Vacuum System (산소나 수분에 의한 영향을 최소화)

※ Dry process

① gas

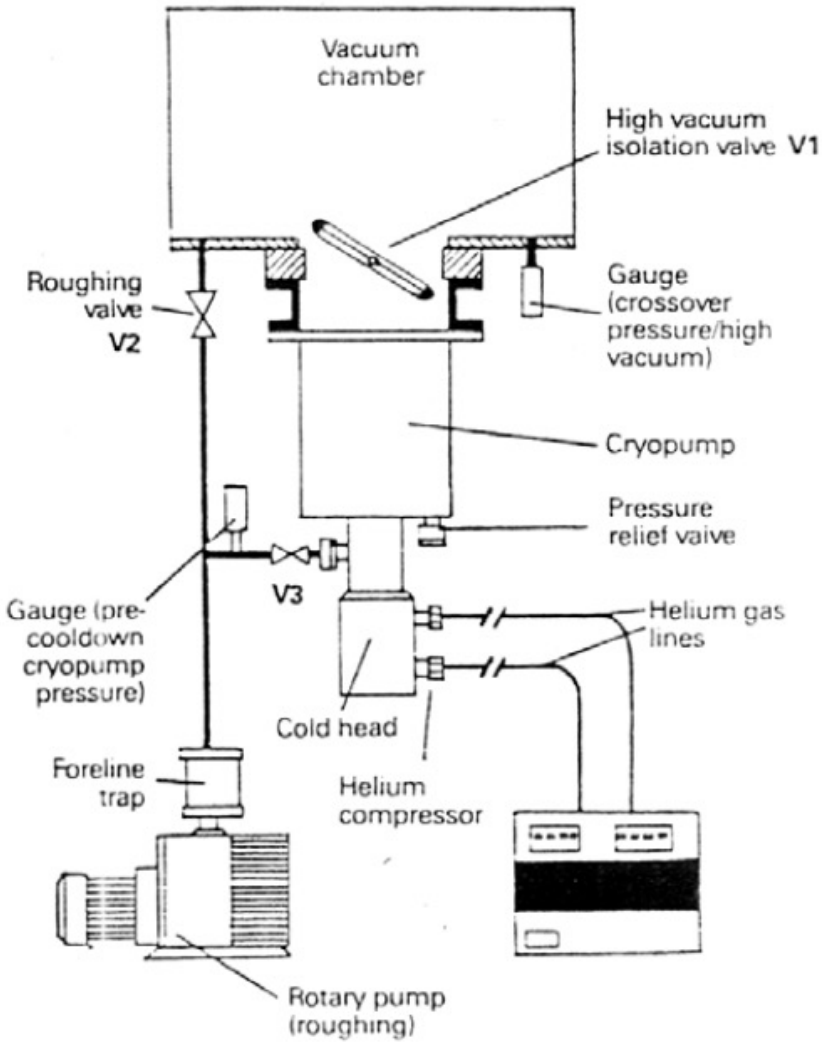
② vacuum technology

③ gas phase collision process

④ plasma in deposition process

⑤ dc and rf glow discharge

※ Deposition of thin films involves vacuum system



(MBE – molecular beam epitaxy)

Vacuum and Gases

- Recall Ideal Gas law

$$PV = nRT$$

where P = pressure (atm)
V = Volume
N = numl n · of moles of gas
R = Gas constant
T = temperature (°K)

- R = 22.4 V nole at Standard temperature & Pressure: STP
- Avogadro's Number = 6.03×10^{23} molecules/mole

표준상태 – STP
- 온도: 0 ℃
- 압력: 1atm

Value of the gas constant R:
= 0.08205 liters atm mole^{-1} $°\text{K}^{-1}$
= 8.314 J mole^{-1} $°\text{K}^{-1}$
= 62.4 liters torr mole^{-1} $°\text{K}^{-1}$
= 1.987 cal molecule^{-1} $°\text{K}^{-1}$
= 22.40

$$V = \frac{nRT}{P} = \frac{1mole * 0.0821\ l \cdot atm/mole \cdot K * 273.15\ K}{1\ atm}$$
$$= 22.41\ liter$$

1) Average distance between gas molecules at STP (0℃, 1atm)

2)Kinetic energy and temperature

The energy of the gas is stored in the form of kinetic energy (and in the case of molecules, also in vibrational and rotational states).

Average kinetic energy of a gas molecule ;

$$K.E. = \frac{1}{2} m\overline{c^2} = \frac{3}{2} kT \qquad \overline{c^2} = \text{mean square speed}$$

$$k = \text{Bolzmann's constant} = 1.38 \times 10^{-23}\ J/K$$

$$\bar{c} = \sqrt{\frac{3kT}{m}}$$

기체의 분자는 각자 다른 방향으로 다른 속도로 이동 ~ 평균속도 = 0
→ 속도의 제곱에 평균 : 평균제곱속도 (mean square speed)

통계적으로 운동 자유도 (degree of freedom) 하나당 에너지는 $\frac{1}{2}kT$

3) Pressure

Total force (=rate of momentum change) exerted by the bombarded molecules per unit area

$P = nm\overline{c_x^2}$ where c_x = velocity in x-direction

n = gas molecular density

$\overline{c_x^2} = \frac{\overline{c^2}}{3}$ $\therefore P = \frac{nm\overline{c^2}}{3} = nkT$

As temperature ↑ → $\overline{c^2}$ ↑ → P↑

※ Pressure units

1 atmosphere = 760 mmHg = 760 torr = 1.01×10^5 Pa

1 Pa = 1 N/m² = 10 dynes/cm² = 7.5 mtorr

1 torr = 133 Pa = 10^3 mtorr = 10^3 μmHg

* Most plasma processes take place between 1 mtorr and 1 torr.

- Standard units are Pascals: 1 Newton force per sq m
  official SI unit
- Everyone in the industry still uses torr (1 mm of mercury)
- Vacuum is High when pressure is low (<1 mTorr)

1 pascal	=	7.5×10^{-3} torr	=	7.5 microns of Hg
1 torr	=	133.3 pascal		
1 bar	=	1×10^5 Pa	=	750 torr
1 atm	=	1.013×10^5 Pa	=	760 torr

※ Density of Gases

At STP ; a gram molecule of any gas contatins 6.02×10^{23} molecules and occupies 22.4 liters.

At STP ; 2.7×10^{19} molecules/cm^3

At 1 mtorr, 20℃ ; 3.3×10^{13} molecules/cm^3 = 33 molecules/ μm^3

1 torr-liter =3.3×10^{19}molecules at 20℃

1 scc (standard cc) = (760 torr). (10^{-3} liter) = 0.76 torr-liter

4) Impingement flux

The number of molecules striking per unit area per unit time

$$flux\ N = \int_0^\infty n(c_x)c_x dc_x$$
$$= \frac{n\bar{c}}{4}$$
$$= 3.5 \times 10^{22} \frac{P}{(MT)^{1/2}}$$

- 보통 표면에 ~ 10^{15} atoms/cm^2
- 1 torr = 1000 mtorr

P = pressure (torr), M = molecular mass unit (g/mol), T = temperature (K)

For Ar, $N = 3.2 \times 10^{17}/cm^2$. sec at 1 mtorr, 20°C
$N = 3.2 \times 10^{14}/cm^2$. sec at 10^{-6} torr, 20°C
Each atom of a surface in a chamber experiences about 300 collisions/sec at 1 mtorr.
When the surface of the substrate is clean, reactions such as oxidation and nitridation will occur instantly at the surface without need for heat or high temperature even at 1 mtorr.

* Monolayer formation time : about 1 sec at 10^{-6} torr.
(assuming sticking probalility is unity)
* Typical sputter deposition rate : about 1 monolayer /sec
∴ The partial pressure of a contaminant gas << 10^{-6} torr

In the evaporation process, a low pressure (< 10^{-6} torr) is required to avoid contamination.

5) Mean free path (λ) 진공도 판단 기준의 하나

* The average distance travelled by a gas atom between collisions with other gas atoms.
* MFP is inversely proportional to gas density (n) and thus gas pressure (P)

$$\lambda \propto 1/n \propto 1/P$$

λ(cm) = 5 / P (mtorr) for Ar and air molecules at 20℃

* Collision frequency = $\bar{c}$ /λ

eg) In argon at 1 mtorr, collision frequency = 8000 collisions/sec

* Mean deflection path = 10 λ

The average distance travelled by a gas atom before it has been deflected significantly.

Table 7-2 Properties of gases of interest in thin-film deposition

Gas (formula)	Molecular weight (g/mole)	Molecular diameter† (nm)	Abundance in air	Boiling point (°K)	Comment
Nitrogen (N_2)	28	0.316	78.08%	77.4	—
Oxygen (O_2)	32	0.296	20.95%	90.2	—
Argon (Ar)	40	0.286	0.93%	87.4	Usual choice for sputtering
Carbon dioxide (CO_2)	48	0.324	0.031%	194.7‡	—
Water (H_2O)	18	0.288	Varies	373.15	Absorbs strongly on most materials
Hydrogen (H_2)	2	0.218	0.5 ppm	20.3	Formed by breakdown of water
Helium (He)	4	0.200	5 ppm	4.2	Used for leak detection

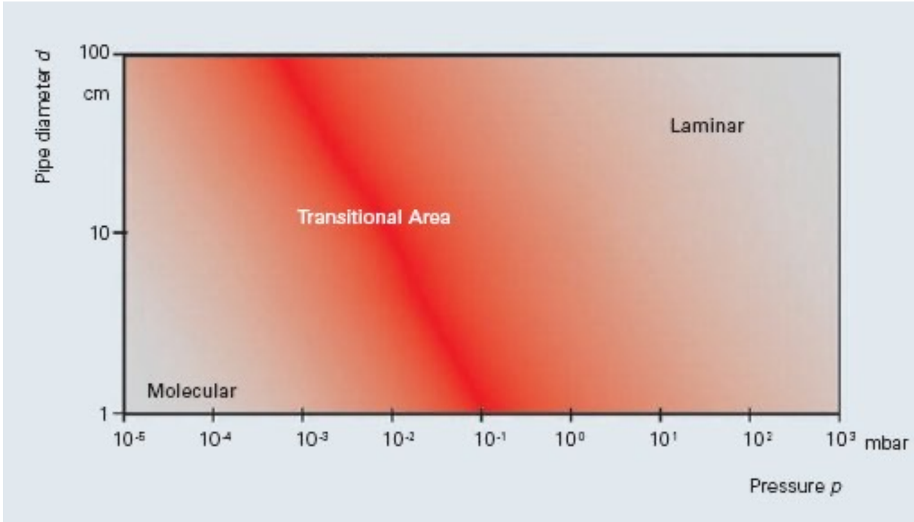
† Derived from gas viscosity (Ref. 14).
‡ Carbon dioxide sublimes rather than boils.

6) Types of gas flow

Viscous flow ; λ < 0.01d at high pressure
Transition flow ; 0.01d < λ < d
Molecular flow ; λ > d at low pressure
where, d = dimension of vacuum chamber

Viscous Flow
- At high pressure MFP is short
- Molecules collide with each other: Viscous Flow

Molecular Flow
- At low pressure MFP is long
- Molecules collide with walls: Molecular flow



http://www.pfeiffer-vacuum.com/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/technology.action?chapter=tec1.2.6

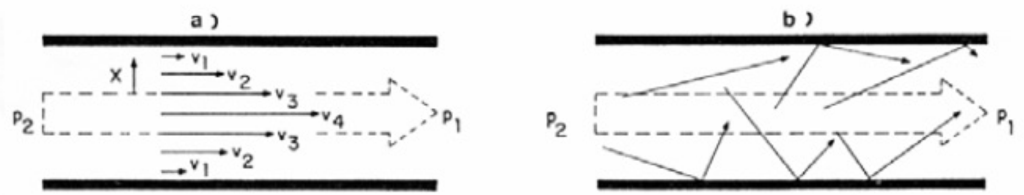


Fig. 2 (a) Schematic representation of particle velocities for viscous flow through a narrow tube. (b) Schematic representation of particle velocities for free molecular flow through a narrow tube. From L. Maissel and R. Glang, Eds., *Handbook of Thin Film Technology*, 1970[3]. Reprinted with permission of McGraw-Hill Book Company.

Vacuum Technology

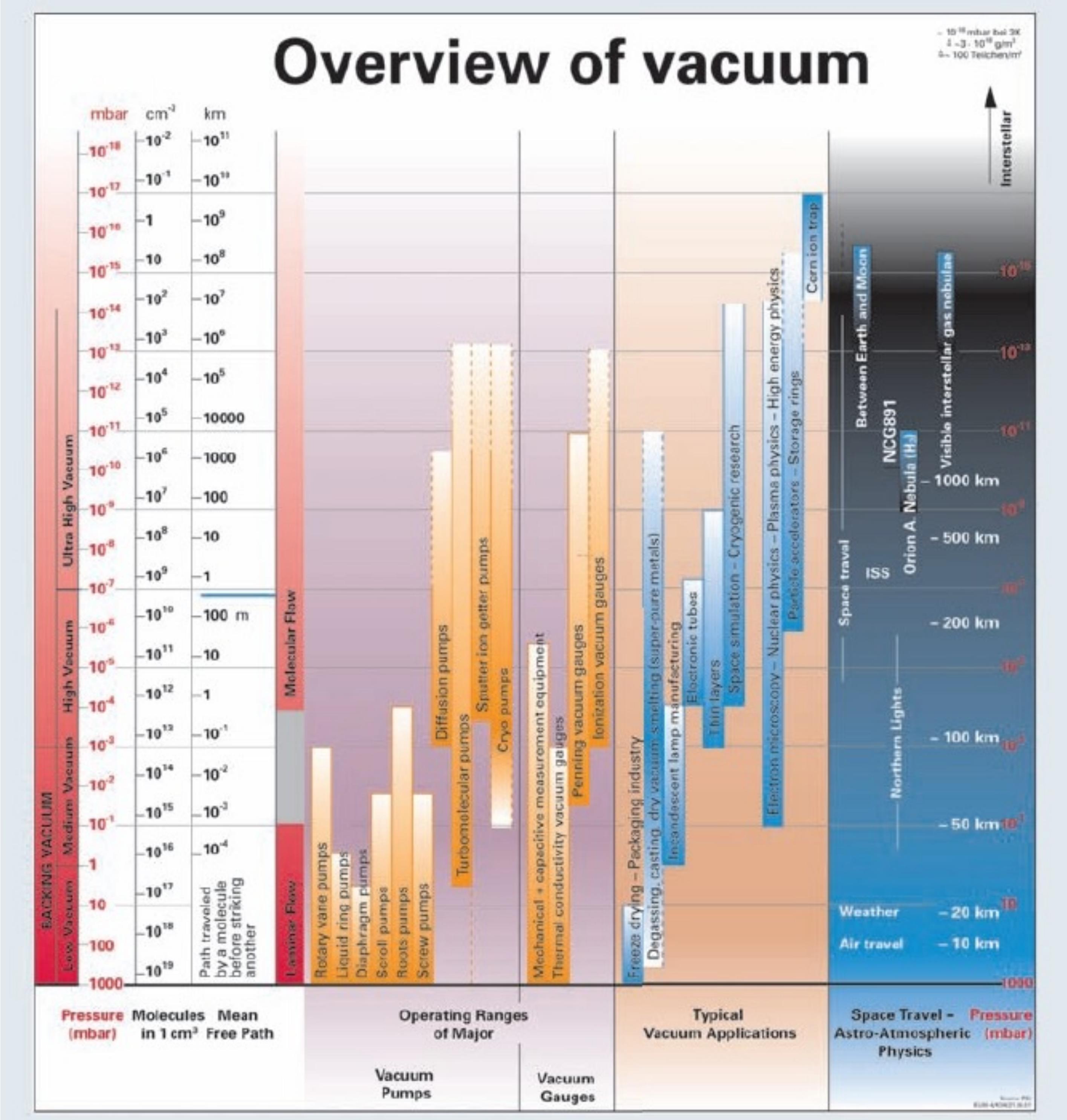
1) Vacuum ranges

* Range of vacuum

Low	-	10^5 Pa	(750 torr)	to 3.3×10^3 Pa	(25 torr)
Medium	-	3.3×10^3 Pa	(25 torr)	to 10^{-1} Pa	(7.5×10^{-4} torr)
High	-	10^{-1} Pa	(7.5×10^{-4} torr)	to 10^{-4} Pa	(7.5×10^{-7} torr)
Very High	-	10^{-4} Pa	(7.5×10^{-7} torr)	to 10^{-7} Pa	(7.5×10^{-10} torr)
Ultra High	-	10^{-7} Pa	(7.5×10^{-10} torr)	to 10^{-10} Pa	(7.5×10^{-13} torr)

* Most fab processes use either 10^{-2} to 10^{-6} torr pressure (medium to high vacuums)

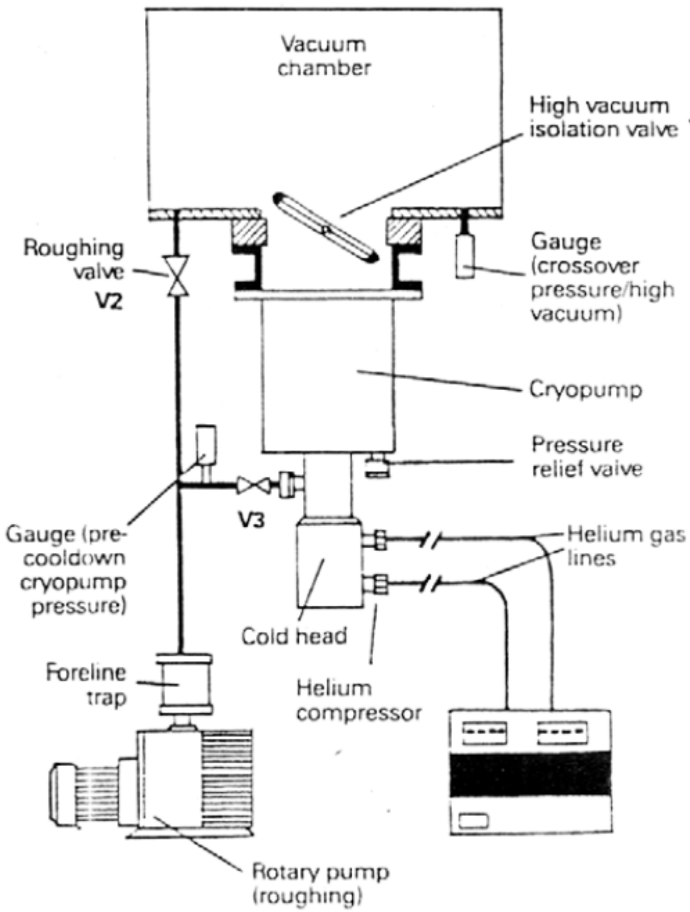
* Pumping systems needed to reach these vacuums



http://www.pfeiffer-vacuum.com/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/technology.action?chapter=tec1.2.6

2) Typical classic vacuum system

- Systems usually contain two pump systems
- Medium vacuum section (Roughing or Fore pumps):10's mTorr
- High Vac pump (diffusion or cryo pumps) to microTorr range
- Pump chamber is switched between each using roughing and high vac values



3) Rotary or fore pump 기계적으로 눌러서 밀어냄

- Also called mechanical or roughing pump
- Rotation of vanes pushes air around
- When at atm pressure oil spews out exhaust
- Why - exhaust passes through oil
- Pump flow rate is

$$Q = PS$$

where Q = gas volume remove (l)
P = pressure
S = pumping speed in l/min

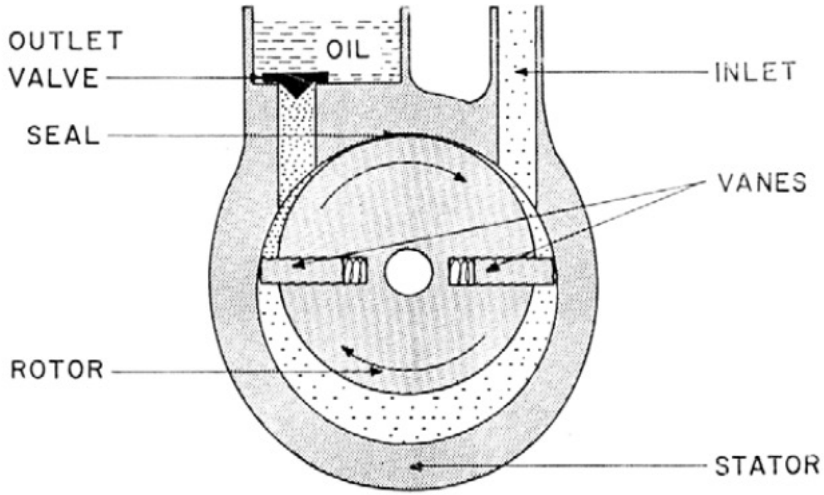
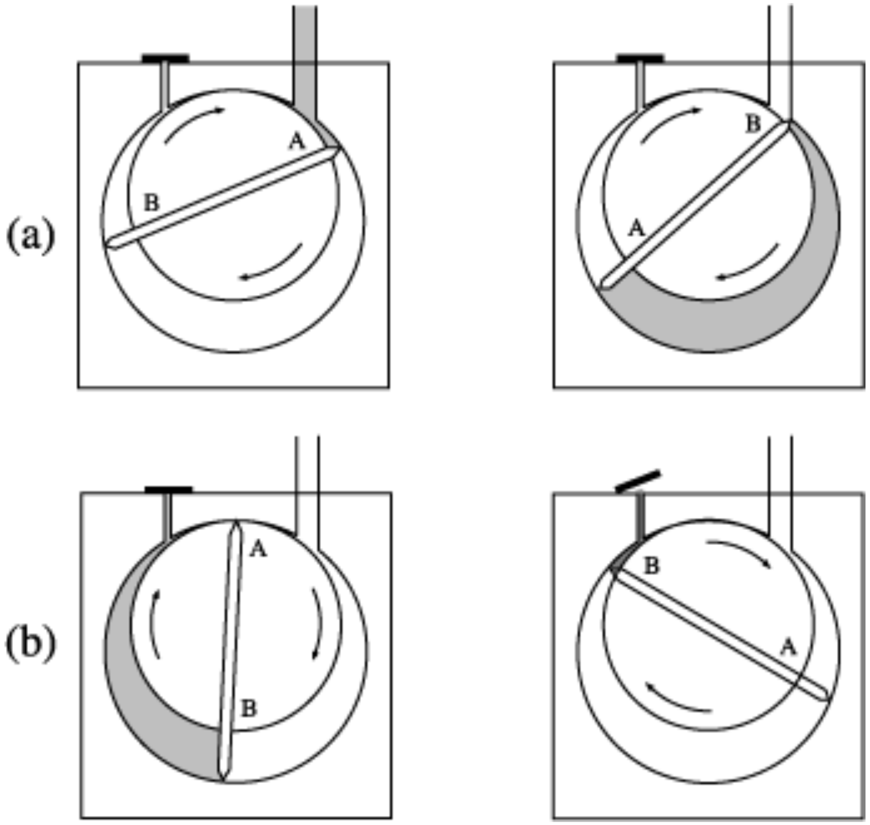


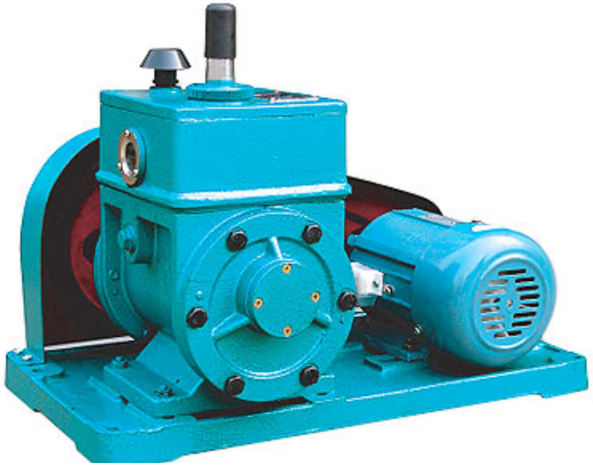
Fig. 1 Schematic of a vane-type rotary oil pump.

일반적으로 가장 많이 쓰이는 진공펌프로, 기본 원리는 그림과 같다. 그림에서 보면 내부 구조가 로타 베인 및 실린더로 되어 있는데, 로타의 중심과 실린더의 중심은 편심되어 있다.
베인은 스프링 또는 원심력에 의해서 실린더 내면에 밀착된 상태로 돌아가게 되는데, 이때 베인과 베인 사이에 공간이 생기게 되고, 이 공간은 로타의 회전에 따라 용적이 달라지게 된다.
한쪽, 베인이 흡기부를 지나면서 공간의 용적은 점차 커지게 되고, 다음 베인이 흡기부 끝단을 통과할 때 공간용적은 최대가 된다. 이렇게 하여 흡기부로부터 빨아들인 공기는 다음 단계에서 압축이 되고 이것이 배기부를 지나면서 배출이 되는 것이다.
로타리 베인 펌프의 최대 진공도는 10^{-3}Torr정도의 영역에 그치고 있으나, 루츠펌프 및 확산펌프와 연결되어 고진공이 요구되는 공정에도 다양하게 쓰이고 있으므로, 오늘날 산업 전반에 걸쳐 가장 널리 쓰이고 있고 기종이라 할 수 있다.

Rotary vane pump



https://www.youtube.com/watch?v=AFHogF-9eGA&t=6s&ab_channel=PPlusVac
https://www.youtube.com/watch?v=IIKOx0JqE08&ab_channel=TheVacuumator



- Roughing typically saturates about ~10^{-3} torr (milliTorr)
- Double stage pumps better
- Real chamber pressure depends on leakage rate

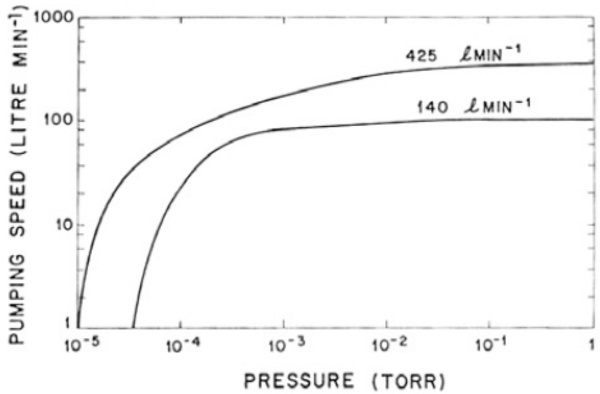
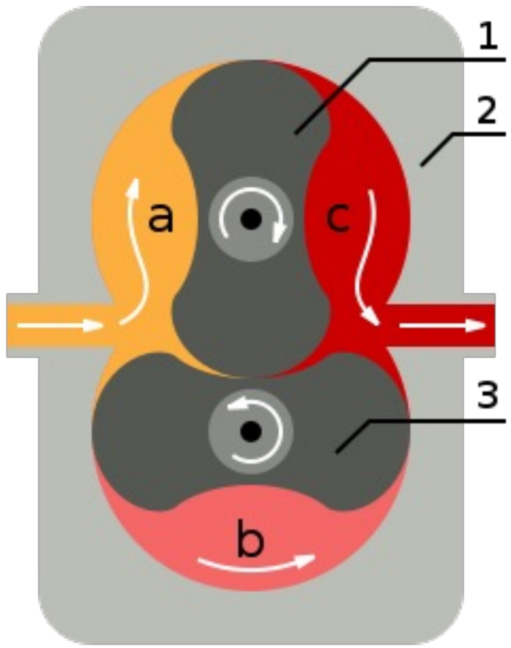


Fig. 2 Two-stage rotary oil pump speeds as functions of pressure (for models from Welch Scientific Co., Skokie, Ill.).

Root pump

두 개의 리본모양의 회전 로타가 쌍을 이루며 회전함으로써 공기를 함입하여 배기시키는 것이다. 주로 저진공, 중진공 영역에서 많이 쓰이며, 용량이 대용량이므로 다량의 공기를 배기시키는데 유리하다.

특히 1Torr부터 10Torr 의 영역에서 대용량의 배기능력을 가지고 있으므로, 식품의 동결건조 공정등에서 우수한 성능을 발휘한다. 그러나 배기부가 대기압인 경우 배기 능력을 상실하므로, 로타리 베인 펌프 등 다른 보조펌프와 연결하여 사용되고 있다.



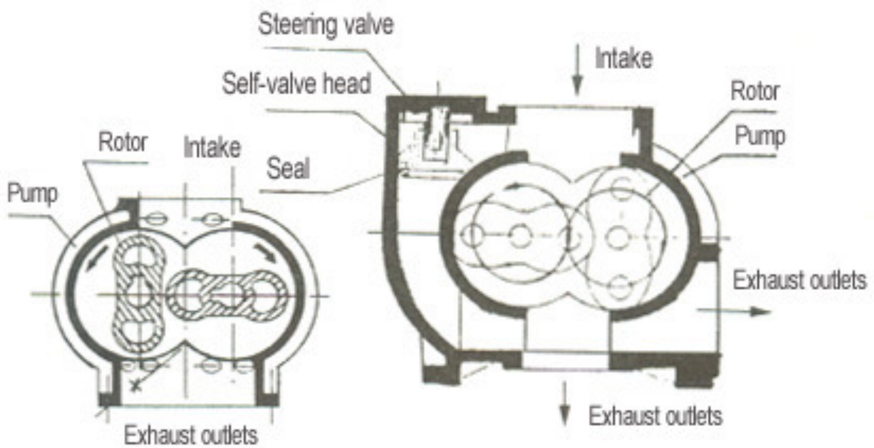
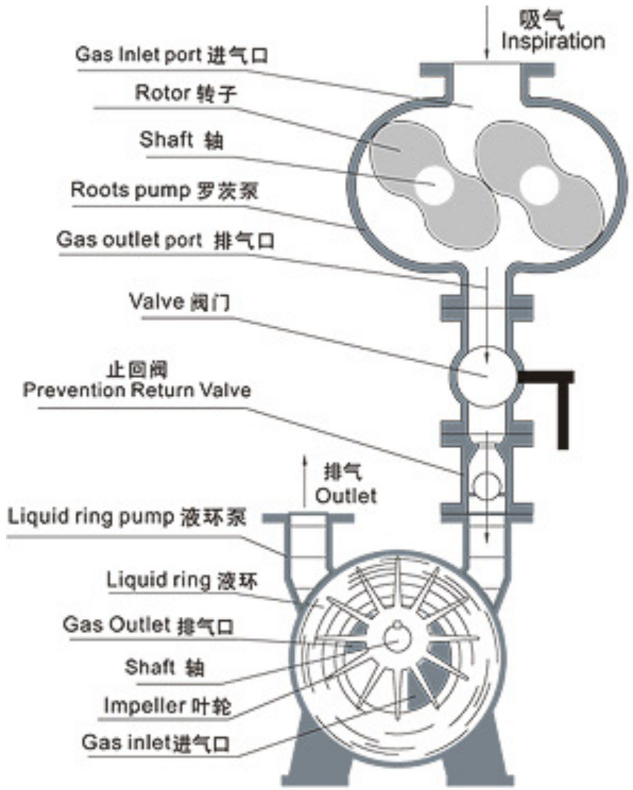


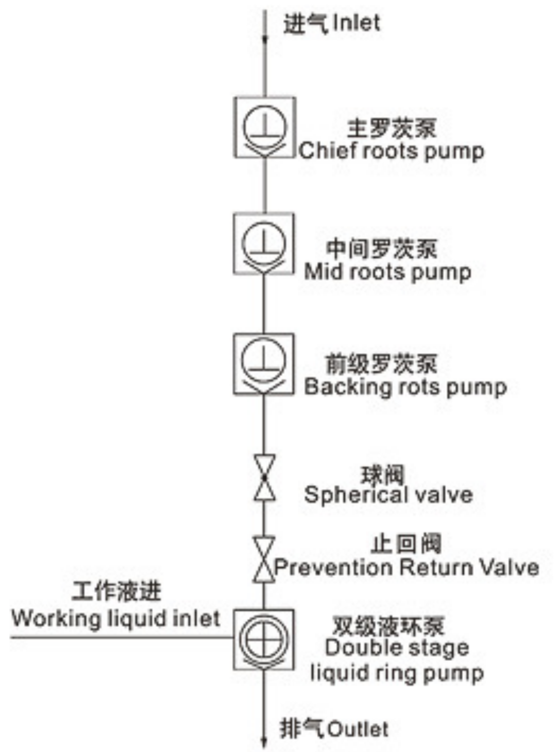
Chart 1 structure diagram   Chart 1 (A) structure diagram

https://www.youtube.com/watch?v=ON_PAtyblaY&ab_channel=Leybold



罗茨液环真空机组工作示意图

Roots Pump Systems With Water(Oil) Ring Vacuum Pumps working sketch drawing



三罗茨双级液环真空机组系统原理图

Three Roots Pump & double stage rotary hquid ring Vacuum Pumps principle drawing

Diffusion pump

확산펌프는 액체(일반적으로 확산유)를 가열하여 증발시킨 다음 이를 노즐을 통해 고속으로 분사 시킴으로써, 이때 충돌하는 공기입자를 아래로 끌어 내려 보조펌프(일반적으로 로타리 베인 펌프)를 통해 배출시키는 것이다.
이 기종의 펌프들은 대체로 구조가 간단하고 기계적인 운동을 하지 않으므로 사용이 간편하여, 고진공 (10^{-7} torr)을 얻는데 많이 사용되고 있다. 그러나 다른 고진공용 펌프와 마찬가지로 반드시 보조펌프를 써야만 한다.

- 오일 역류 가능성을 조심 (cold trap 필요)

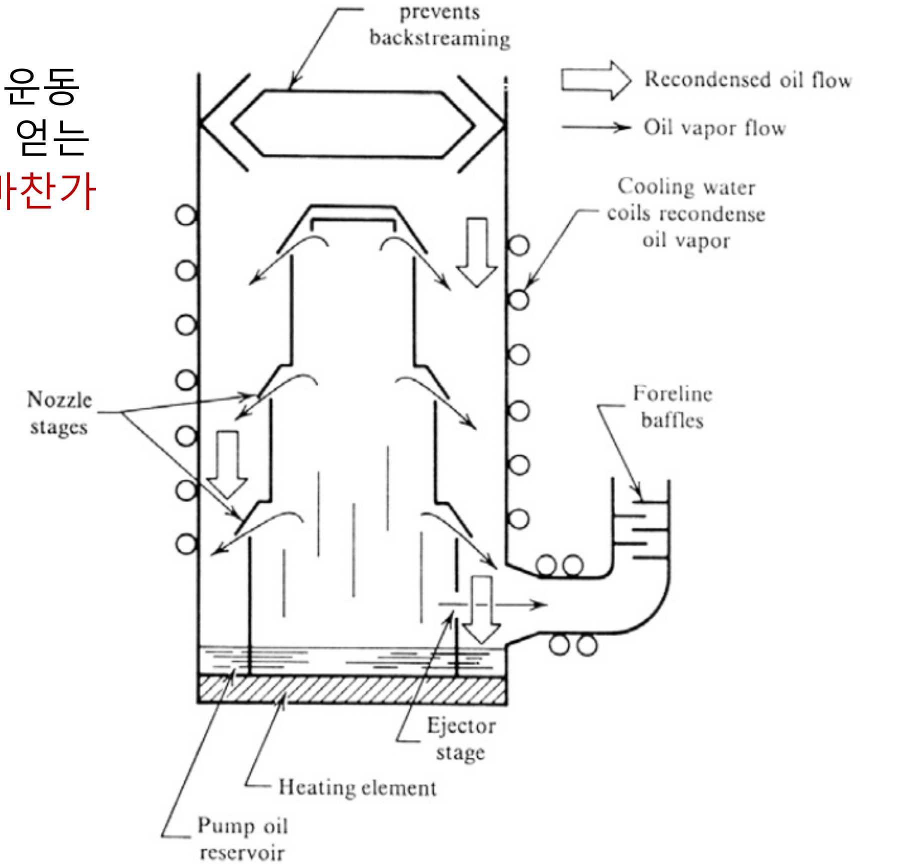
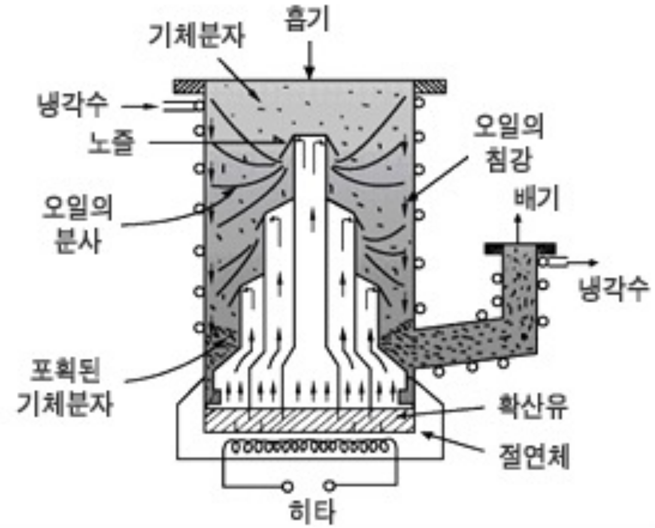
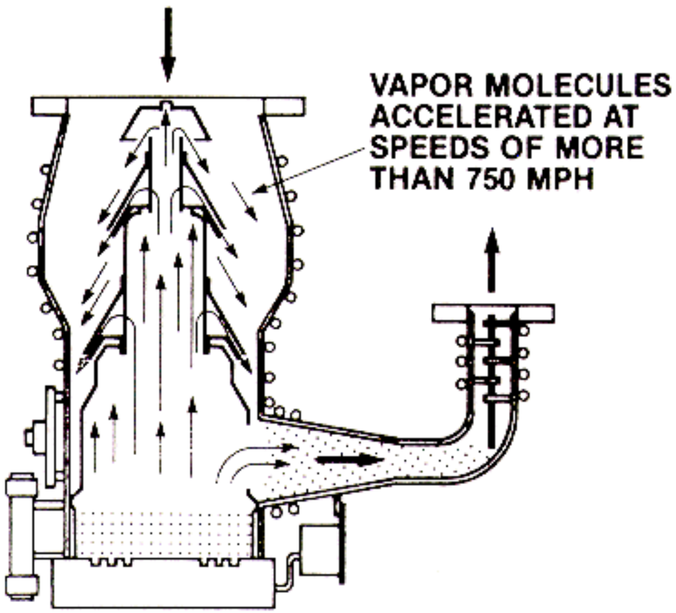
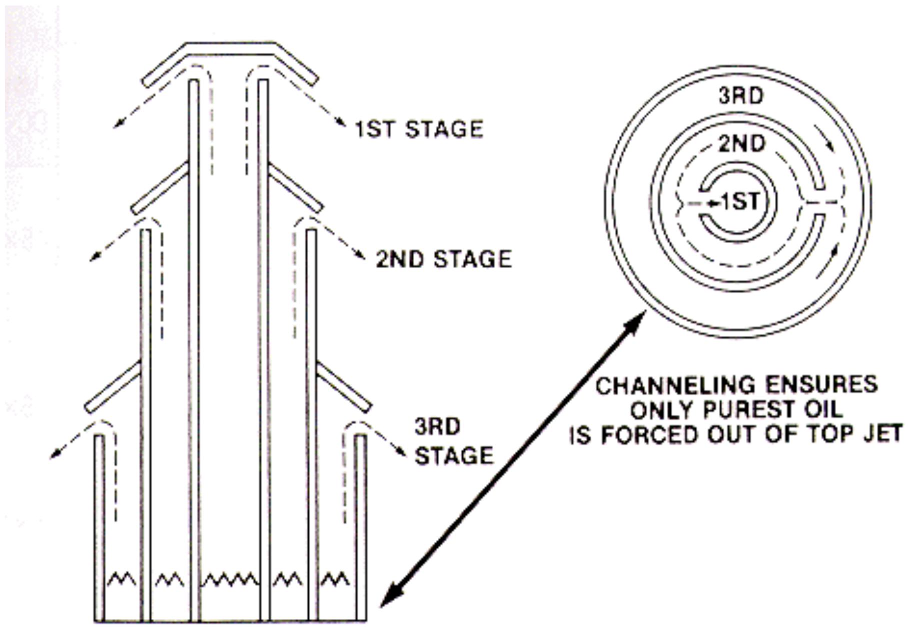


Figure 7-2 A diffusion pump. Oil heated in the reservoir emerges from the jets and collides with gas molecules, driving them into the roughing pump.

[확산 펌프의 구조와 원리]


흡기
기체분자
냉각수
노즐
오일의
침강
배기
오일의
분사
냉각수
포획된
기체분자
확산유
절연체
히타


VAPOR MOLECULES
ACCELERATED AT
SPEEDS OF MORE
THAN 750 MPH


1ST STAGE
2ND STAGE
3RD
STAGE
3RD
2ND
1ST
CHANNELING ENSURES
ONLY PUREST OIL
IS FORCED OUT OF TOP JET

https://www.youtube.com/watch?v=Y0xKZPhMS30&ab_channel=CaptainCorrosion

Diffusion pump

- Must rough out chamber first: **Do not use above 10^{-2} torr**
- High vac pump operating by boiling pump oil
- Pump tower directs vapour downward
- Oil molecules push gas down by collision & momentum transfer
- Creates high pressure at foreline (above millitorr)
- Roughing pump on output removes gases to atm
- Water jacket cools pump walls: oil condenses for evaporation
- Diff pumps rated by pump throat diameter (eg 6 inch, 8 inch)
- Pumps are very heavy
- Oil in pump destroyed by air when hot (expensive oils better)
- Do not bring up to air when pump hot
- Pump must be hot before high Vac valve opened
- May hear gurgling sound when high vac value first opened.

Diffusion pump

※ Cold trap system

증기가 된 오일을 식혀서 역류하지 못하도록
(펌프와 챔버 사이에 설치)

- Used to trap water vapour & oil from diff pump
- Cold trap filled with liquid Nitrogen (77 °K)
- Most important: stops back streaming of Diff pump oil
- If oil gets in chamber contaminates vacuum system
- Also freezes out water, some carbon dioxide
- Significantly reduces pressure
- Must keep cold trap filled! Do not open high vac if trap warm

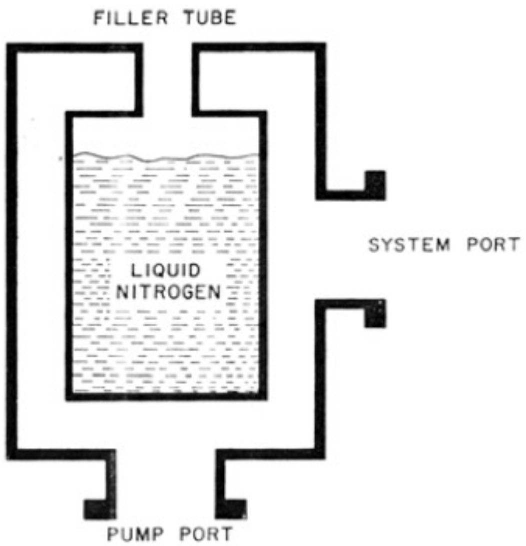


Fig. 9 Liquid-nitrogen container trap for oil diffusion pumps.

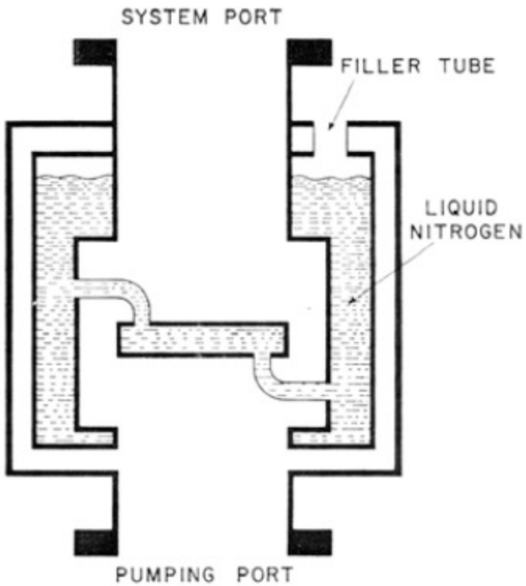
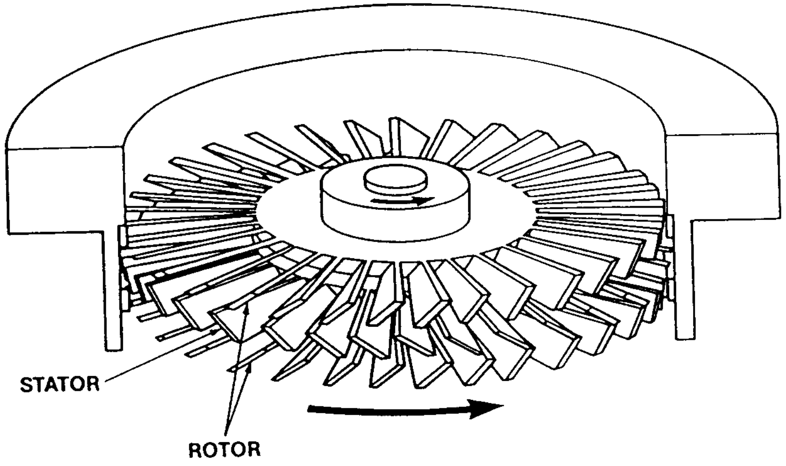


Fig. 10 Dewar trap with cooled baffle.

Turbomolecular pump



이 펌프는 공기 입자성에 근거를 두고, 일정한 각도를 가지고 고속으로 회전을 하는 많은 날개를 가진 회전자 와 그사이에 있는 고정자를 써서, 공기의 입자운동에 일정한 방향성을 부여함으로써 공기를 배출시키는 것이다.

터보 분자 펌프는 고진공 영역에서 일정한 배기량을 유지하므로, 고진공이 지속적으로 요구되는 전자 현미경이나 각종 반도체 생산 및 실험실 장비등에 많이 쓰이고 있다.

그러나 중,저진공 영역에서는 배기량이 저하됨으로 로타리 베인 펌프 등의 보조펌프와 함께 사용되고 있는 것이 일반적이다.

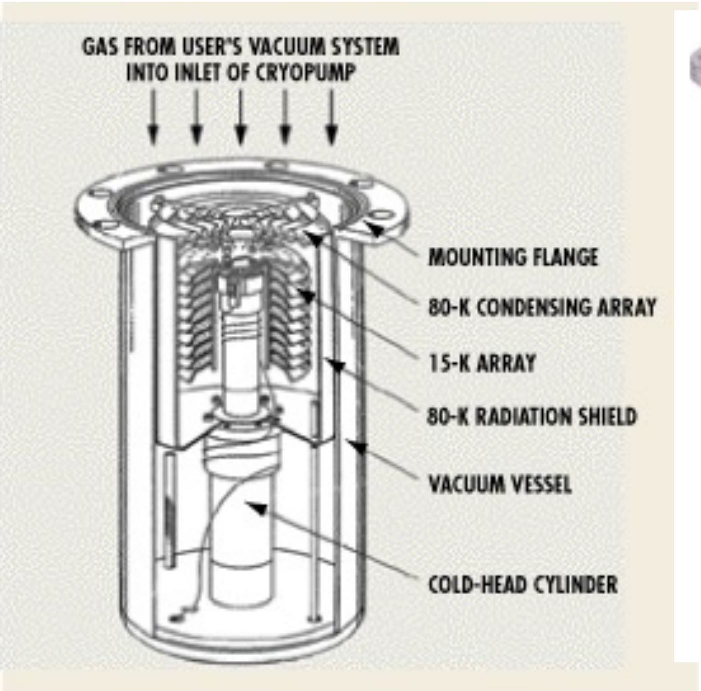
Turbomolecular pump

https://www.youtube.com/watch?v=x3XaW7UFIjI&t=3s&ab_channel=CaptainCorrosion

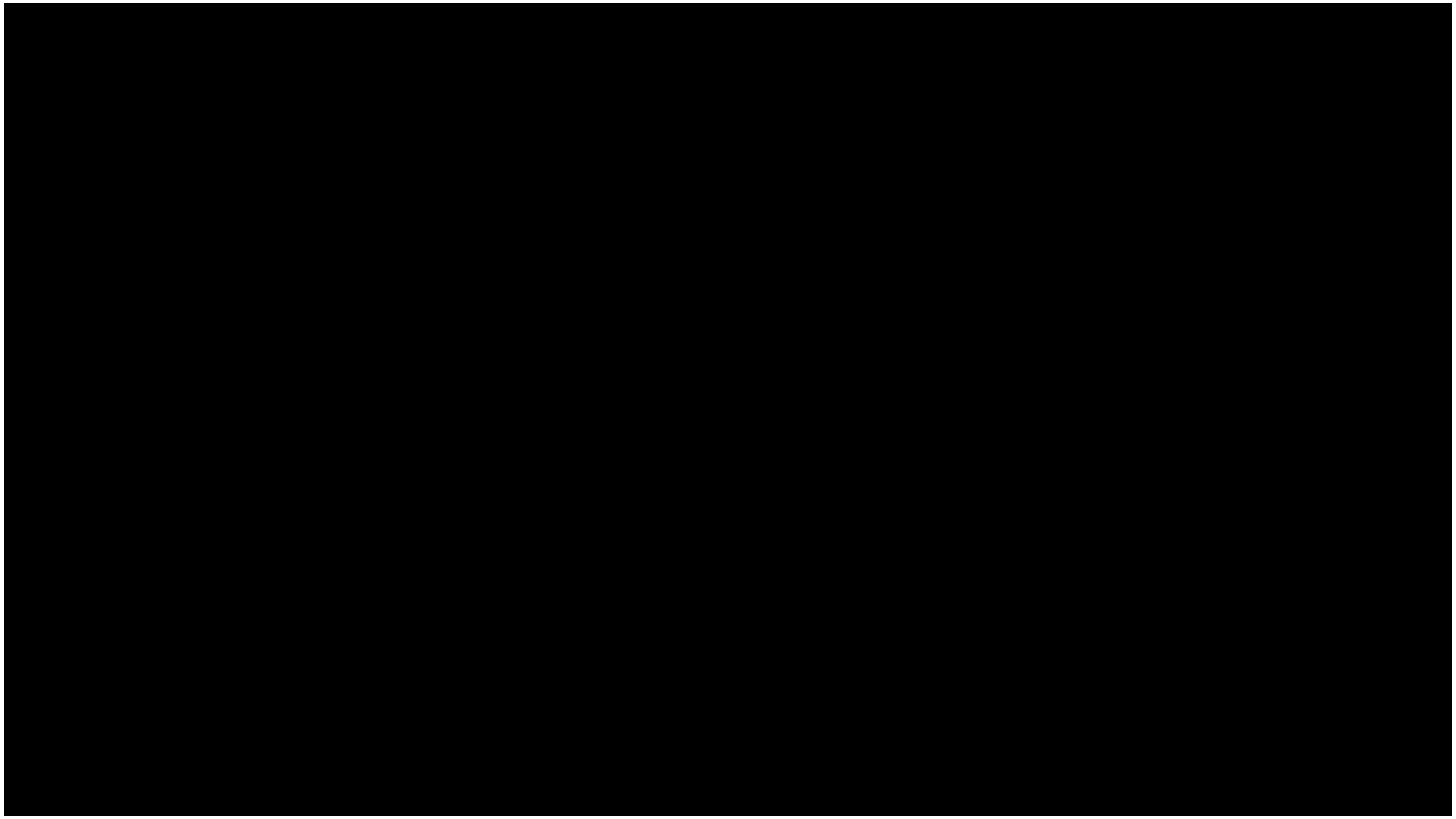
https://www.youtube.com/watch?v=8gNDDItrlBc&ab_channel=EdwardsVacuum

Cryo pump (or cryogenic pump)

크라이오 펌프에 사용되는 냉동기는 2단으로 되어 있고 1단은 냉동 능력이 큰 80K 이하로 냉각 할 수가 있고 2단은 냉동능력이 작은 10K~20K(켈빈)으로 냉각할 수가 있다. 15K Cryo Panel(1) (응축 Panel)과 15K Cryo Panel(2) (흡착 Panel)은 냉동기의 2단에 부착되어 있고 냉동능력이 큰 1단에 부착되어 있는 80K Shield와 80K Baffle은 실온의 방사(복사)열로부터 펌프를 보호를 하고 있다.



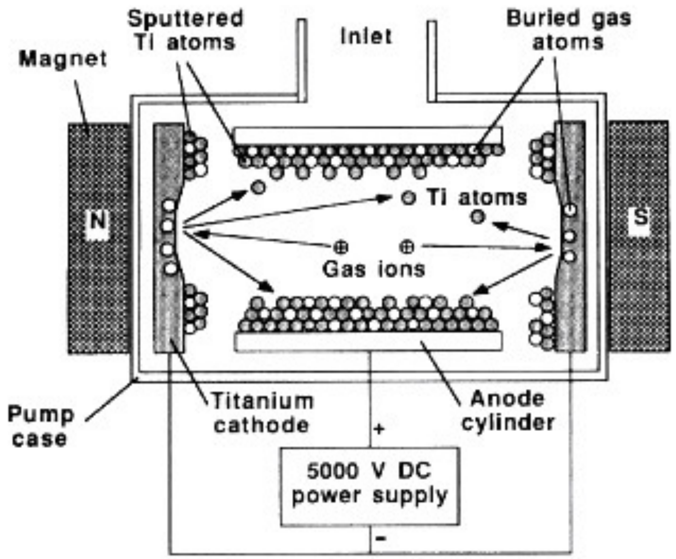
Cryo pump (or cryogenic pump)

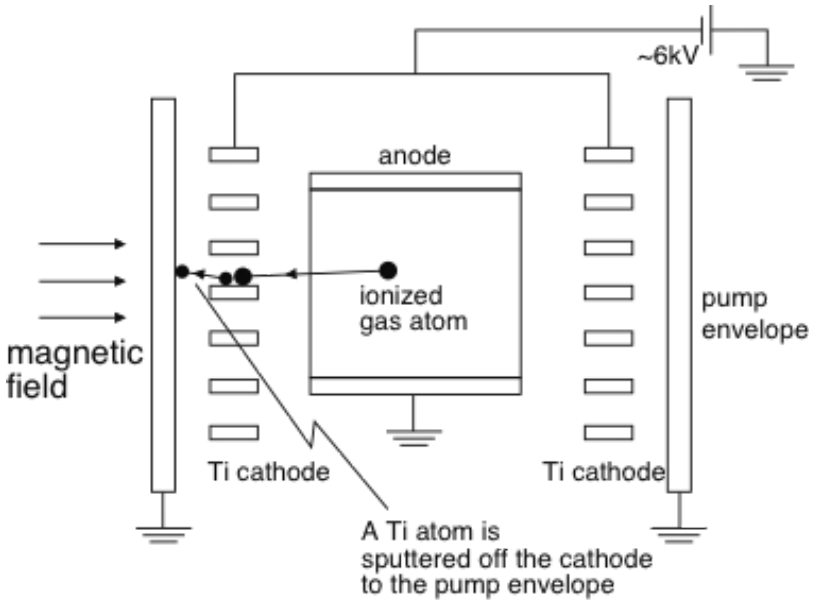


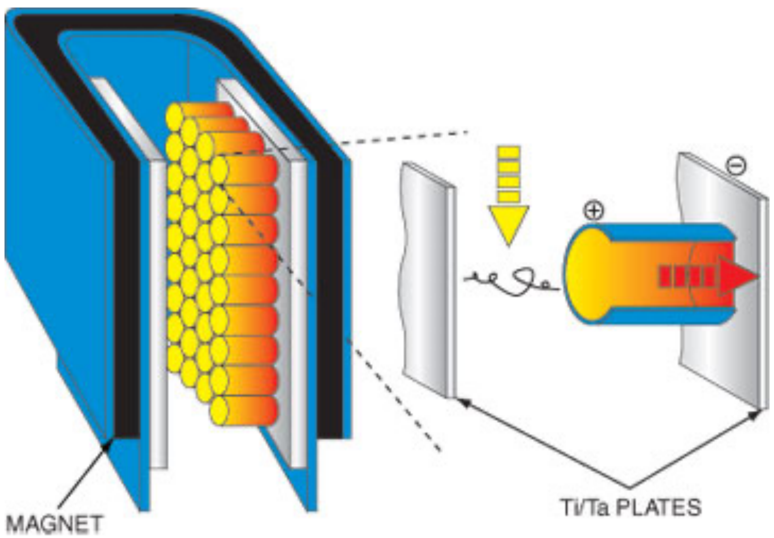
https://www.youtube.com/watch?v=TTwxhzVxvk8&ab_channel=CaptainCorrosion

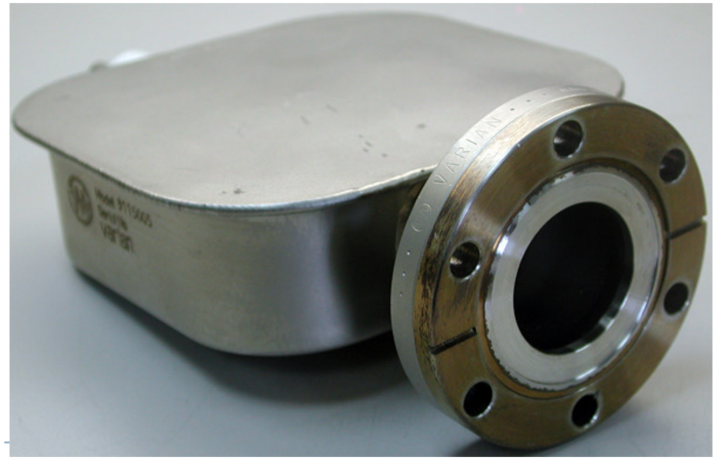
Ion pump

N_2, O_2, CO 등 이온화 가능한 대부분의 기체는 가능
(He, H_2 는 어려움)







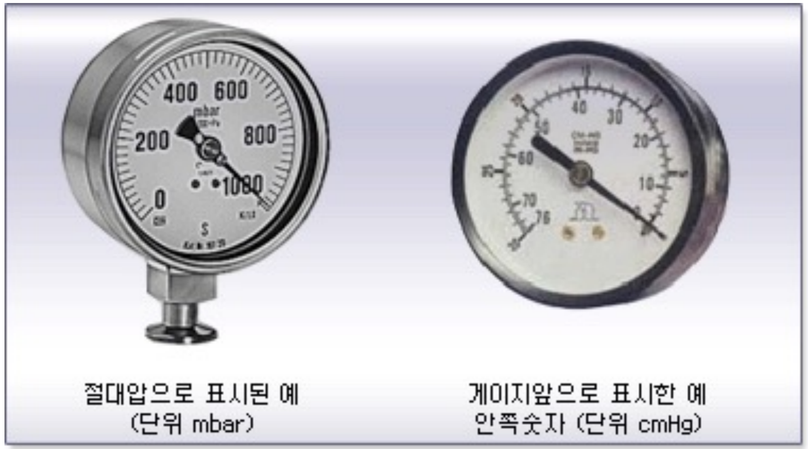


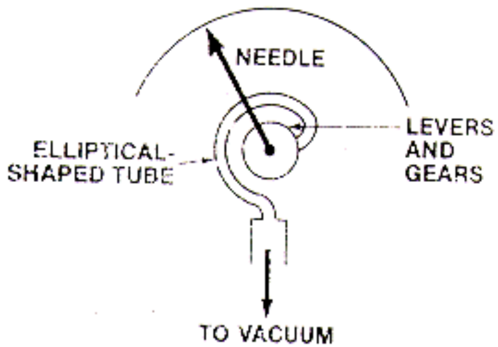
Ion pump

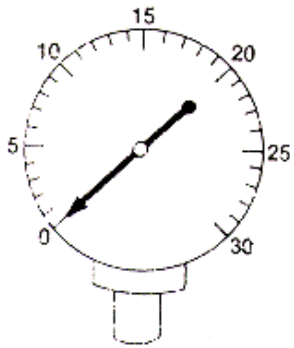
https://www.youtube.com/watch?v=_SiJtauhhHs&ab_channel=CaptainCorrosion

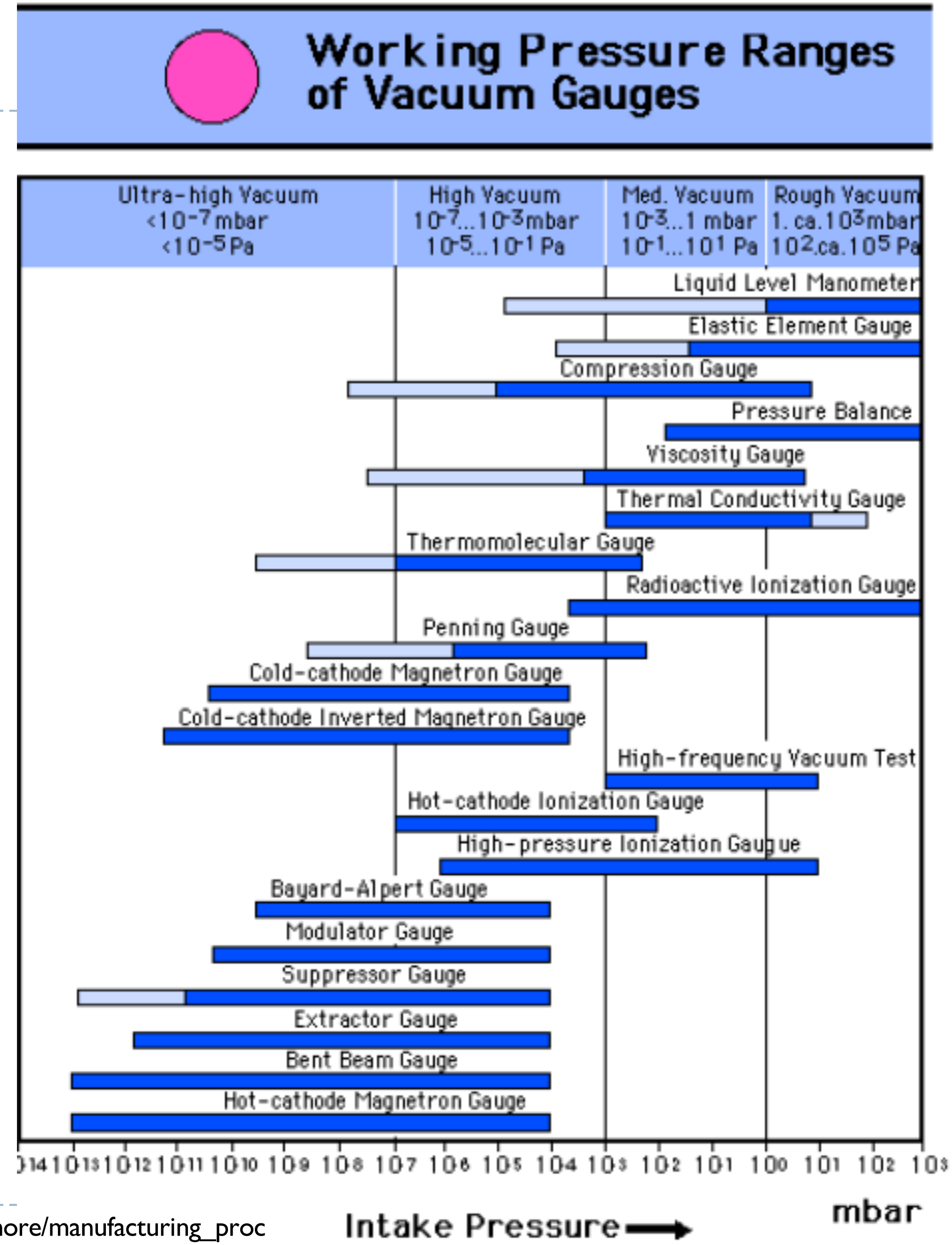
Vacuum gauges

Bourdon gauge









http://www.globalspec.com/learnmore/manufacturing_process_equipment/vacuum_equipment/vacuum_gauges

Pirani gauge, Thermocouple gauge

- Rough Vacuum gauges for above 10^{-3} torr
- Work by measuring heat loss to air
- Pirani Gauge: compare heat loss to standard tube
  uses a Wheatstone bridge setup
- Thermocouple gauge: measure T of hot wire
  uses thermocouple attached to wire
- Both low cost ($50) & robust
- Electronics cost about $1000 but supports many guag

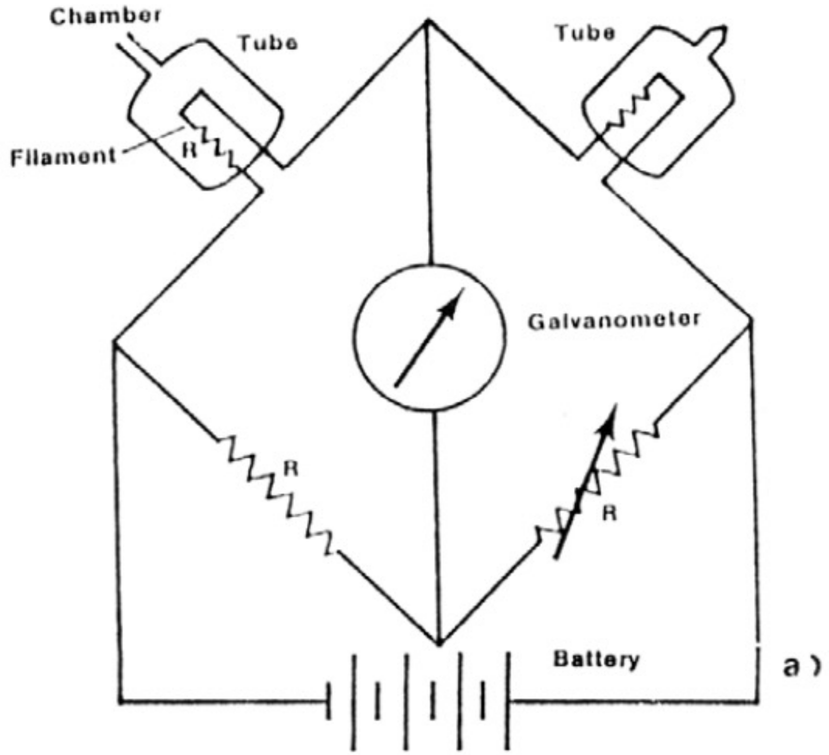
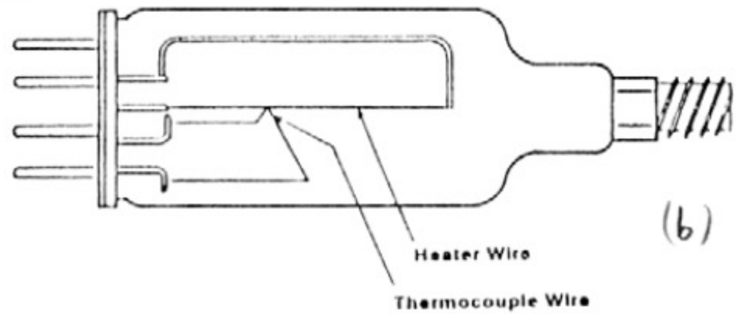
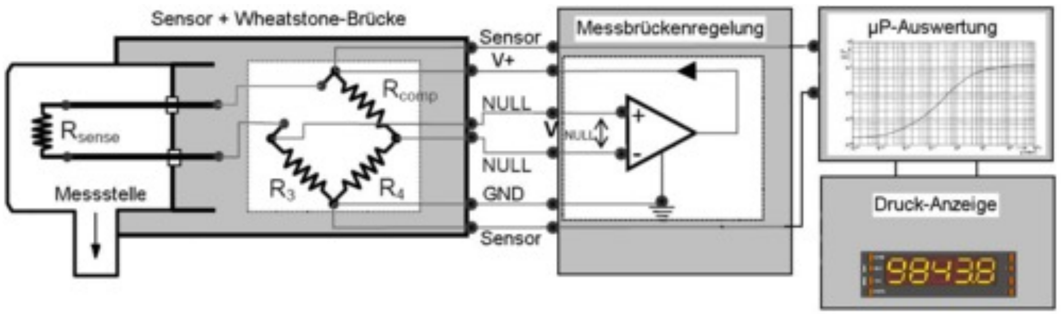


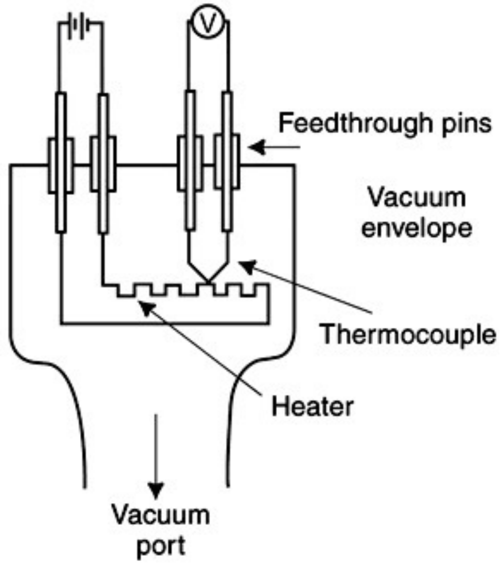
Fig. 18 (a) Pirani gauge. (b) Thermocouple gauge.



Pirani gauge

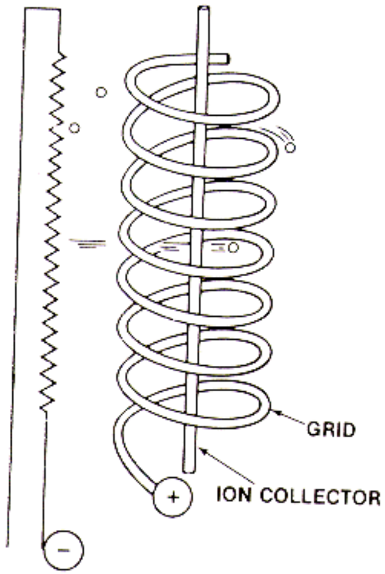


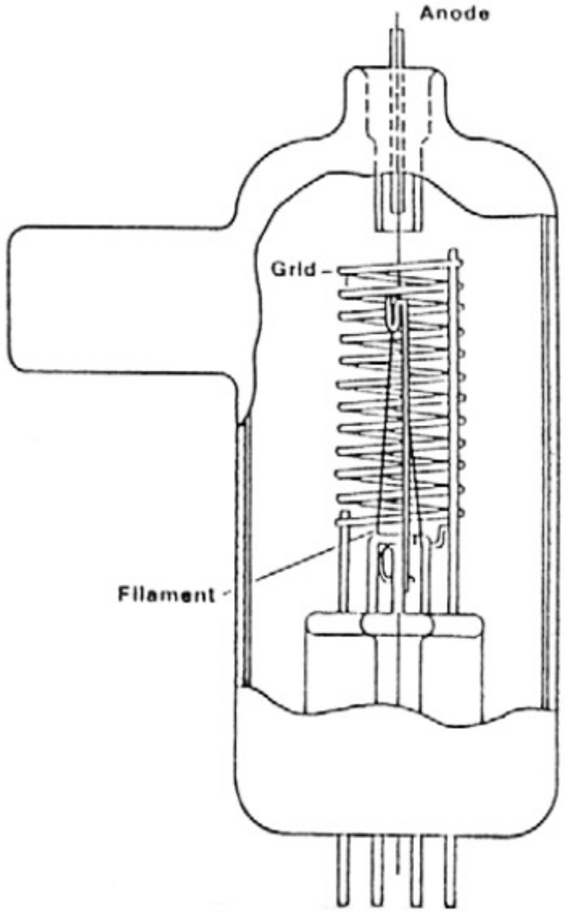
Thermocouple gauge



Ionization high vacuum gauge

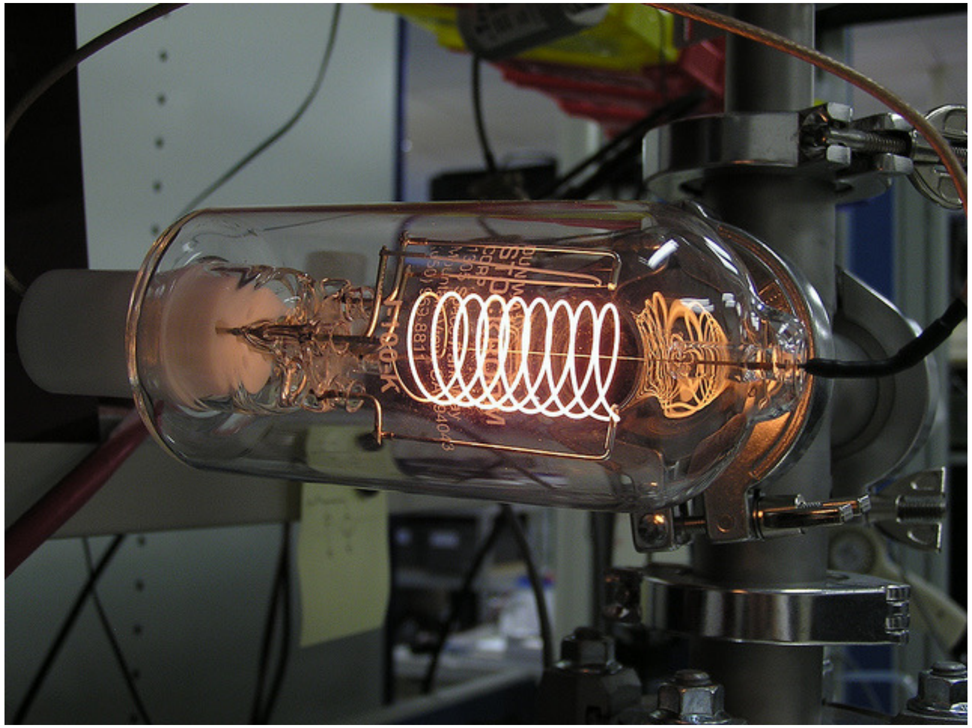
- Ionization gauge: works only a pressure $<10^{-3}$ torr
- Heater filament ionizes gas
- Measure current flow to anode
- Good till about 10^{-8} torr
- Burn out if brought into roughing pressure (10^{-2} torr)
  electronics have cutoff for high pressure: not always fast enough
- Walls and electrodes collect gases at higher pressure
- For true pressure must outgas
- Done by running heater in tube
- Baking out system drives off gases/water (for gauges & chamber)
- Expensive: tube costs $300 - $500
- Electronics about $2000

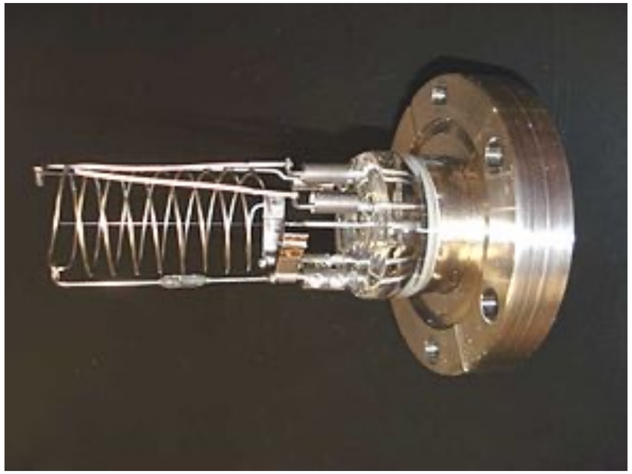




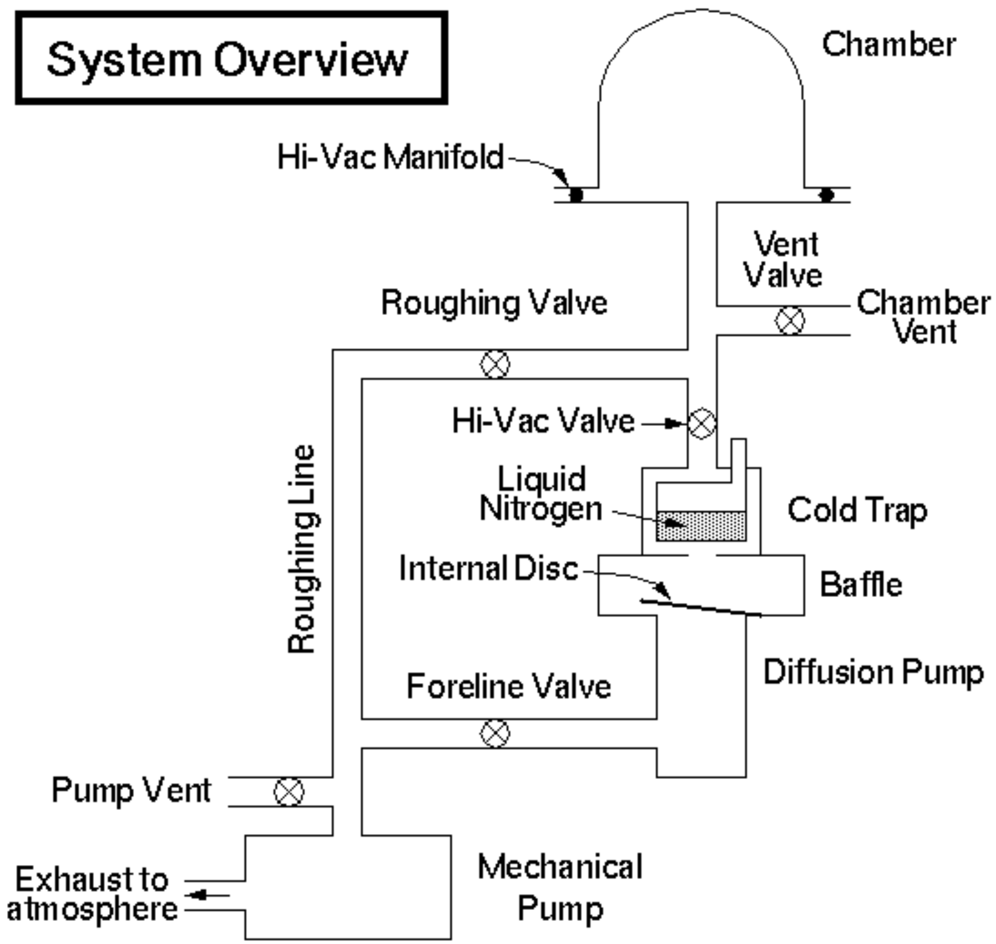
https://www.youtube.com/watch?v=ls6kfQLQWPk&ab_channel=PPlusVac

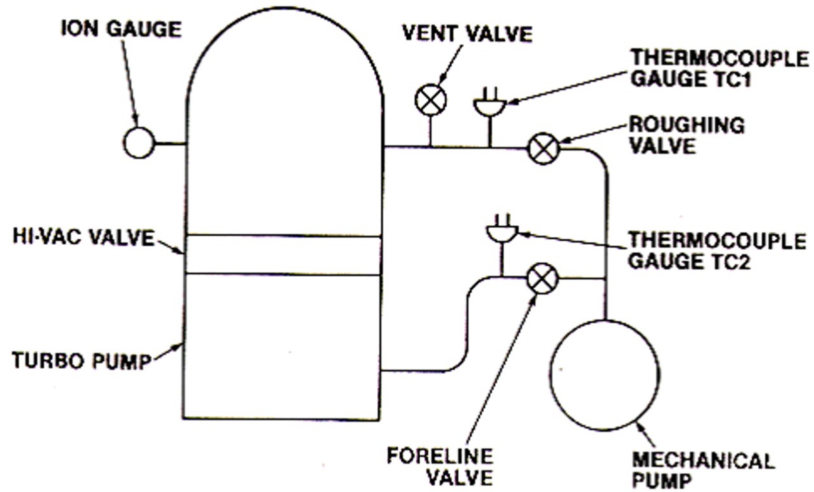
Ionization high vacuum gauge



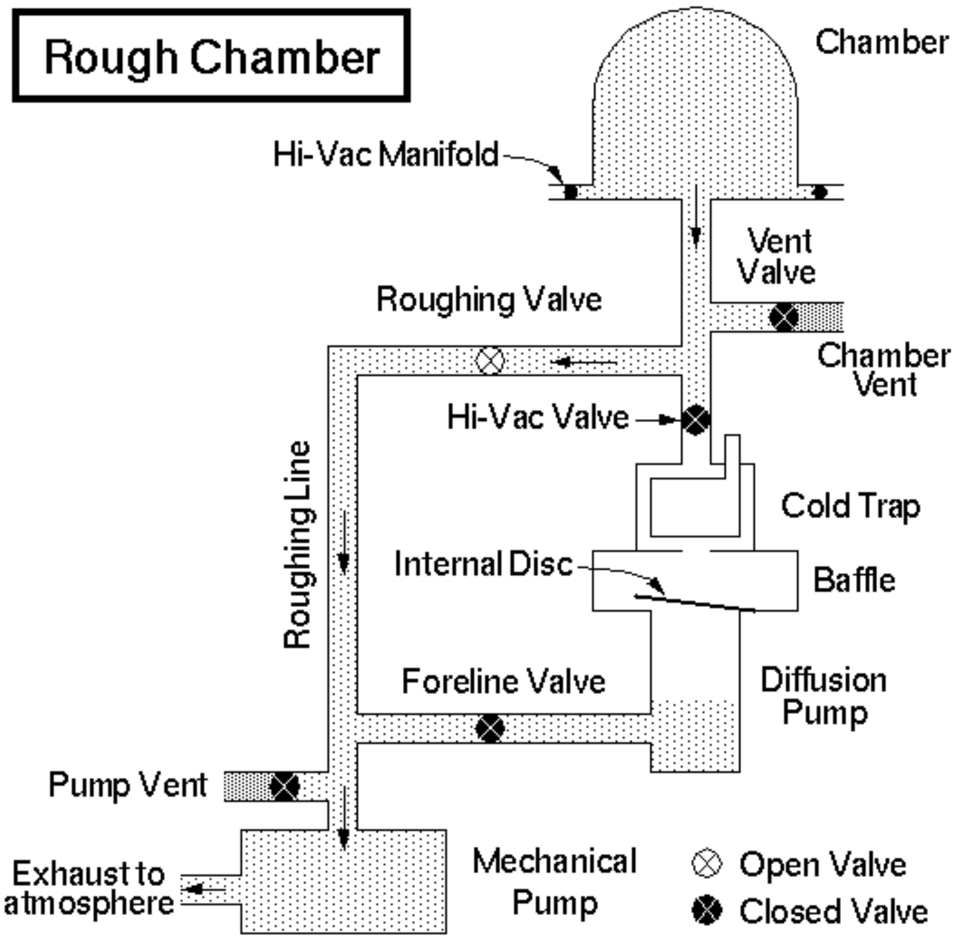


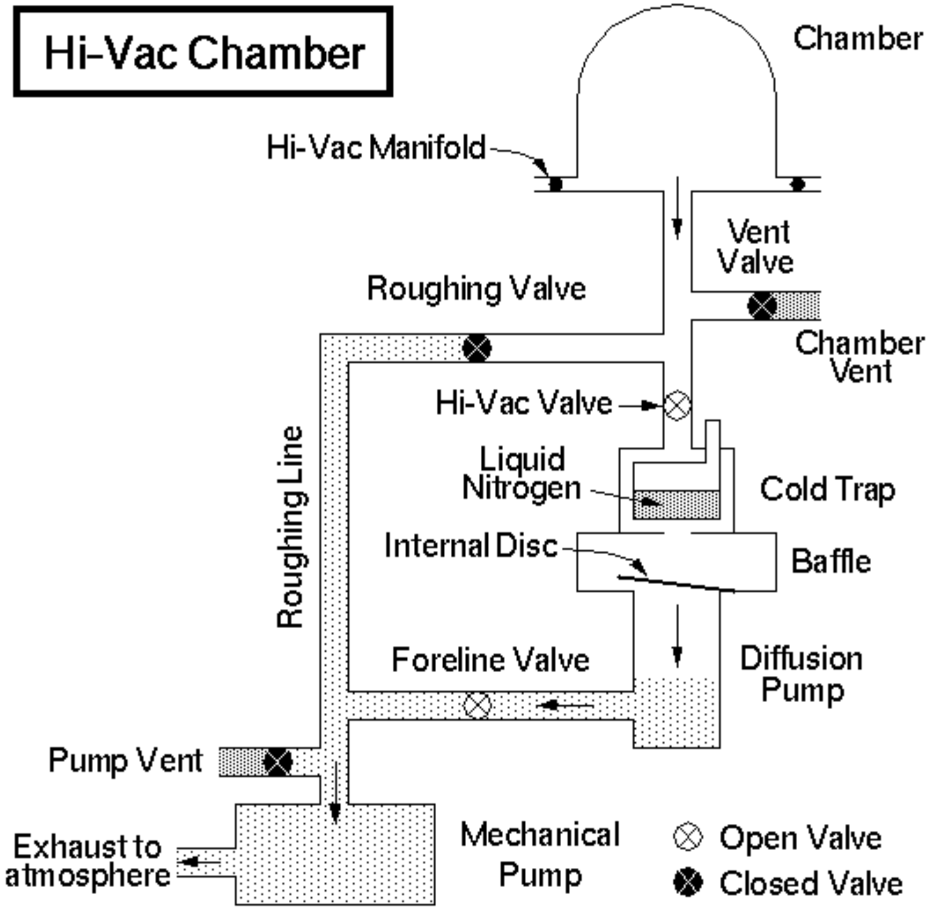
Vacuum System





TURBO PUMP SYSTEM





http://privatewww.essex.ac.uk/~bolat/basicvacuumsystem.html

Vacuum system operation

- Close chamber & make certain seals tight
- All vac valves closed at this point but pumps running

Roughing Cycle

- Rough out chamber: open Foreline value to roughing pump
  Note: diff pump isolated: roughing value to diff closed!
- When first open foreline gurgles & may put out oil
- If pressure does not drop much then leak
- Watch thermocouple guage: get pressure to millitorr level

High Vacuum Cycle

- Diff pump must be hot & cold trap filled
- Close foreline value, open roughing line to diff pump
- Then open high vac value
- Turn on ionization guage
- Degas ionization when pressure gets $<10^{-5}$ torr
  & before final pressure reading

To Bring to Atmosphere

- Close High Vac, pause then close roughing to diff pump value
- Make certain foreline value to chamber closed
- Possibly back fill chamber with nitrogen (to keep clean)
- Bring to Atm, and break chamber seal

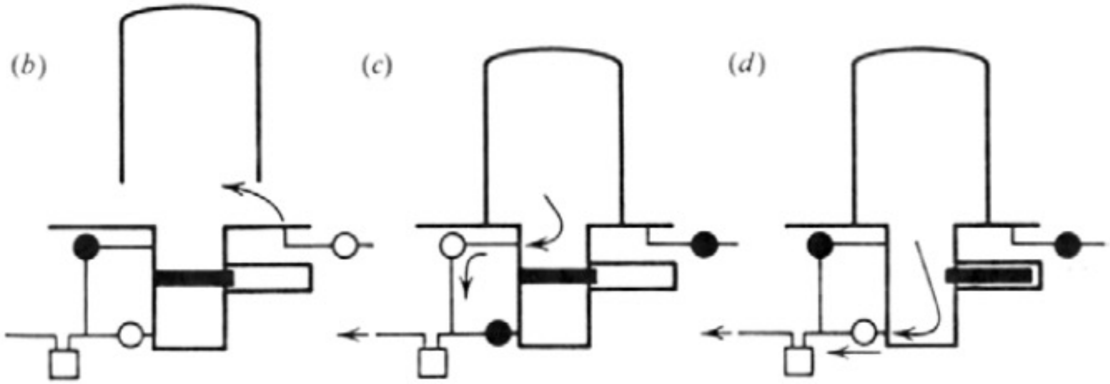


Figure 7-1 A typical apparatus for achieving high vacuum. (*b*) Valve configuration when chamber is open. (*c*) Valve configuration when rough pumping chamber from atmospheric pressure. (*d*) Valve configuration in high-vacuum operation.