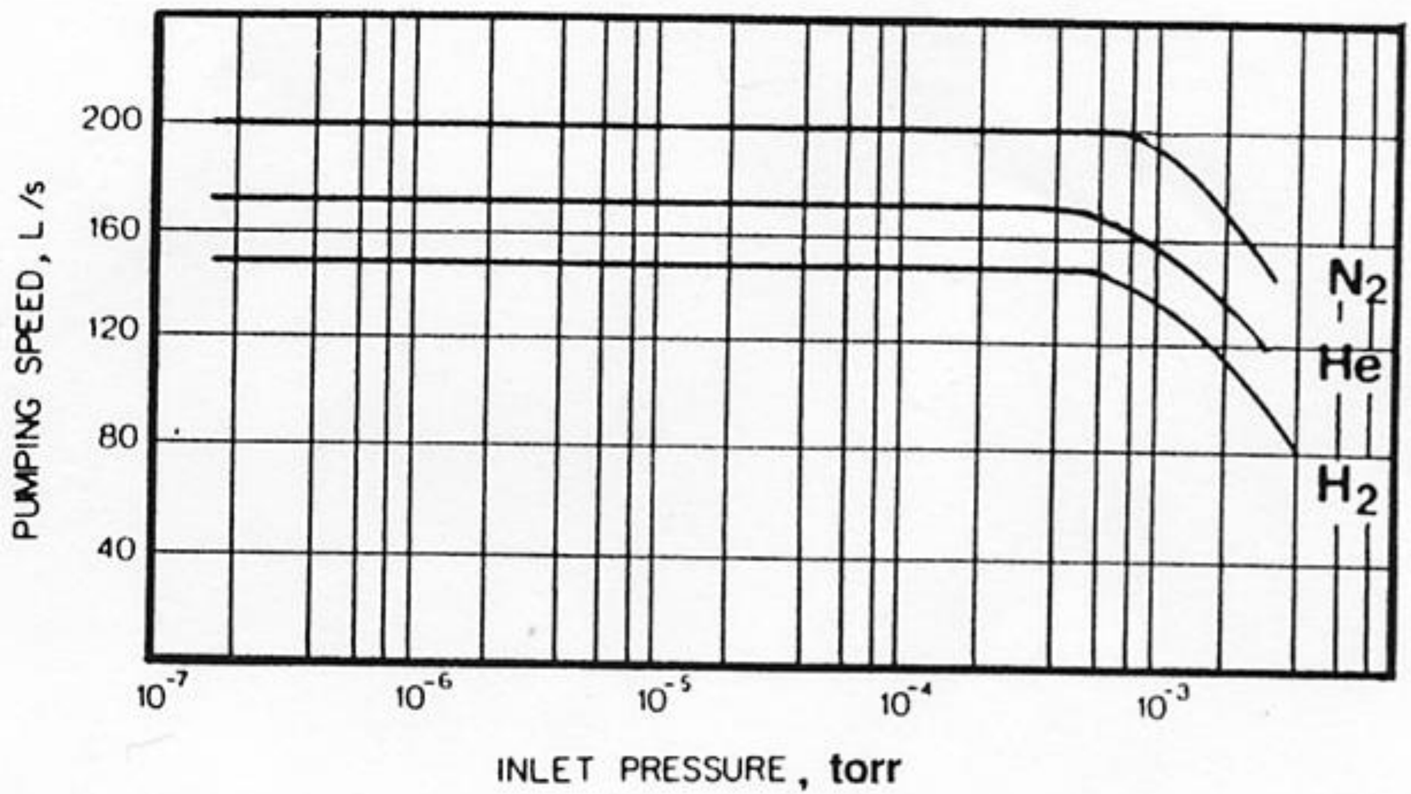


Air side



"Stators redistribute directions of molecules at each stage"

❖ Pumping speed of TMP

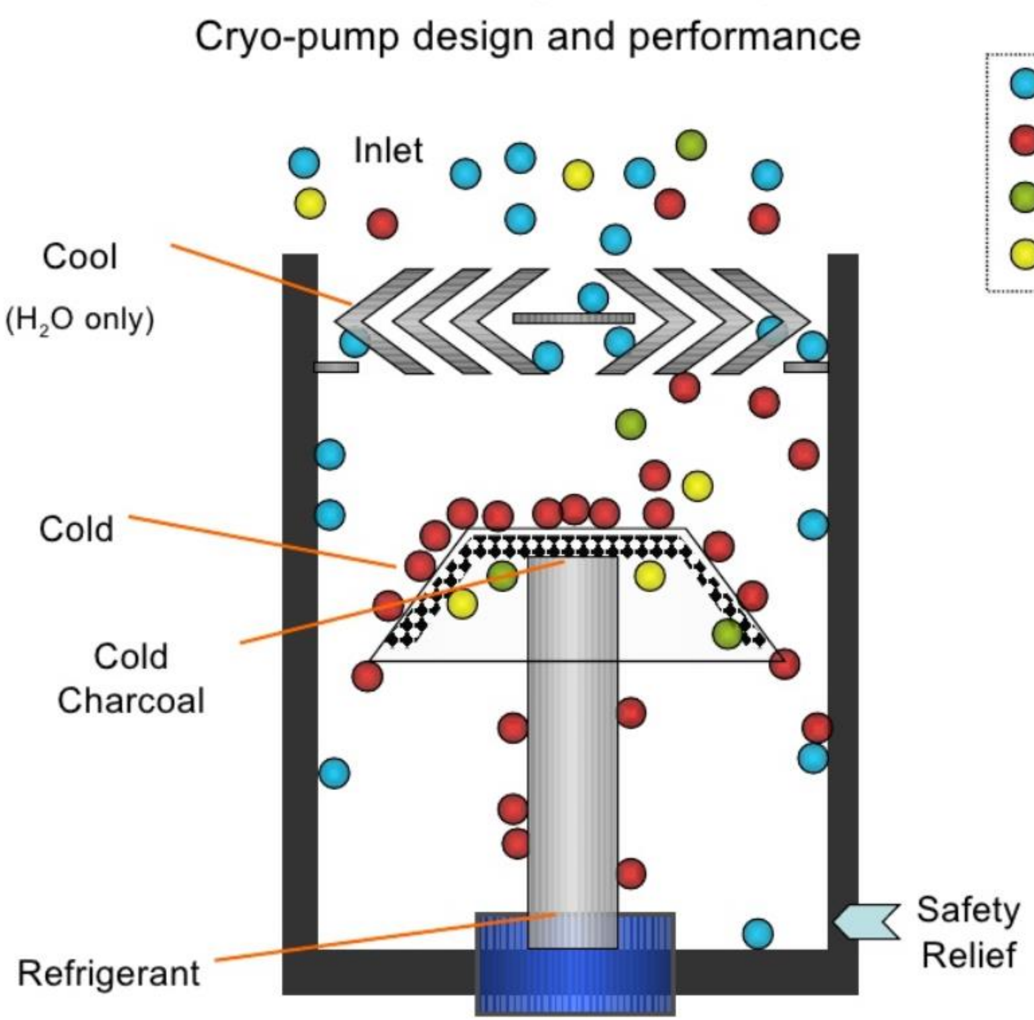


$$v_a = \int_0^\infty v f(v) dv = \sqrt{\frac{8kT}{\pi m}} = 146\sqrt{\frac{T}{M}}$$

Cryo-pump

[S. R. In]

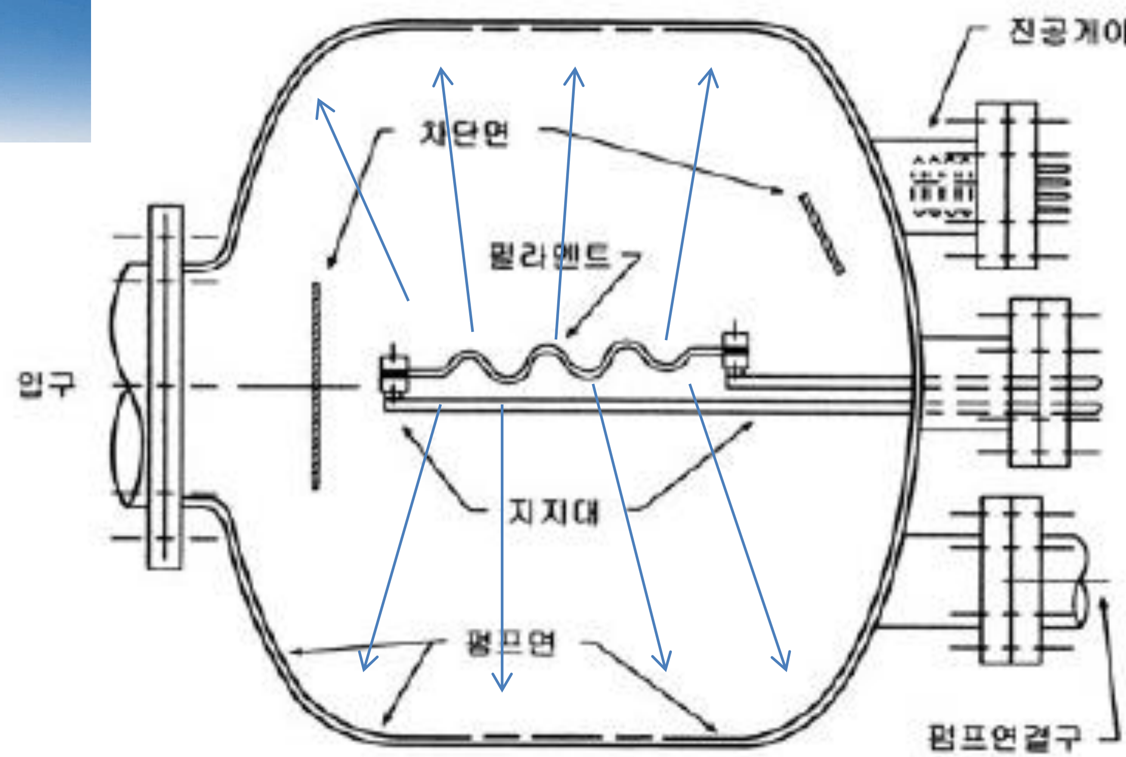
Physical combination



Titanium Sublimation Pump (TSP)

Ti filament

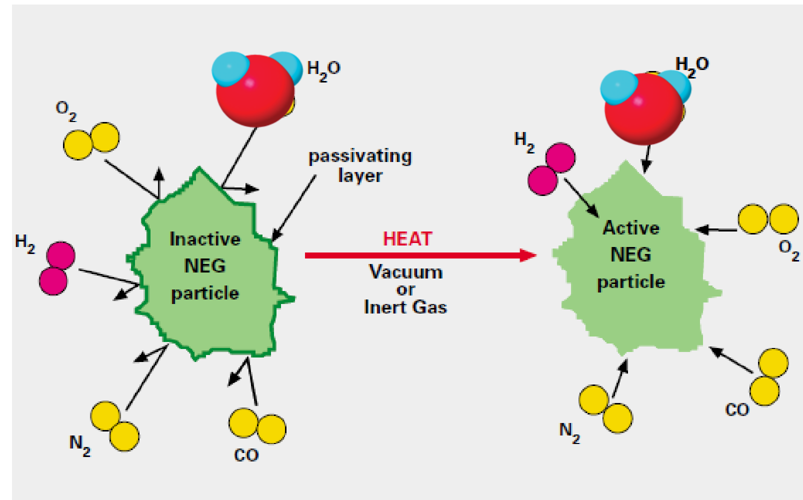
Chemical combination

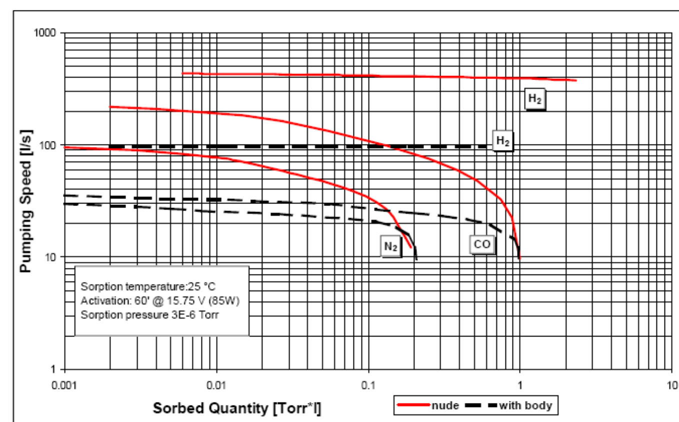


- ✓ Ti evaporation → Deposited fresh Ti layer → Gas-Ti chemical combination
- ✓ No pumping ability for inactive gas (Ar, He, CH_4)

Non Evaporable Getter (NEG)

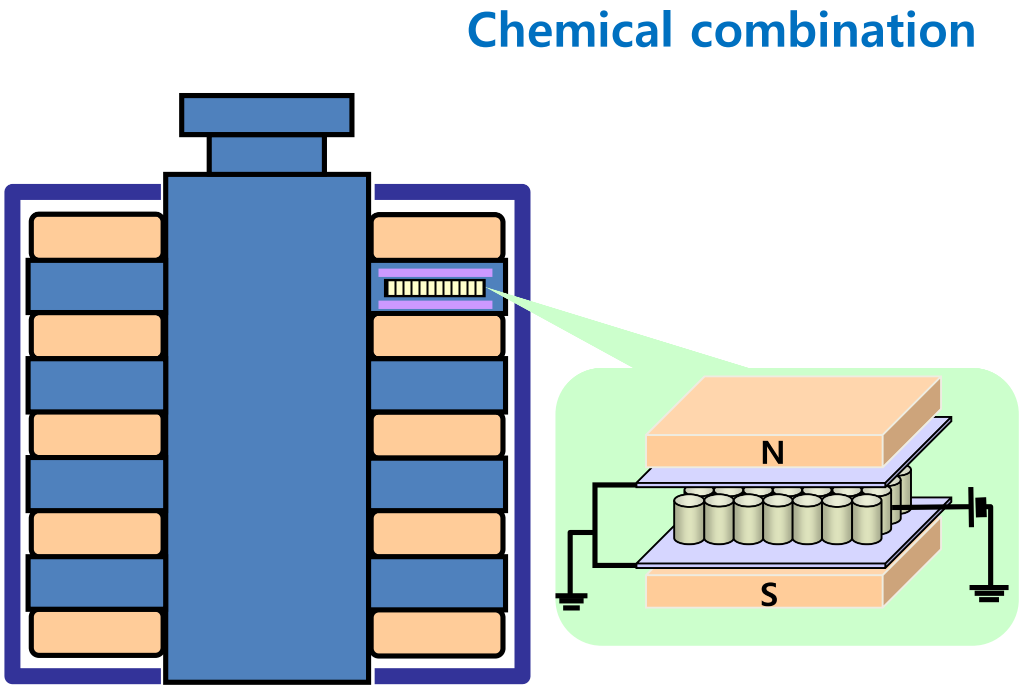
Chemical combination





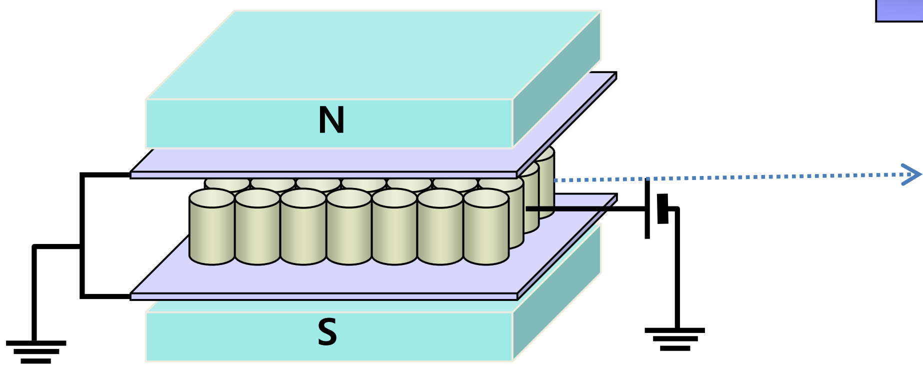
- ✓ **Activation of surface (by heating) → chemical combination**
- ✓ **No pumping ability for inert gas (Ar, He, CH4)**

Sputter Ion Pump (SIP)

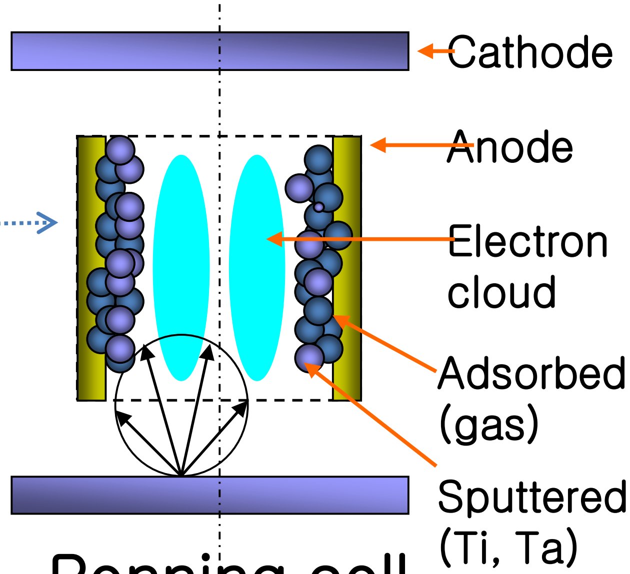


- ✓ **Electron cloud → ionization → high energy impact on Ti plate → Ti Sputtering → Deposited fresh Ti layer → chemical combination**
- ✓ **Pumping ability for CH_4**
- ✓ **Low pumping speed for noble gas (Ar, He)**

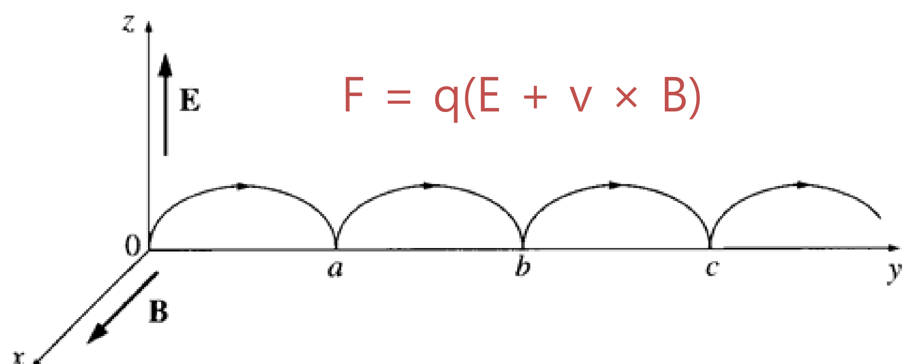
❖ Principle of SIP



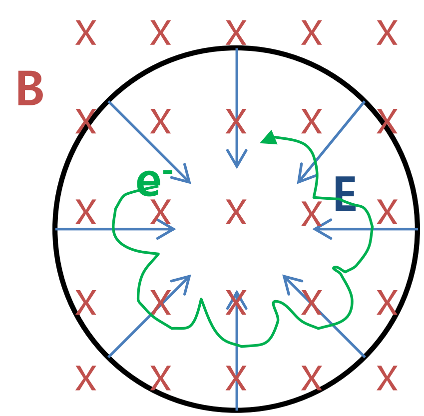
SIP cell module



Penning cell



Cycloid motion in cross field



❖ Argon instability

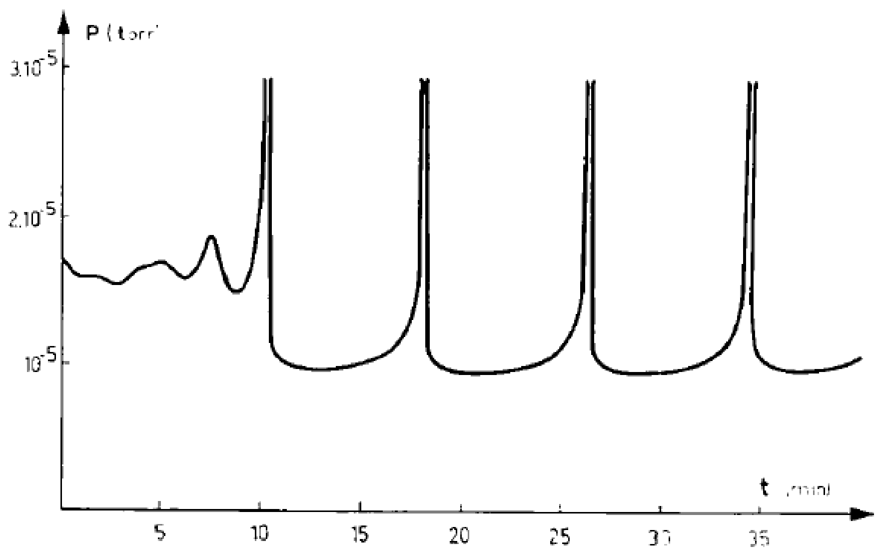
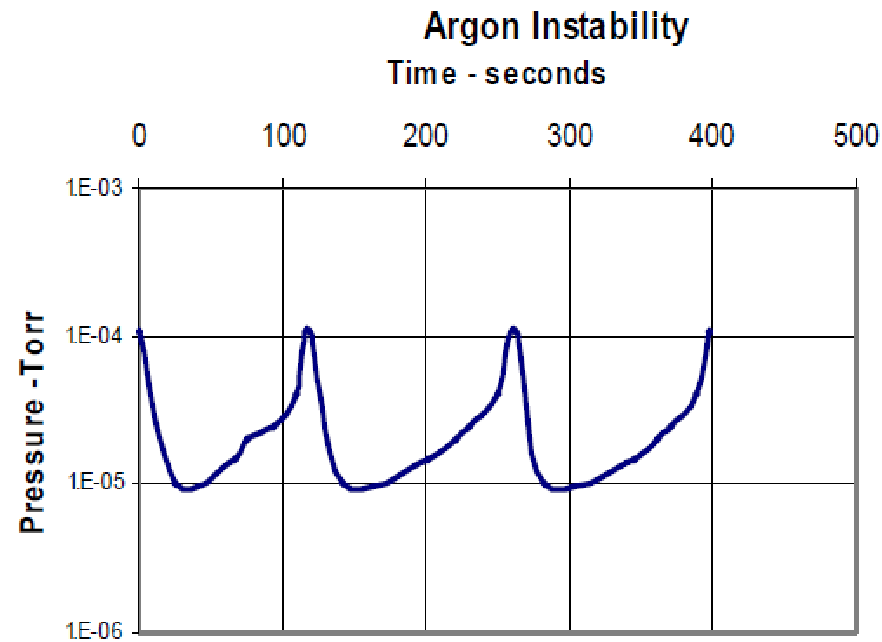
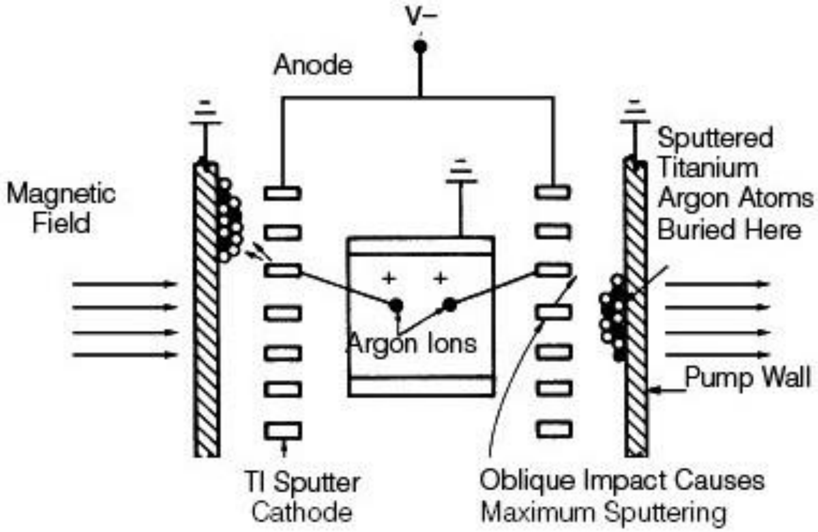


Figure 1. Cyclic instability of Penning pump with a tantalum cathode and a titanium cathode pumping a continuous leak of xenon.

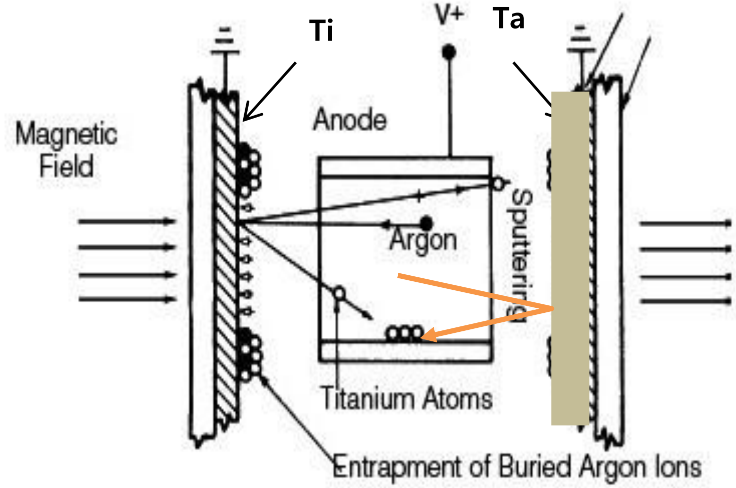
[VACUUM 20(3) 1970, Pages 109–111]



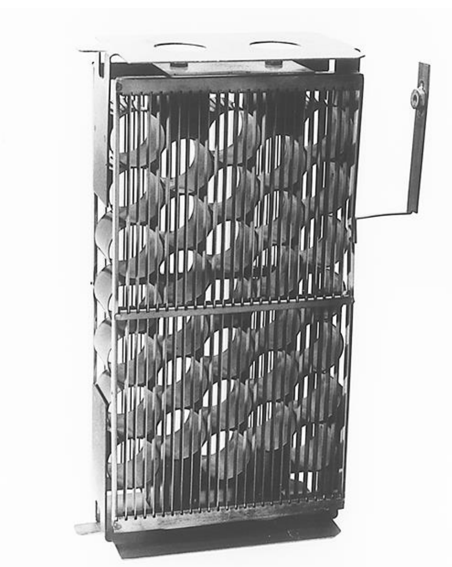
[www.duniway.com]



Triode Ion Pump



Noble diode pump



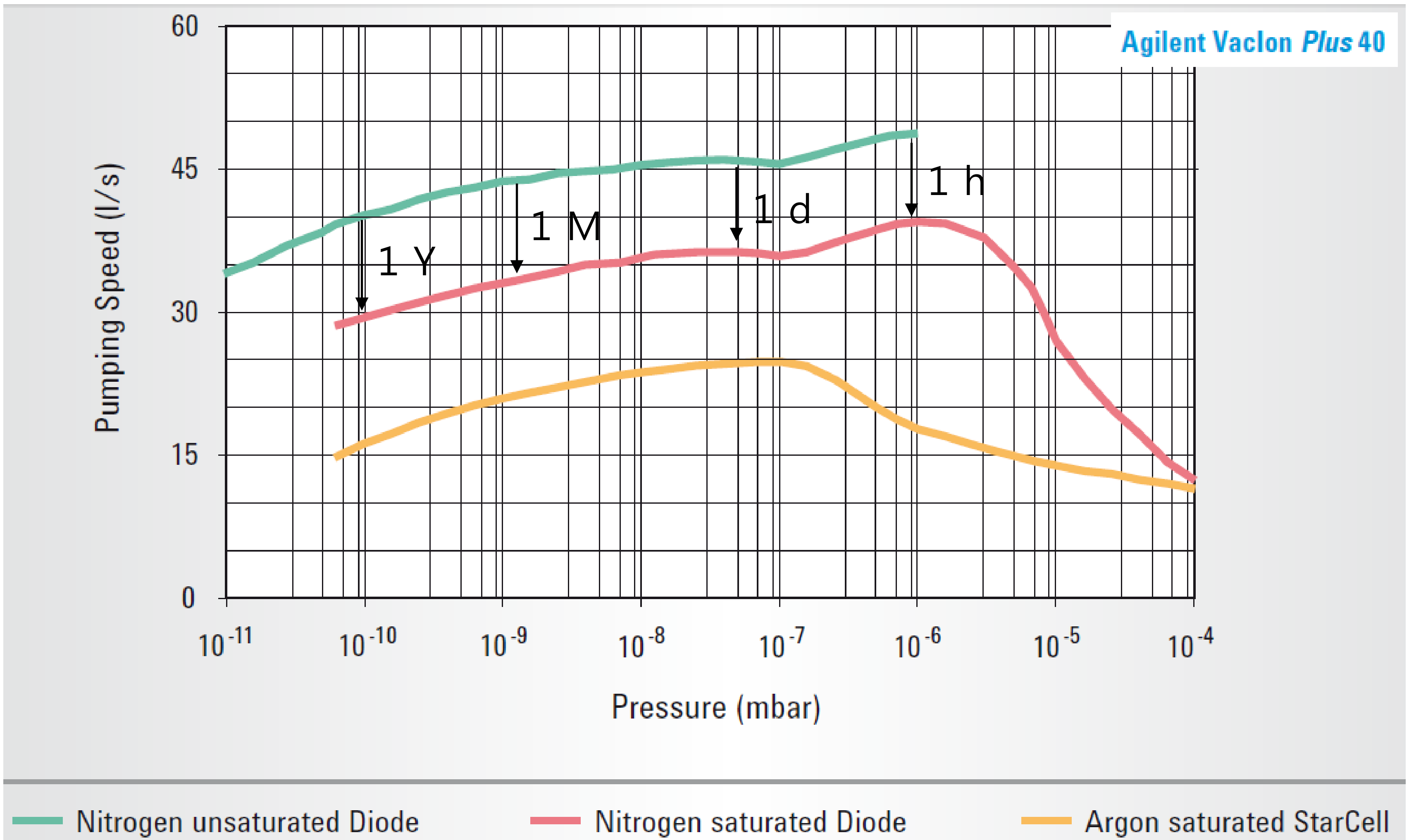
triode

Triode (starcell)

Triode (galaxy)

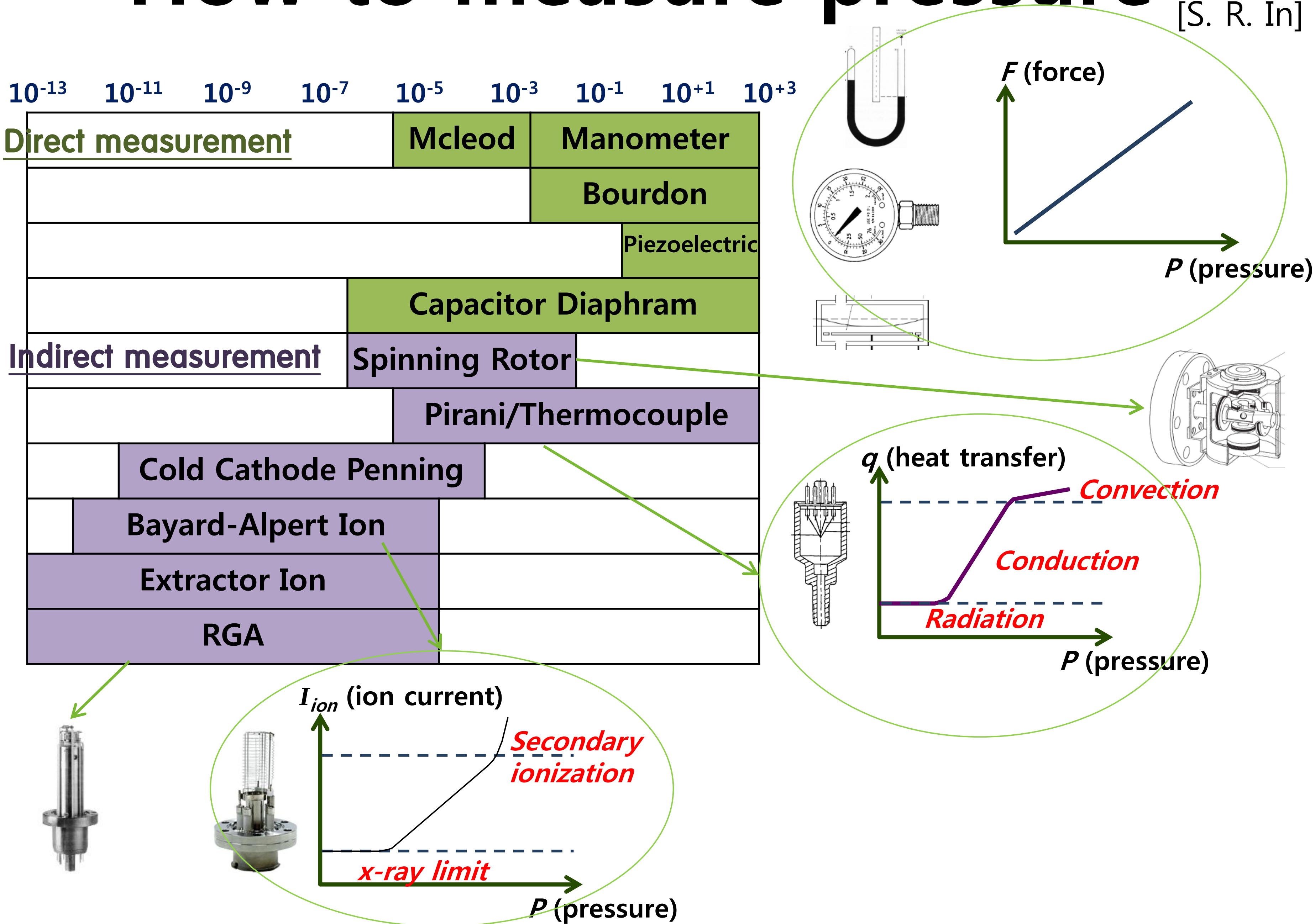
diode

❖ Typical pumping speed curve of SIP

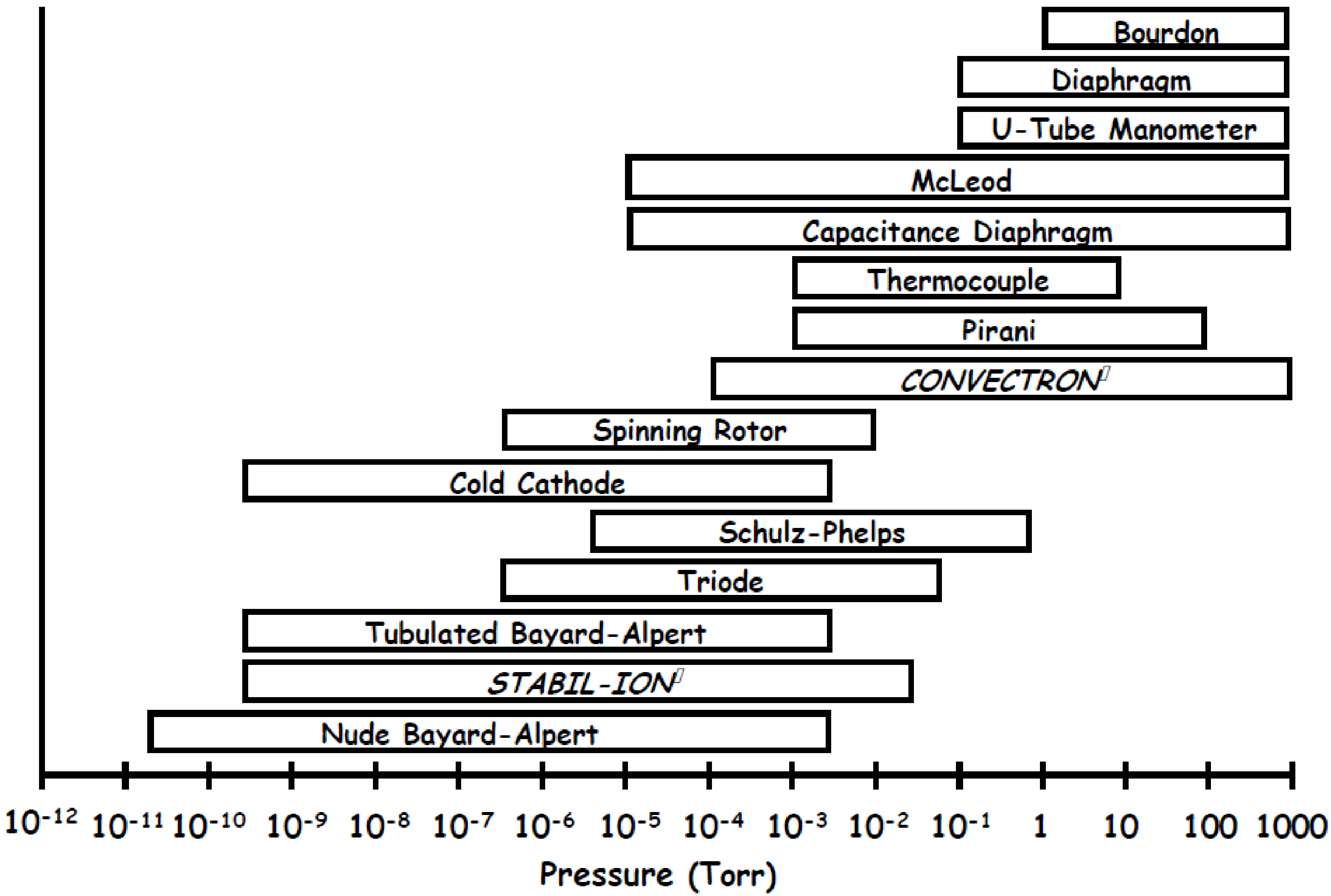


How to measure pressure

[S. R. In]

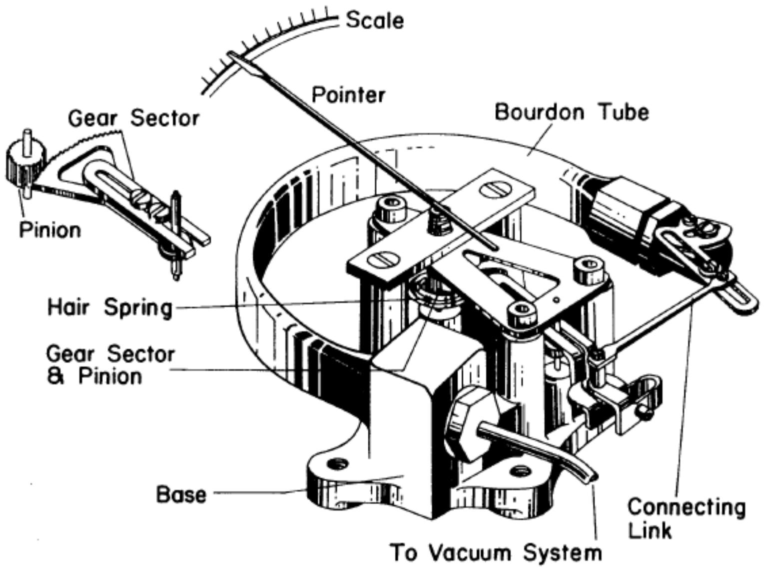


How to measure pressure

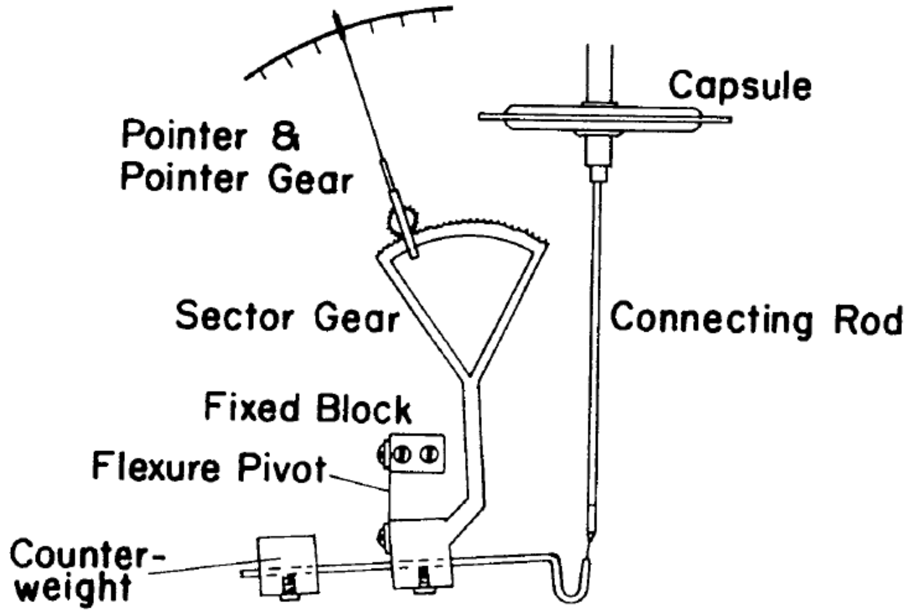


Direct pressure measurement

Direct force on surface



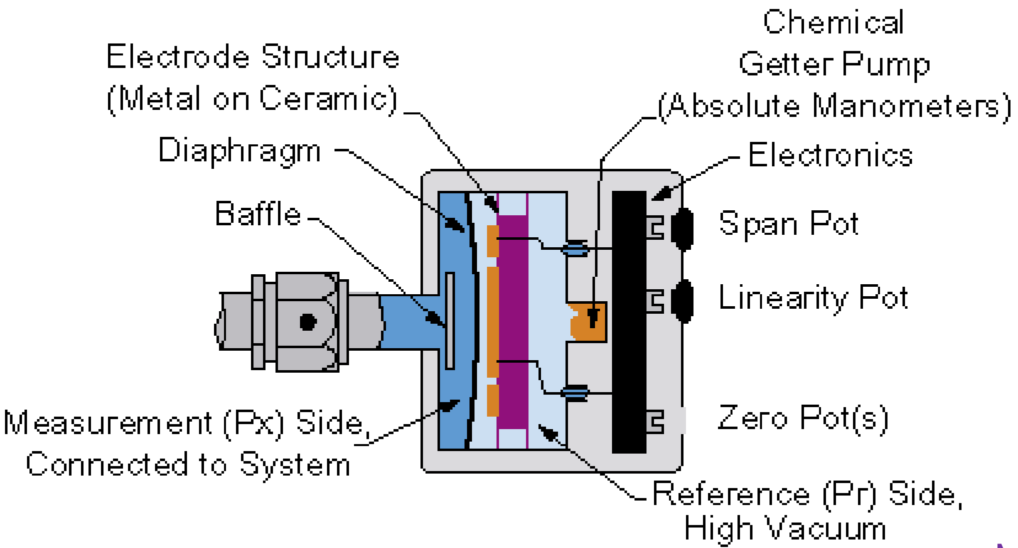
Burdon gauge



Diaphram gauge

Capacitance manometer

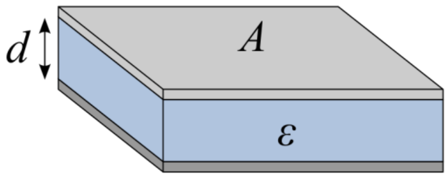
Direct force on surface



MKS

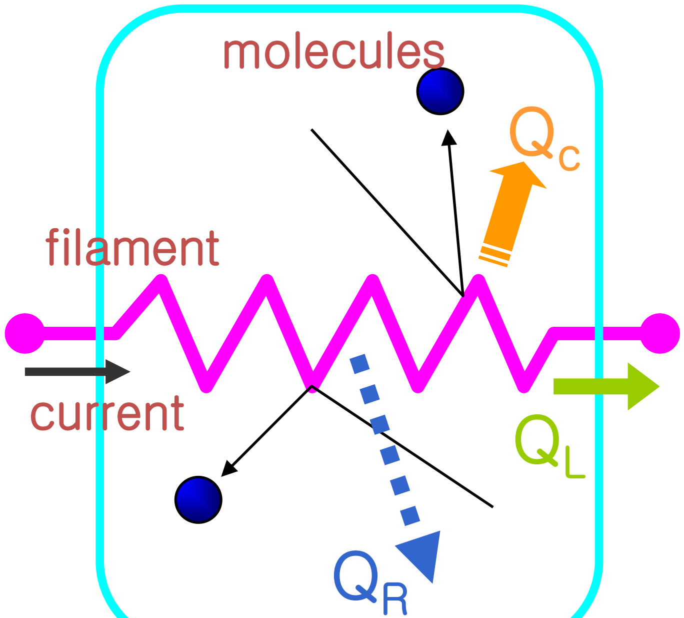
$$C = \varepsilon A/d$$

capacitance

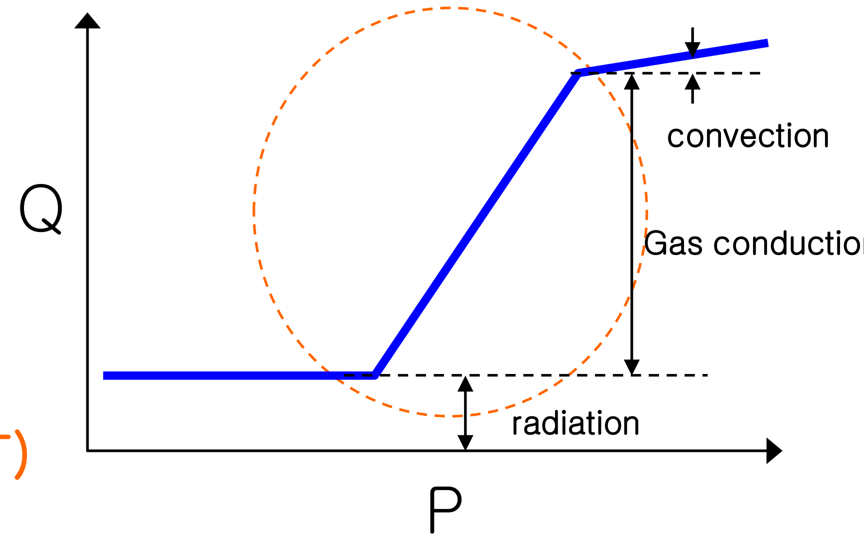


Thermal conduction gauge

Indirect (neutral gas)



$$Q_S = Q_R + Q_L + Q_C$$



Q_R : radiation ($\propto T^4$)

Q_L : wire conduction ($\propto \Delta T$)

Q_C : gas conduction ($\propto P\Delta T$)

Circuit for Pirani type

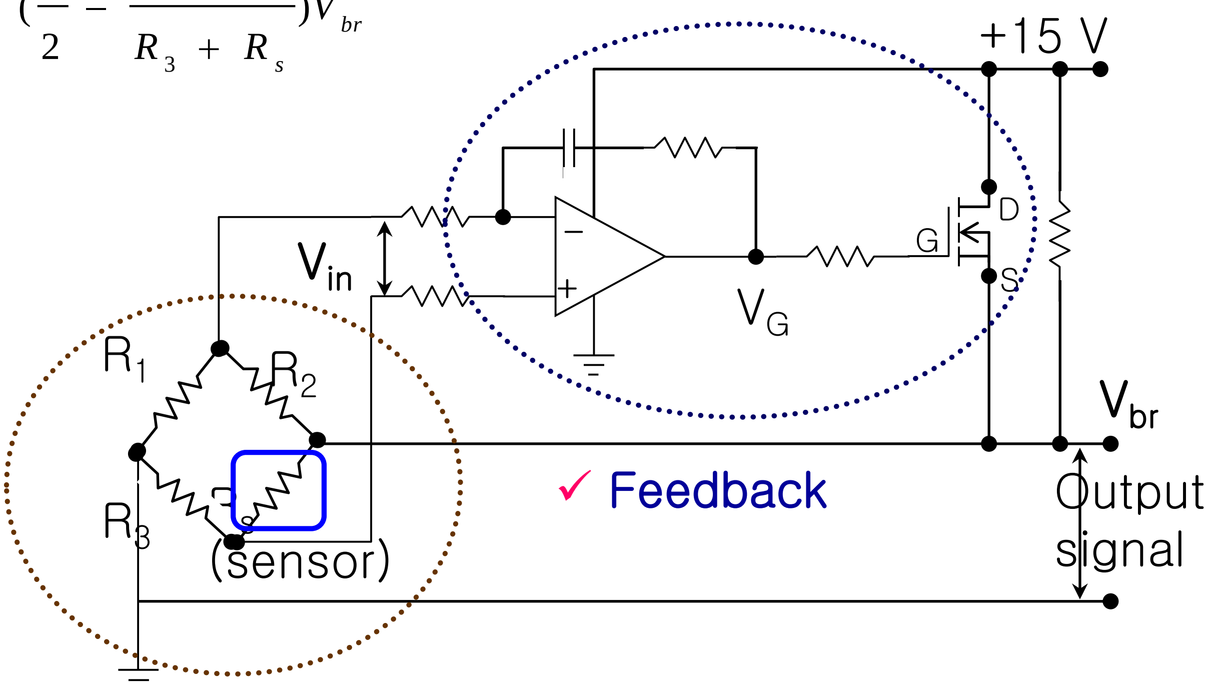
✓ Wheatstone bridge

$$V_{in} = \left(\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_s}\right)V_{br}$$

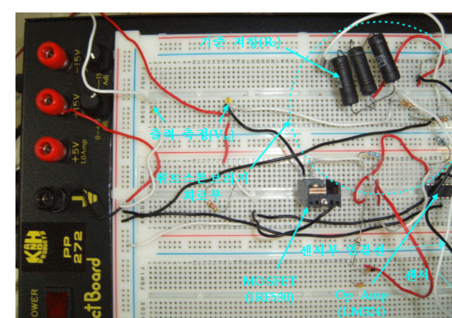
$$= \left(\frac{1}{2} - \frac{R_3}{R_3 + R_s}\right)V_{br}$$

✓ Feedback

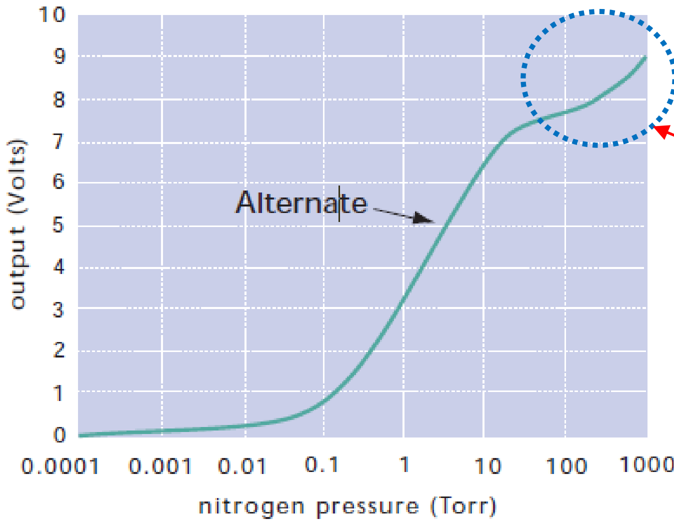
- $R_s < R_3 \rightarrow V_{in} < 0 \rightarrow V_G > 0 \rightarrow I_{DS} > 0 \rightarrow R_s > R_3$
- $R_s > R_3 \rightarrow V_{in} > 0 \rightarrow V_G = 0 \rightarrow I_{DS} = 0 \rightarrow R_s < R_3$



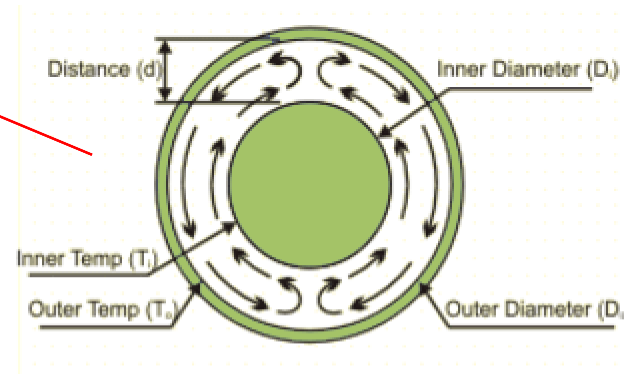
✓ Wheatstone bridge



Convection gauge



Indirect (neutral gas)



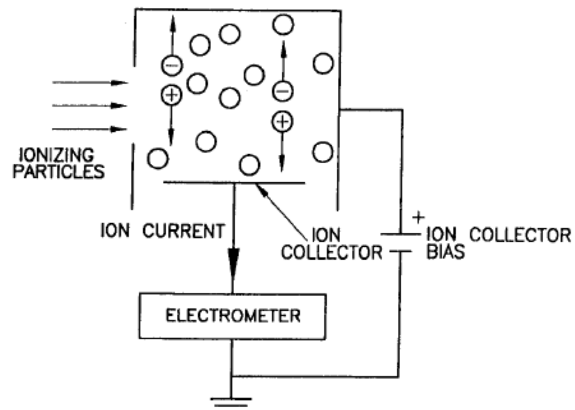
(O)

(X)

Hot filament ion gauge

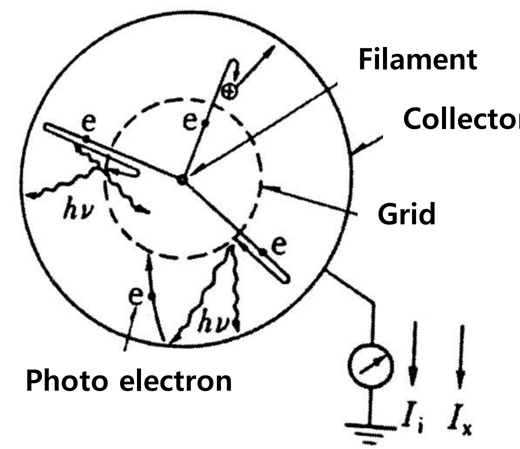
Indirect (ionized gas)

Triode ionization gauge



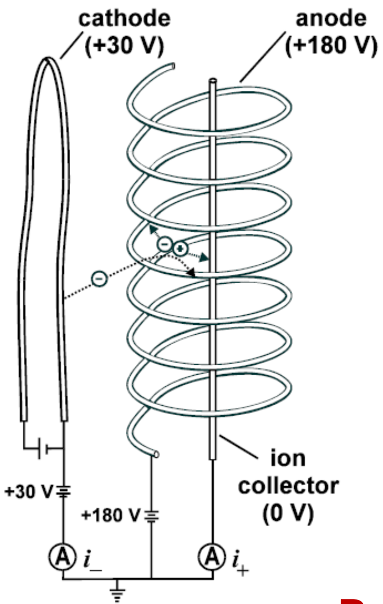
$$I_i = S\, I_e\, P$$

principle

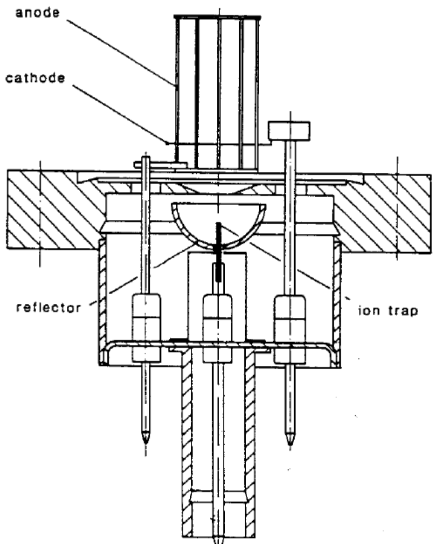


X-ray limit

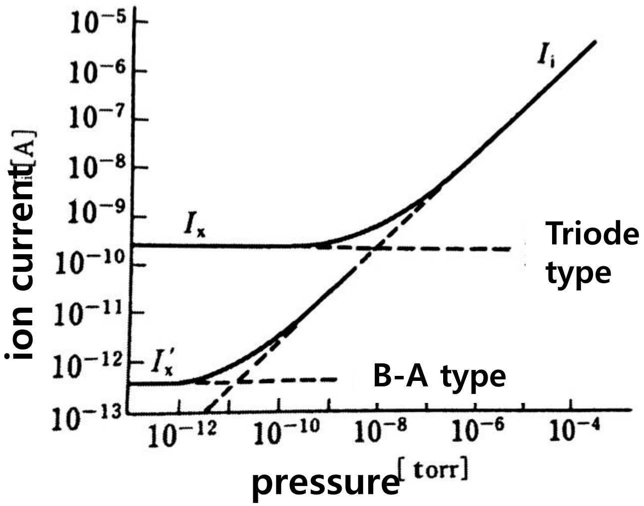
Lower limit of ion gauge



B-A gauge (<10^{-10} mbar)

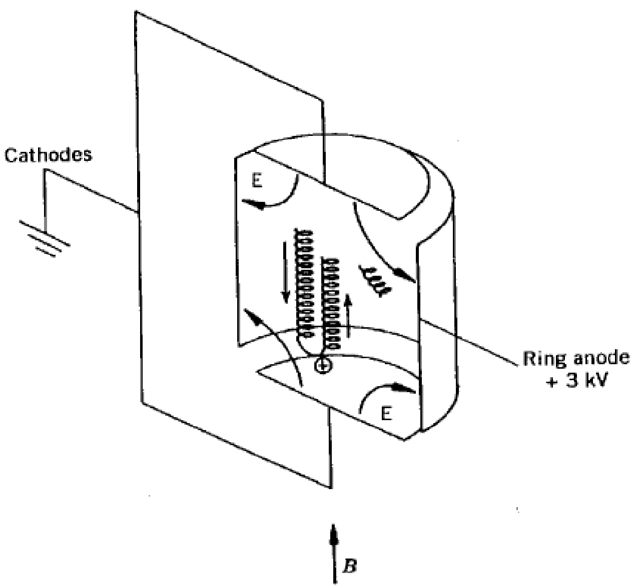


Extractor gauge (~10^{-12} mbar)



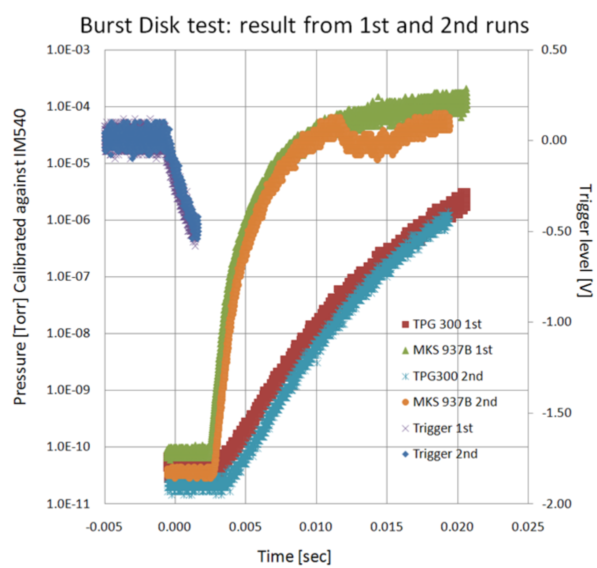
3B gauge (<10^{-14} mbar)

Cold cathode gauge



Penning discharge

Fast response time



Time interval upto 1 x 10^{-7} Torr:
- MKS 937B 1st run = 4.8 ms
- MKS 937B 2sd run = 5.2 ms
- TPG 300 1st run = 13.8 ms
- TPG 300 2st run = 15.0 ms

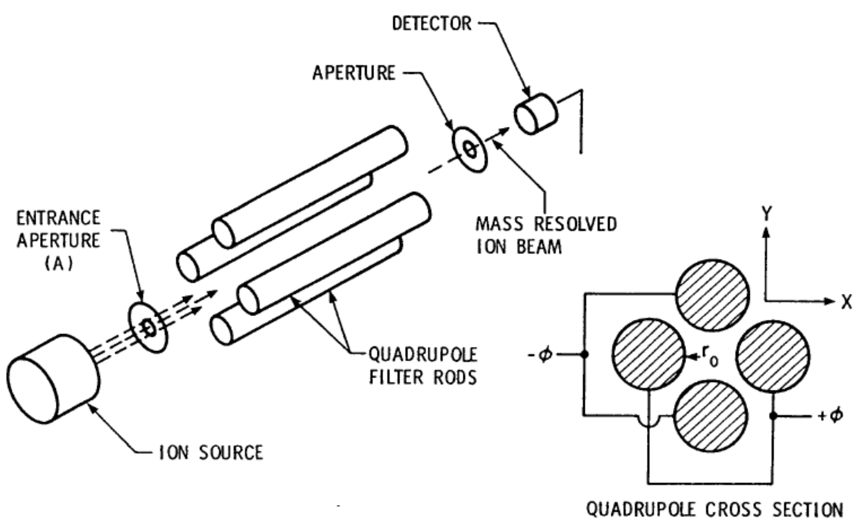
Time travel for the gas reach the gauge using the most probable velocity equation:

Temp = 24 C
M = 28 g/ mol (N_2)
Distance = 100 cm
Time = 2 ms

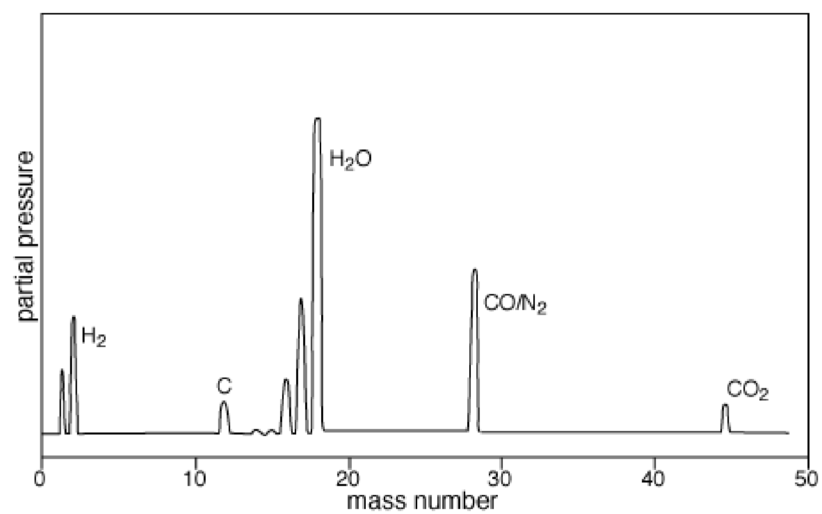
Time response of the controllers at analog port:

MKS 937B = 3-4 ms
TPG300 = 12-13 ms

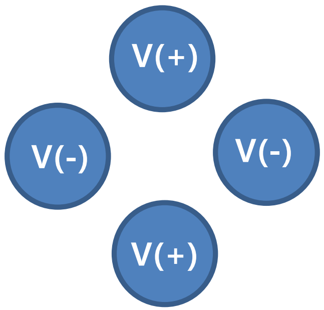
Quadrupole mass filter (RGA)

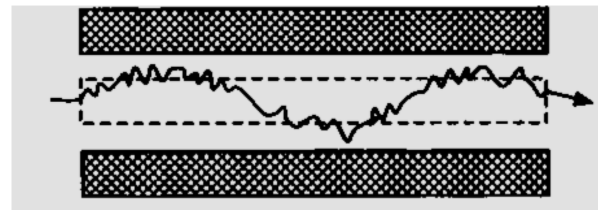


Quadrupole mass filter.

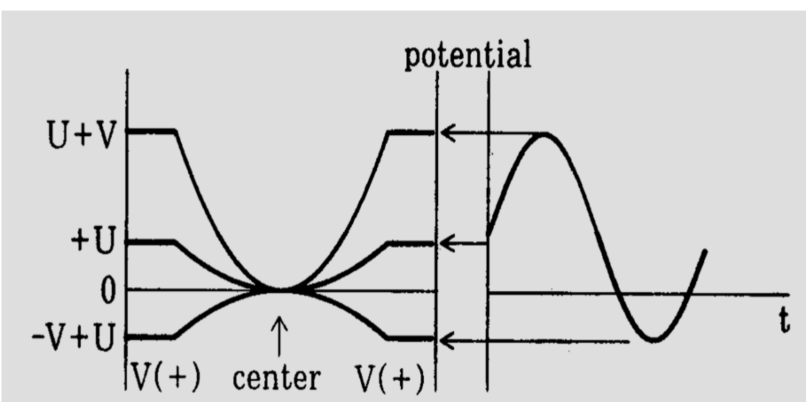


Quadrupole mass filter (RGA)

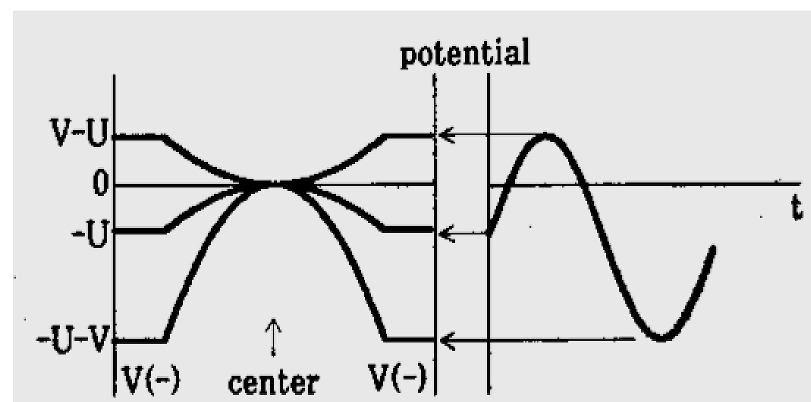




$V(+) = U + V \cos(wt)$
$V(-) = -U - V \cos(wt)$



High pass filter

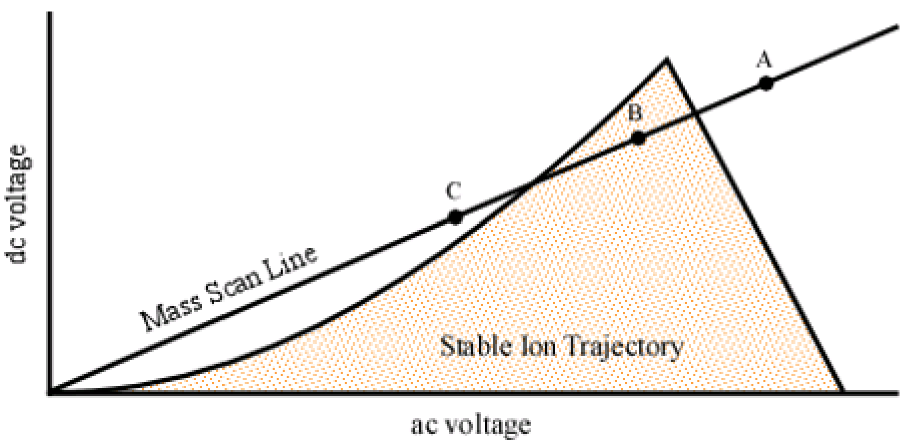


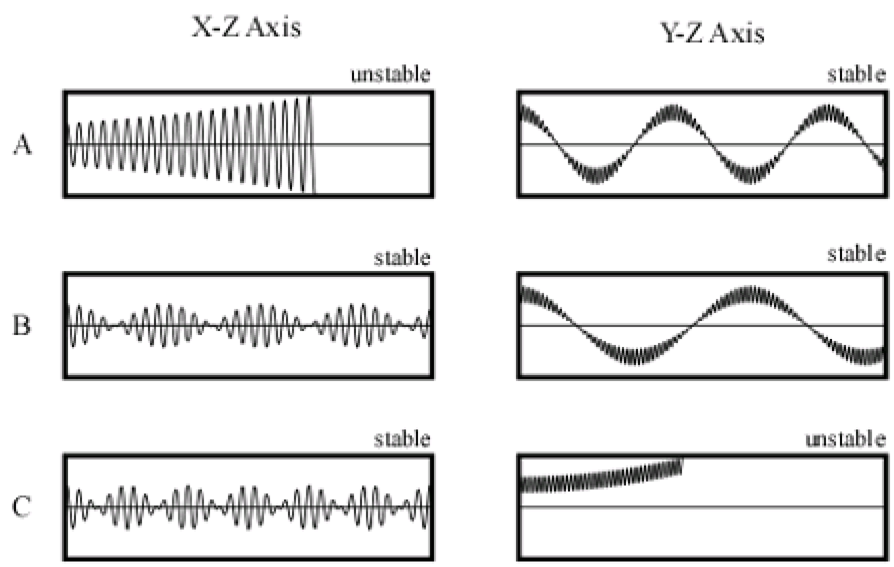
Low pass filter

Quadrupole mass filter (RGA)

"Mathieu Equation"

$$\frac{d^2u}{d\xi^2} + (a_u - 2q_u \cos 2\xi)u = 0 \qquad a_u = \frac{8eU}{mr_0{}^2\Omega^2} \qquad q_u = \frac{4eV}{mr_0{}^2\Omega^2}$$

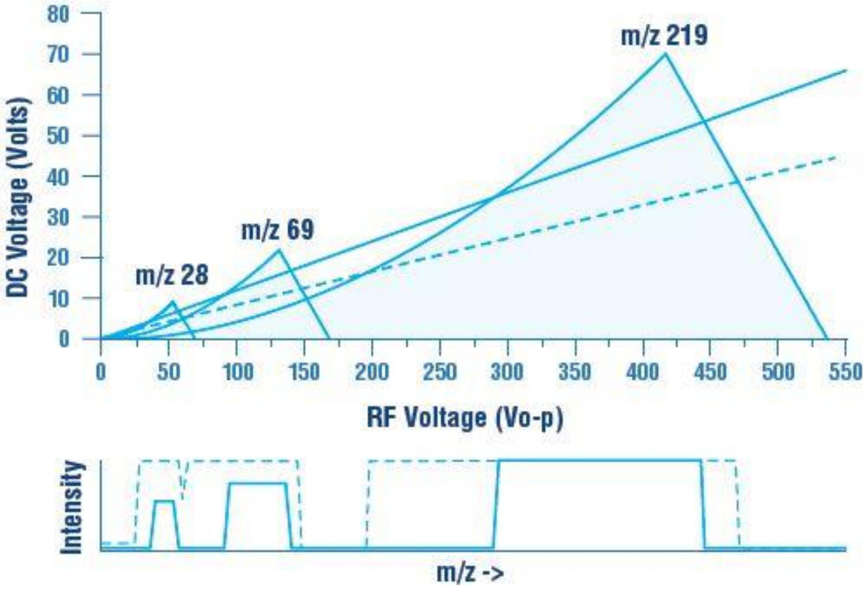




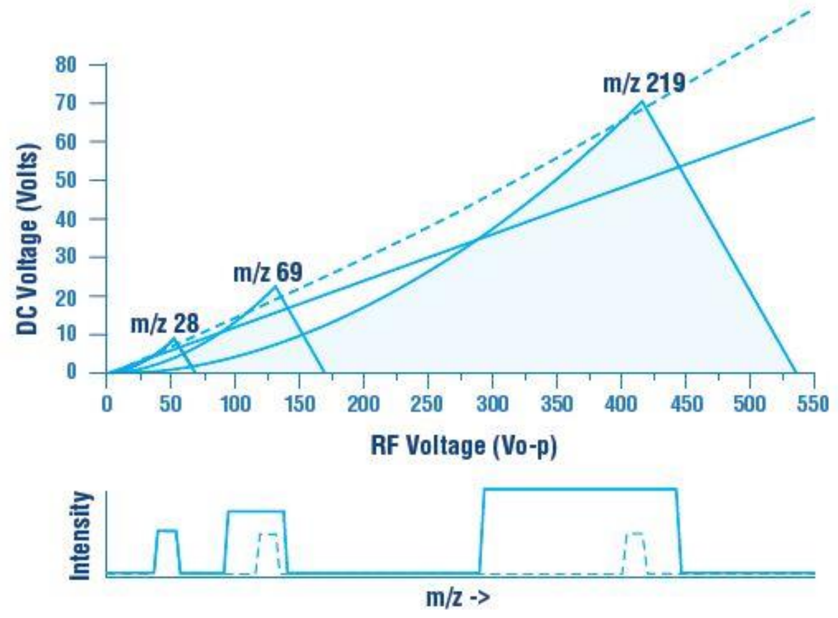
Quadrupole mass filter (RGA)

"Mathieu Equation"

$$\frac{d^2u}{d\xi^2} + (a_u - 2q_u \cos 2\xi)u = 0 \qquad a_u = \frac{8eU}{mr_0^2\Omega^2} \qquad q_u = \frac{4eV}{mr_0^2\Omega^2}$$

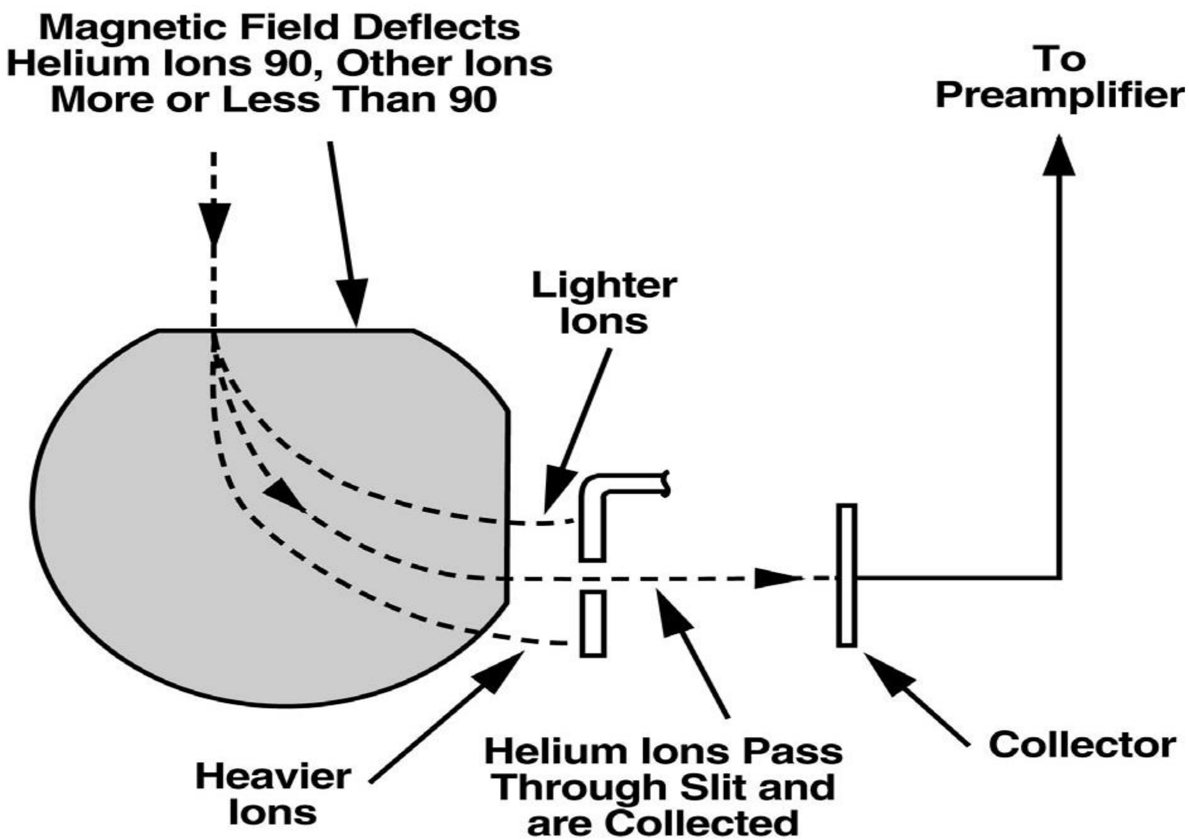


Constant resolution scan

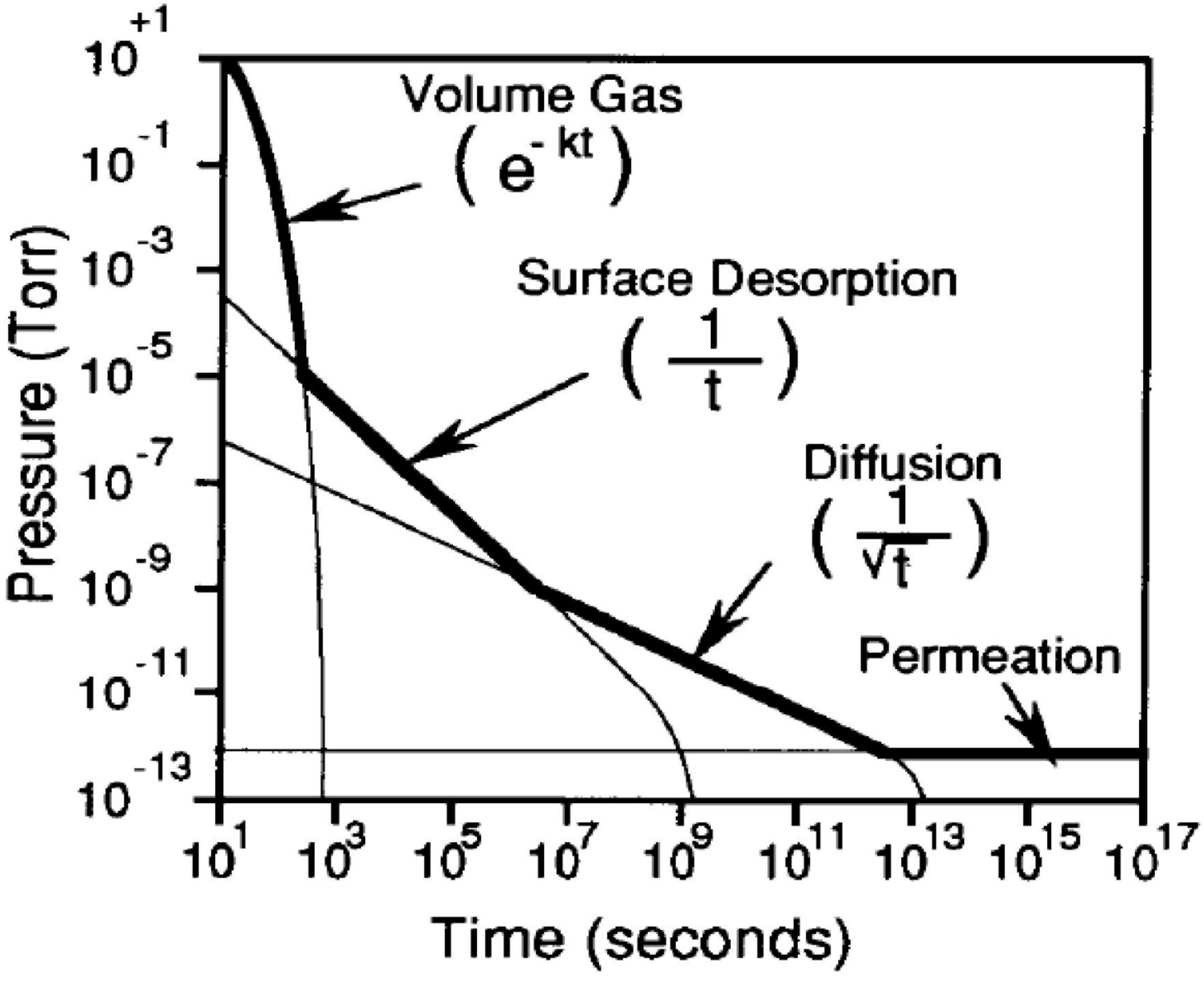


Unit mass resolution scan

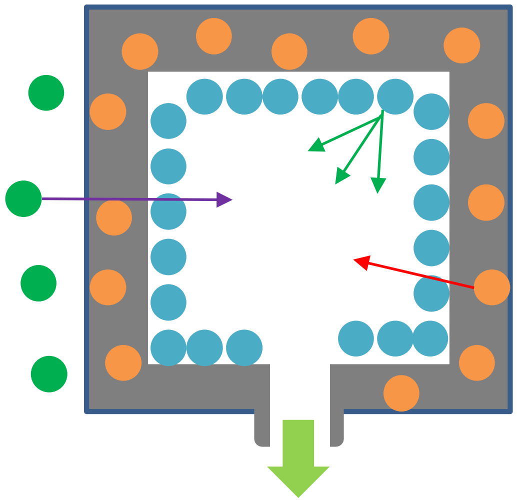
Helium Leak Detection



Pumping Down Process



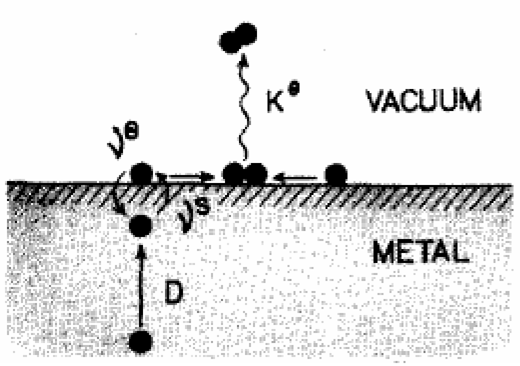
Outgassing Mechanism



- Diffusion and Permeation
  - Well understood

- Adsorption and desorption
  - No clear explanation for the surface desorption
  - 2D Fermion behavior of water on surface

Hydrogen outgassing model



- Diffusion Limited Model (DLM)
  - Concentration gradient

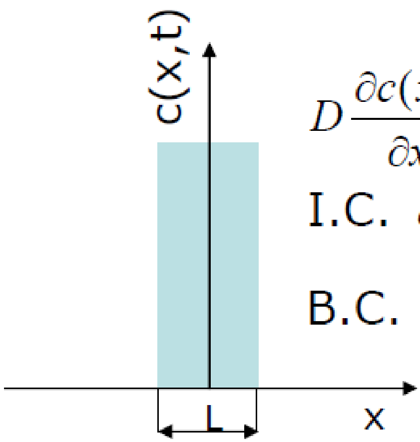
$$q(t) \propto -\frac{\partial c}{\partial x}$$

- Recombination Limited Model (RLM)
  - Concentration on the surface

$$q(t) \propto c_s^{\ 2}$$

Intensity of heat treatment (F_o)

- Solution of diffusion equation for slab



$$D\frac{\partial c(x,t)}{\partial x^2} = \frac{\partial c(x,t)}{\partial t}$$

I.C. $c(x,0) = c_o$

B.C. $c(\pm\frac{L}{2},t) = c_w$

$$q \approx \frac{4\cdot(c_0 - c_w)\cdot D}{L}\exp\left[-\pi^2\cdot\frac{D(T_H)\cdot t_H}{L^2}\right]$$

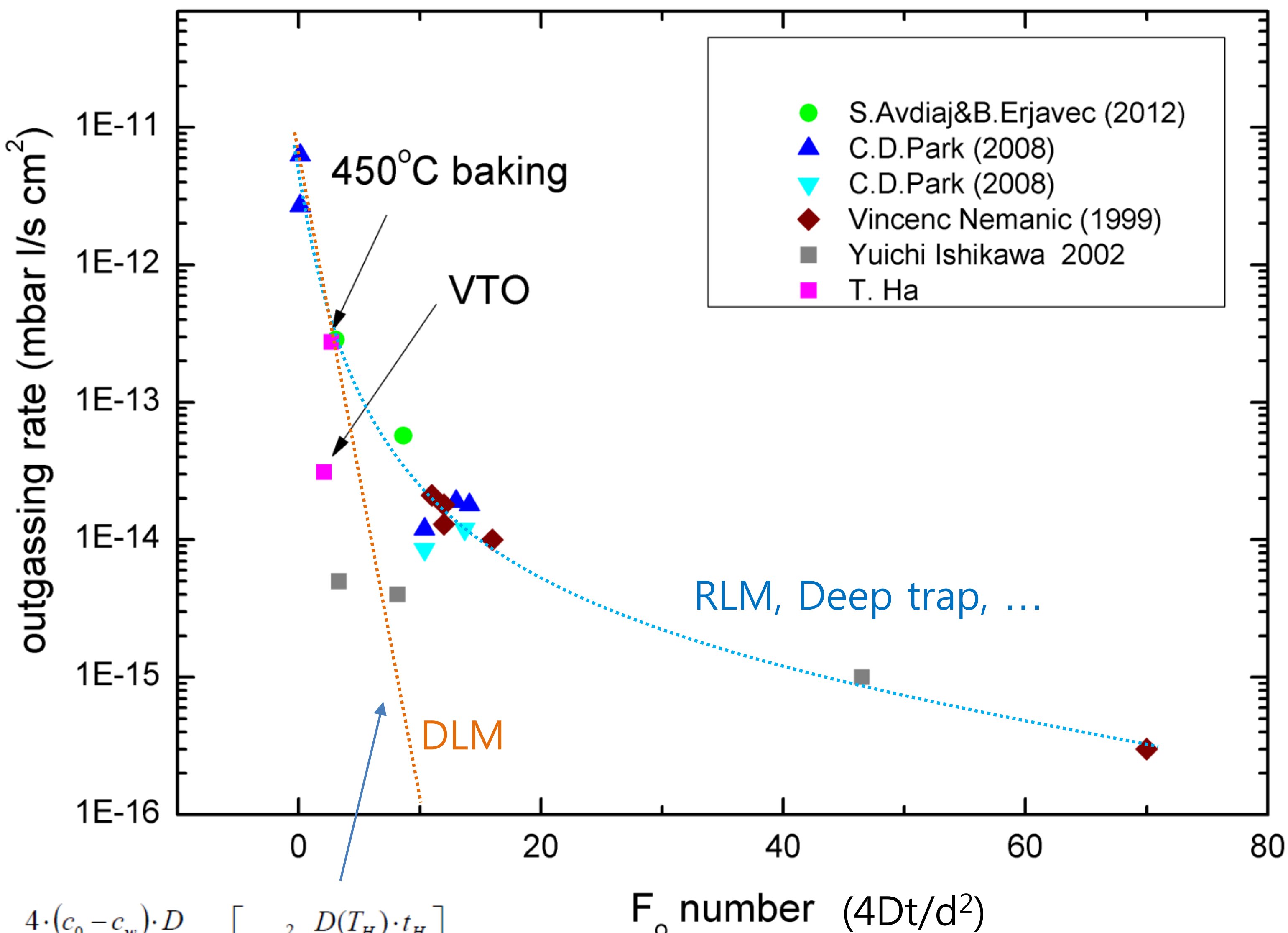
- For arbitrary thermal cycle (thermal history)

$$q \approx \frac{4\cdot(c_0 - c_w)\cdot D}{L}\exp\left[-\pi^2\cdot\frac{\int_0^{t_H} D(T)\cdot dt}{L^2}\right]$$

Fourier number

$$F_o = \frac{\int_0^{t_H} D(T)\cdot dt}{L^2}$$

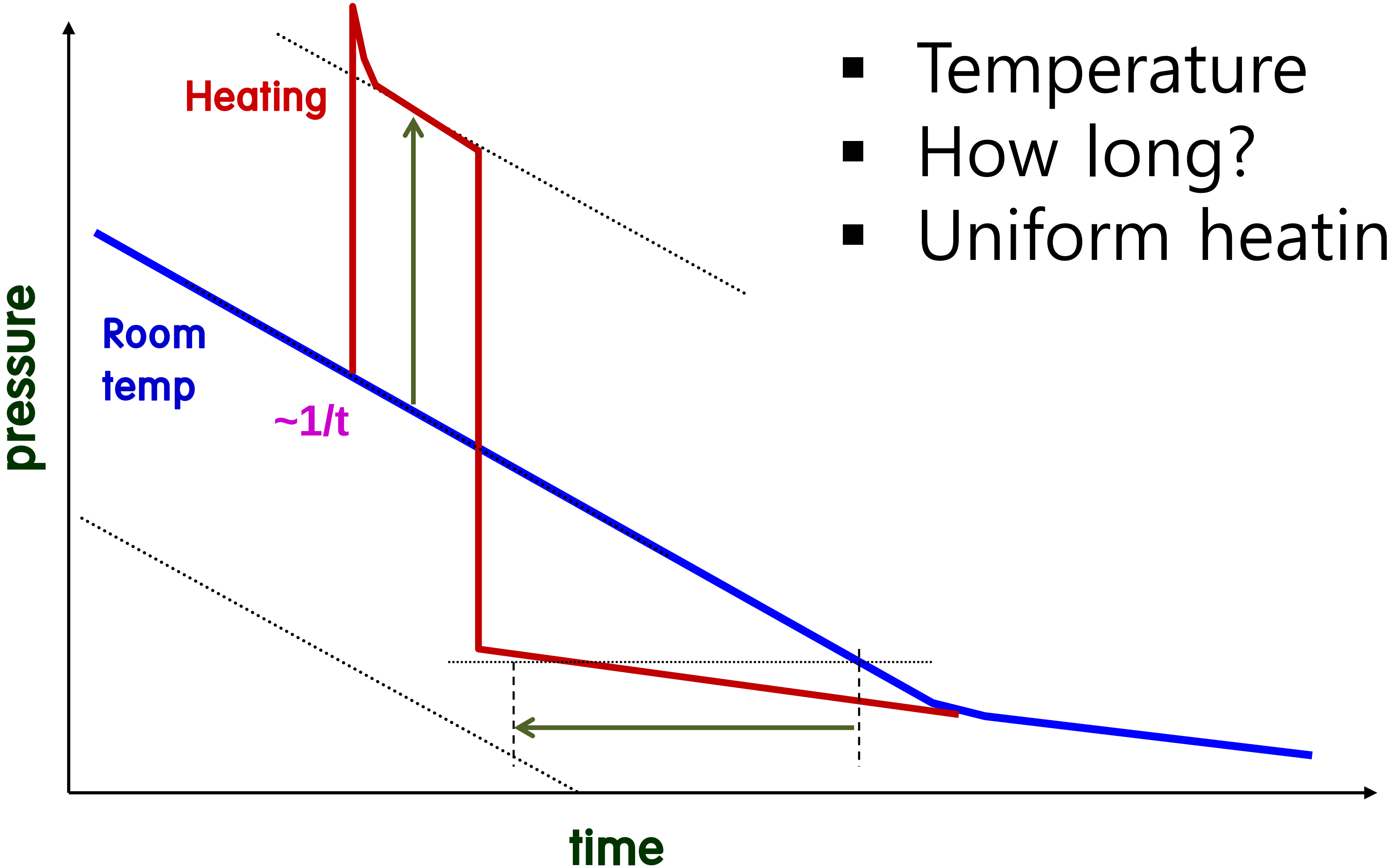
Outgassing rate vs. Fourier number (F_o)



$$q \approx \frac{4 \cdot (c_0 - c_w) \cdot D}{L} \exp\left[-\pi^2 \cdot \frac{D(T_H) \cdot t_H}{L^2} \right]$$

Bake-out

[S. R. In]



- Temperature
- How long?
- Uniform heating

Vacuum Materials

Steels

Stainless Steel

Aluminum (alloy)

Copper (alloy)

Other metals

Ceramics

Glass

Plastics

Steels

- Mild/structural steels
  - ✓ Carbon < 0.3 %
  - ✓ outgassing rate
    - ■ ~~q > (20~200)x STS~~
    - ⇢ q_{rd} > (20~200)x STS, $q_{H2} \lesssim$ STS
    - ■ ~~HV compatible (10^{-6} mbar), endless emission of CO~~
    - ⇢ UHV compatible, $RegGas_{ST}$ ~ $RegGas_{STS}$
  - ✓ Weldable
  - ✓ Easy to corrode
    - ✓ Needs anti-corroding coating
  - ✓ Magnetic
    - ✓ Shielding material for magnetic field

[C.D. Park et al., JVSTA **34**, 021601 (2016)]

Steels

- Mild/structural steels
  - ✓ S235, S355, S20C
  - ✓ UHV compatible
    - plate, pipe, rod
    - ~ 10^{-11} mbar
    - $\lesssim$ $5x10^{-12}$ (mbar l/s cm^2) after bake
  - ✓ MV, RV compatible
    - Cast parts; pump and valve housing
    - ~ 10^{-3} mbar

Stainless steel

18-8 Steel Family

Stainless steel

- Role of ingredients
  - Cr(10%) Resistance to oxidation
  - Ni(8%) Austenitic structure/Anticorrosion
  - Mo Accelerates passivating film formation
  - W Mechanical resistance at high temperature
  - Ti During welding and cycles stabilizes the austenitic structure
  - N Mechanical characteristics

Mechanical properties

	Yield strength (0.2%)	Tensile strength
	MPa	MPa
316	206.8	517.1
316L	172.4	482.6
A6061-T6	241	289.4
A6063-T5 - T6	110	152

Aluminum (alloys)

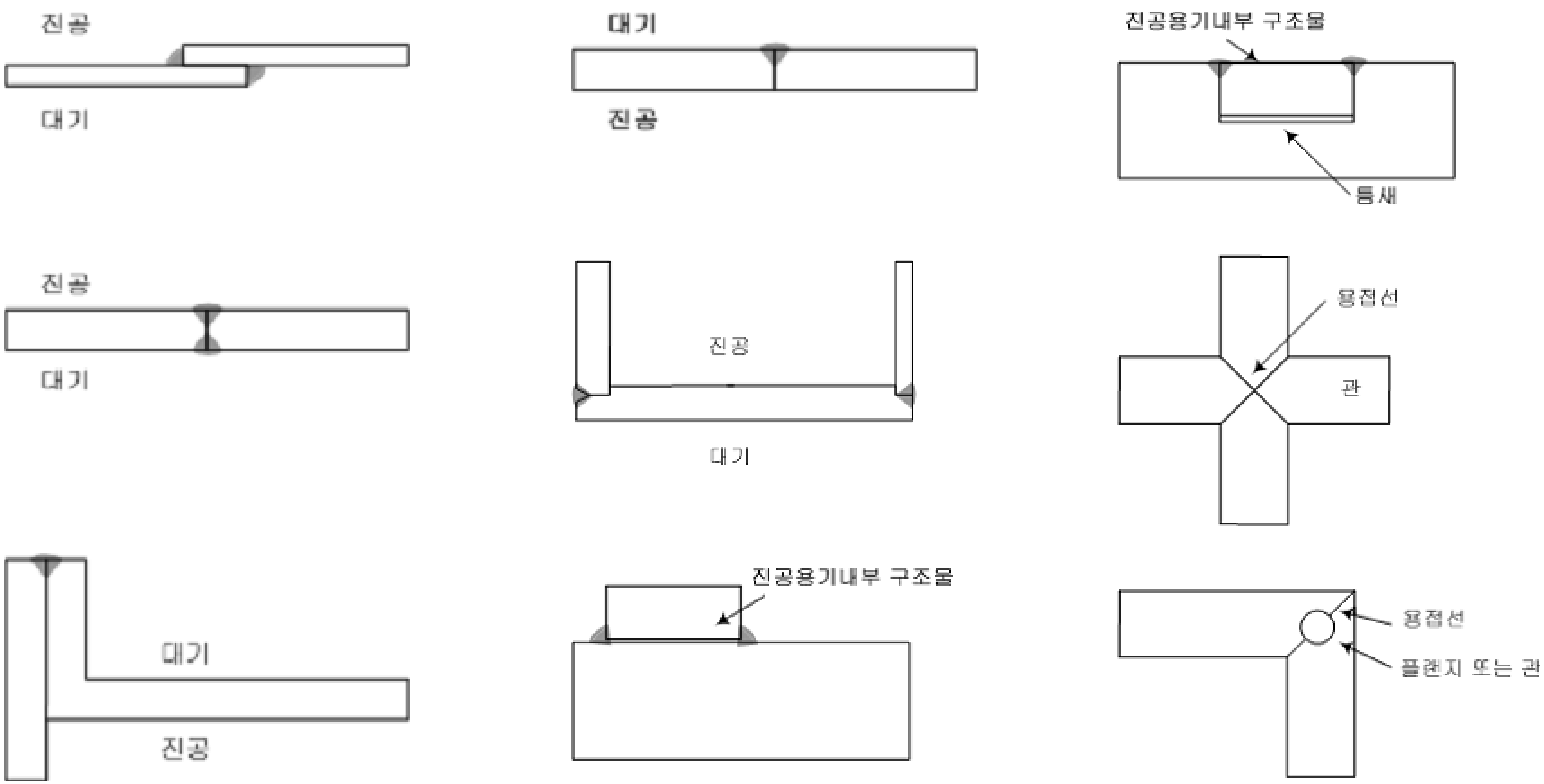
- 1xxx pure aluminum
  - ✓ > 99% Al by weight
  - ✓ A1050; suitable for metal gaskets

- 2xxx copper alloys
  - ✓ Duralumin; once the most common aerospace alloys (they were susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs.)
  - ✓ A2219; suitable for Conflat flange (weldable)

Aluminum (alloys)

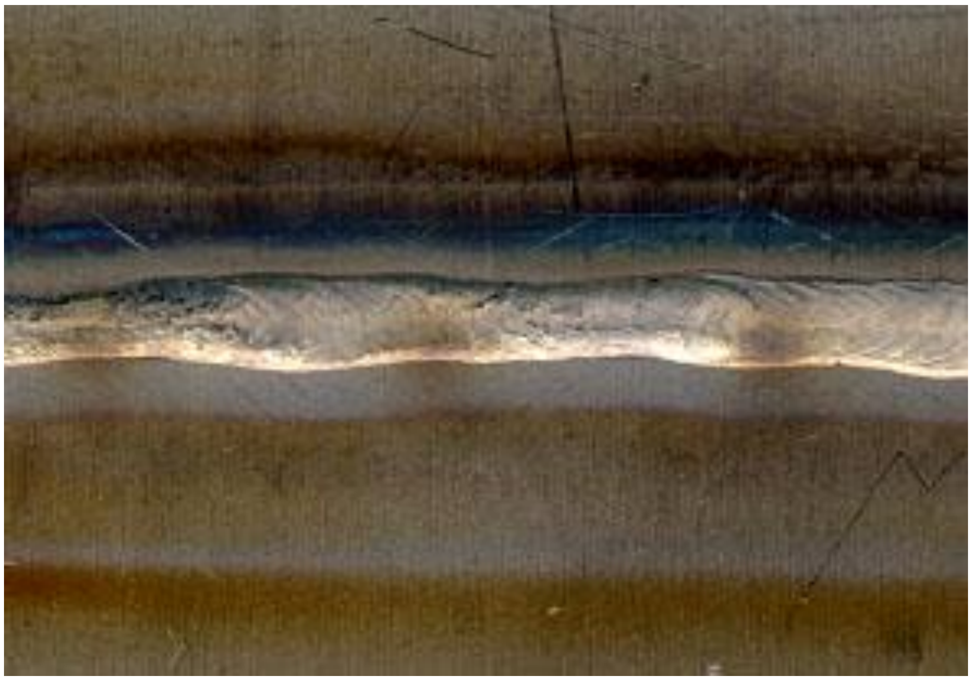
- 3xxx manganese alloys
  - ✓ A3004; suitable for vacuum bellows
- 5xxx magnesium alloys
  - ✓ easy to machine, higher strength, good weldibility
  - ✓ A5083; for a large scale chamber
- 6xxx magnesium and silicon alloys
  - ✓ Easy to machine and extrude
  - ✓ A6063; most common materials in vacuum technology
  - ✓ A6061; one of the most vacuum materials
  - ✓ A6060; extrusion

피해야 하는 용접

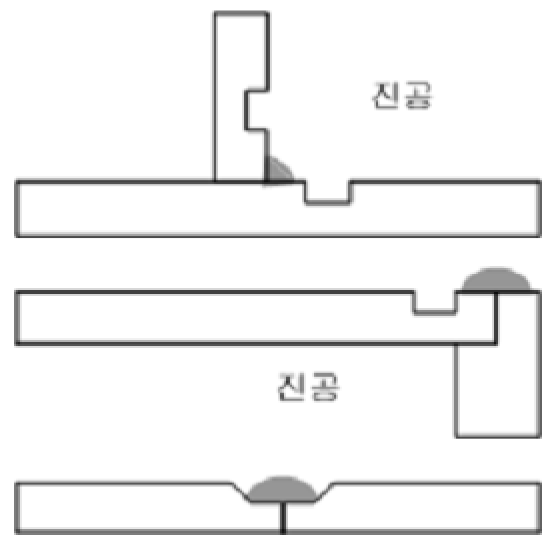


→ “초고진공 용접핸드북*(KRISS)*”

Stainless steel



Aluminum alloy



Copper (alloy)

- High thermal and electrical conductivity
  - Suitable for electrical feedthrough
  - Suitable for thermal/radiation absorber
  - Suitable for cryogenic applications
- Hydrogen embrittlement
  - For HV and UHV, coppers(alloys) with oxygen free or reduce d oxygen contents are required.
- Bakeout; Up to 300^{o}C in vacuum
- Cold welding; OFHC gasket for ConFlat flanges
- Joining techniques; brazing, soldering, welding
- Outgassing rate; ~ 10^{-9} mbar liter/sec cm^2

Copper alloy

- To increase its strength
  - OFC + Al_2O_3(0.1-0.5%) GlidCop
    - Yield strength(at 0.2% offset) > 200 MPa (OFC < 100 MPa)
  - OFC + Ag or $Au_{0.2\%}$ Expensive (x 4)
  - OFC + Zr High outgassing rate
  - OFC + Be Brazing(X), EBW(O)
  - OFC + Cr

Ceramics

- Pure oxide ceramics
  - ✓ Alumina, Zrconia, Beryllium oxide,…
  - ✓ Alumina (Al_2O_3)
    - Mostly used ceramics
    - Max temperature; 1,800^{o}C
    - > 92% in vacuum technology
    - Can be brazed
    - Mainly used as electrical *feedthroughs/insulator*
      - Bakable upto 350-550^{o}C
    - Tensile strength 25 kpsi (96% density)
  - ✓ Sapphire (monocrystalline Al_2O_3)
    - UV and IR transparent
    - Used as *vacuum window*

Ceramics

- Silicate ceramics
  - ✓ Steatite (MgO-SiO_2)
    - Max temperature 1,000°C
    - Tensile strength 15 kpsi
- Glass-ceramics
  - ✓ Crystalline ceramic
    - Can be machined with standard tools
    - Macor®, Corning 9658

Ceramics

- Kovar
  - ✓ Fe-Ni-Co alloy (thermal expansion ~ glass)
  - ✓ Magnetic
  - ✓ Intermediate material between ceramic and metal for brazing joint

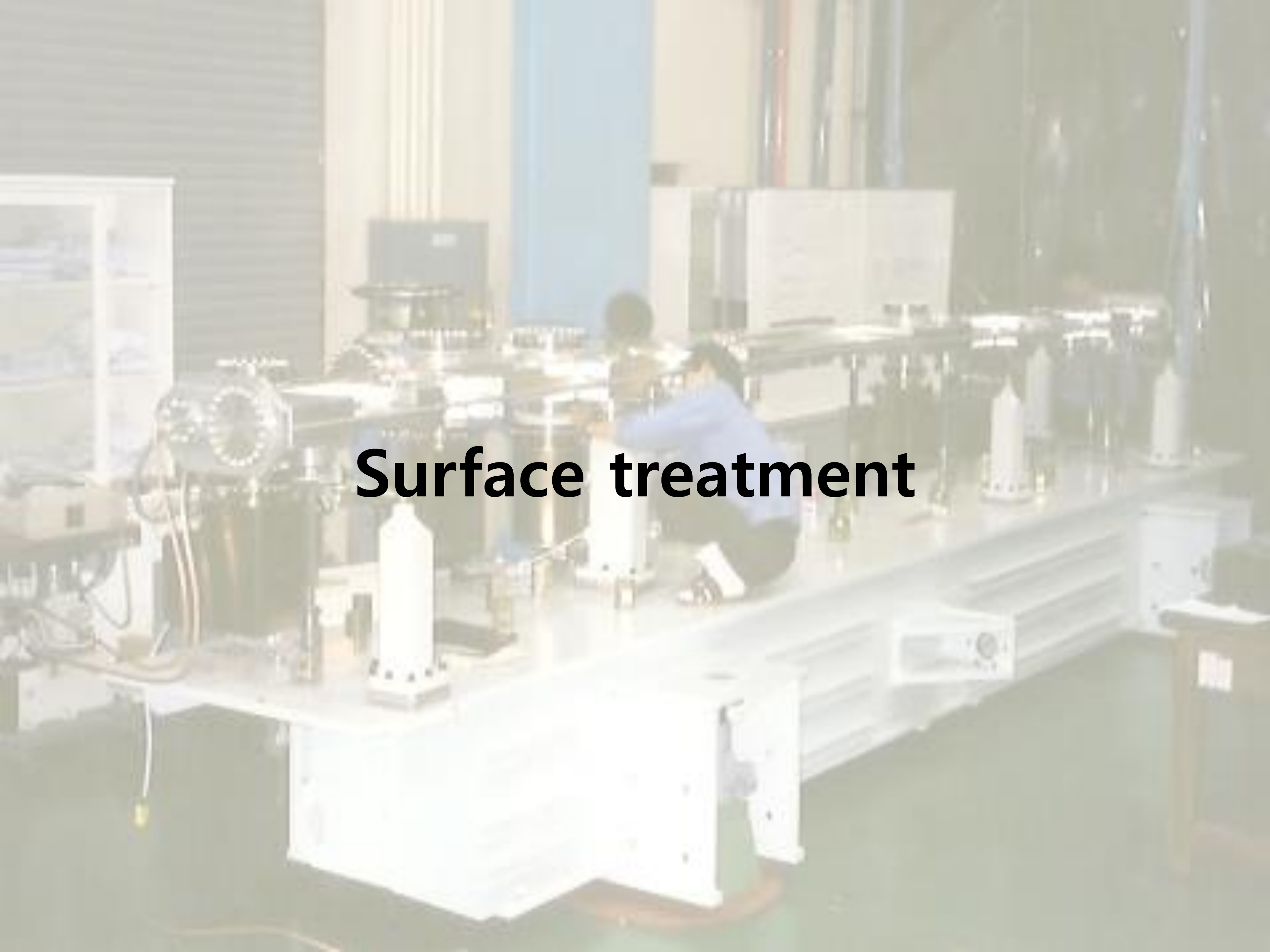
Glass

- Glasses
  - ✓ Non-metal, inorganic materials
  - ✓ Mainly used as *vacuum windows*
    - ✓ Also used in helium permeation leaks
- Three types of glasses
  - ✓ Soft glass: $60 \cdot 10^{-7}\ K^{-1} – 120 \cdot 10^{-7}\ K^{-1}$
  - ✓ Hard glass: $<50 \cdot 10^{-7}\ K^{-1}$
  - ✓ Quartz glass: $\sim 5 \cdot 10^{-7}\ K^{-1}$

Glass

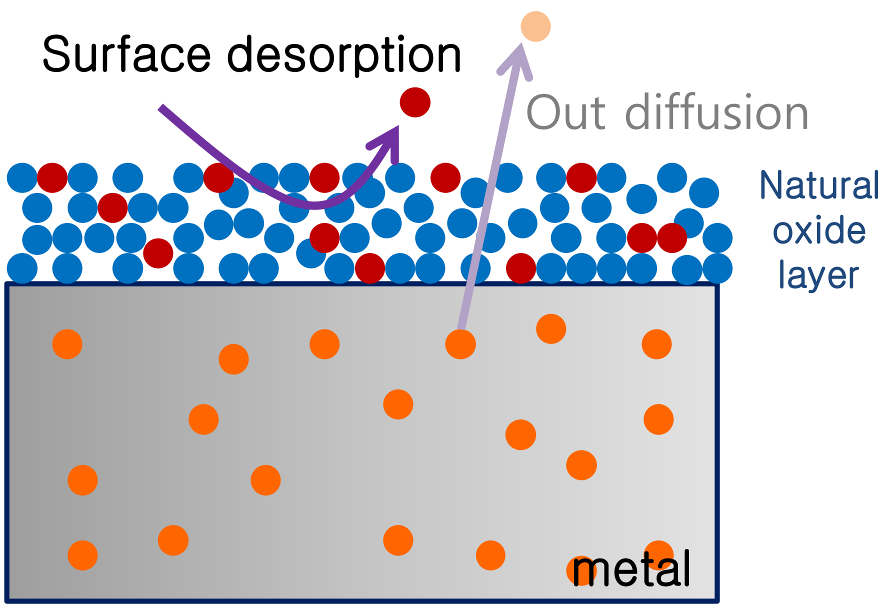
- Soft glass(SiO_2 +Alkali)
  - 65–70% SiO_2, 2.5–15% Na_2O, 5–15% CaO
- Hard glass (SiO_2 > 70% + Boron)
  - Corning 7056, Duran, Pyrex
  - Most common glass in vacuum tech.
- Quartz (SiO_2 100%)
  - Used as optical vacuum window

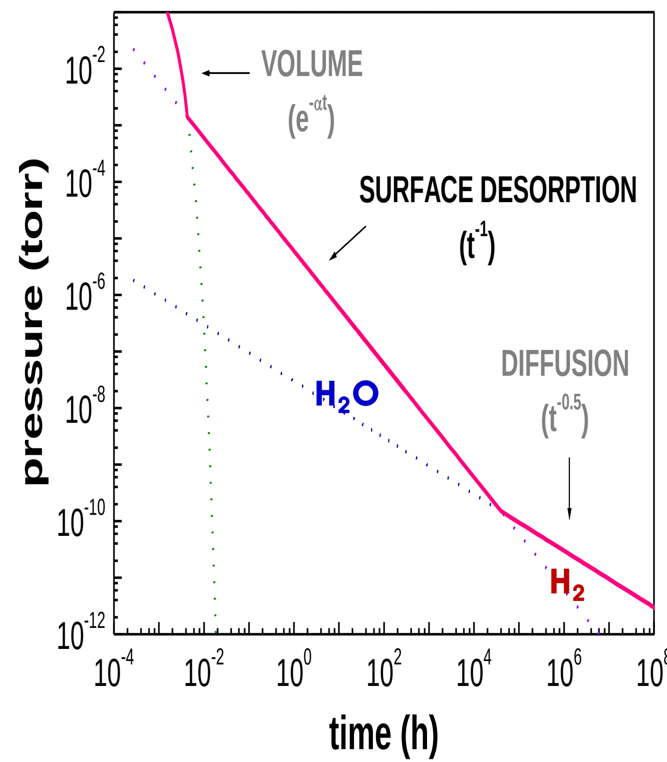
Surface treatment



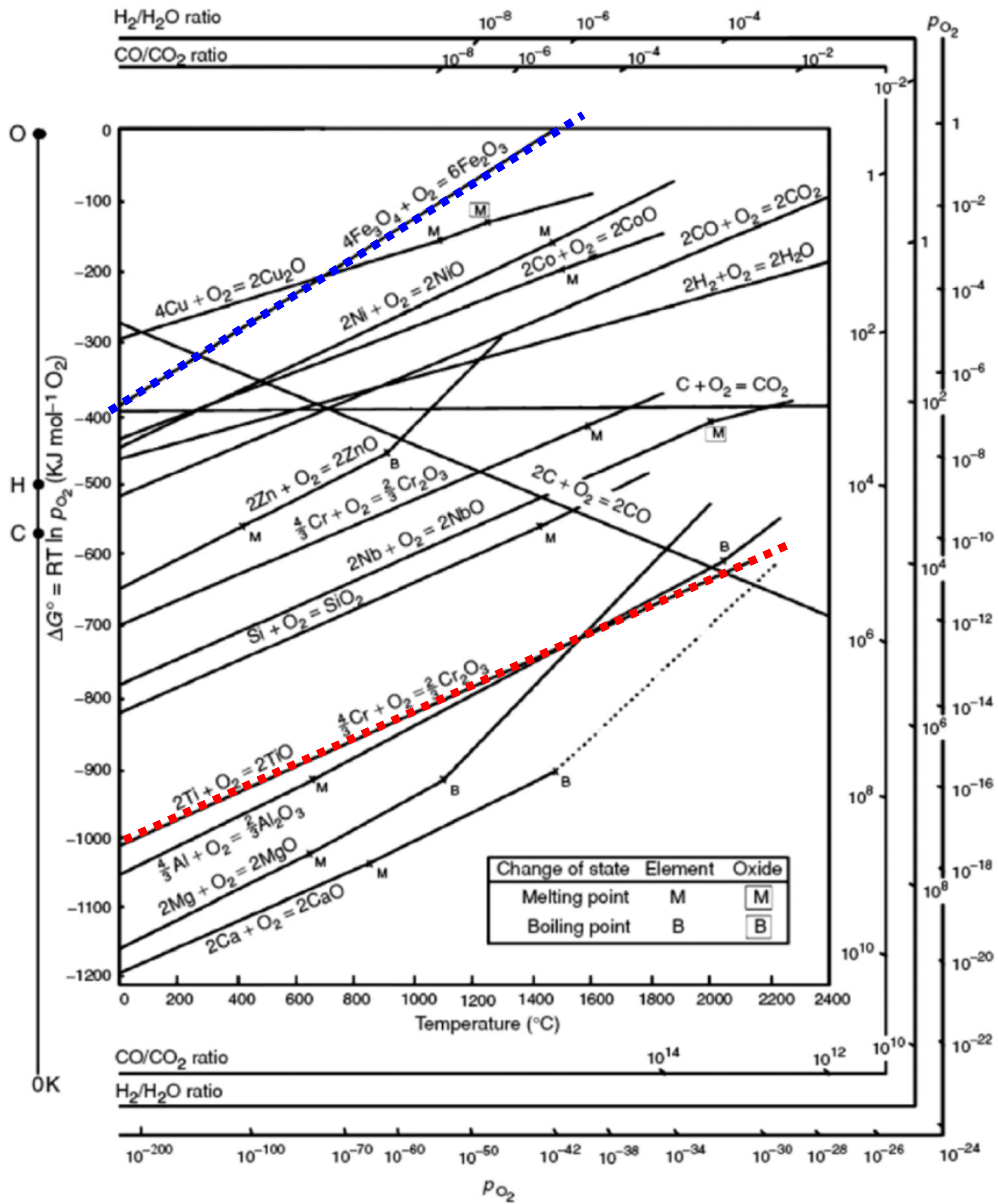
일반 스테인리스강의 진공특성

- ✓ 일반 금속(스테인리스강)의 표면은 다공질의 산화막이 형성되어 있음.
- ✓ 공기 노출 시 다공질 표면에 물과 같이 흡착성이 강한 입자가 다량으로 흡착됨.
- ✓ 진공 배기하면 흡착된 물 분자가 서서히 방출되므로 압력은 시간의 역수에 비례하며 ($p \propto 1/t$) 느리게 떨어짐.



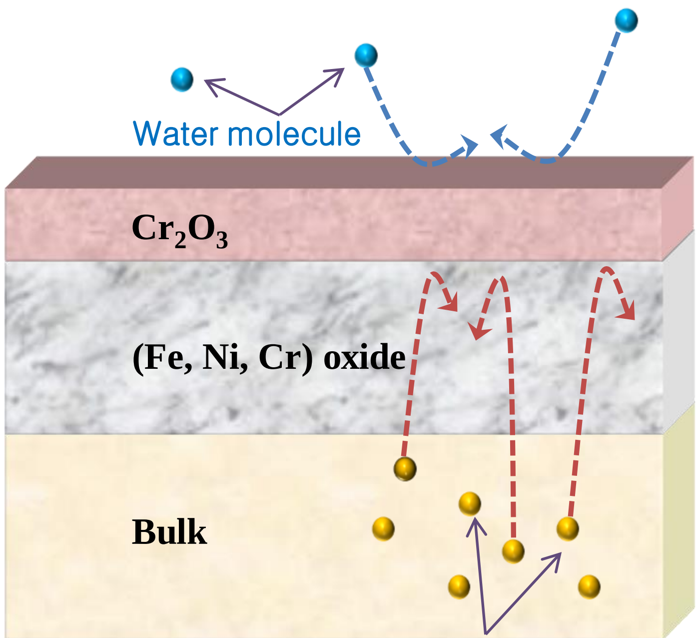


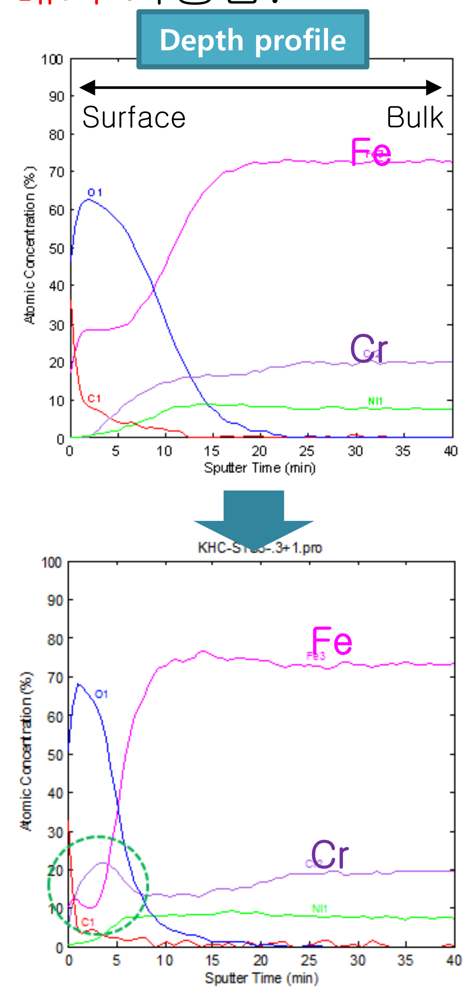
Ellingham Diagrams



Vacuum Thermal Oxidation (VTO)

- ✓ VTO 표면 처리를 하면 다공질 산화막 위에 순수한 크롬산화막이 형성됨.
- ✓ 크롬산화막에 의해 공기 노출 시 물 분자의 흡착량이 크게 감소하고 흡착된 물 분자도 비교적 쉽게 떨어져나가므로 급속 배기 가능함.

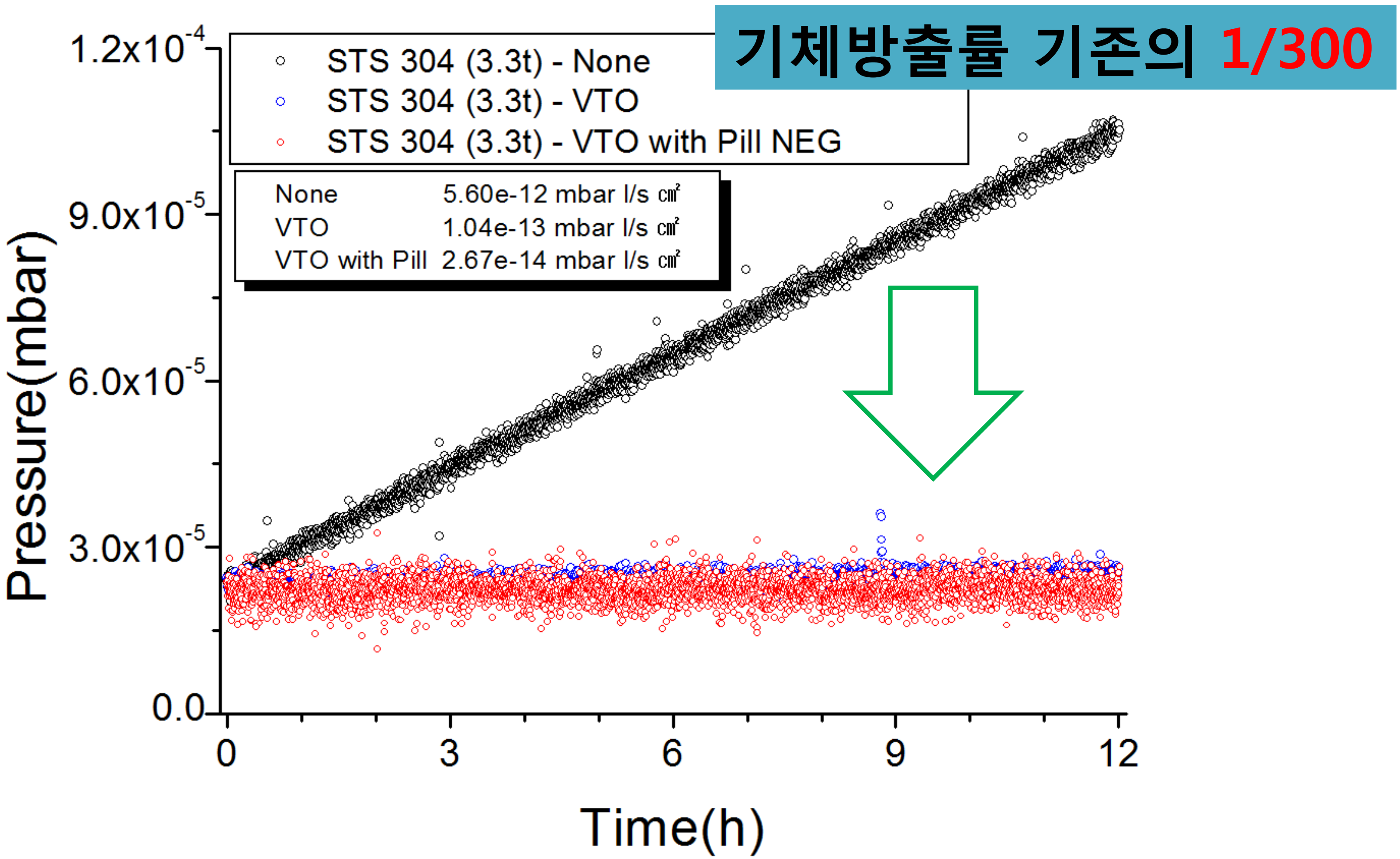




일반 (STS304)
:표면에 철산화물 많음

VTO (STS304)
:표면이 순수한 크롬산화물

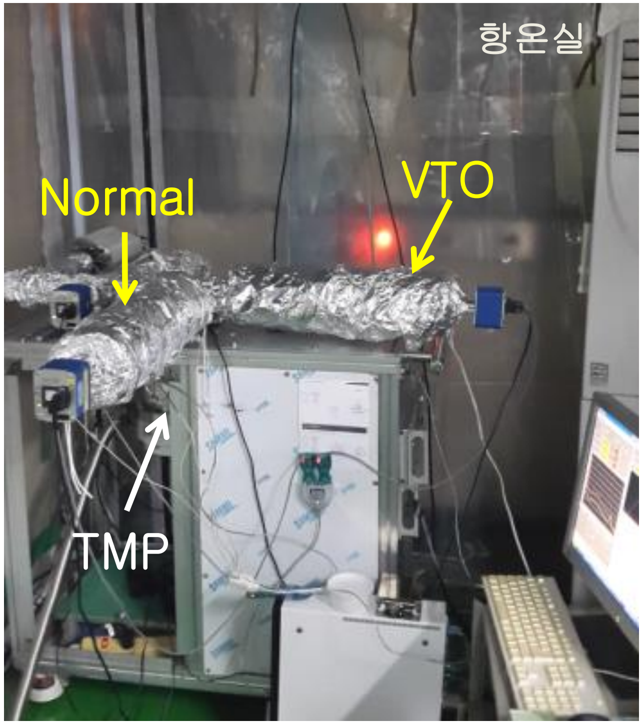
기체방출률 비교

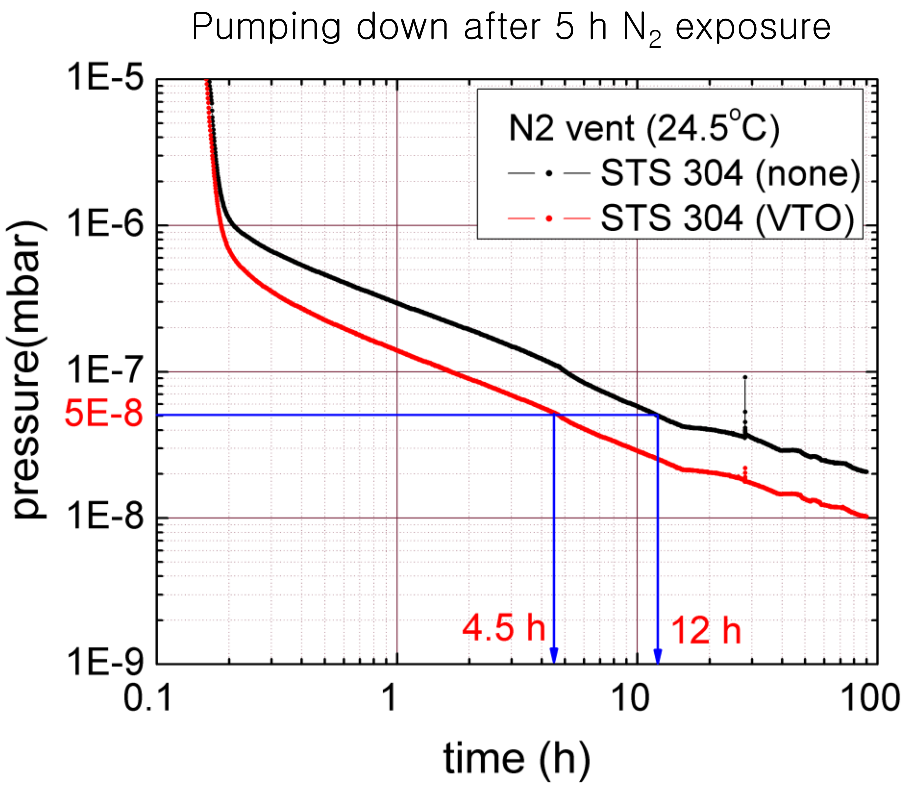


기체방출률 기존의 1/300
STS 304 (3.3t) - None
STS 304 (3.3t) - VTO
STS 304 (3.3t) - VTO with Pill NEG
None 5.60e-12 mbar l/s ㎠
VTO 1.04e-13 mbar l/s ㎠
VTO with Pill 2.67e-14 mbar l/s ㎠
1.2x10-4
9.0x10-5
6.0x10-5
3.0x10-5
0.0
0
3
6
9
12
Pressure(mbar)
Time(h)

배기 시간 비교

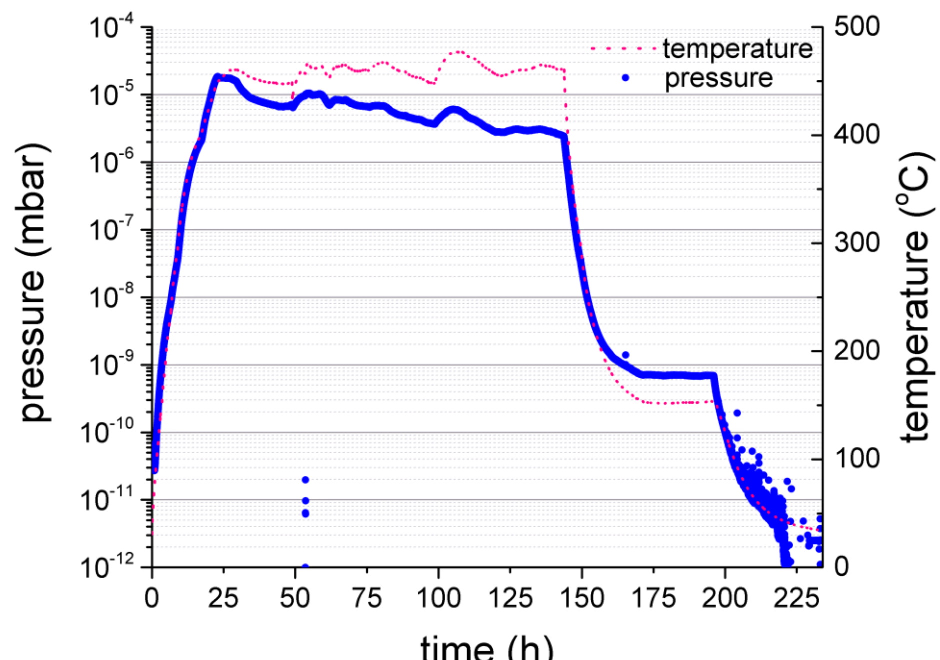
✓ 동일한 STS304 진공용기(6 리터) 2 set 제작하여 1 set는 VTO 표면처리 함.
✓ 동시에 같은 조건으로 baking 후 질소 벤팅하여 5시간 유지한 이후 진공배기 함.
✓ 일반 STS304 진공용기와 VTO 처리한 진공용기의 배기시간 비교
: 고진공 (5E-8 mbar) 도달 시간이 일반 STS의 1/3





극고진공 챔버

- 1000 리터 급 극고진공 시스템: 상용 진공게이지의 측정 하한 도달.



References (Korean)

- “Introductory Vacuum Science & Technology” (청문각, 정석민 외)
- “Handbook of Vacuum Technology” (청문각, 홍승수 외 역)
- “진공공학” (인상열 외)