진공 배기 과정

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   - Ceramics, Glass, Plastics
2. 진공 배기 과정
   - 공간 배기, 표면탈착, 확산 방출
   - 가열탈기체
   - 기체방출의 저감

Vacuum Materials

Steels

Stainless Steel

Aluminum (alloy)

Copper (alloy)

Other metals

Ceramics

Glass

Plastics

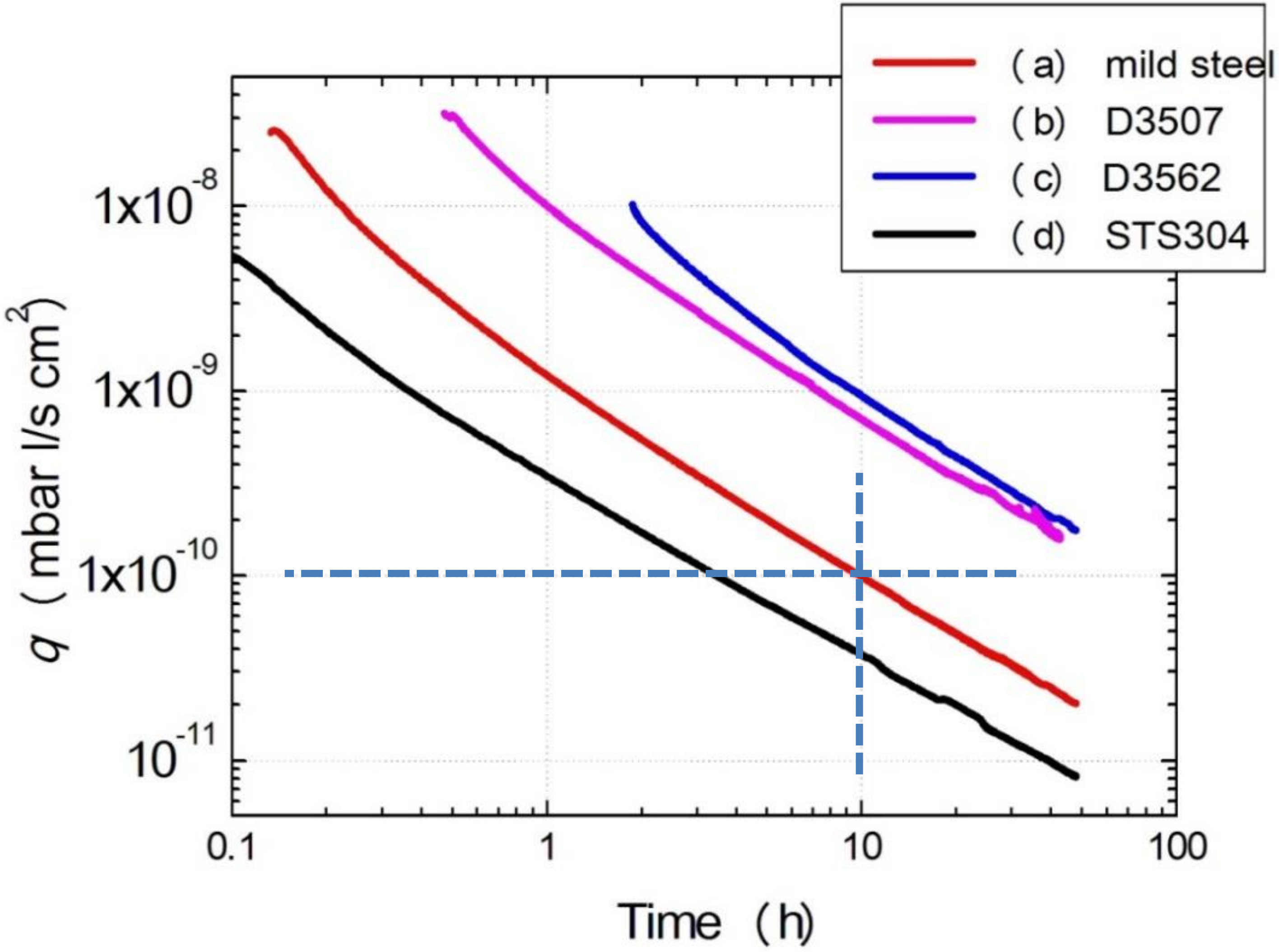
탄소강 (Steels)

- 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)]

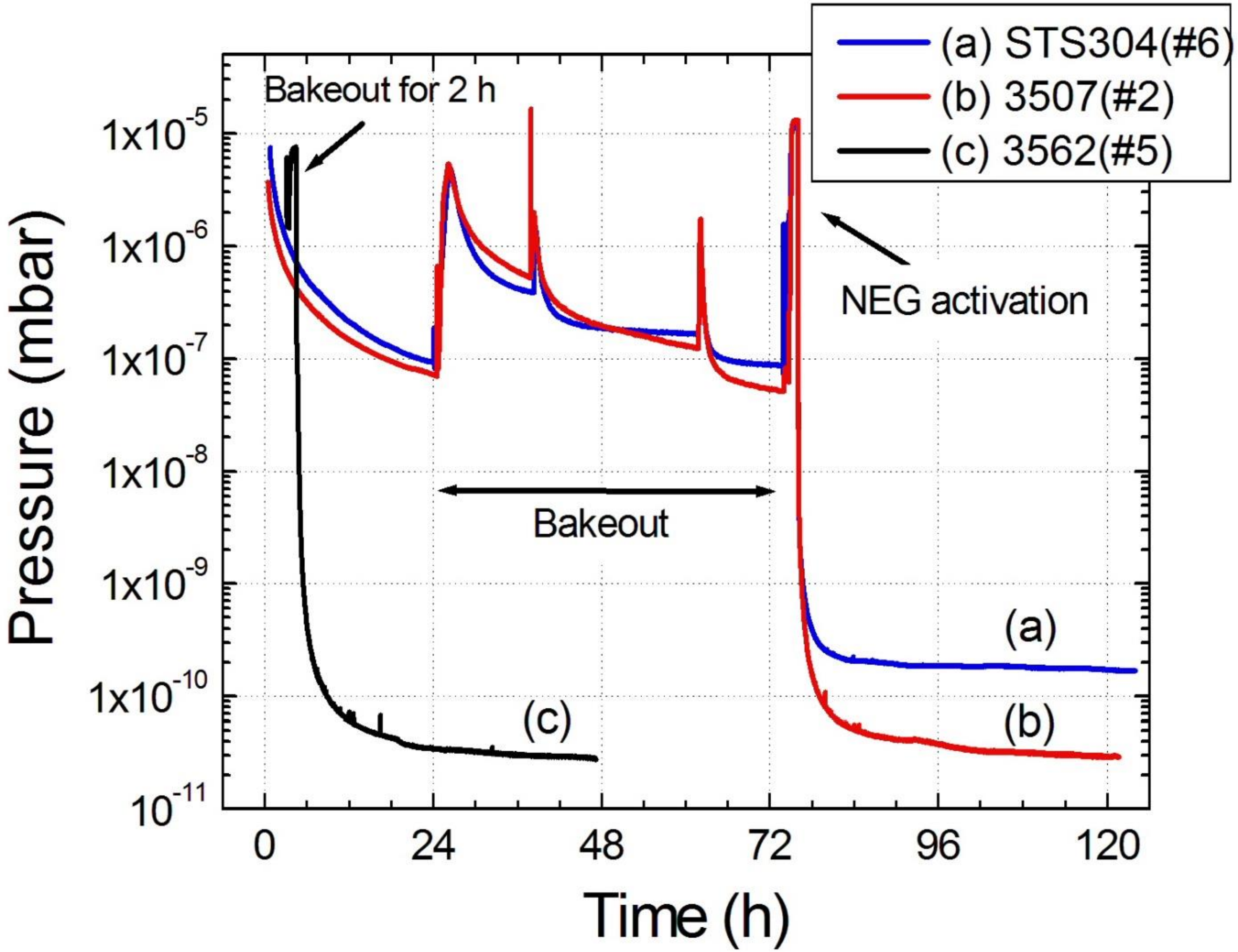
- Mild/structural steels
  - ✓ S235, S355, S20C
  - ✓ UHV compatible
    - plate, pipe, rod
    - ~ 10^{-11} mbar
    - $\lesssim$ 5×10^{-12} (mbar l/s cm^2) after bake
  - ✓ MV, RV compatible
    - Cast parts; pump and valve housing
    - ~ 10^{-3} mbar

❖ 탄소강 (초기배기곡선: H_2O)



Ref) JVST A34, 021601 (2016)

❖ 탄소강 (최종도달진공도: H_2)



스테인레스 스틸 (Stainless steel)

18-8 Steel Family

스테인레스 스틸 (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

대표적 진공 소재의 기계적 특성

	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

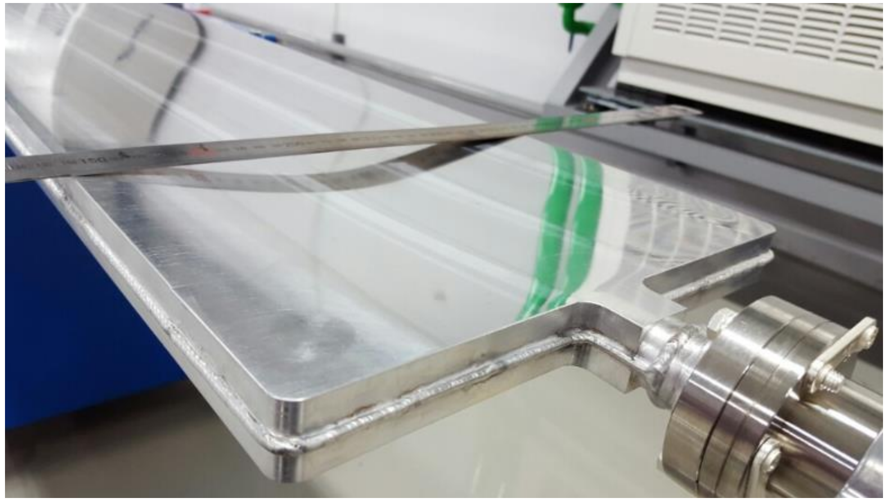
알루미늄 합금 (Aluminum alloys)

- 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)

알루미늄 합금 (Aluminum alloys)

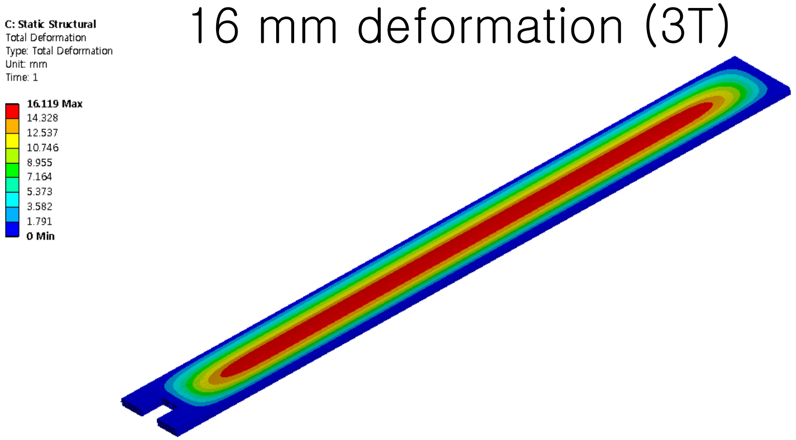
- 3xxx manganese alloys
  - ✓A3004; suitable for vacuum bellows
- 5xxx magnesium alloys
  - ✓easy to machine, higher strength, good weldibility
  - ✓A5083; for a large scale chamber
- 6xxx magnesium and silicon alloys
  - ✓Easy to machine and extrude
  - ✓A6063; most common materials in vacuum technology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

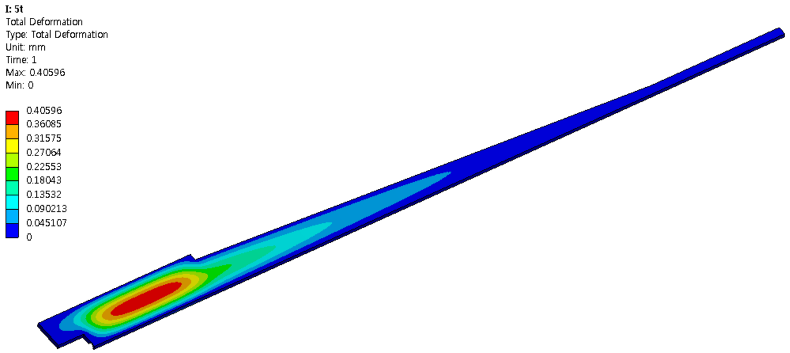
Deformation : Al alloy



(Thickness=3 mm, width = 270 mm)

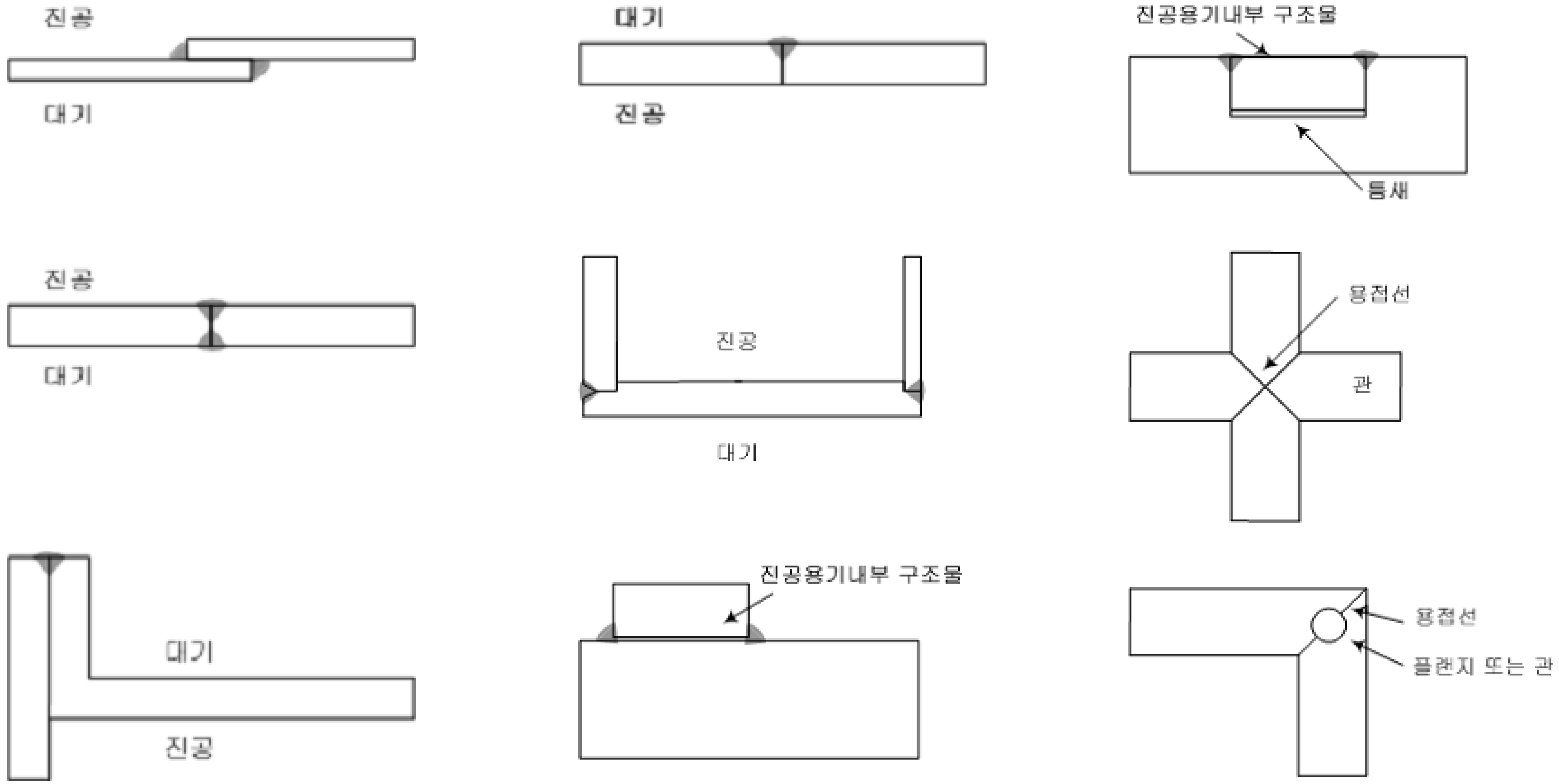
16 mm deformation (3T)





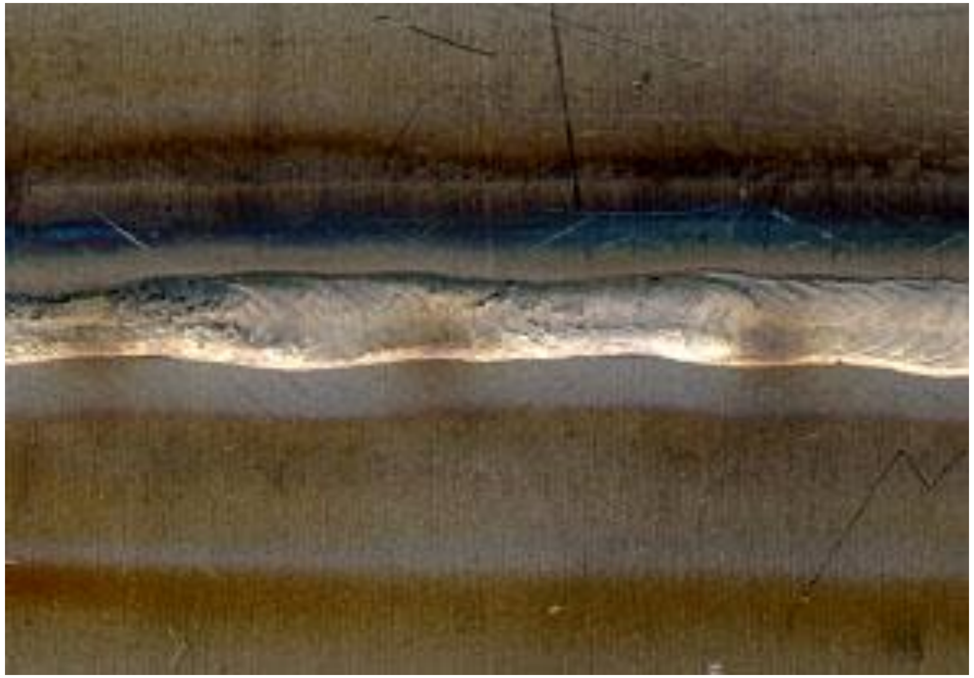
0.4 mm deformation (4T)

피해야 하는 용접

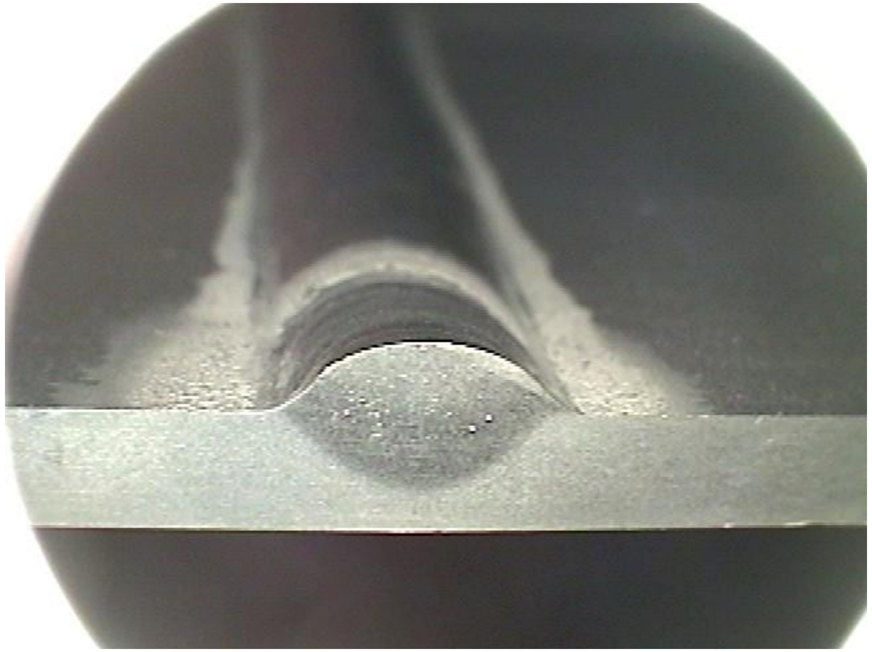


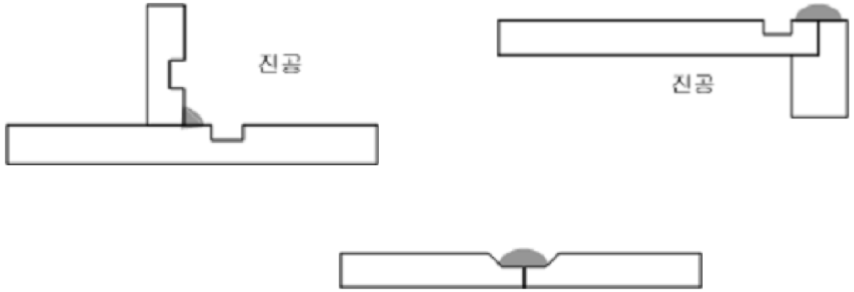
→ "초고진공 용접핸드북(KRISS)"

❖ Stainless steel



❖ Aluminum alloy





구리 합금 (Copper alloys)

- 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 reduced oxygen contents are required.
- Bakeout; Up to 300°C in vacuum
- Cold welding; OFHC gasket for ConFlat flanges
- Joining techniques; brazing, soldering, welding
- Outgassing rate; ~ 10^{-9} mbar liter/sec cm^2

구리 합금 (Copper alloys)

- 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

세라믹 (Ceramics)

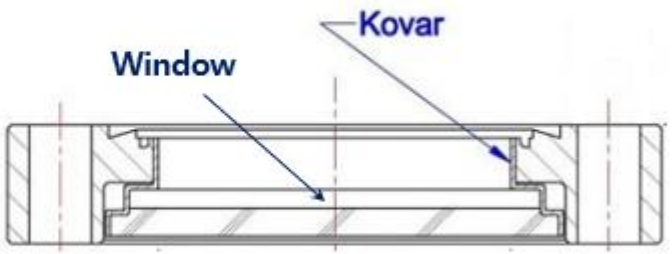
- Pure oxide ceramics
  - ✓Alumina, Zirconia, Beryllium oxide,…
  - ✓Alumina (Al_2O_3)
    - Mostly used ceramics
    - Max temperature; 1,800°C
    - > 92% in vacuum technology
    - Can be brazed
    - Mainly used as electrical *feedthroughs/insulator*
      - Bakable upto 350-550°C
    - Tensile strength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

세라믹 (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

세라믹 (Ceramics)

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



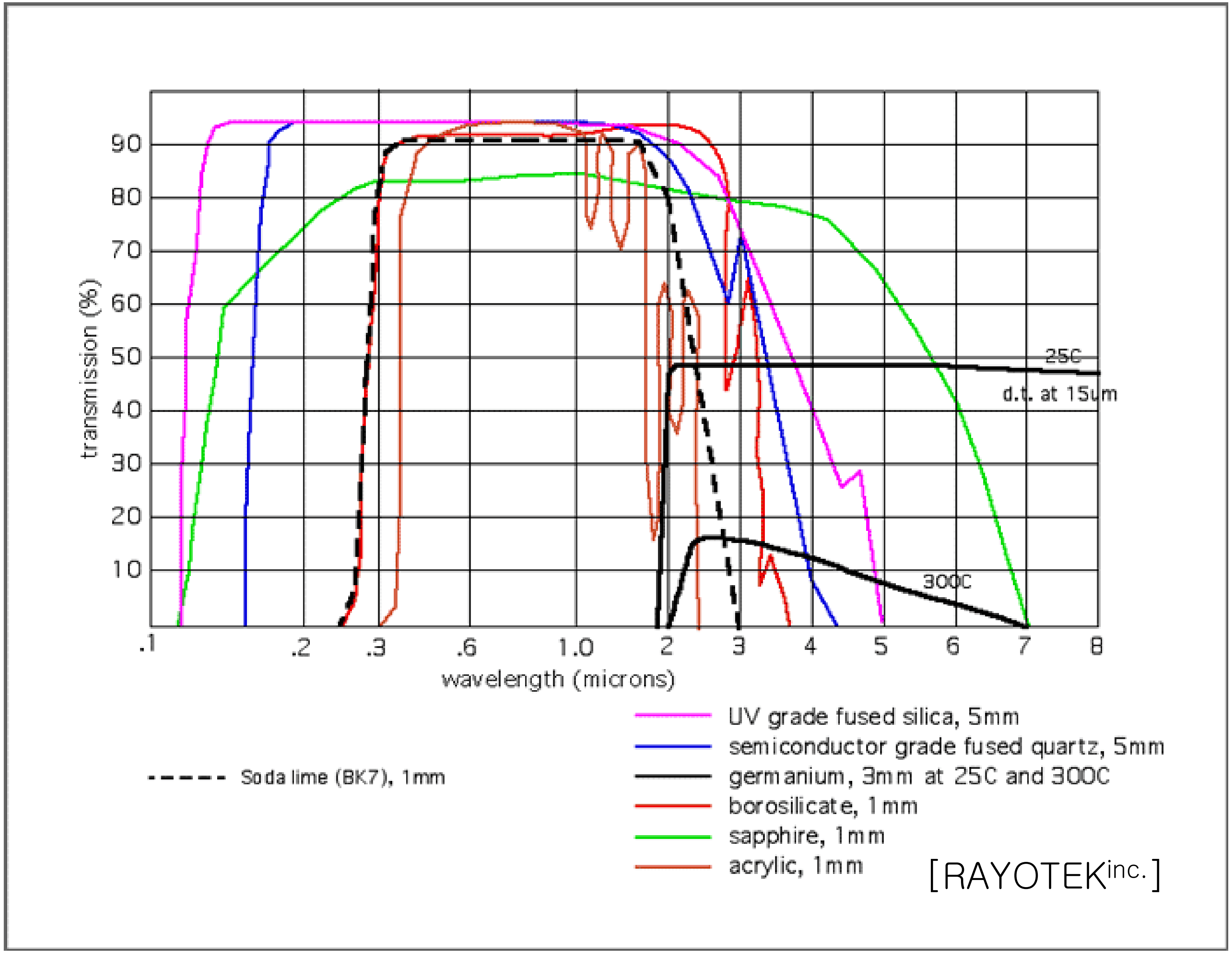
유리 (Glass)

- 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: $\sim 5 \cdot 10^{-7}\ K^{-1}$

유리 (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

Optical transmission



재료별 기체방출률

재료	기체방출률[10^{-7}Pa.m^3/s.m^2=10^{-10}mbar.L/s.cm^2]		
	q(1시간)	q(10시간)	베이킹 후 상온
알루미늄	80	8	0.001(150℃, 24h)
구리	250	17	0.0025(160℃, 24hr)
철강	7000	650	
스텐레스강	200	18	0.001(150℃, 24h)
탄소	5000	10	0.03(350℃, 10h)
파이렉스	100	7	10(450℃, 4hr)
네오프렌	400000	160000	
바이톤-A	15000	2500	3(200℃, 12h)
캡톤	3000-	500	0.4(300℃, 12h)
마일러	40000	15000	
아랄다이트(에폭시)	26000	13000	
나일론	160000	50000	8(120℃, 24h)
테플론	65000	2000	
아크릴	13000	6000	
Kel-F	530	100	
PVC	70000	35000	

진공시스템 사양 결정

기본사양

크기 V
기저진공도 P_0
유량 Q
작동압력 P
온도 T
분위기 (Air, H_2, Ar, - -)
펌프 위치

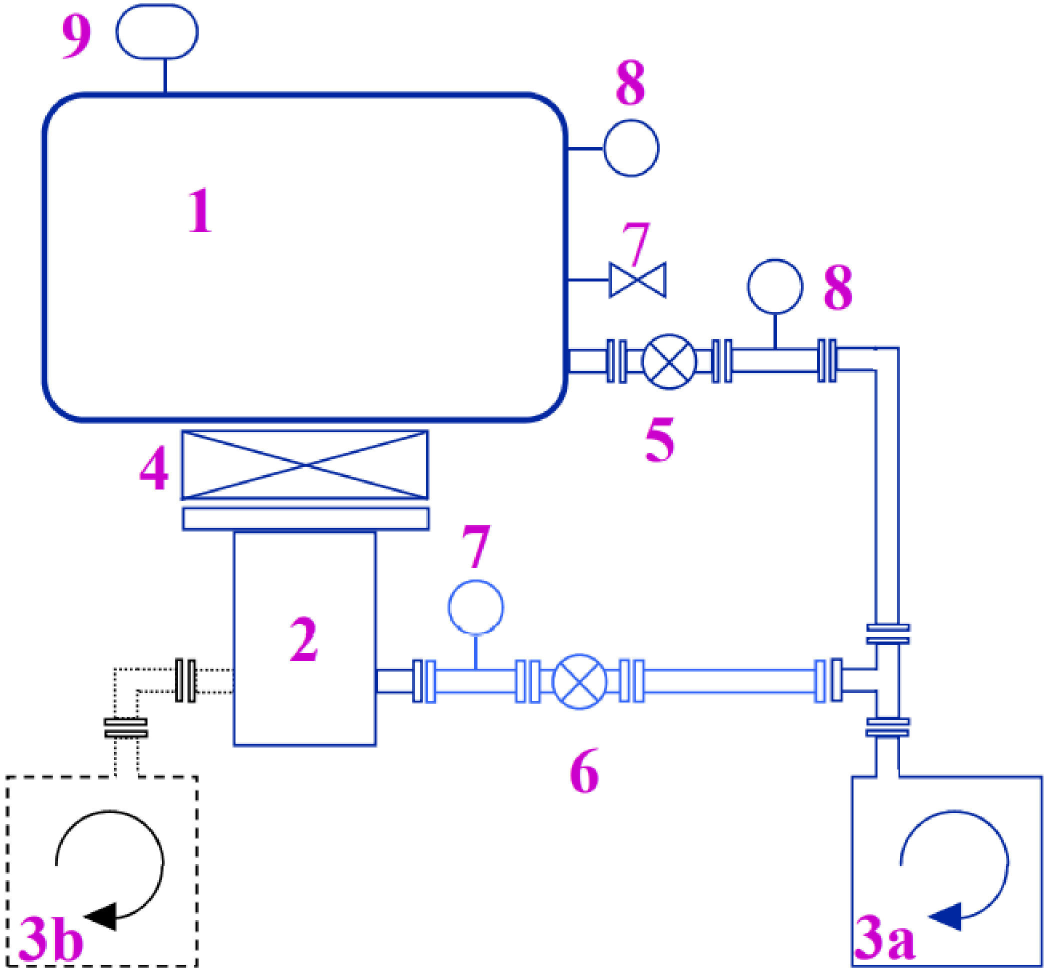
1차 결정사항

용기 재료 (SS, Al, - -)
가공, 표면처리
기체방출률 Q
도관
밸브
진공 게이지

2차 결정사항

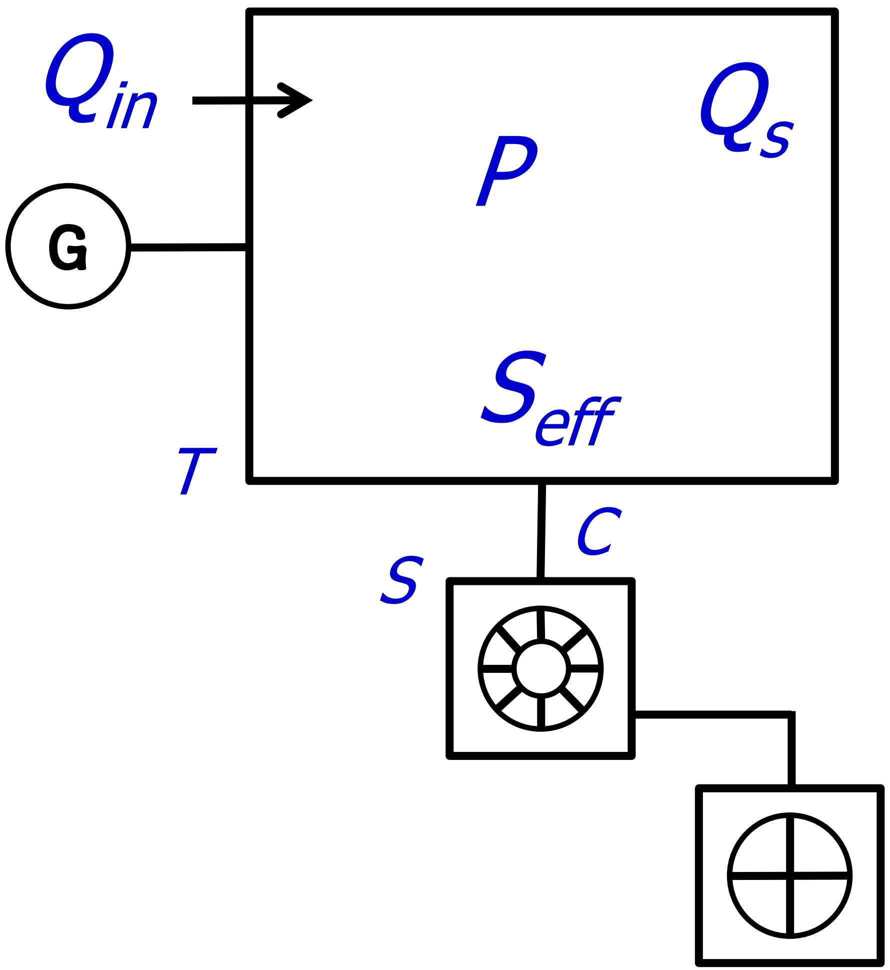
진공펌프 종류
배기속도 S
보조펌프 여부
보조펌프 용량

진공시스템의 구성 예



1	Chamber
2	High Vac. Pump
3a	Roughing Pump
3b	Foreline Pump
4	Hi-Vac. Valve
5	Roughing Valve
6	Foreline Valve
7	Vent Valve
8	Roughing Gauge
9	High Vac. Gauge

진공시스템의 배기 (공간 배기)



- $d(PV)/dt = Q - PS_{eff}$
- If $Q=0$: $dP/dt = -P(S_{eff}/V) = -P/\tau$

  → $P = P_0 e^{-t/\tau}$

  τ(=V/S)는 배기계의 시간상수로 공간에 있던 입 자들의 수가 약 2.7분의 1로 떨어지는 데 걸리는 시간이다.
- If $Q>0$: $dP/dt = Q/V - P/\tau$

  → $P = Q/S_{eff} + (P_0 - Q/S_{eff})e^{-t/\tau}$

  → $(P - Q/S_{eff})/(P_0 - Q/S_{eff}) = e^{-t/\tau}$

진공용기의 대기개방 (Vent)

1. 일정한 유량을 유지

→ $Q=V*dP/dt$ → $t = V/Q*(P_{atm}-P)$

2. 대기압 또는 약간 높은 압력의 기체 저장용기와 연결

→ $V(dP/dt) = C(P_{atm} - P) = k(P_{atm}^2 - P^2)/2$,   ※ $C=k(P_{atm}+P)/2$

→ $t = (V/kP_{atm}) \ln[(P_{atm}+P)/(P_{atm}-P)]$

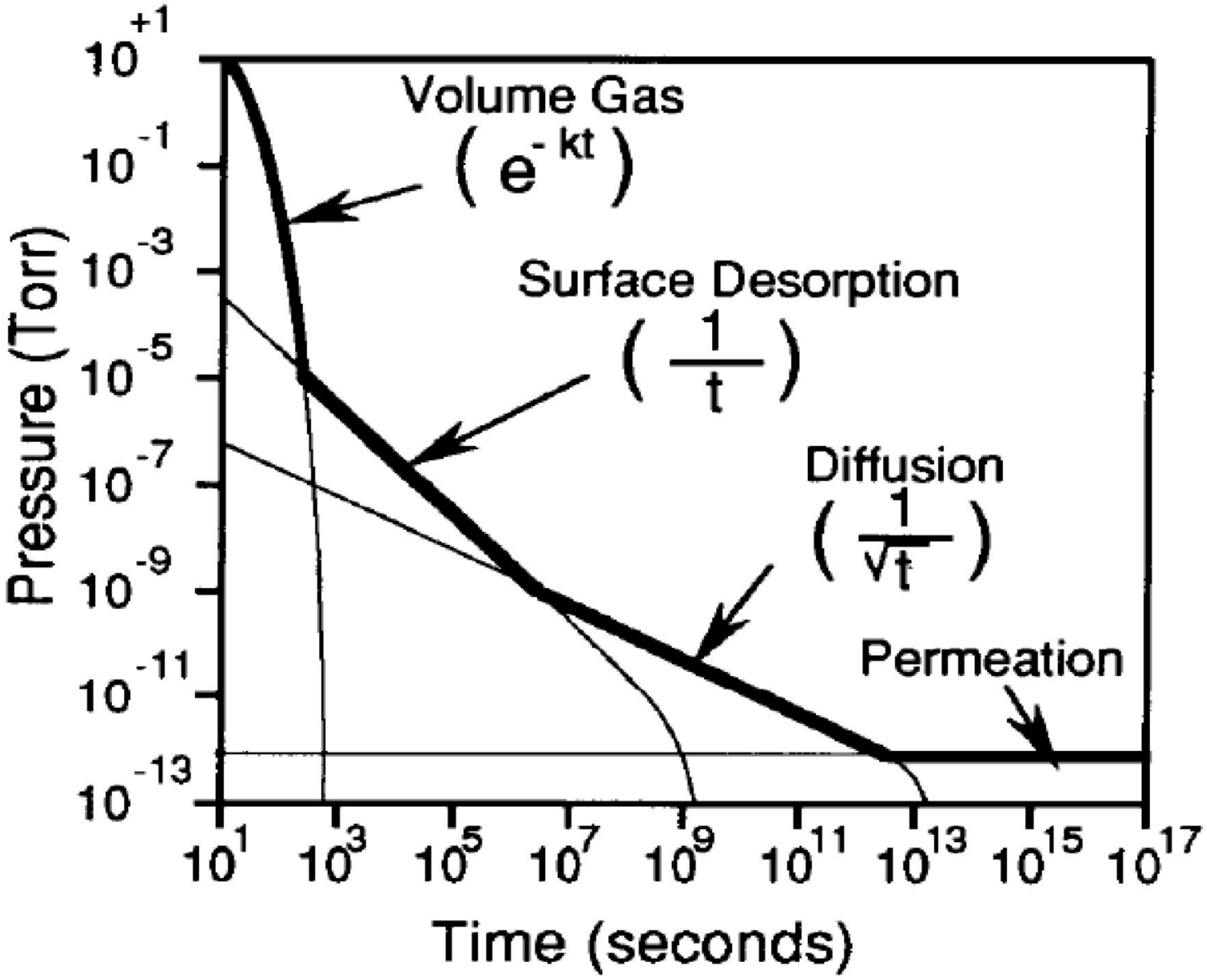
$\sim V/2C \ln[(P_{atm}+P)/(P_{atm}-P)]$

예제 (대기개방 시간)

부피가 100 m^3인 진공용기에 공기를 채우기 위해 1.1기압의 저장용기를 연결했다면 진공용기가 1기압으로 차는 데 얼마나 걸리나?
(연결도관의 컨덕턴스는 10(P_0+P) L/s라고 하자.)

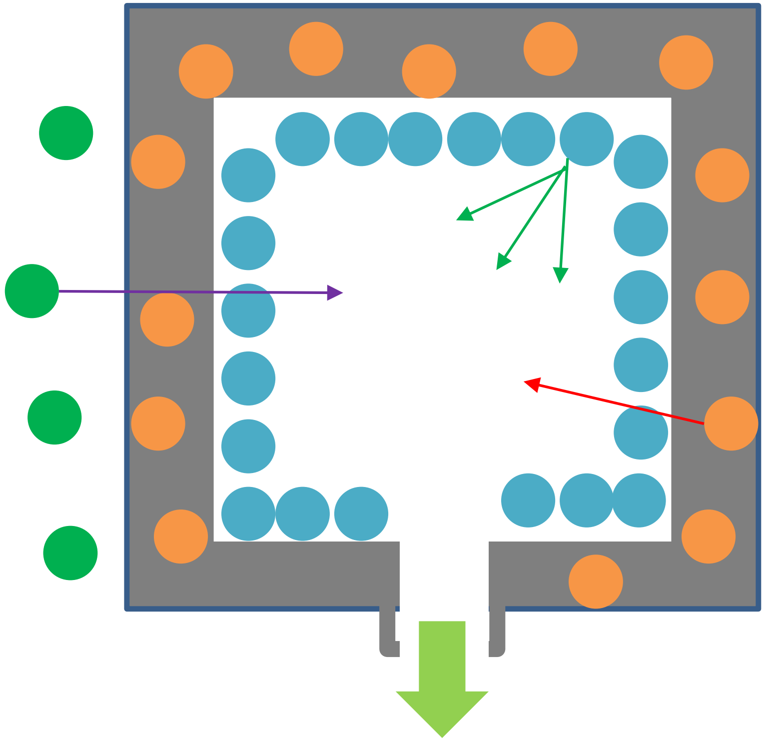
$$
\begin{aligned}
t &= (100 \times 1000/20/1.1)\ \ln[(1.1+1)/(1.1-1)] \\
&= 5000/1.1 \times \ln(21) \\
&= 13839\ \mathrm{s} \\
&= 3.84\ \mathrm{hr}
\end{aligned}
$$

진공 배기 과정

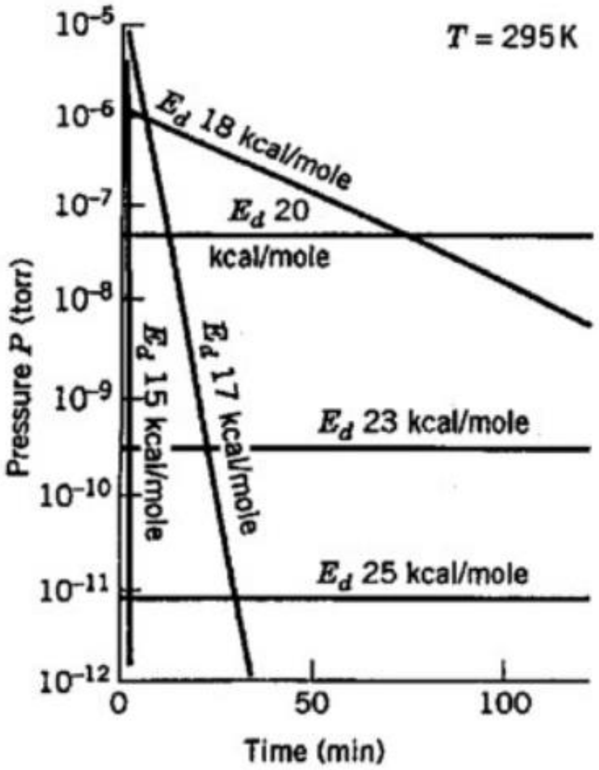

Volume Gas
(e- kt)
Surface Desorption
(1/t)
Diffusion
(1/√t)
Permeation
Pressure (Torr)
Time (seconds)
10+1
10-1
10-3
10-5
10-7
10-9
10-11
10-13
101
103
105
107
109
1011
1013
1015
1017

기체방출원

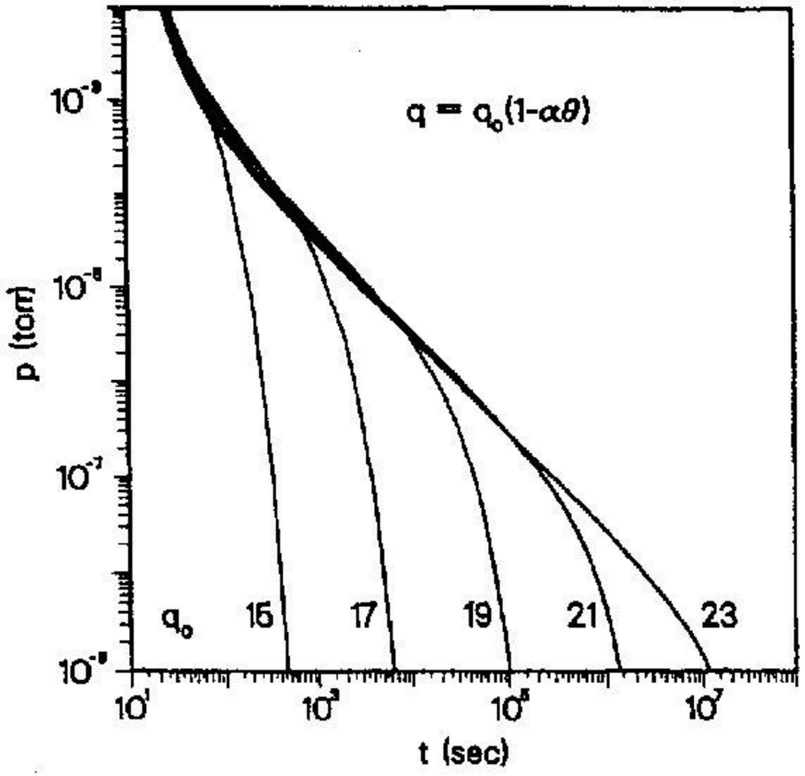
- 확산과 투과 (Diffusion and Permeation)
  - Well understood
- 흡착과 탈착 (Adsorption and desorption)
  - No clear explanation for the surface desorption
- 기타: 증발, 누출, 역류, …



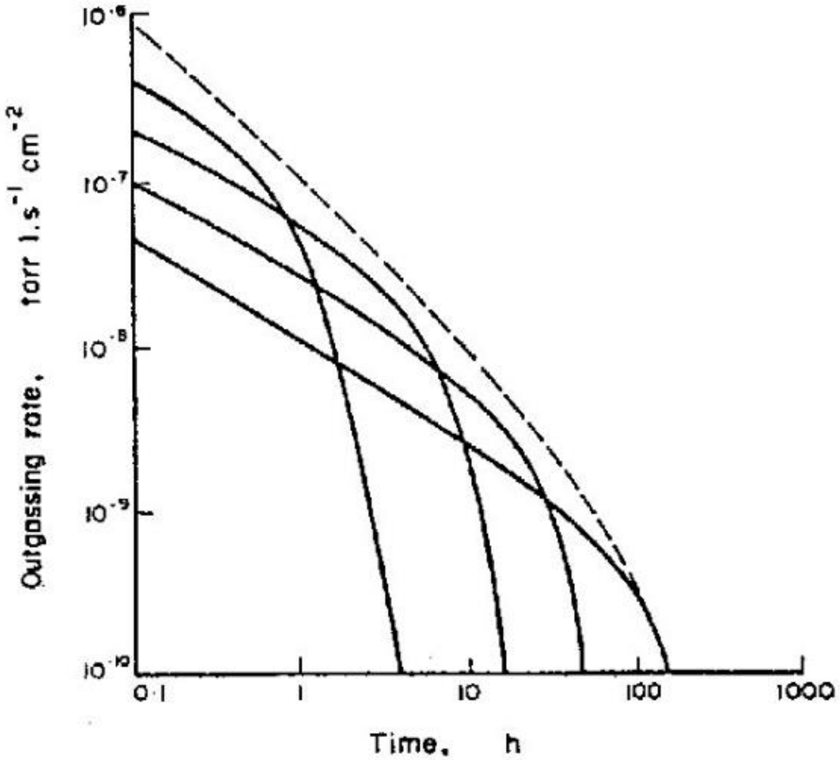
표면 탈착



T = 295 K
E_d 18 kcal/mole
E_d 20 kcal/mole
E_d 15 kcal/mole
E_d 17 kcal/mole
E_d 23 kcal/mole
E_d 25 kcal/mole
Pressure P (torr)
Time (min)

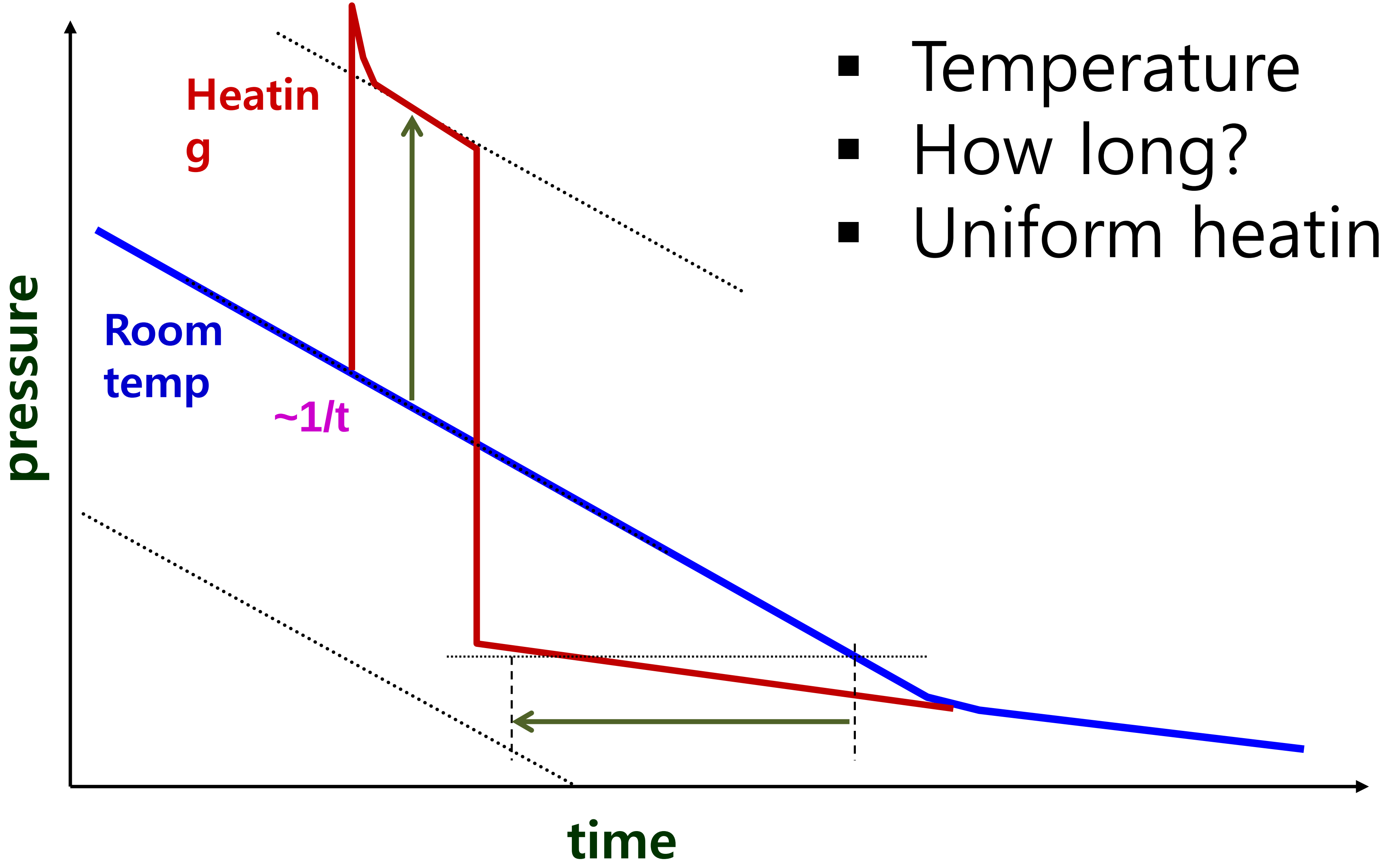


$q = q_o(1-\alpha\theta)$
p (torr)
t (sec)
q_o
15
17
19
21
23



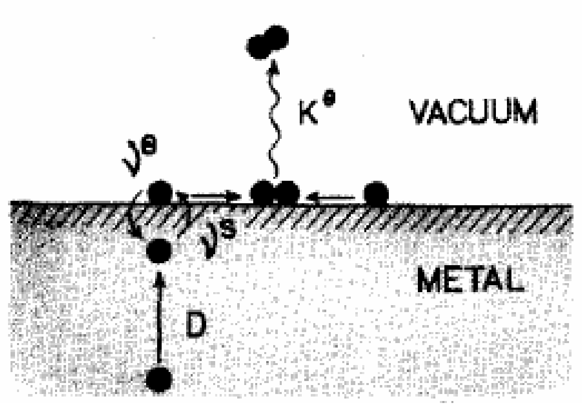
Outgassing rate, torr l.s^{-1} cm^{-2}
Time, h

가열 탈기체 (Bake-out)



- Temperature
- How long?
- Uniform heating

수소 확산 방출 모델



[P. Chiggiato, IVC-16 (2004)]

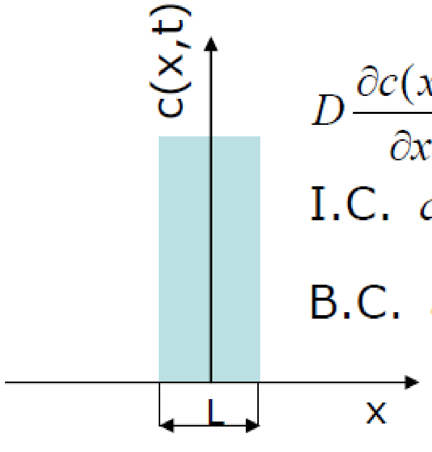
- Diffusion Limited Model (DLM)
  - Concentration gradient

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

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

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

- Solution of diffusion equation for slab (DLM)



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

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

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

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

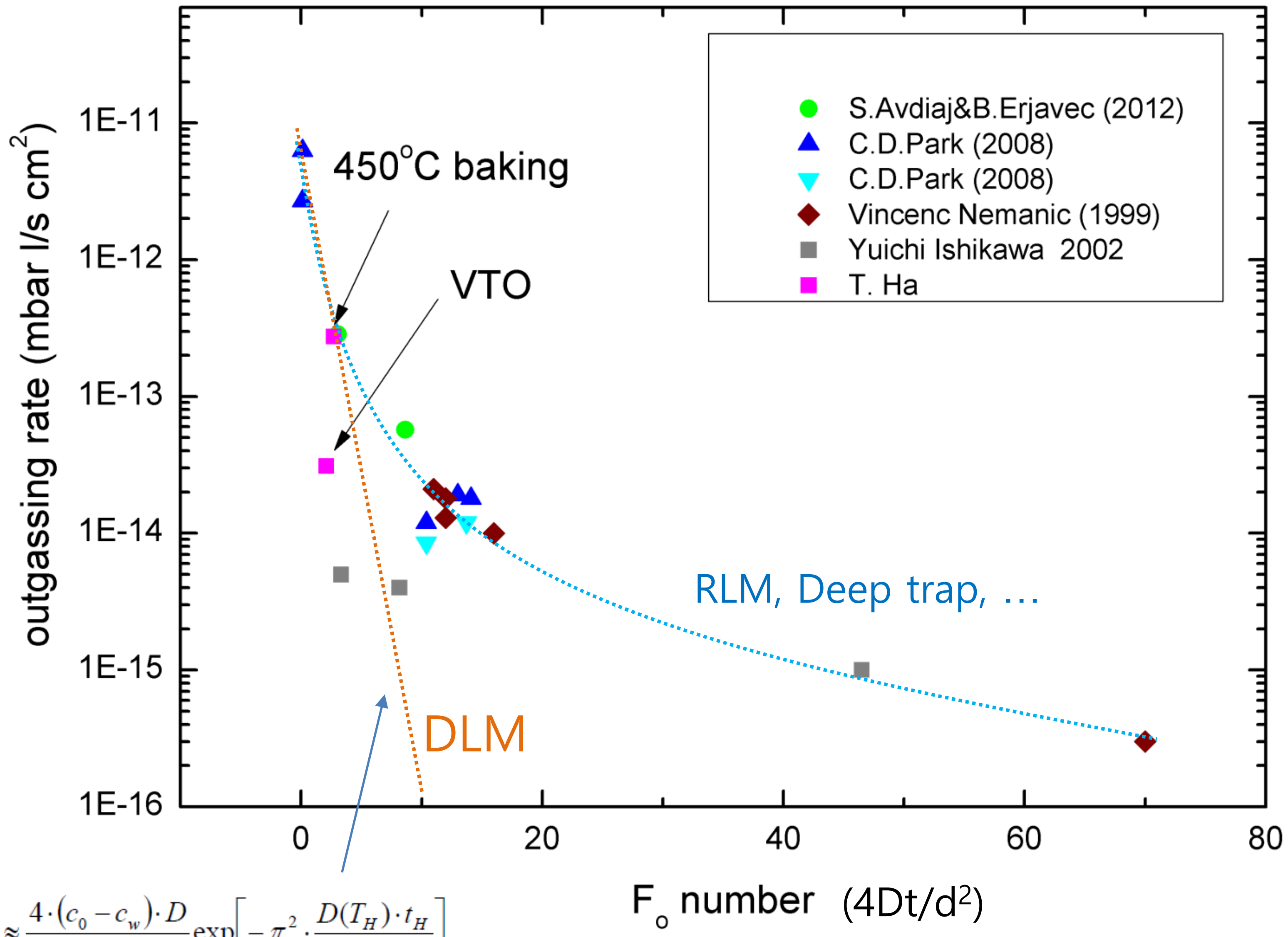
- For arbitrary thermal cycle (thermal history)

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

Fourier number

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

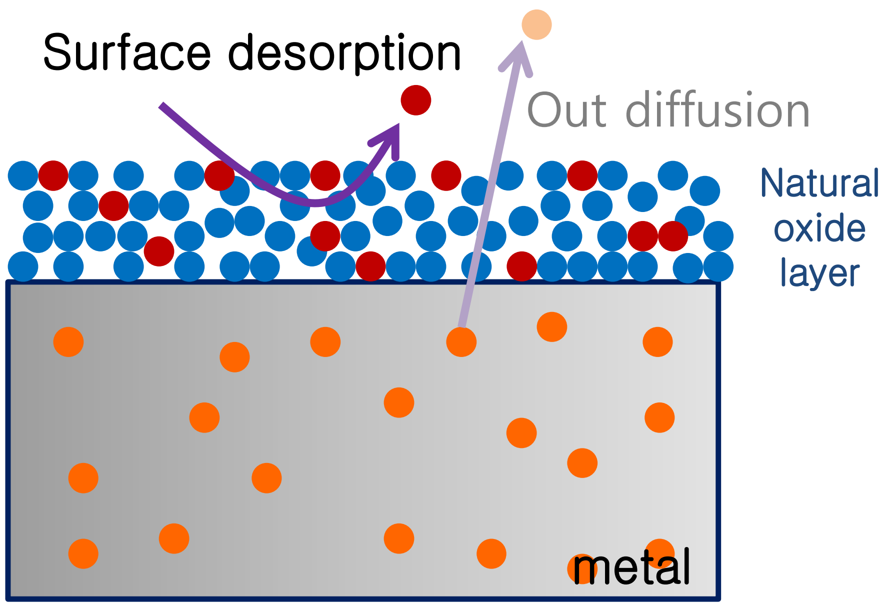
열처리 강도(F_o)와 기체방출률

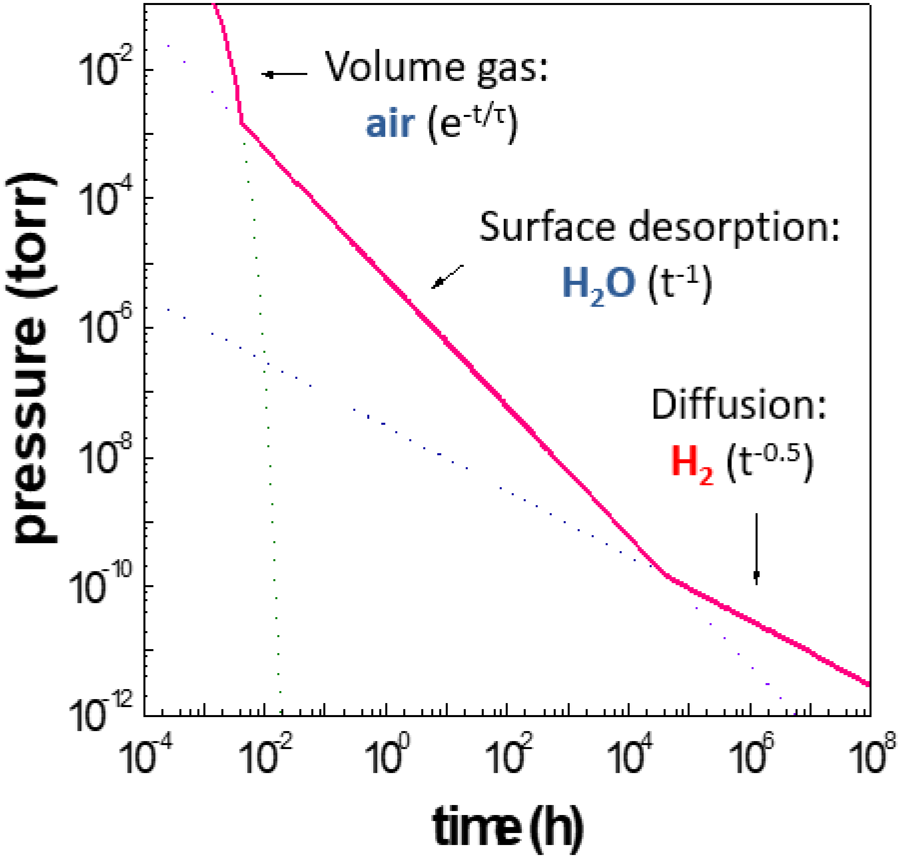


$$q \approx \frac{4\cdot(c_0 - c_w)\cdot D}{L}\exp\left[-\pi^2\cdot\frac{D(T_H)\cdot t_H}{L^2}\right]$$

일반 스테인리스강의 진공특성

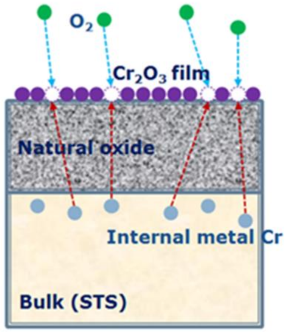
- ✓ 일반 금속(스테인리스강)의 표면은 다공질의 산화막이 형성되어 있음.
- ✓ 공기 노출 시 다공질 표면에 물과 같이 흡착성이 강한 입자가 다량으로 흡착됨.
- ✓ 진공 배기하면 흡착된 물 분자가 서서히 방출되므로 압력은 시간의 역수에 비례하며 ($p \propto 1/t$) 느리게 떨어짐.



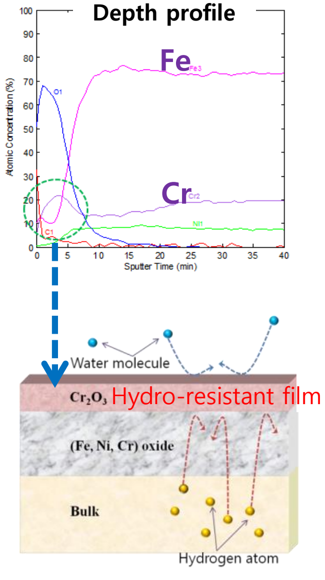


진공 중 산화처리 기법

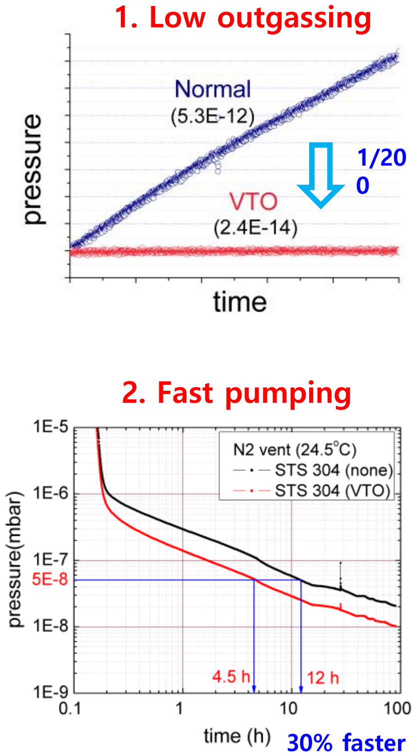
Vacuum Thermal Oxidation (VTO)



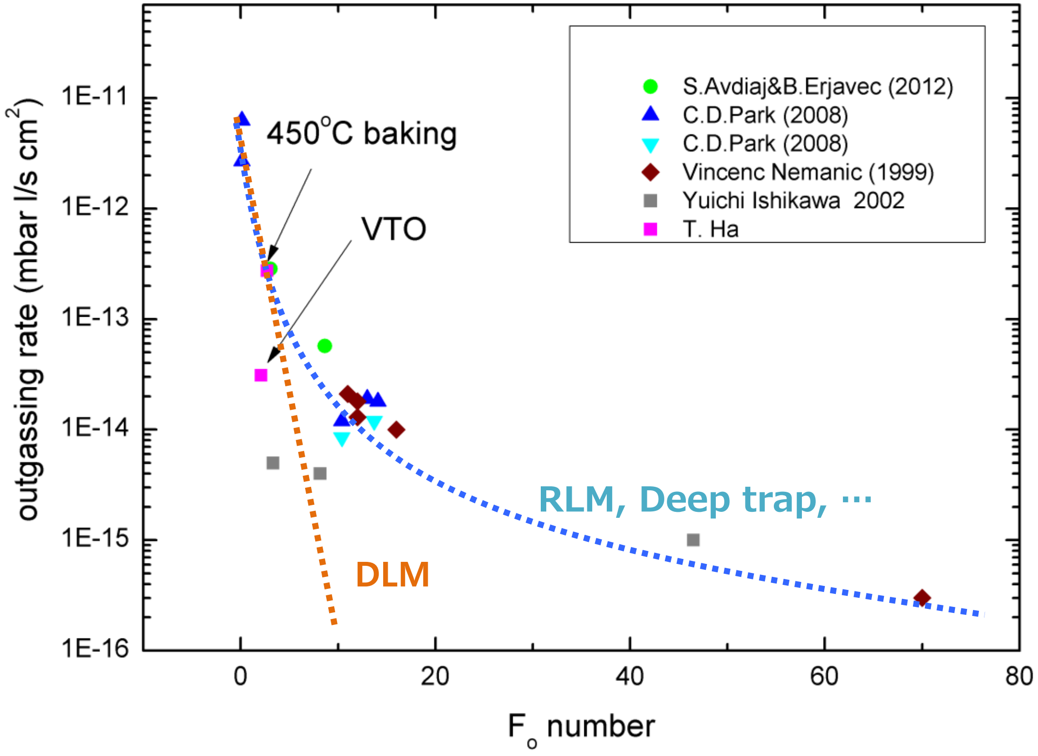
Vacuum Thermal Oxidation
→ $P(O_2)$=1E-9 torr @ 450℃



Hydrogen barrier of the Cr_2O_3 layer



q vs. F_o



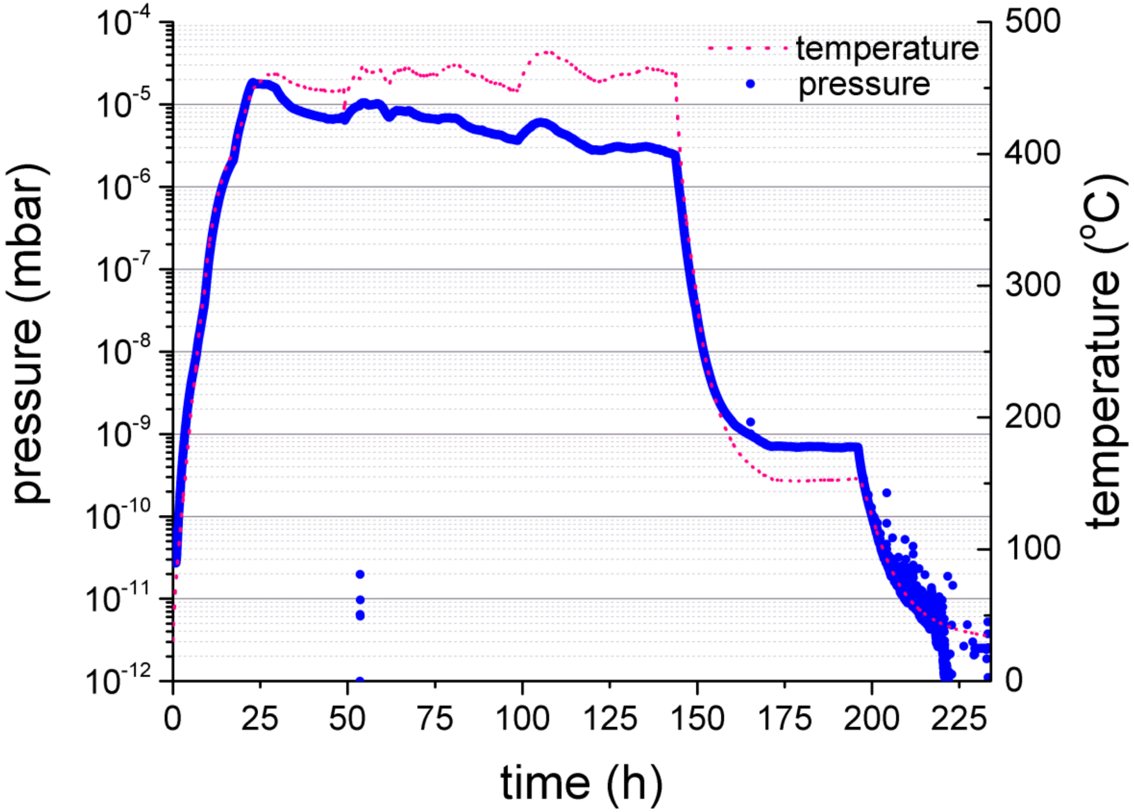
Material	In vacuum heat treatment	Post bakeout	F_o	RoR - 48 h q (mbar l/s ㎠)
SST 304 (d=3.3 mm)	None	150 ℃, 48 h		5.54E-12
	Baking 450 ℃, 36 h	150 ℃, 48 h	2.7	2.75E-13
	VTO 450 ℃, 28 h	150 ℃, 48 h	2.1	3.1E-14

대형 극고진공 시스템

Vacuum Thermal Oxidation (VTO)

- **Large XHV system (PAL)**
  - Volume = 1000 L
  - Area = 6,500 cm^2
  - q = 3E-14 mbar L/s cm^2
  - 30 x WP950 NEG pumps
  - P < 1E-13 mbar

3B gauge



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