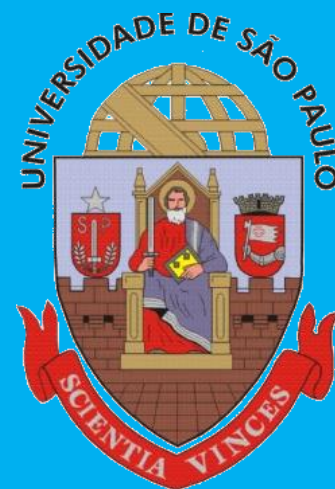
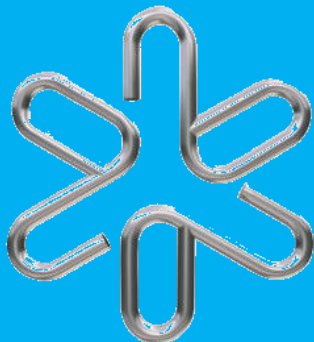


Ciência e Tecnologia do Vácuo

430323



N. H. Medina

Instituto de Física da Universidade de São Paulo

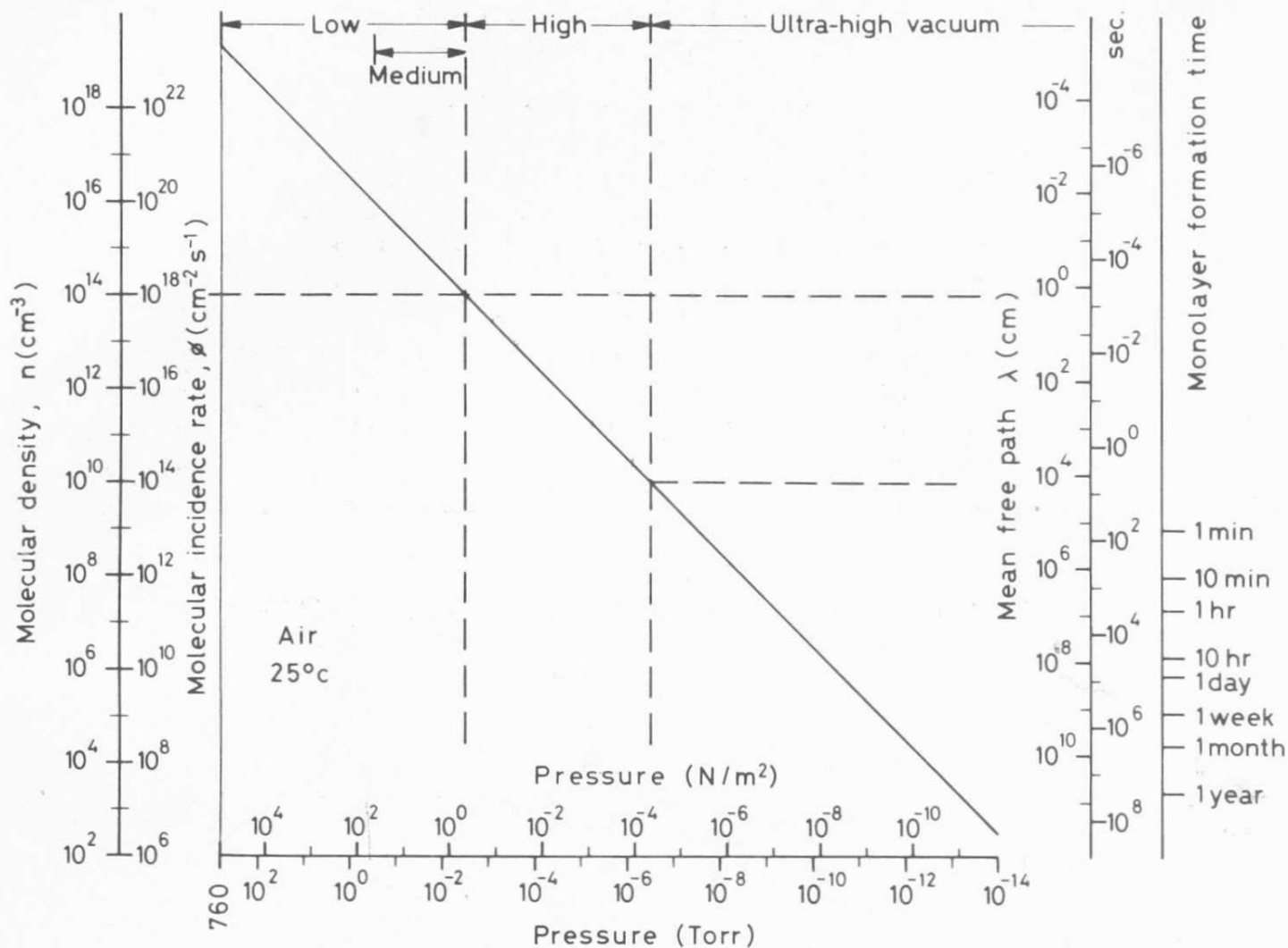


Fig. 1.1 Relationship of several concepts defining the degree of vacuum.

Table 1.3.
Gas compositions.

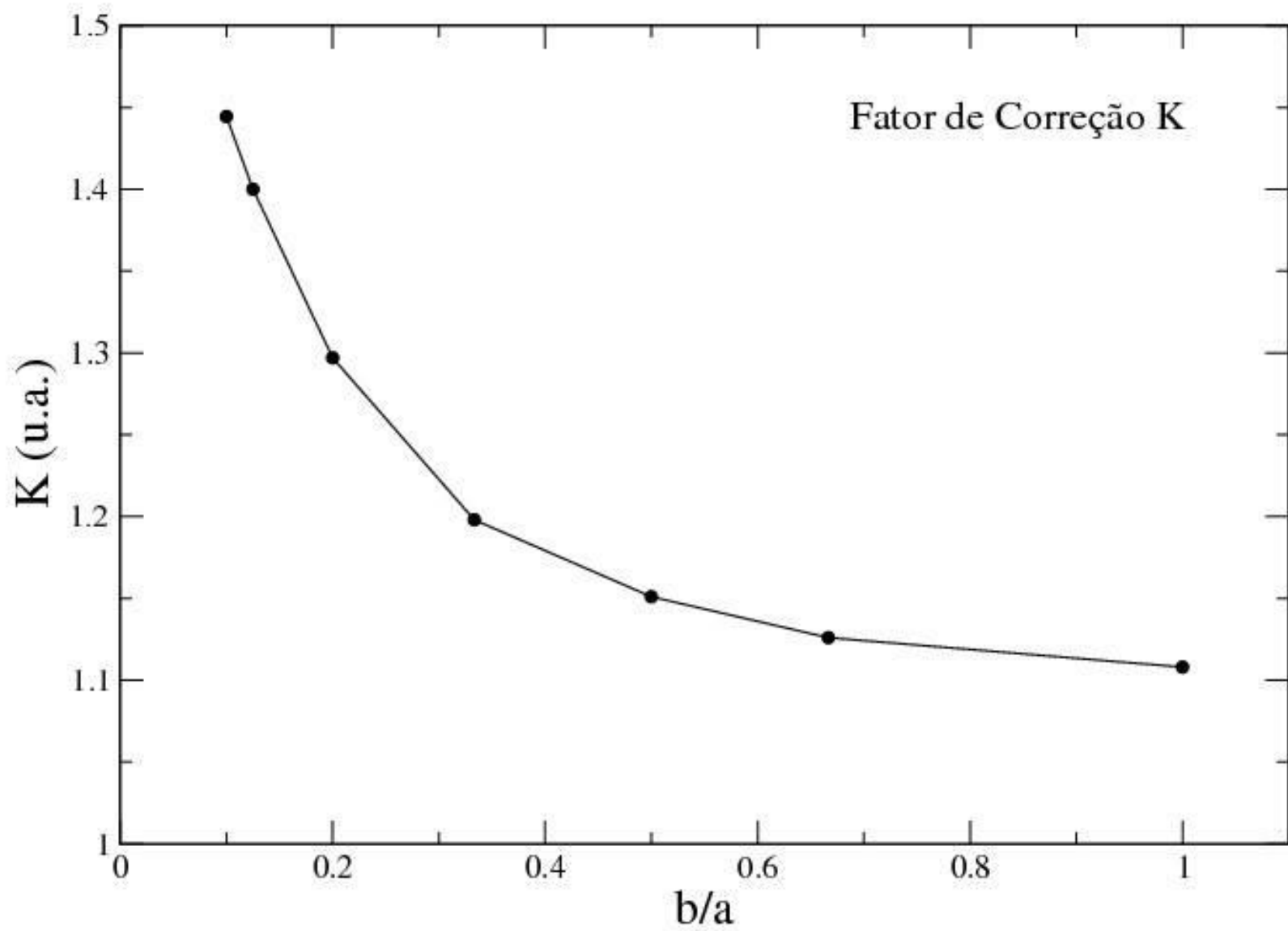
Component	Atmosphere ⁽¹⁾		Ultra-high vacuum	
	Percent by volume	Partial pressure Torr	(2) Partial pressure Torr	(3)
N ₂	78.08	5.95×10^2	2×10^{-11}	—
O ₂	20.95	1.59×10^2	—	3×10^{-13}
Ar	0.93	7.05	6×10^{-12}	—
CO ₂	0.033	2.5×10^{-1}	6.5×10^{-11}	6×10^{-12}
Ne	1.8×10^{-3}	1.4×10^{-2}	5.2×10^{-11}	—
He	5.24×10^{-4}	4×10^{-3}	3.6×10^{-1}	—
Kr	1.1×10^{-4}	8.4×10^{-4}	—	—
H ₂	5.0×10^{-5}	3.8×10^{-4}	1.79×10^{-9}	2×10^{-11}
Xe	8.7×10^{-6}	6.6×10^{-5}	—	—
H ₂ O	1.57	1.19×10^1	1.25×10^{-10}	9×10^{-13}
CH ₄	2×10^{-4}	1.5×10^{-3}	7.1×10^{-11}	3×10^{-13}
O ₃	7×10^{-6}	5.3×10^{-5}	—	—
N ₂ O	5×10^{-5}	3.8×10^{-4}	—	—
CO	—	—	1.4×10^{-10}	9×10^{-12}

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

Table 1.5.
Stages in the history of vacuum techniques.

Year	Author	Work (Discovery)
1643	Evangelista Torricelli	Vacuum in the 760 mm mercury column
1650	Blaise Pascal	Variation of Hg column with altitude
1654	Otto von Guericke	Vacuum piston pumps, Magdeburg hemispheres
1662	Robert Boyle	Pressure-volume law of ideal gases
1679	Edme Mariotte	
1775	A.L. Lavoisier	Atmospheric air : a mixture of nitrogen and oxygen
1783	Daniel Bernoulli	Kinetic theory of gases
1802	J.A. Charles	Volume temperature law of gases
	J. Gay-Lussac	
1810	Medhurst	Propose first vacuum post lines
1811	Amedeo Avogadro	Constant molecular density of gases
1843	Clegg and Samuda	First vacuum railways (Dublin)
1850	Geissler and Toepler	Mercury column vacuum pump
1859	J.K. Maxwell	Gas molecule velocity laws
1865	Sprengel	Mercury drop vacuum pump
1874	H. McLeod	Compression vacuum gauge
1879	T.A. Edison	Carbon filament, incandescent lamp
1879	W. Crookes	Cathode ray tube
1881	J. Van der Waals	Equation of state of real gases
1893	James Dewar	Vacuum insulated flask
1895	Wilhelm Roentgen	X-rays
1902	A. Fleming	Vacuum diode
1904	Arthur Wehnelt	Oxide-coated cathode
1905	Wolfgang Gaede	Rotary vacuum pump
1906	Marcello Pirani	Thermal conductivity vacuum gauge
1907	Lee de Forest	Vacuum triode
1909	W.D. Coolidge	Powder metallurgy of tungsten, Tungsten filament lamp
1909	M. Knudsen	Molecular flow of gases
1913	W. Gaede	Molecular vacuum pump
1915	W.D. Coolidge	X-ray tube
1915	W. Gaede	Diffusion pump
1915	Irving Langmuir	Gas filled incandescent lamp
1915	Saul Dushman	The kenotron
1916	Irving Langmuir	Condensation diffusion pump
1916	O.E. Buckley	Hot cathode ionization gauge
1923	F. Holweck	Molecular pump
1935	W. Gaede	Gas-ballast pump
1936	Kenneth Hickman	Oil diffusion pump
1937	F.M. Penning	Cold cathode ionization gauge
1950	R.T. Bayard and D. Alpert	Ultra-high vacuum gauge
1953	H.J. Schwartz, R.G. Herb	Ion pumps





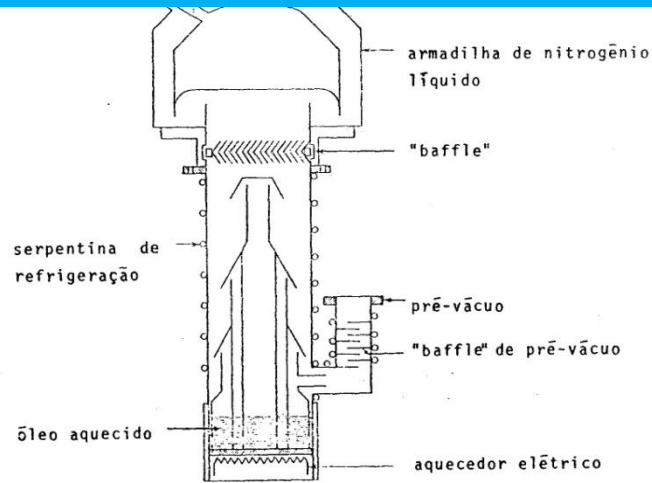


Fig. 29 - Bomba de Difusão com "baffle" chevron e armadilha de nitrogênio líquido ("cold trap")

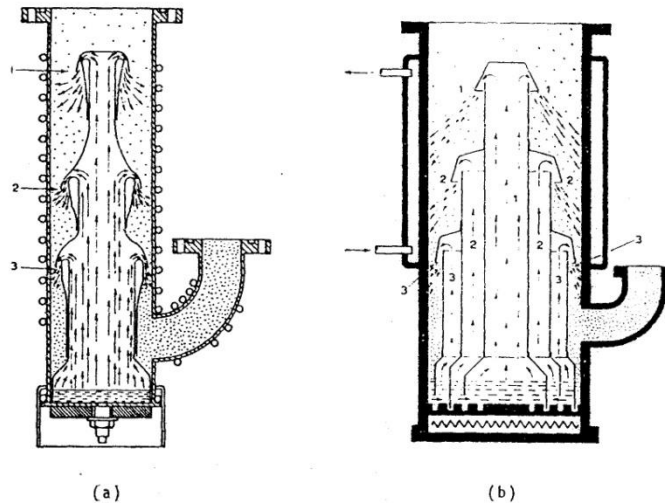


Fig. 30 - Esquemas de Bombas de Difusão de três estágios

- a) desenho mais antigo; o óleo aquecido não sofre nenhum processo de purificação
- b) com tubos concêntricos permitindo a purificação do óleo por destilação fracionada, durante o funcionamento (o vapor de óleo mais aquecido e limpo sai pelo chapéu ("nozzle") 1.

Bomba de Difusão

Jato de vapor empurra as moléculas da câmara criando um gradiente de pressão.

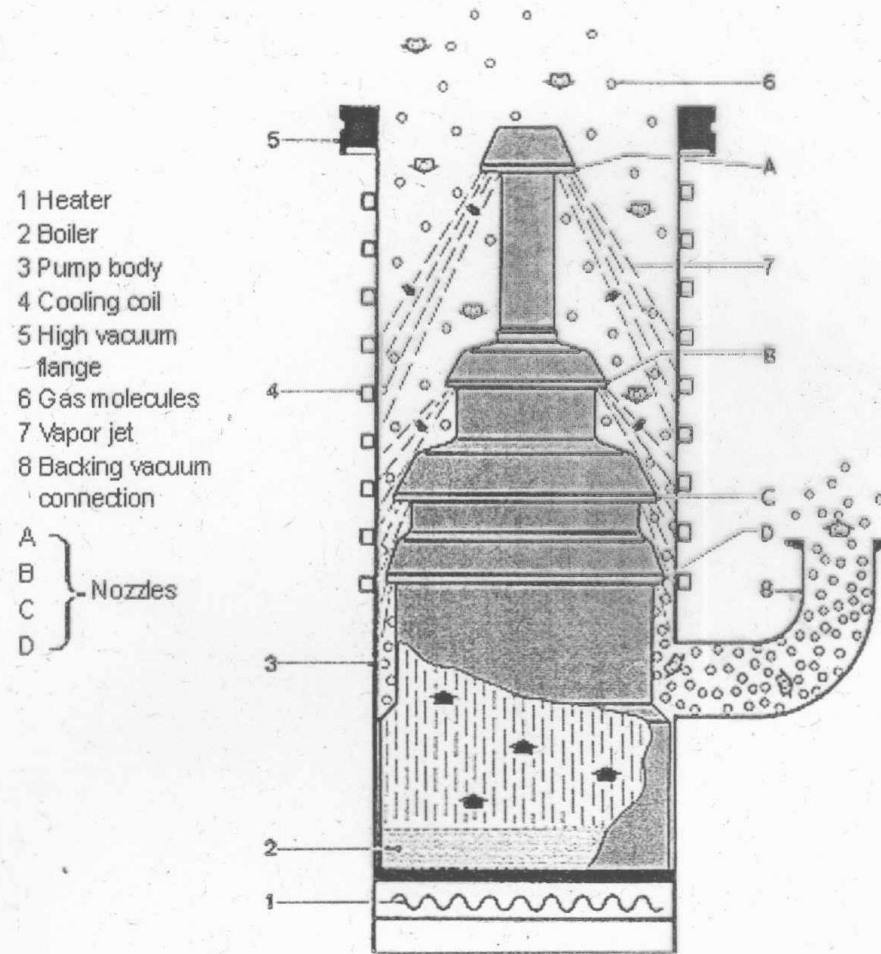


Fig. 2.44
Mode of operation of a diffusion pump

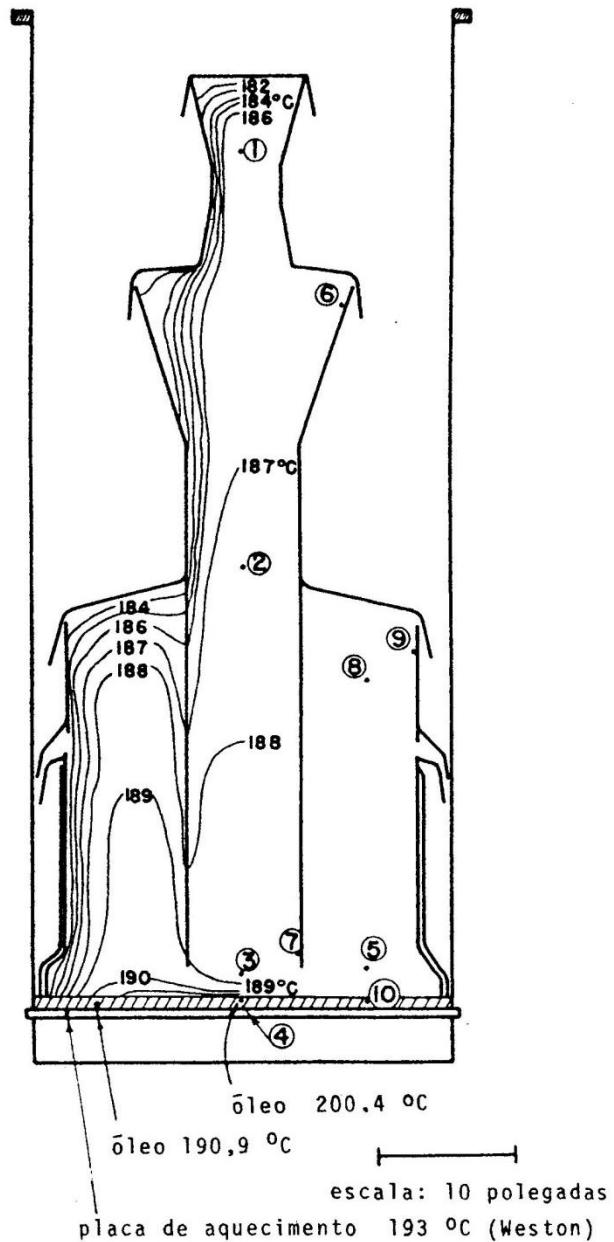
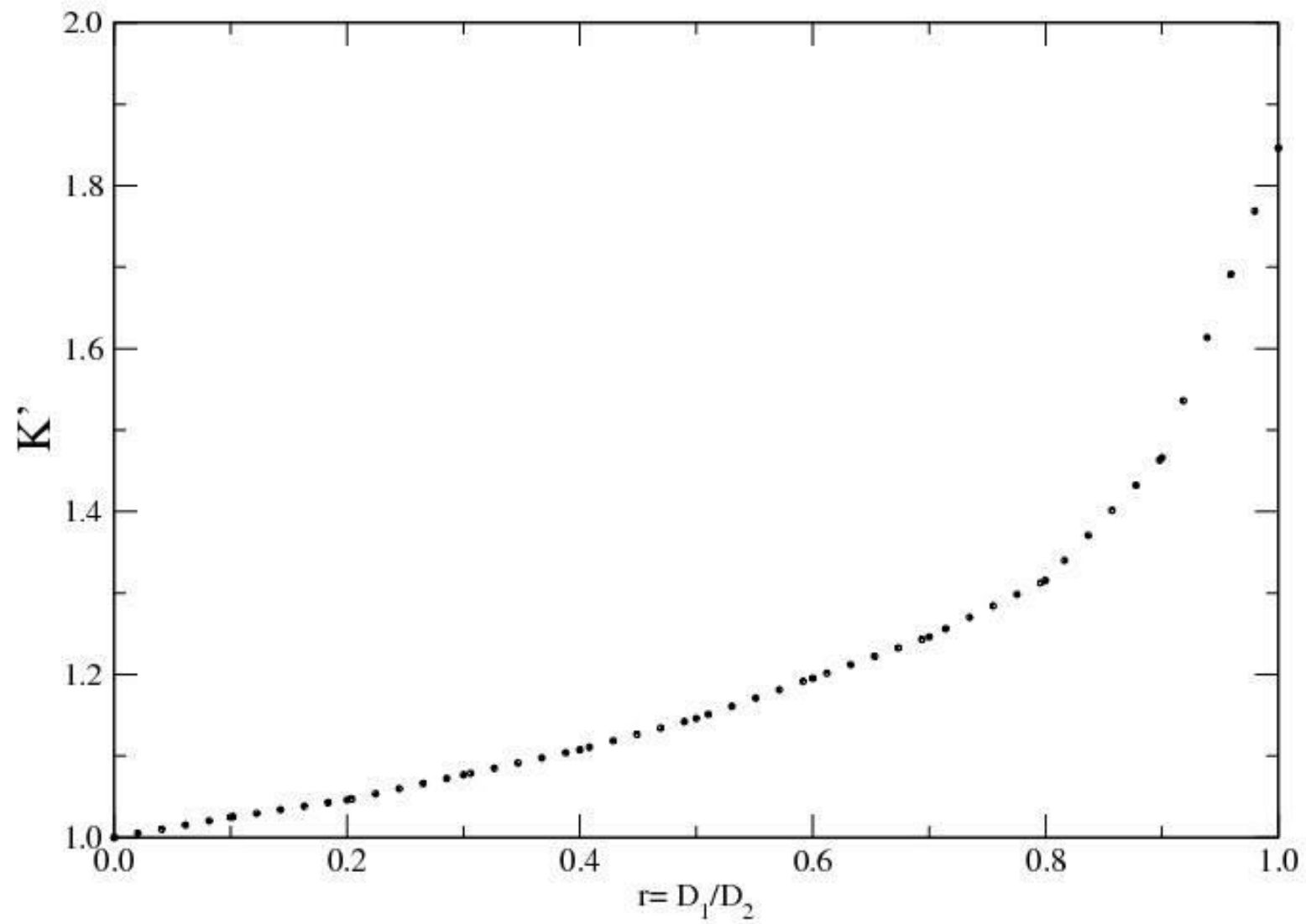
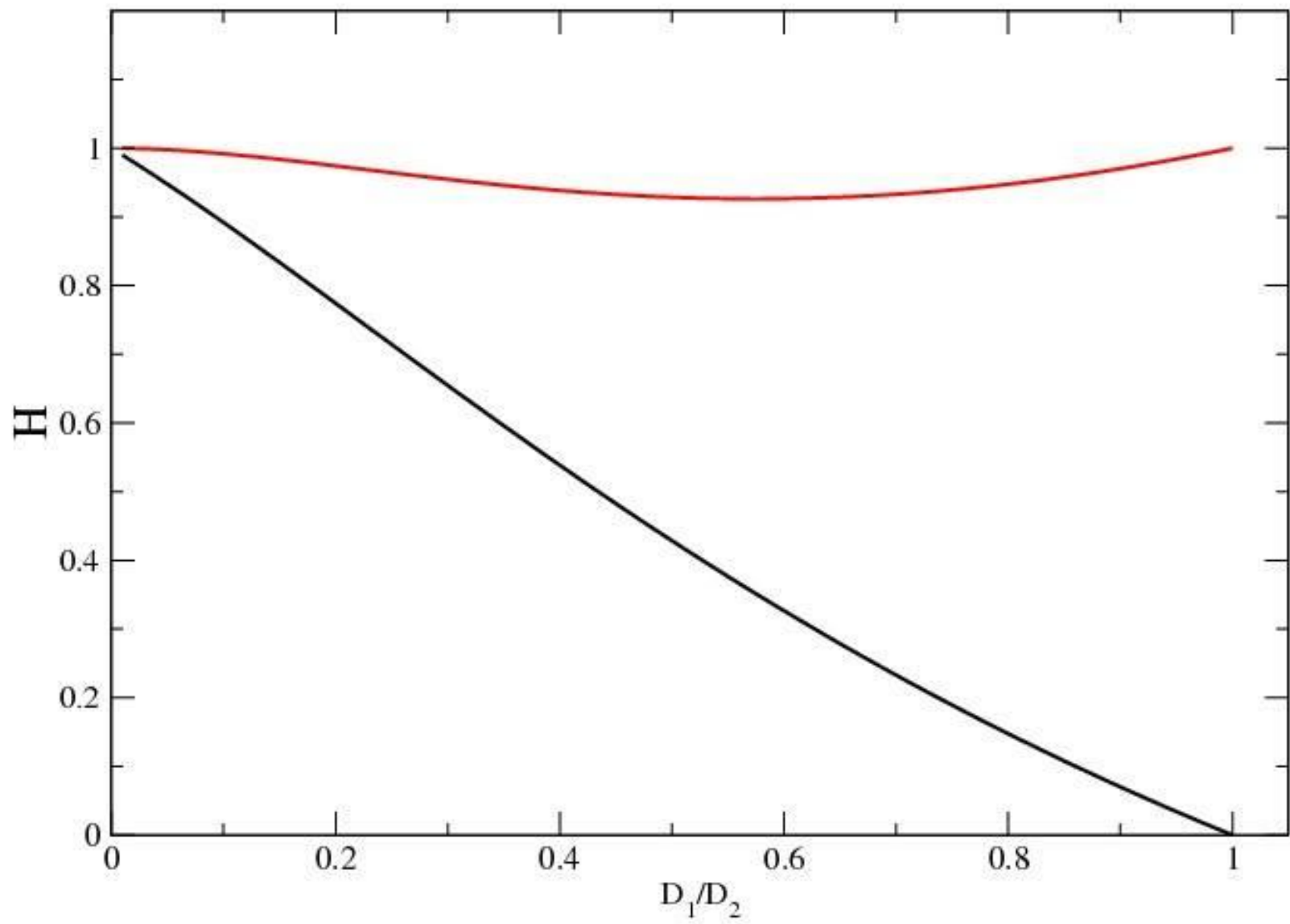


Fig. 31 - Diagrama isotérmico de uma Bomba de Difusão de 32".
 Os pontos numerados representam a localização dos
 termopares utilizados nas medições das temperaturas.





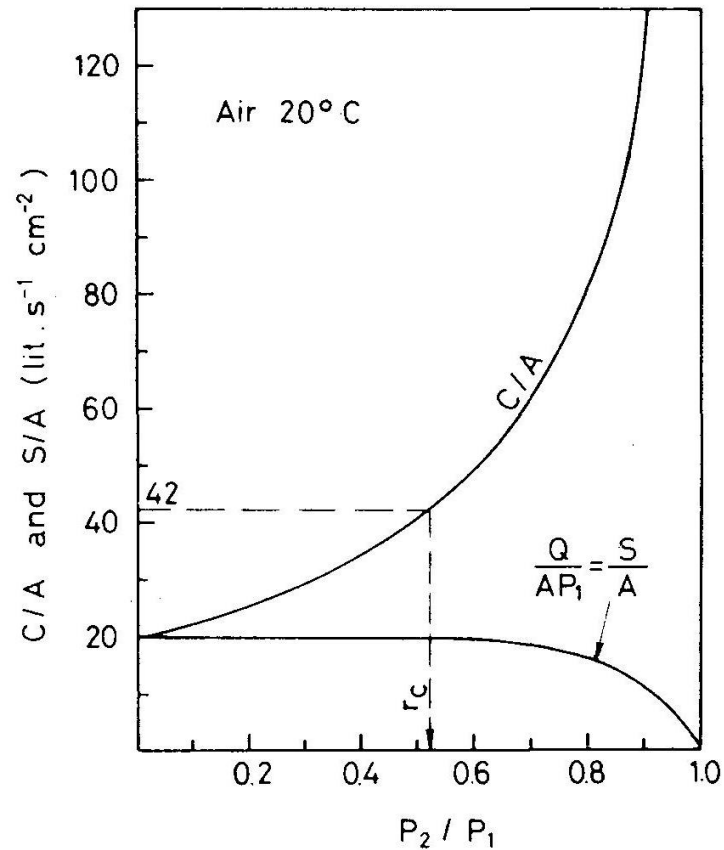


Fig. 3.6 Conductance C and pumping speed S of apertures (viscous flow). A is the cross section area of the aperture.

This equation is plotted for air in fig. 3.36, by using as a parameter the value

$$D^4/L = (128/\pi) \eta E$$

and considering $P_i = 10^6$ dyne/cm² (760 Torr), and $P = 10^2$ dyne/cm² (7.6×10^{-2} Torr), i.e. the pressure range in which usually the flow is viscous. If a volume of $V = 100$ liter is evacuated by a pump of $S_p = 2$ lit/sec through a pipe $D = 2$ cm and $L = 200$ cm, then $D^4/L = 8 \times 10^{-2}$. On the curve 8×10^{-2} , for $S_p = 2$, it results $t/V = 6$ sec/liter. Thus the time required for 100 liter is $t = 600$ sec. If the volume is connected directly to the pump, the line $D^4/L = \infty$ gives $t/V = 4.5$ sec/liter, thus $t = 450$ sec.

It is interesting to mention that if the pump is connected directly to the vessel, $L = 0$, thus $E = \infty$, eq. (3.252) becomes

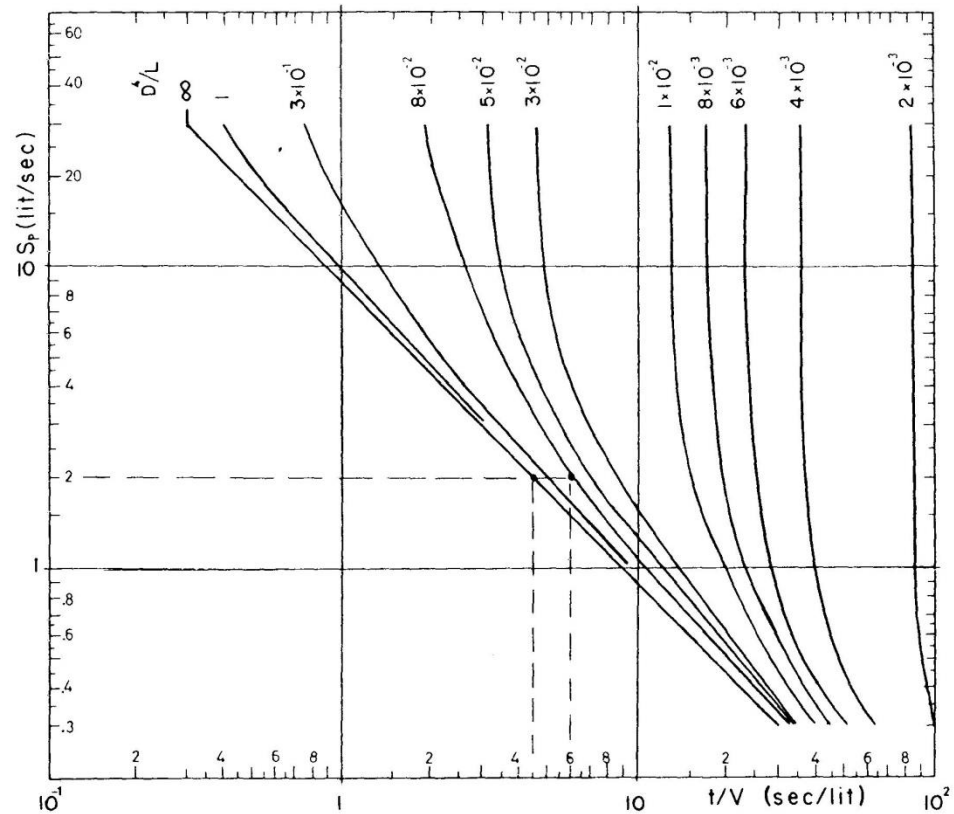


Fig. 3.36 Time required to decrease the pressure from 760 Torr to 7.6×10^{-2} Torr in a volume $V(l)$, connected by a pipe of diameter $D(cm)$ and length $L(cm)$ to a pump of pumping speed $S_p(l/s)$. After Delafosse and Mongodin (1961).

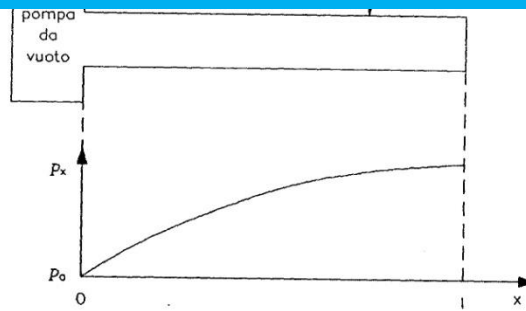


Figura 4.2 - Andamento della pressione in una camera da vuoto tubolare, chiusa ad una estremità e collegata con una pompa all'altra.

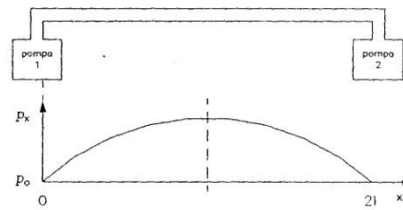


Figura 4.3 - Andamento della pressione in una camera da vuoto tubolare pompata ad entrambe le estremità.

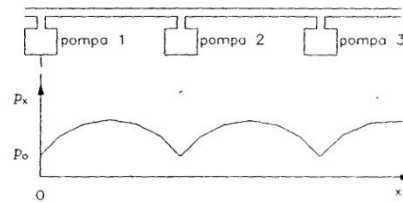


Figura 4.4 - Andamento della pressione in una camera da vuoto tubolare pompata con una serie di pompe disposte ad intervalli regolari di spazio e di uguali caratteristiche.

Bruno Ferrario

Introduzione alla tecnologia
del VUOTO

seconda edizione riveduta ed ampliata da
ANITA CALCATPELLI

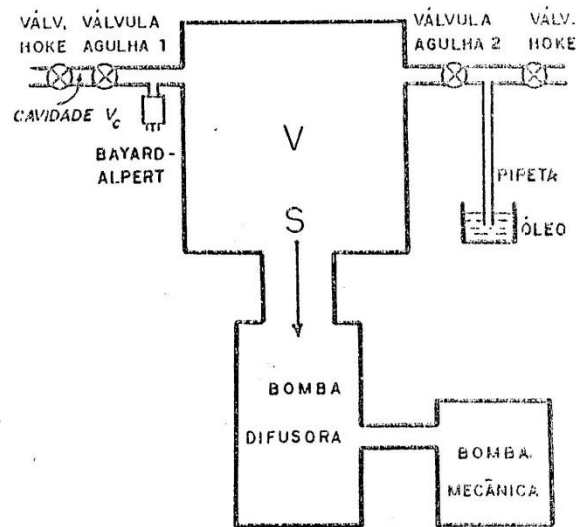


Fig. 4 - Esquema de montagem para simulação de vazamentos reais e virtuais.

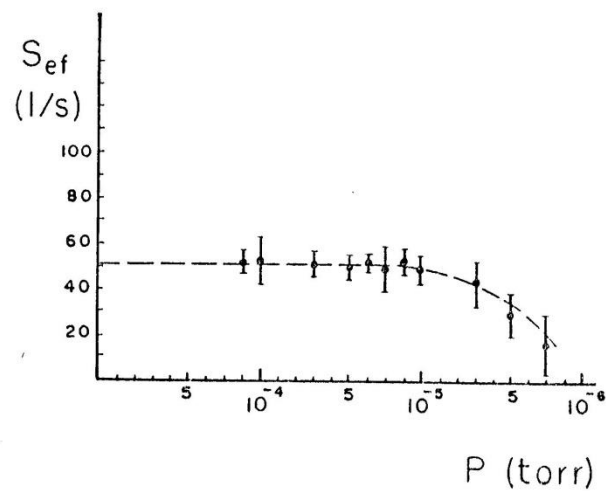


Fig. 6 - Velocidade Efetiva da Bomba Difusora.

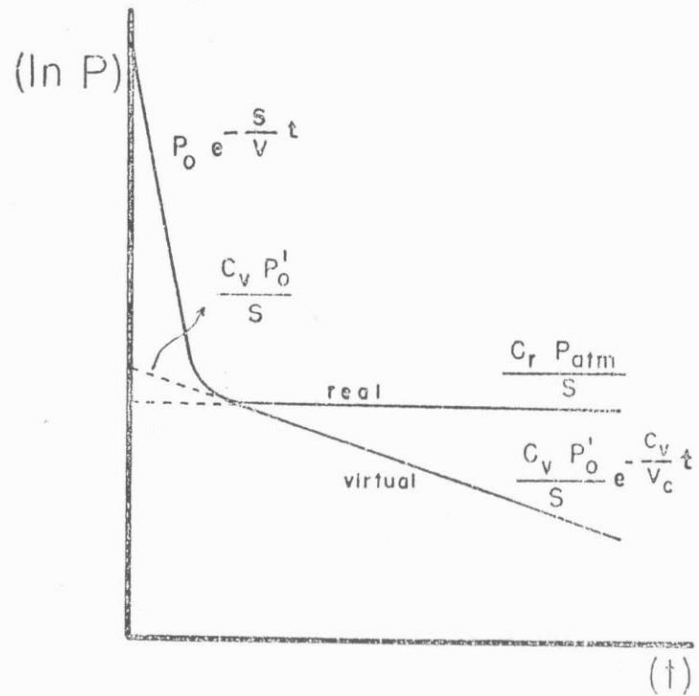


Fig. 2 - Vazamentos: real e virtual.

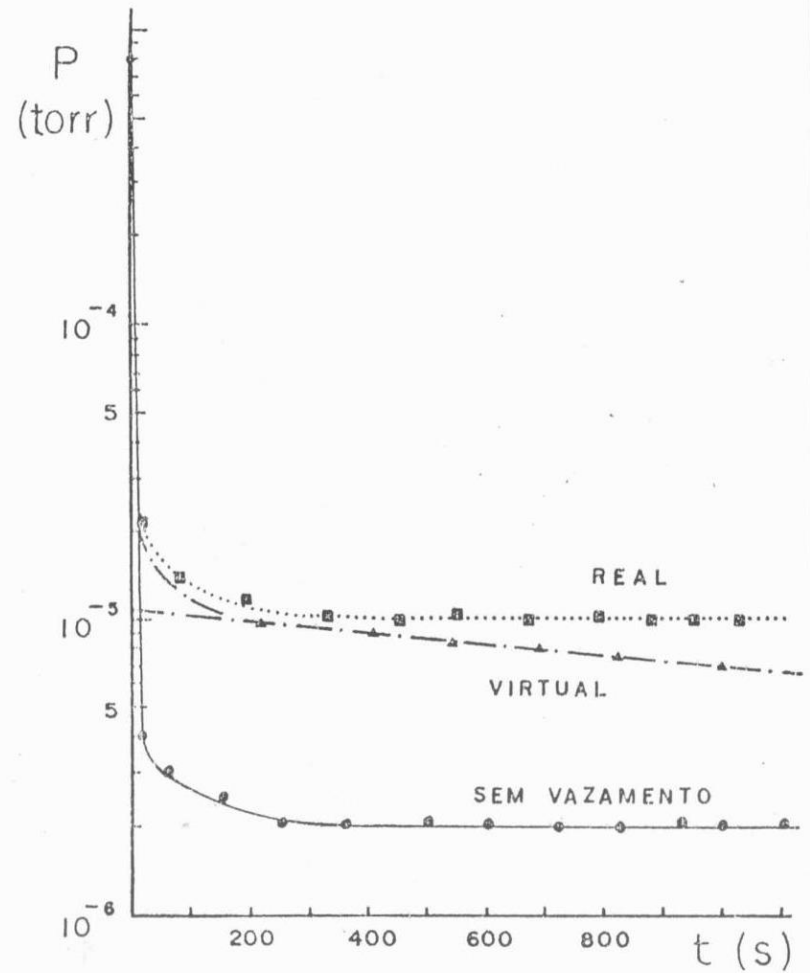
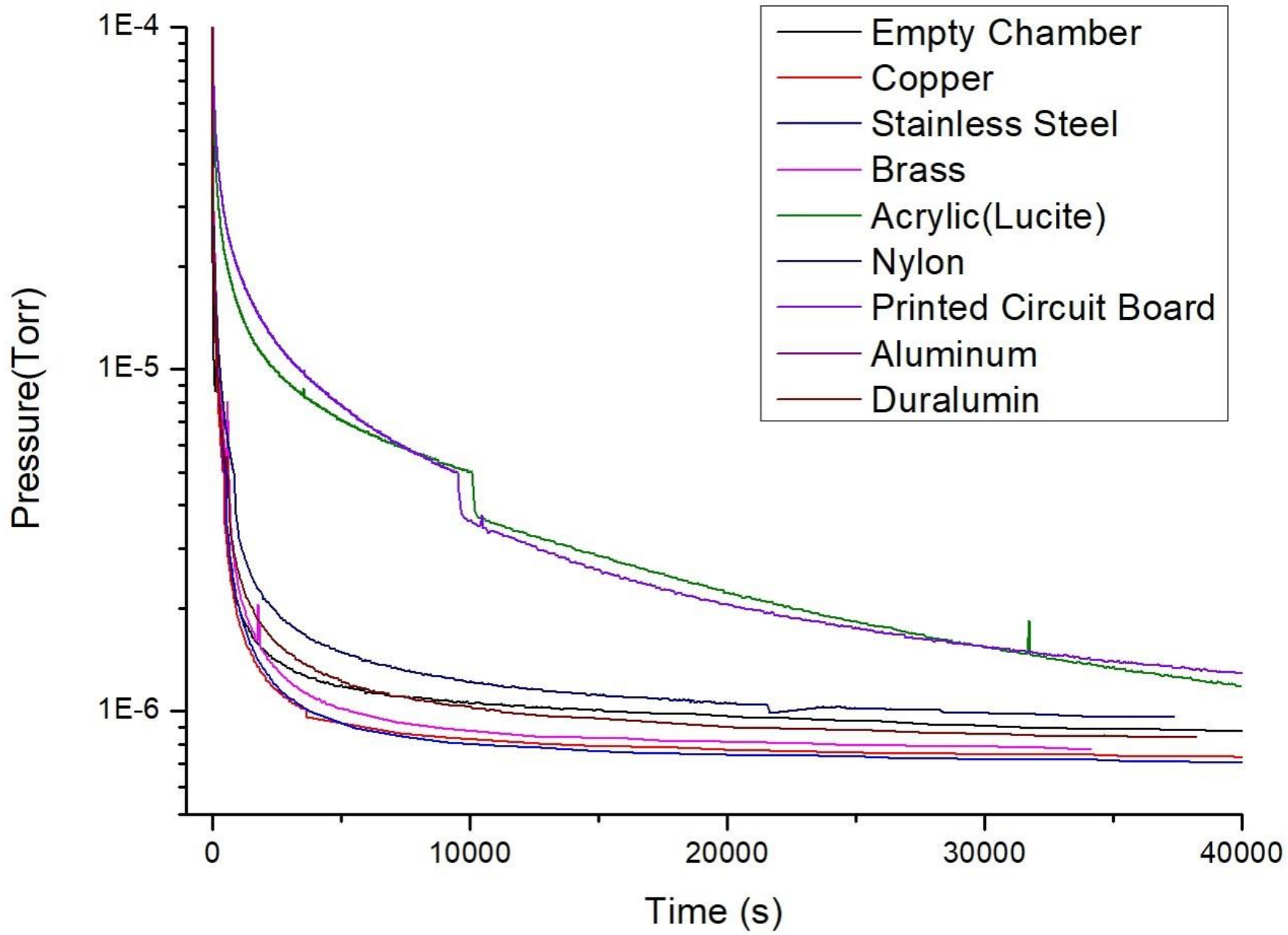
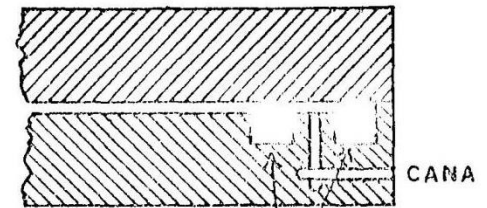
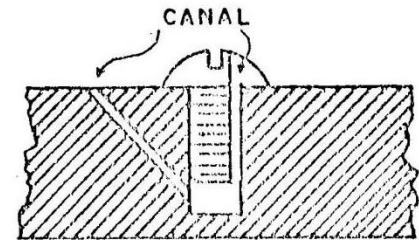
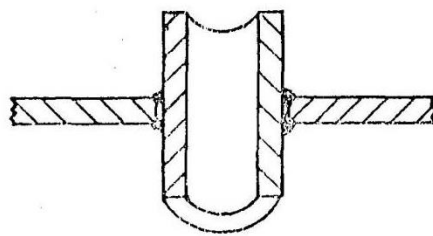
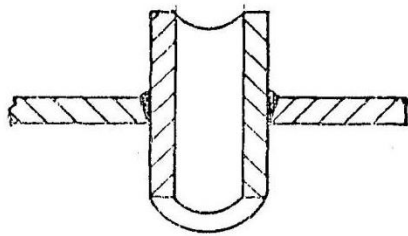
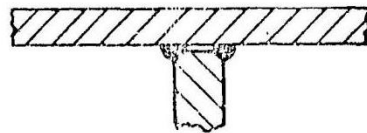
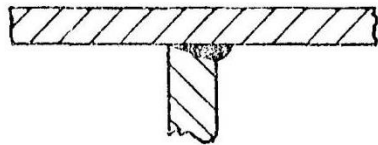
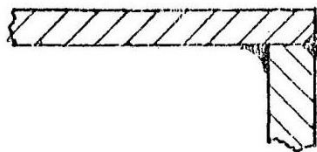
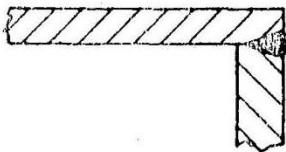
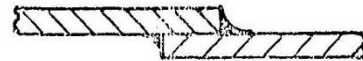


Fig. 5 - Medidas de Simulação de Vazamentos.



CORRETO

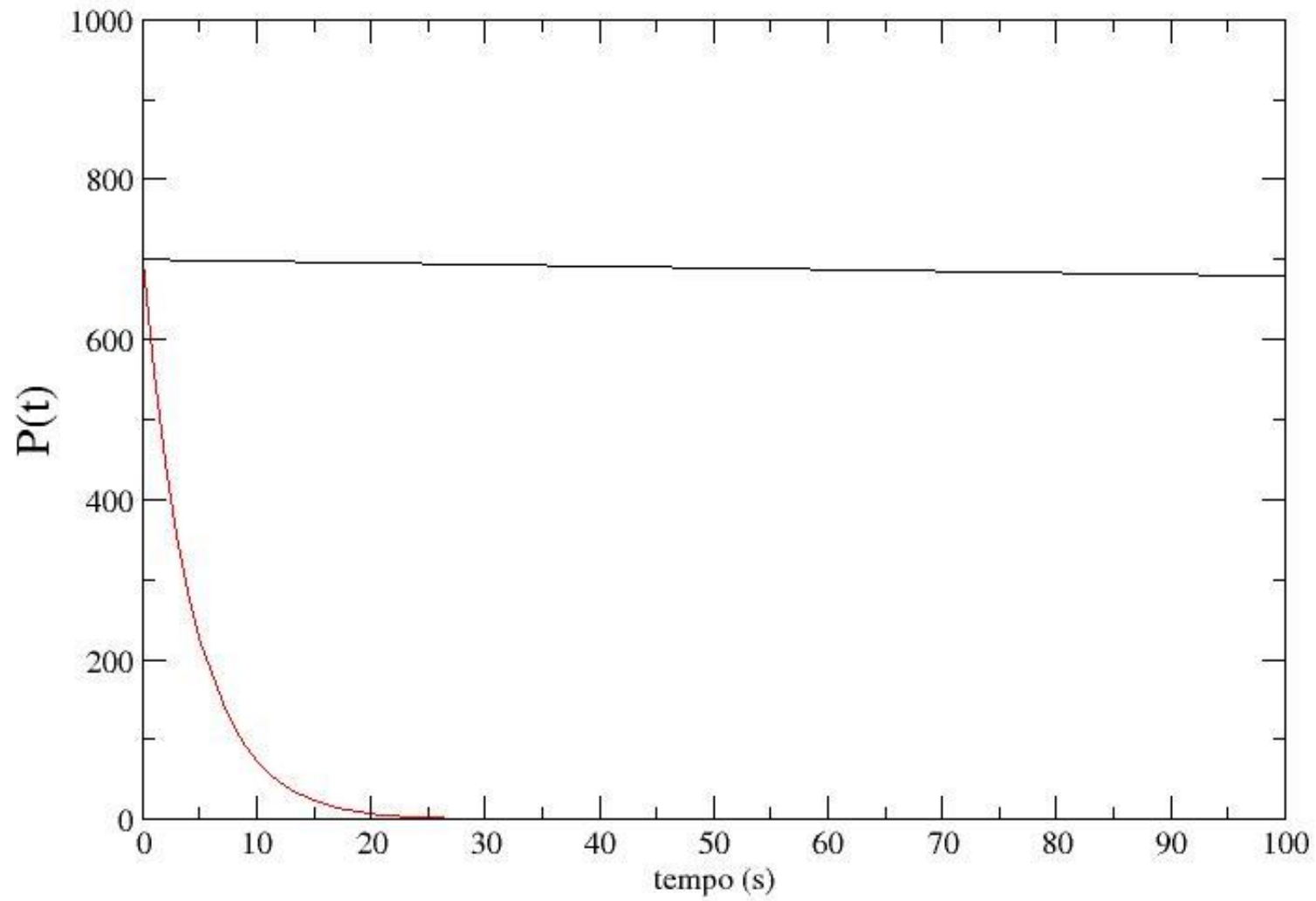
INCORRETO



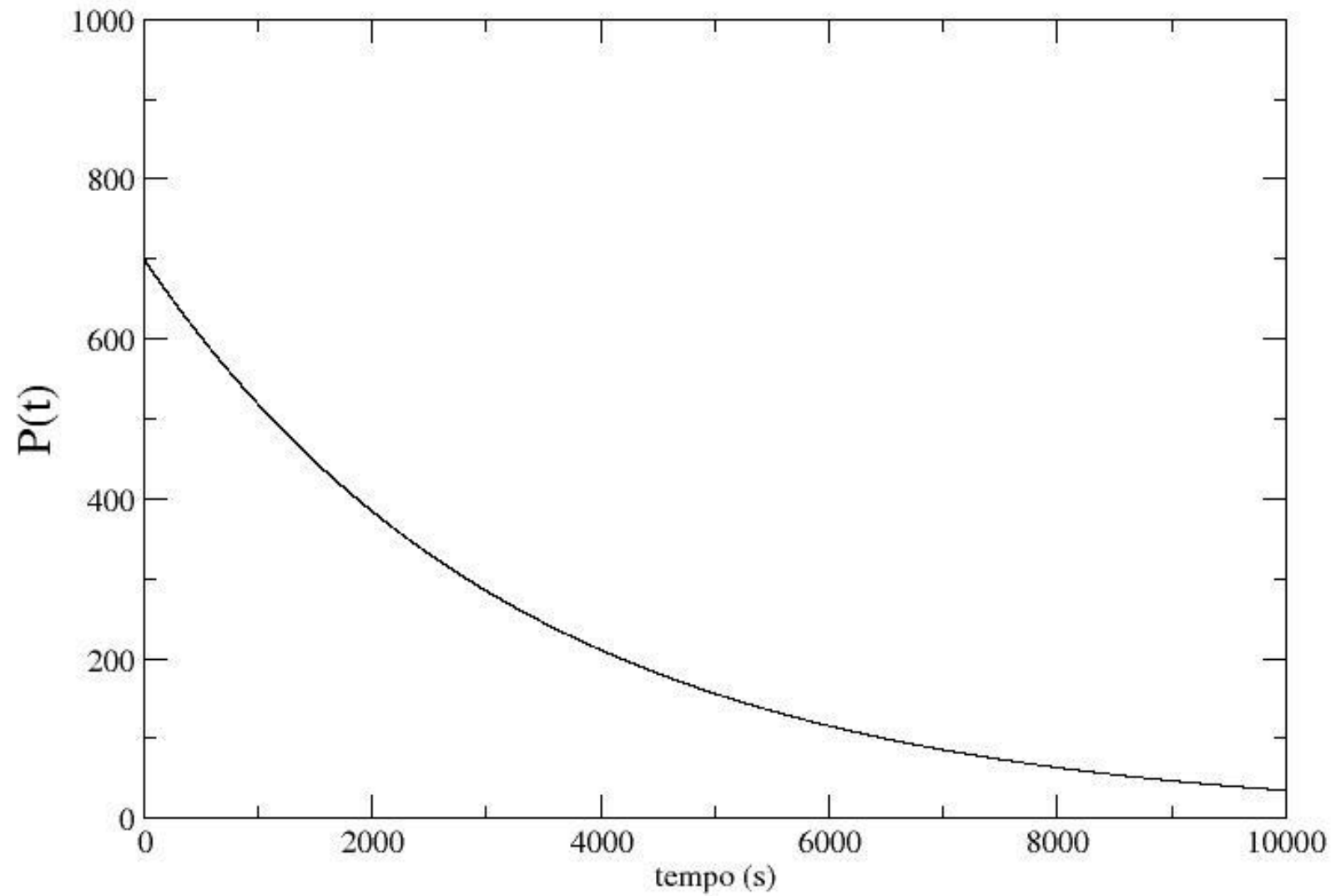
O'RINGS

Fig. 8 - Exemplos de Vazamentos Virtuais e suas correções.

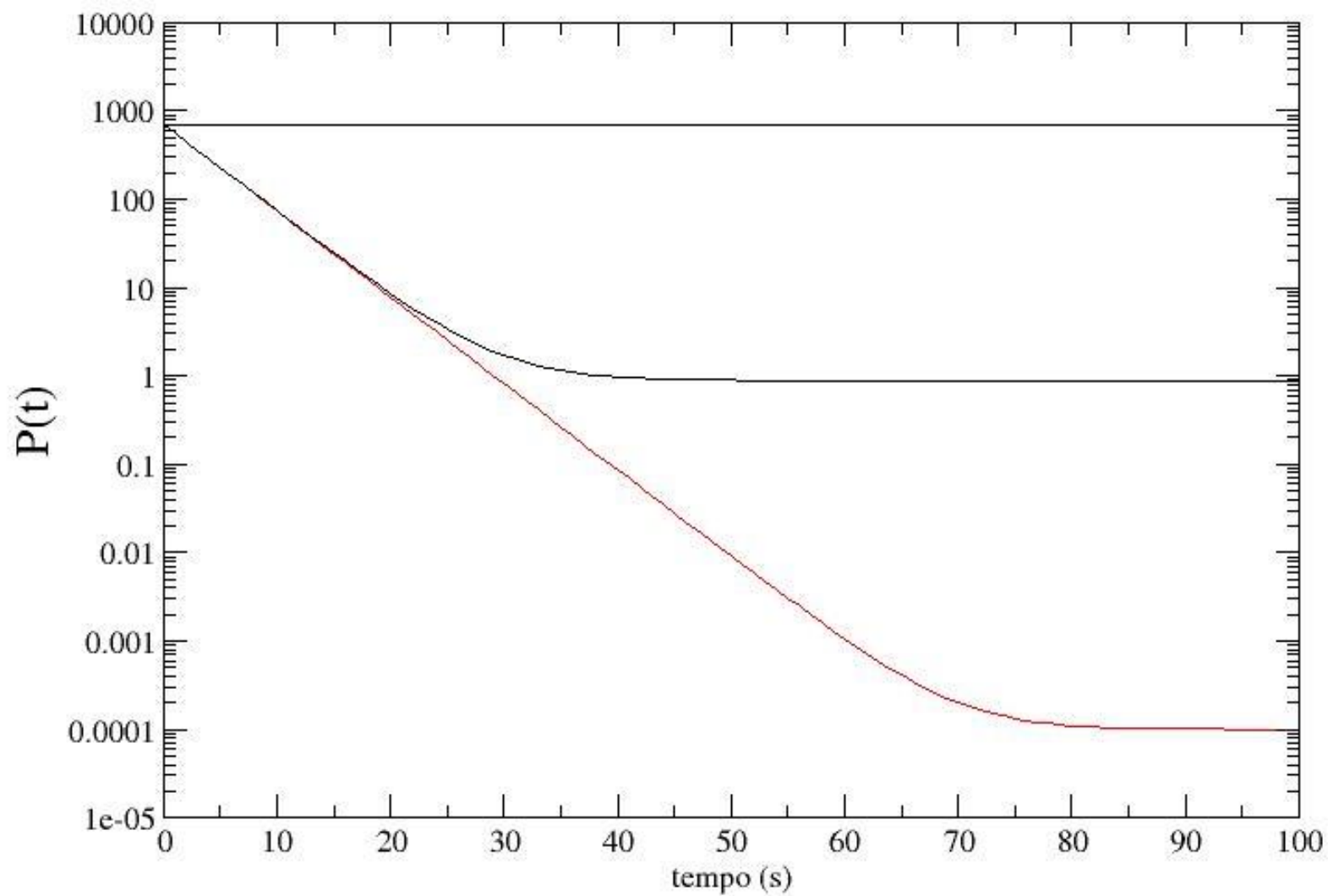
P1



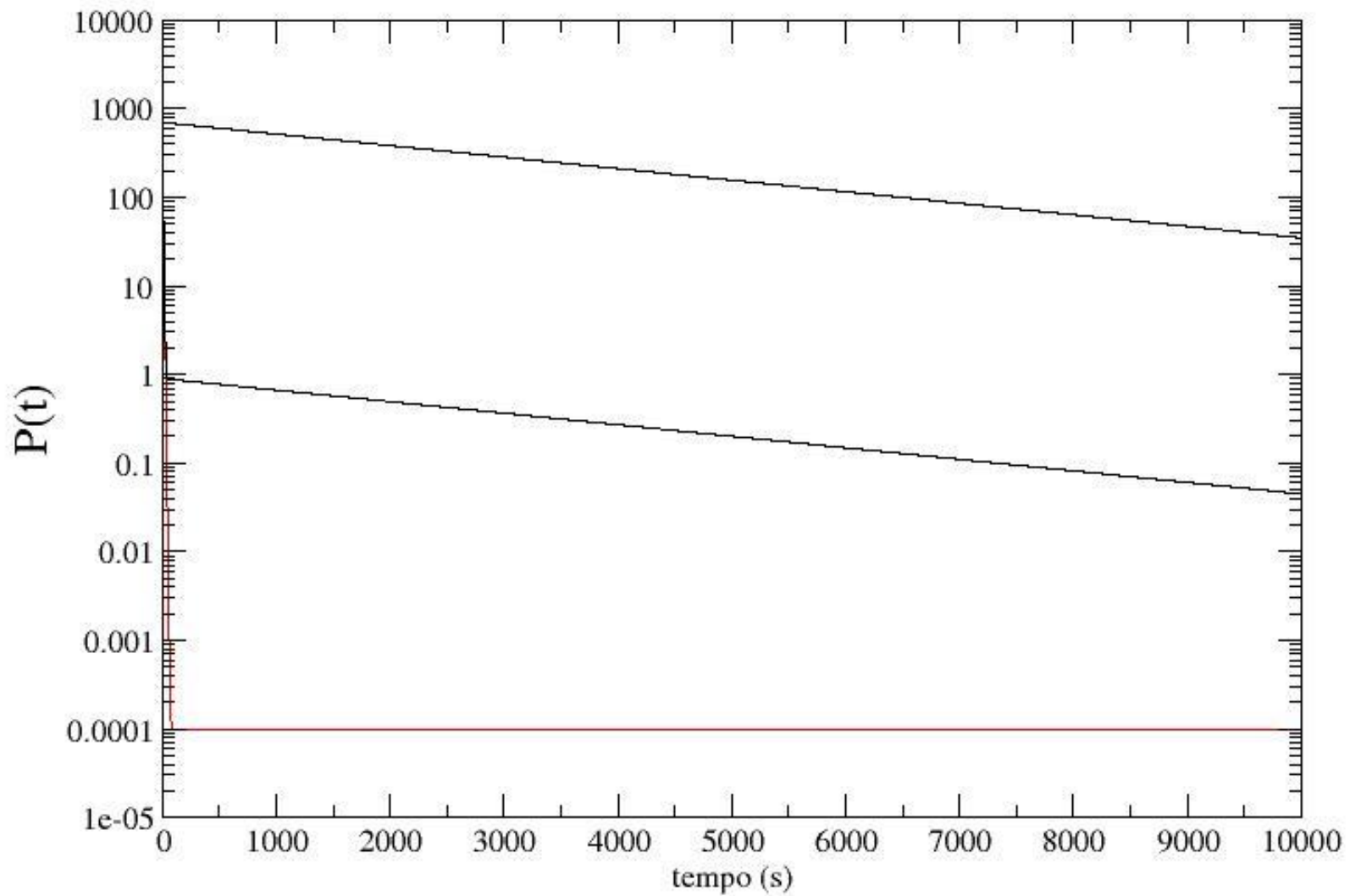
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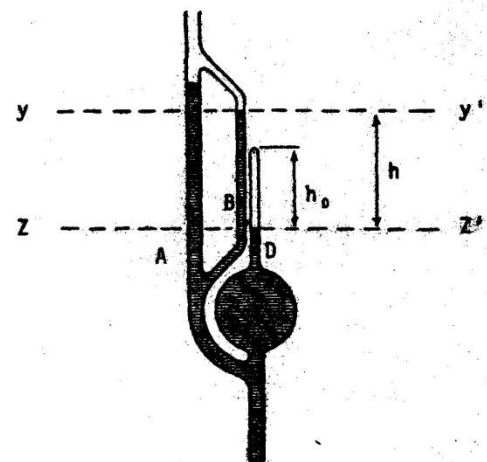
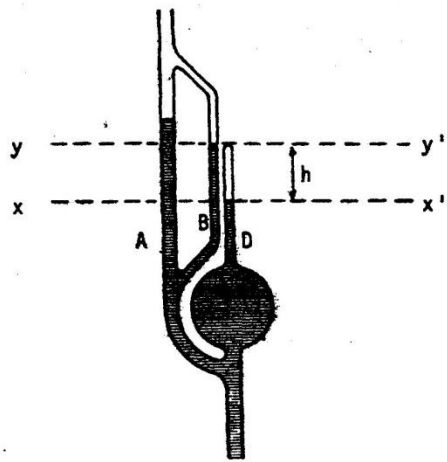
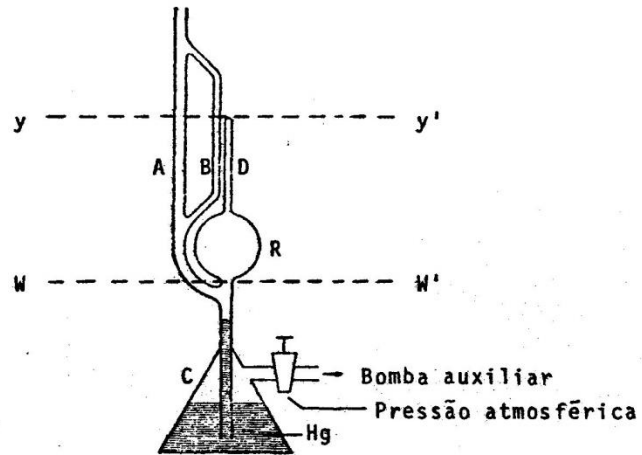


P1P2

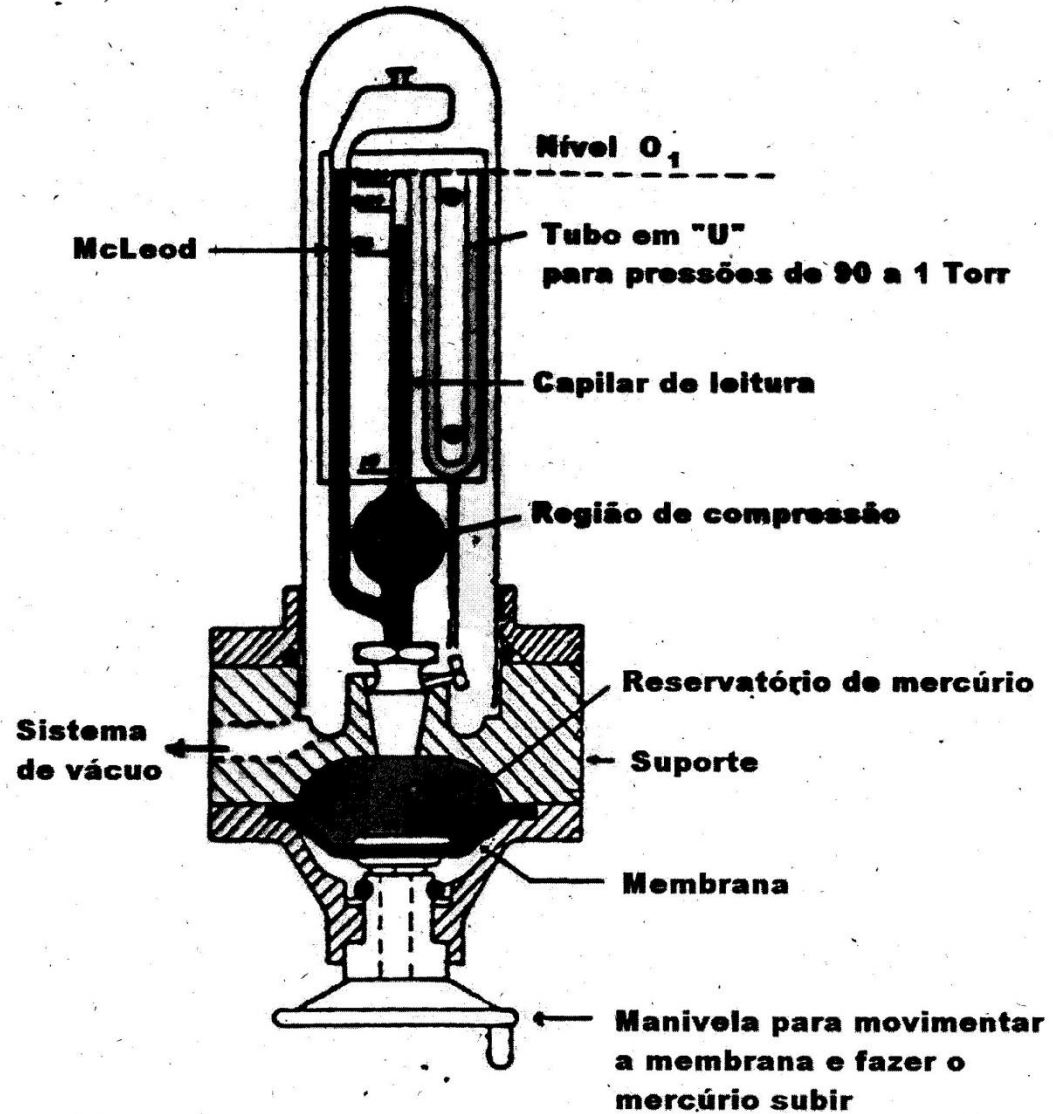


P1P2





Kammerer (McLeod)



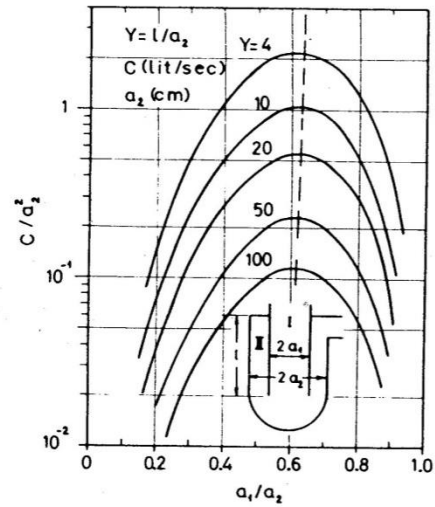


Fig. 3.12 Conductance of traps, for air, 25°C. From Dushman and Lafferty (1962), by permission of J. Wiley & Sons Inc., New York.

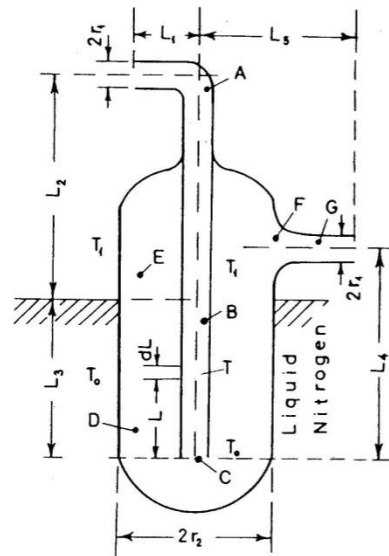
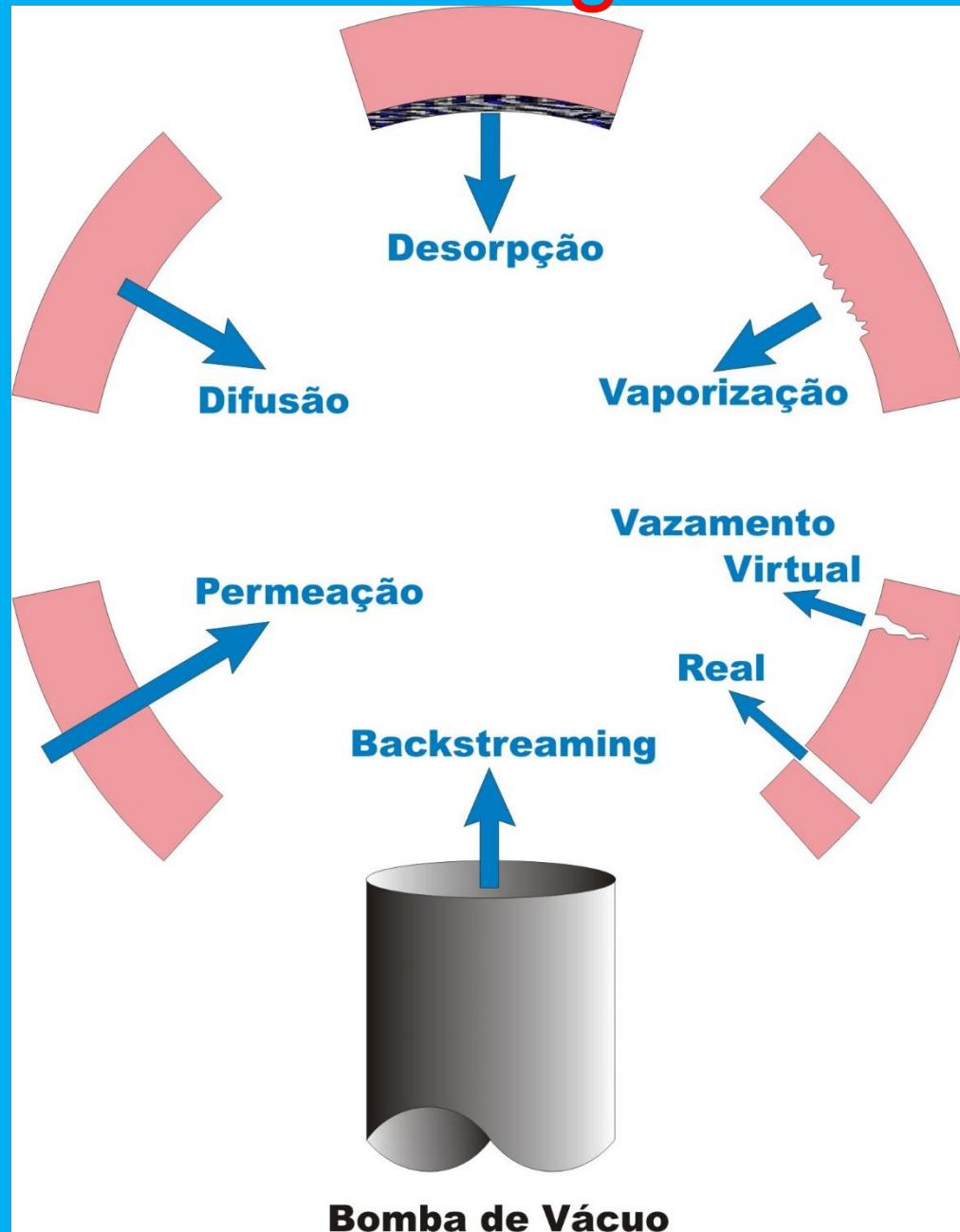
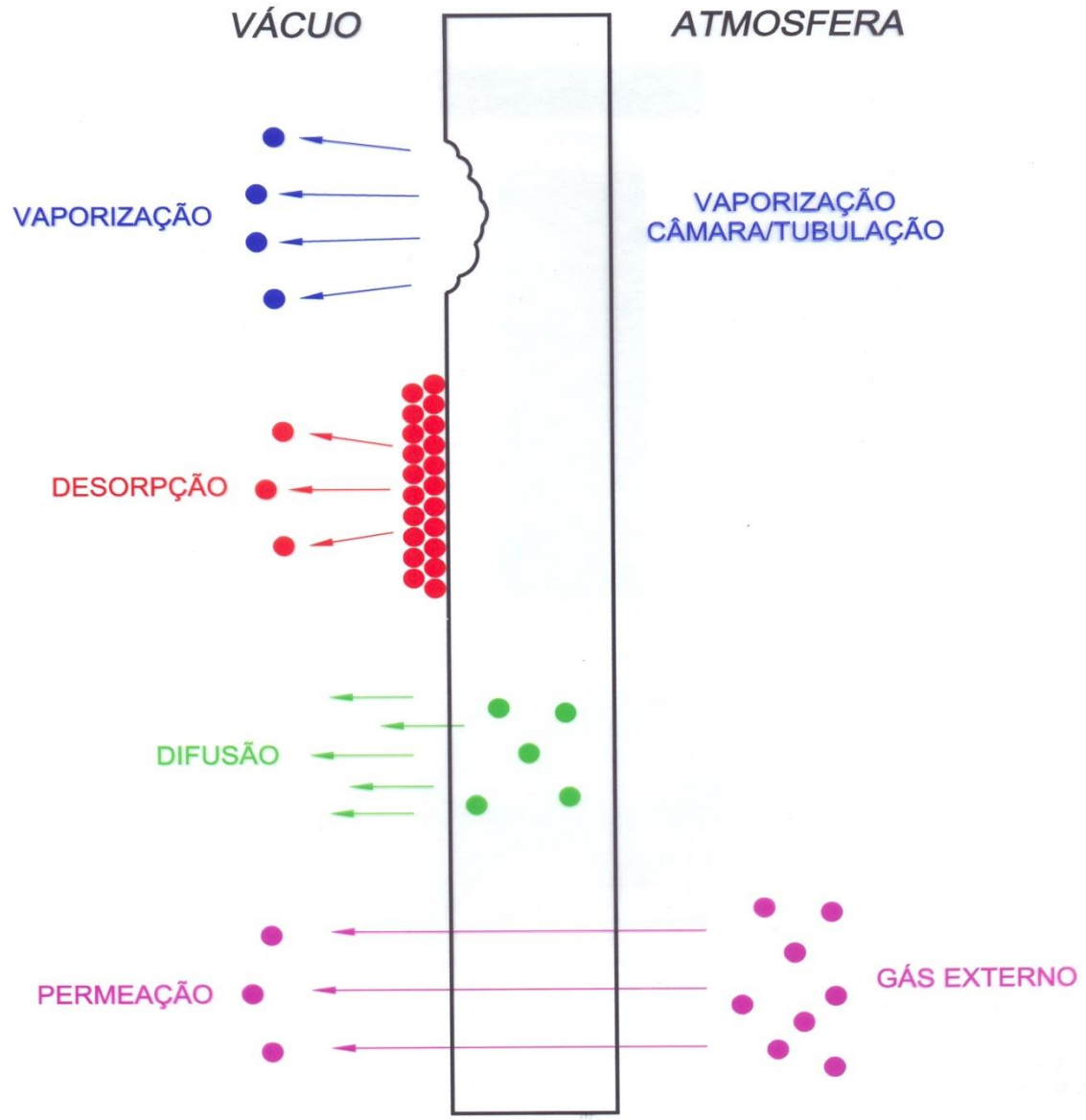


Fig. 3.13 Parts of a liquid nitrogen trap, for calculating its conductance. After Henry (1971).

Fontes de gases



DEGASIFICAÇÃO



Modelos de Fontes de gases

Fonte de gás	Característica	Comentário
Volume	$P = P_o e^{\frac{-S}{v}t}$	Pressão cai exponencialmente dependendo de S e V
Vazamento Real	$P_{res} = \frac{Q_{Vr}}{S}; Q_{Vr} \approx C_{Vr} P_{atm}$	Fluxo constante. Utilizar detector de vazamentos. Deve ser eliminado
Vazamento Virtual	$Q_{vv} = C_v P_o' e^{\frac{-C_v}{V_c}t}$	$C_v \ll S_b$ Queda da pressão depende de C_v e V_c . Evitar no projeto
Difusão	$Q(t) = c_o \frac{\sqrt{D}}{\sqrt{\pi t}}$	Q(t) é proporcional a $\frac{1}{\sqrt{t}}$
Permeação	$Q = \frac{K(P_e^n - P_i^n)}{d}$	N=1 para não metais; n=1/2 para moléculas diatômicas em metais. Constante de permeação K(T) é proporcional a $10^3/T$
Evaporação	$W = 0.058 P_v \sqrt{\frac{M}{T}} \frac{g}{cm^2 s}$ $Q = WA \text{ (g/s)}$ $Q = \frac{\Delta N}{\Delta t} kT \frac{Torrl}{s}$	Crescimento de P_v em função da temperatura é exponencial e por isso mais rápido do que $\frac{1}{\sqrt{T}}$
Desorção Térmica (desgaseificação)	Primeira ordem: $\frac{dc}{dt} = c_o k_1 e^{-\frac{t}{\tau_m}}$ $\frac{1}{k_1} = \tau_{res} = \tau_o e^{\frac{E_d}{N_o kT}}$	Rápido $\tau_{res} = 10^{-12} s$
Temperatura (cozimento)	Segunda ordem: $\frac{dc}{dt} = \frac{-k_2 C_o^2}{(1 + C_o K_2 t)^2}$	Cai lentamente A molécula de H_2s se dissocia na adsorção e recombina na desorção
Superfícies Reais	$q_n = \frac{q}{t^\alpha}$ $0.7 \leq \alpha \leq 2$	Fórmula geral $q_n = qt^{-1}$ Adsorção química Adsorção física

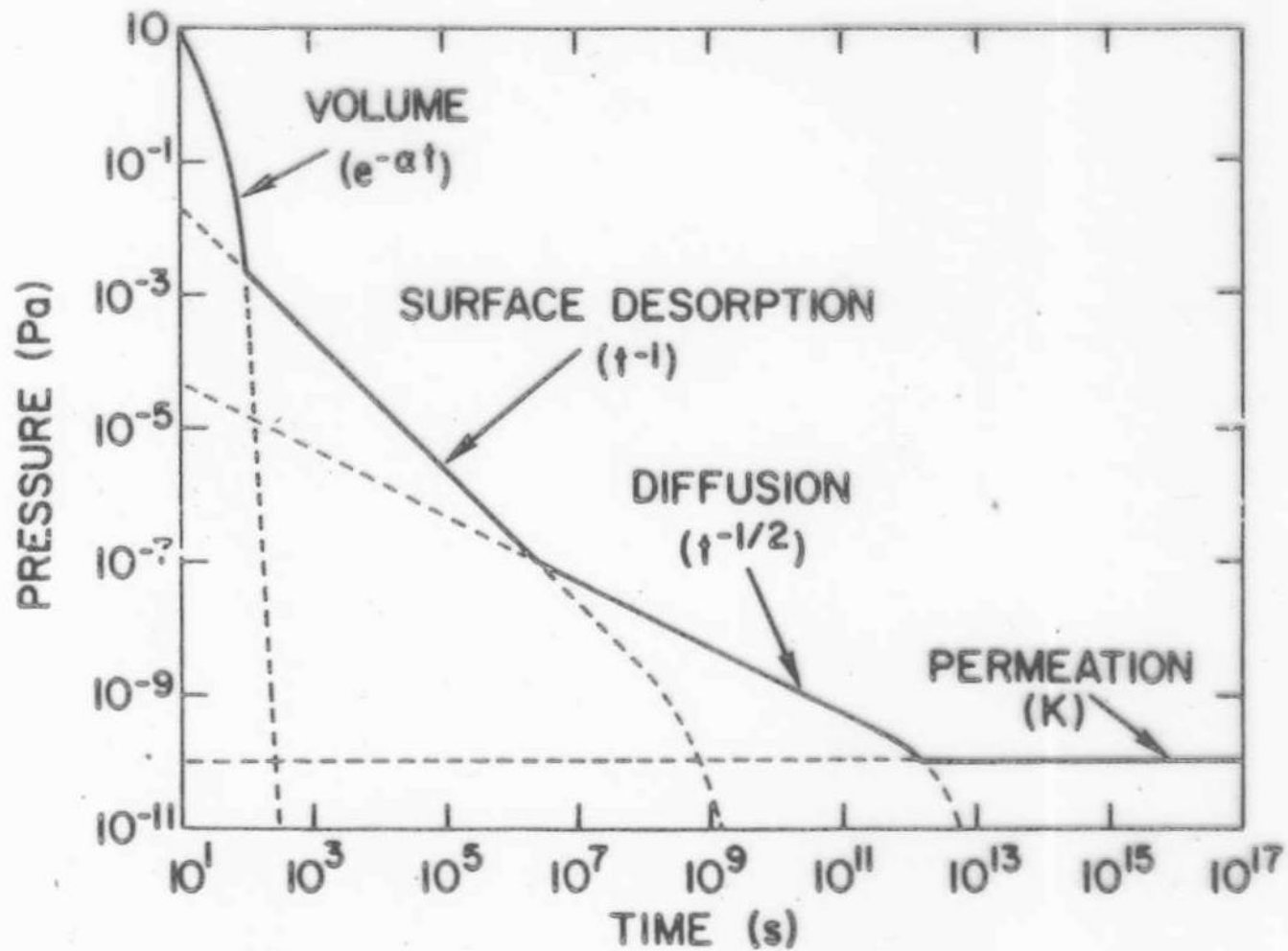
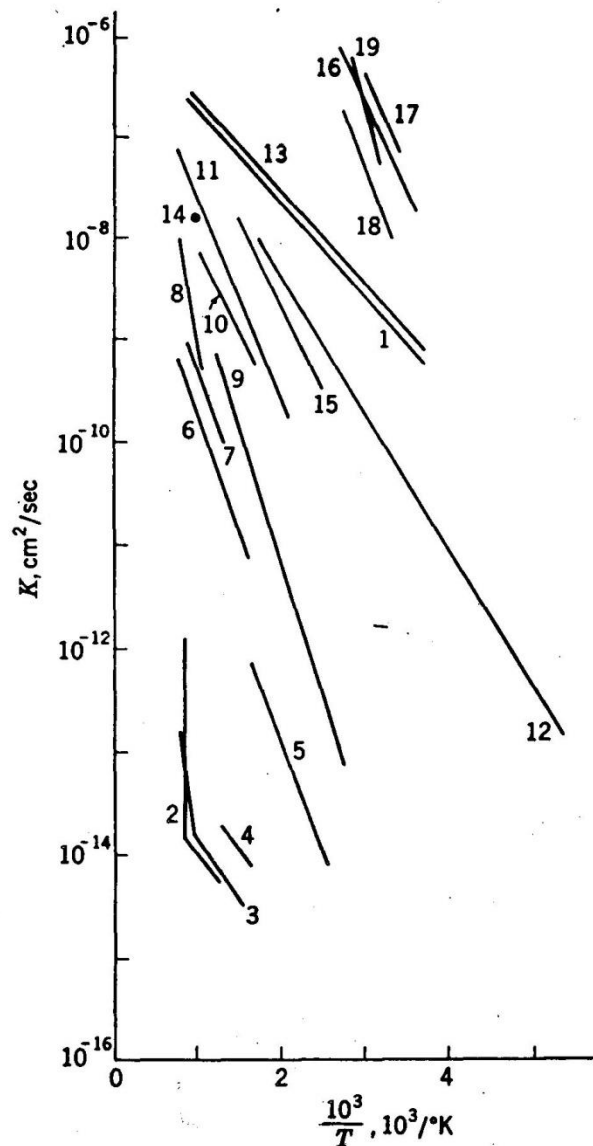


Fig. 4.6 Rate limiting steps during the pumping of a vacuum chamber.

Fig. 3-2 Permeation constants for various gas-non-metal combinations as a function of temperature. Units are square centimeters per second. [Quantity of gas in cubic centimeters (STP) passing per second through a wall of 1-cm² area and 1-cm thickness, when a pressure difference of 1 atm exists across the wall.] (Numbers 2 to 12 and 14 from P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *Adv. Electron. Electron Phys.*, vol. 17, p. 323, 1962; Nos. 1, 13, and 15 from V. O. Altemose, *J. Appl. Phys.*, vol. 32, p. 1309, 1961; and 16 to 19 from B. B. Dayton, 1959 *Vacuum Symp. Trans.*, p. 101, 1960.)

1. He-fused silica
2. Air-Pyroceram
3. Air-97% alumina ceramic
4. Air-Pyrex
5. He-lead borate glass G
6. N₂-97% alumina ceramic
7. Ne-Vycor
8. N₂-SiO₂
9. He-1720 glass
10. He-Pyroceram 9606
11. H₂-SiO₂
12. He-Pyrex 7740
13. He-Vycor 7900
14. H₂-Pyrex
15. He-Pyrex 7052
16. He-Neoprene
17. H₂-Neoprene
18. N₂-Neoprene
19. A-Neoprene



Permeação

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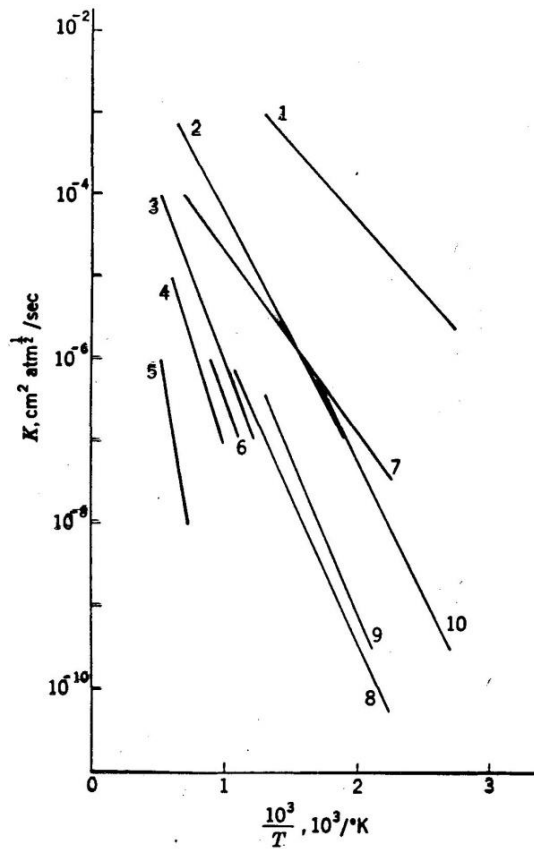


Fig. 3-3 Permeation constants for various diatomic gas-metal combinations as a function of temperature. Units are $\text{cm}^2 \text{ atm}^{1/2} / \text{sec}$. [Quantity of gas in cubic centimeters (STP) passing per second through a wall of 1-cm^2 area and 1-cm thickness, when a pressure difference of 1 atm exists across the wall.] (Numbers 1 to 8 from P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *Adv. Electron. Electron Phys.*, vol. 17, p. 323, 1962; Nos. 9 and 10 from H. L. Eschbach, F. Gross, and S. Schulien, *Vacuum*, vol. 13, p. 543, 1963.)

- | | |
|---------------------------|--|
| 1. $\text{H}_2\text{-Pd}$ | 6. CO-Fe |
| 2. $\text{H}_2\text{-Ni}$ | 7. $\text{H}_2\text{-Fe}$ |
| 3. $\text{H}_2\text{-Mo}$ | 8. $\text{H}_2\text{-Cu}$ |
| 4. $\text{N}_2\text{-Fe}$ | 9. $\text{H}_2\text{-300 series stainless steel}$ |
| 5. $\text{N}_2\text{-Mo}$ | 10. $\text{H}_2\text{-400 series stainless steel}$ |

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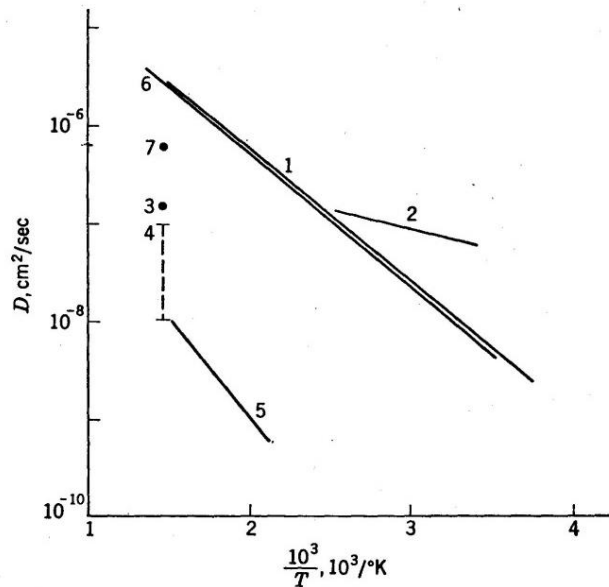


Fig. 3-8 Diffusion constants for various gas-nonmetal combinations. Units are square centimeters per second. (Numbers 1 to 6 from P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *Adv. Electron. Electron Phys.*, vol. 17, p. 323, 1962, and No. 7 from V. O. Altemose, *J. Appl. Phys.*, vol. 32, p. 1309, 1961.)

- 1. He-Pyrex 7740
- 2. He-Vycor
- 3. H₂-Vycor
- 4. N₂-Vycor
- 5. H₂-SiO₂
- 6. He-Duran glass
- 7. He-Pyrex 7052

Table 3-2 Degassing of a Finite Slab. Error of Approximation [Eq. (3-14)] and fraction of gas removed

Dt/d^2	$\frac{[2Q_T/c_0d]_{Eq. (3-14)} - [Q_T/c_0d]_{Eq. (3-19)}}{[Q_T/c_0d]_{Eq. (3-19)}}$	$[Q_T/c_0d]_{Eq. (3-19)}$
0.06	0.0029	0.55
0.07	0.0057	0.59
0.08	0.014	0.63
0.09	0.016	0.67
0.10	0.023	0.70
0.15	0.072	0.82
0.20	0.14	0.89
0.25	0.21	0.93
0.30	0.29	0.96

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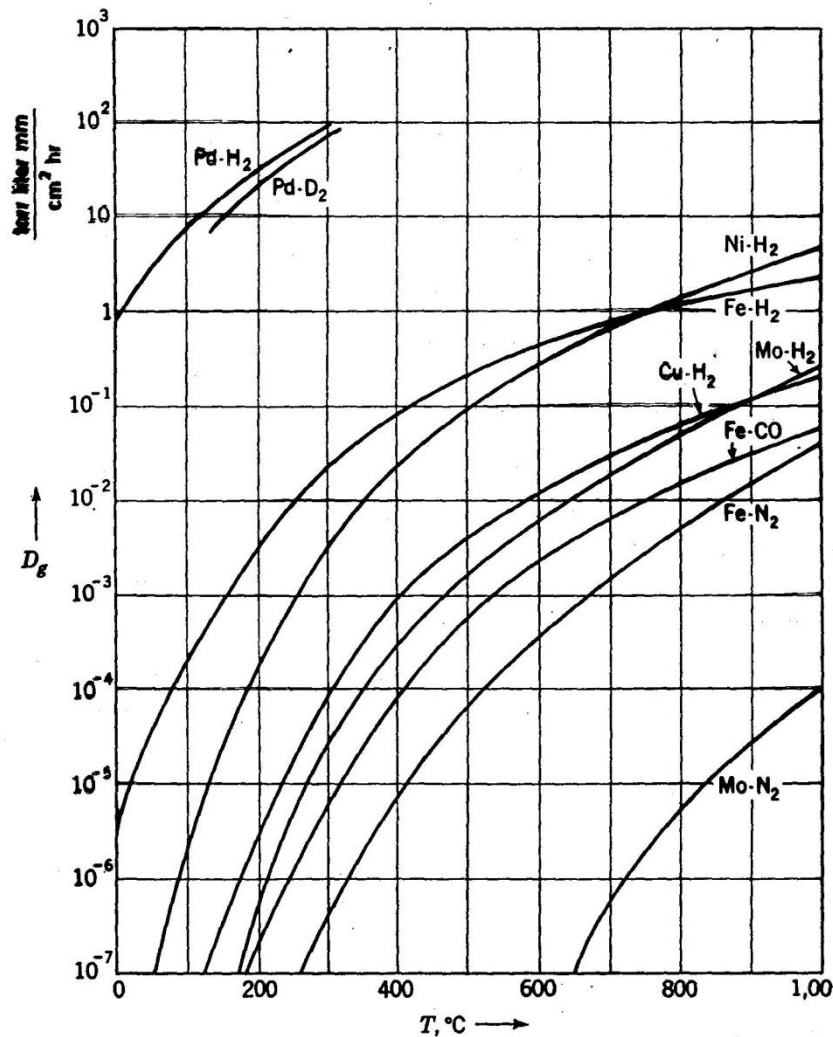


Fig. 3-25 Gas permeation of metal walls versus temperature. Permeation rate D_g is the pressure rise per hour in a vessel of 1-liter volume for a wall area of 1 cm^2 , a wall thickness of 1 mm, and a gas pressure of 760 torr on the outside. T is the temperature of the wall. (From M. von Ardenne, Tabellen Elektronenphysik Ionenphysik und Übermikroskopie, vol. 2, VEB Deutscher Verlag der Wissenschaften, Berlin, 1956.)

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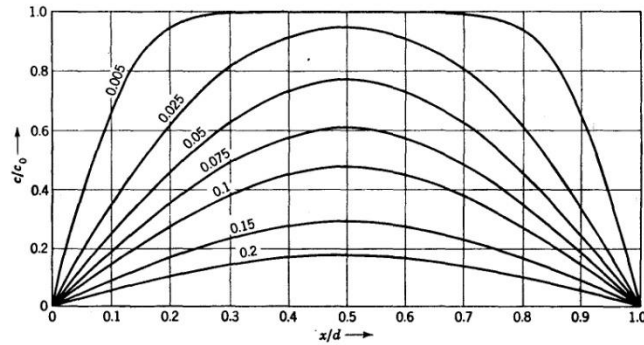


Fig. 3-7 Relative concentration in a finite slab of thickness d for various (dimensionless) times Dt/d^2 as parameter.

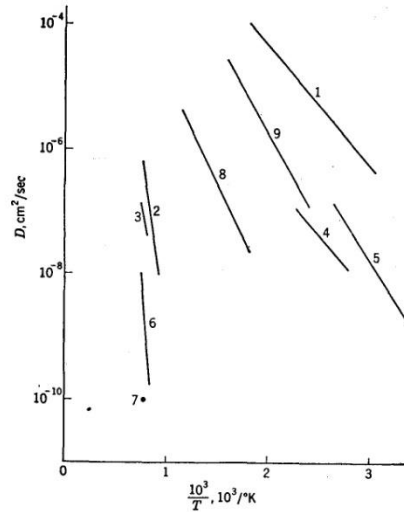


Fig. 3-9 Diffusion constants for various gas-metal combinations. Units are square centimeters per second. (Numbers 1 to 7 from P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *Adv. Electron. Electron Phys.*, vol. 17, p. 323, 1962; Nos. 8 and 9 from H. L. Eschbach, F. Gross, and S. Schullien, *Vacuum*, vol. 13, p. 543, 1963.)

- | | |
|-----------------------|---|
| 1. H ₂ -Pd | 6. O ₂ -Ni |
| 2. N ₂ -Fe | 7. O ₂ -Fe |
| 3. CO-Ni | 8. H ₂ -300 series stainless steel |
| 4. H ₂ -Ni | 9. H ₂ -400 series stainless steel |
| 5. H ₂ -Fe | |

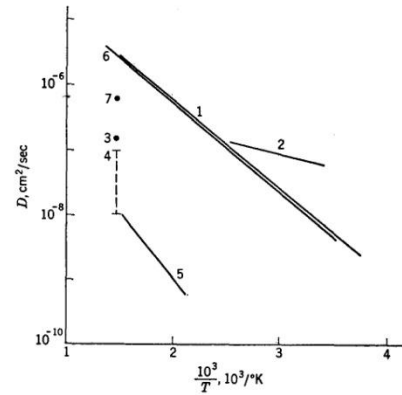


Fig. 3-8 Diffusion constants for various gas-nonmetal combinations. Units are square centimeters per second. (Numbers 1 to 6 from P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *Adv. Electron. Electron Phys.*, vol. 17, p. 323, 1962, and No. 7 from V. O. Altemose, *J. Appl. Phys.*, vol. 32, p. 1309, 1961.)

- | | |
|--------------------------|-------------------------------------|
| 1. He-Pyrex 7740 | 5. H ₂ -SiO ₂ |
| 2. He-Vycor | 6. He-Duran glass |
| 3. H ₂ -Vycor | 7. He-Pyrex 7052 |
| 4. N ₂ -Vycor | |

Desorção Térmica

4.2 THERMAL DESORPTION

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Table 4.1 Average Residence Time of Chemisorbed Molecules

System	Desorption Energy (MJ/(kg-mole))	Residence time at		
		77 K (s)	22°C (s)	450°C (s)
H ₂ O/H ₂ O	40.6	10 ¹⁵	10 ⁻⁵	10 ⁻⁹
H ₂ O/metal	96	-	10 ⁵	10 ⁻⁵
H ₂ /Mo	160	-	10 ¹⁷	1

amount of gas is expressed in torr liters at the temperature T :

$$\frac{d(PV)_A}{dt} = 3.64sP \left(\frac{T}{M}\right)^{\frac{1}{2}} \quad \text{torr liters/sec cm}^2 \quad (3-21)$$

Here T is the temperature of the impinging molecules. At pressure P and temperature T , n_A molecules occupy a volume V . The temperature of the surface may be different.

Table 3-3 Chemical Adsorption of Gases on Metals at Room Temperature

Metal	Gas							
	N ₂	H ₂	CO	C ₂ H ₄	C ₂ H ₂	O ₂	CO ₂	CH ₄
Ag	N	N	N, Y*					
Al	N	N	Y	Y	Y	Y		
Au	N	N	N, Y*	Y	Y	N		
Ba	Y	Y	Y	Y	Y	Y	Y	Y
Ca	Y	Y	Y	Y	Y	Y		
Cd	N	N	N	N	N	Y		
Co	N	Y	Y			Y		N
Cu	N	N	Y	Y	Y	Y		
Cr	N	Y	Y	Y	Y	Y		Y
Fe	Y	Y	Y	Y	Y	Y		N
Hg	N	N	N					
In	N	N	N	N	N	Y		
Mg			Y					
Mn						Y		
Mo	Y	Y	Y	Y	Y	Y		Y
Nb	Y	Y	Y			Y		
Ni	N	Y	Y	Y	Y	Y		N
Pb	N	N	N	N	N	Y		
Pd	N	Y	Y	Y	Y	Y		Y
Pt	N	Y	Y	Y	Y	Y		
Rh	N	Y	Y	Y	Y	Y		Y
Sn	N	N	N	N	N	Y		
Sr			Y					
Ta	Y	Y	Y	Y	Y	Y		Y
Ti	Y	Y	Y	Y	Y	Y	Y	Y
W	Y	Y	Y	Y	Y	Y		Y
Zn	N	N	N	N	N	Y		
Zr	Y	Y	Y	Y	Y	Y		

N = No, Y = Yes.

* Two different investigators.

SOURCE: J. P. Hobson, *Brit. J. Appl. Phys.*, vol. 14, p. 544, 1963.

Table 3-5 Heats of Adsorption in Kilocalories per mole for Dilute Layers

Chemisorption:			
Rb on W	60	O ₂ on Ni	115
Cs on W	64	H ₂ on Fe	32
B on W	140	N ₂ on Fe	40
Ni on Mo	48	H ₂ on Ir	26
Ag on Mo	35	H ₂ on Rh	26
H ₂ on W	46	H ₂ on Co	~24
O ₂ on W	194	H ₂ on Pt	27
CO on W	~100	O ₂ on Pt	67
N ₂ on W	85	H ₂ on Pd	27
CO ₂ on W	122	H ₂ on Ni	30
NH ₃ on W	70	NH ₃ on Ni	36
H ₂ on Mo	~40	CO on Ni	35
H ₂ on Ta	46	H ₂ on Cu	8
Physical adsorption:			
Xe on W	8-9	Xe on Mo	~8
Kr on W	~4.5	Xe on Ta	~5.3
A on W	~1.9		

SOURCE: G. Ehrlich, *Ann. N.Y. Acad. Sci.*, vol. 101, art. 3, p. 722, 1963, 1961 *Vacuum Sump. Trans.*, D. 126, 1962.

Table 3-4 Activation Energy for Surface Migration E_m and Energy of Desorption E_D in Dilute Adlayers

	E_m E_D		E_m/E_D
	kcal/mole		
Cs on W	14	64	0.22
W on W (110)	30	134	0.22
Ba on W (100)	15	87	0.17
O on W	30	147	0.22
H on W	16	74	0.22
N on W	35	155	0.23
CO on W	65	~100	0.7
Xe on W	3.8	9	0.4
Kr on W	>1.1	4.5	>0.25
A on W	0.6	1.9	0.3
H on Ni	7	67	0.11

SOURCE: G. Ehrlich, *Ann. N.Y. Acad. Sci.*, vol. 101, art. 3, p. 722, 1963.

Appendix A.3 (Continued)

Conventional unit	→ multiply by →	to get Si unit
Gas flow		
micron-L/s	0.13332	Pa-L/s
Pa-L/s	3.6	Pa-m ³ /h
atm-cc/s	101.323	Pa-L/s
Torr-L/s	133.32	Pa-L/s
Torr-L/s	0.133	J/s
watt	1000	Pa-L/s
kg-mole/s (at 0°C)	2.48 × 10 ⁹	Pa-L/s
molecules/s (at 0°C)	4 × 10 ⁻¹⁸	Pa-L/s
Outgassing rate		
Pa-L/(m ² -s)	0.001	W/m ²
Pa-m ³ /(m ² -s)	1.0	W/m ²
μL/(cm ² -s)	1.33	W/m ²
Torr-L/(cm ² -s)	1333.2	W/m ²
Dynamic viscosity		
poise	10	Pa-s
Newton-s/m ²	1	Pa-s
Kinematic viscosity		
centistoke	1	mm ² /s
Diffusion constant		
cm ² /s	0.0001	m ² /s
Heat conductivity		
watt-cm ⁻¹ -K ⁻¹	100	J-s ⁻¹ -m ⁻¹ -K ⁻¹
Specific Heat		
cal-(g-mole) ⁻¹ -K ⁻¹	4184.	J-(kg-mole) ⁻¹ -K ⁻¹
J-kg ⁻¹ -K ⁻¹	<i>M</i>	J-(kg-mole) ⁻¹ -K ⁻¹
BTU-lb ⁻¹ -°F ⁻¹	4186 <i>M</i>	J-(kg-mole) ⁻¹ -K ⁻¹
Heat capacity		
cal-(g-mole) ⁻¹	4184	J-(kg-mole) ⁻¹
J/kg	<i>M</i>	J-(kg-mole) ⁻¹
BTU/lb	2325.9 <i>M</i>	J-(kg-mole) ⁻¹
Energy, work, or quantity of heat		
kW-h	3.6	MJ
kcal	4184	J
BTU	1055	J
ft-lb	1.356	J
to get Conventional unit ←	divide by ←	SI unit

APPENDIX C

Material Properties

Appendix C.1 Outgassing Rates of Vacuum Baked Metals

Material	Treatment	q (10^{-11} W/m ²)
Aluminum ^a	15 h at 250°C	53.0
Aluminum ^b	20 h at 100°C	5.3
6061 Aluminum ^c	glow disch. + 200°C bake	1.3
Copper ^b	20 h at 100°C	146.0
304 Stainless Steel ^a	30 h at 250°C	400.0
Stainless Steel ^d	2 h at 850/900°C vac. furnace	27.0
316L Stainless Steel ^e	2 h at 800°C vac. furnace	46.0
U15C Stainless Steel ^f	3 h vac. furn. 1000°C + 25-h <i>in situ</i> vac. bake at 360°C	2.1

Source. Adapted with permission from *Vacuum*, **25**, p. 347, R. J. Elsey. Copyright 1975, Pergamon Press.

^a J. R. Young, *J. Vac. Sci. Technol.*, **6**, 398 (1969);

^b G. Moraw, *Vacuum*, **24**, 125 (1974);

^c H. J. Halama and J. C. Herrera, *J. Vac. Sci. Technol.*, **13**, 463 (1976);

^d R. L. Samuel, *Vacuum*, **20**, 295 (1970);

^e R. Nuvolone, *J. Vac. Sci. Technol.*, **14**, 1210 (1977);

^f R. Calder and G. Lewin, *Brit. J. Appl. Phys.*, **18**, 1459 (1967).

Appendix C.2 Outgassing Rates of Unbaked Metals¹

Material	q_1 (10^{-7} W/m ²)	α_1	q_{10} (10^{-7} W/m ²)	α_{10}
Aluminum (fresh) ^a	84.0	1.0	8.0	1.0
Aluminum (degassed 24-h) ^a	55.2	3.2	4.08	0.9
Aluminum (3-h in air) ^a	88.6	1.9	6.33	0.9
Aluminum (fresh) ^a	82.6	1.0	4.33	0.9
Aluminum (anodized 2 μ m pores) ^a	3679.0	0.9	429.0	0.9
Aluminum (bright rolled) ^b	-	-	100.0	1.0
Duraluminum ^b	2266.0	0.75	467.0	0.75
Brass (wave guide) ^b	5332.0	2.0	133.0	1.2
Copper (fresh) ^a	533.0	1.0	55.3	1.0
Copper (mech. polished) ^a	46.7	1.0	4.75	1.0
OHFC copper (fresh) ^a	251.0	1.3	16.8	1.3
OHFC copper (mech. polished) ^a	25.0	1.1	2.17	1.1
Gold (wire fresh) ^a	2105.0	2.1	6.8	1.0
Mild steel ^b	7200.0	1.0	667.0	1.0
Mild steel (slightly rusty) ^b	8000.0	3.1	173.0	1.0
Mild steel (chromium plated polished) ^b	133.0	1.0	12.0	-
Mild steel (aluminum spray coated) ^b	800.0	0.75	133.0	0.75
Steel (chromium plated fresh) ^a	94.0	1.0	7.7	1.0
Steel (chromium plated polished) ^a	121.0	1.0	10.7	1.0
Steel (nickel plated fresh) ^a	56.5	0.9	6.6	0.9
Steel (nickel plated) ^a	368.0	1.1	3.11	1.1
Steel (chemically nickel plated fresh) ^a	111.0	1.0	9.4	1.0
Steel (chemically nickel plated polished) ^a	69.6	1.0	6.13	1.0
Steel (descaled) ^a	4093.0	0.6	3933.0	0.7
Molybdenum ^a	69.0	1.0	4.89	1.0
Stainless steel EN58B (AISI 321) ^b	-	-	19.0	1.6
Stainless steel 19/9/1-electropolished ^c	-	-	2.7	-
-vapor degreased ^c	-	-	1.3	-
-Diversey cleaned ^c	-	-	4.0	-
Stainless steel ^b	2333.0	1.1	280.0	0.75
Stainless steel ^b	1200.0	0.7	267.0	0.75
Stainless steel ICN 472 (fresh) ^a	180.0	0.9	19.6	0.9
Stainless steel ICN 472 (sanded) ^a	110.0	1.2	13.9	0.8
Stainless steel NS22S (mech. polished) ^a	22.8	0.5	6.1	0.7
Stainless steel NS22S (electropolished) ^a	57.0	1.0	5.7	1.0
Stainless steel ^a	192.0	1.3	18.0	1.9
Zinc ^a	2946.0	1.4	429.0	0.8
Titanium ^a	150.0	0.6	24.5	1.1
Titanium ^a	53.0	1.0	4.91	1.0

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¹ $q_n = qt^{-\alpha_n}$, where n is in hours.

^a A. Schram, *Le Vide*, No. 103, 55 (1963),

^b B. B. Dayton, *Trans. 6th Nat. Vac. Symp. (1959)*, Pergamon Press, New York, 1960, p. 101,

^c R. S. Barton and R. P. Govier, *Proc. 4th Int. Vac. Congr. (1968)*, Institute of Physics and the Physical Society, London, 1969, p. 775, and *Vacuum*, 20, 1 (1970).

Appendix C.3 Outgassing Rates of Ceramics and Glasses¹

Material	q_1 (10^{-7} W/m ²)	α_1	q_{10} (10^{-7} W/m ²)	α_{10}
Steatite ^a	1200.0	1.0	127.0	-
Pyrophyllite ^b	2667.0	1.0	267.0	-
Pyrex (fresh) ^c	98.0	1.1	7.3	-
Pyrex (1 month in air) ^c	15.5	0.9	2.1	-

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¹ $q_n = qt^{-\alpha_n}$, where n is in hours.

^a R. Geller, *Le Vide*, No. 13, 71 (1958);

^b R. Jaeckel and F. Schittko, quoted by Elsey;

^c B. B. Dayton, *Trans. 6th Nat. Symp. Vac. Technol. (1959)*, Pergamon Press, New York, 1960, p. 101.

Appendix C.4 Outgassing Rates of Elastomers¹

Material	q_1 (10^{-5} W/m ²)	α_1	q_4 (10^{-5} W/m ²)	α_4
Butyl DR41 ^a	200.0	0.68	53.0	0.64
Neoprene ^a	4000.0	0.4	2400.0	0.4
Perbunan ^a	467.0	0.3	293.0	0.5
Silicone ^b	930.0	-	267.0	-
Viton A (fresh) ^c	152.0	0.8	-	-
Viton A (bake 12 h at 200°C) ^d	-	-	0.027 ^e	-
Polyimide (bake 12 h at 300°C) ^d	-	-	0.005 ^e	-

Source. Adapted with permission from *Vacuum*, **25**, p. 347, R. J. Elsey. Copyright 1975, Pergamon Press.

¹ $q_n = qt^{-\alpha_n}$, where n is in hours.

^a J. Blears, E. J. Greer and J. Nightengale, *Adv. Vac. Sci. Technol.*, **2**, E. Thomas, Ed., Pergamon Press, 1960, p. 473;

^b D. J. Santeler, et al., *Vacuum Technology and Space Simulation*, NASA SP-105, National Aeronautics and Space Administration, Washington, DC, 1966, p. 219;

^c A. Schram, *Le Vide*, No. 103, 55 (1963);

^d P. Hait, *Vacuum*, **17**, 547 (1967);

^e Pumping time is 12 h.

Appendix C.7 Outgassing Rates of Polymers¹

Material	q_1 (10^{-5} W/m ²)	α_1	q_{10} (10^{-5} W/m ²)	α_{10}
Araldite (molded) ^a	155.0	0.8	47.0	0.8
Araldite D ^b	253.0	0.3	167.0	0.5
Araldite F ^b	200.0	0.5	97.0	0.5
Kel-F ^c	5.0	0.57	2.3	0.53
Methyl Methacrylate ^d	560.0	0.9	187.0	0.57
Mylar (24-h at 95 RH) ^e	307.0	0.75	53.0	-
Nylon ^f	1600.0	0.5	800.0	0.5
Plexiglas ^g	961.0	0.44	36.0	0.44
Plexiglas ^b	413.0	0.4	240.0	0.4
Polyester-glass Laminate ^c	333.0	0.84	107.0	0.81
Polystyrene ^c	2667.0	1.6	267.0	1.6
PTFE ^h	40.0	0.45	26.0	0.56
PVC (24-h at 95 RH) ^e	113.0	1.0	2.7	-
Teflon ^g	8.7	0.5	3.3	0.2

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¹ $q_n = qt^{-\alpha_n}$, where n is in hours.

^a A. Schram, *Le Vide*, No. 103, 55 (1963);

^b R. Geller, *Le Vide*, No.13, 71 (1958);

^c B. B. Dayton, CVC Technical Report;

^d J. Blears, E. J. Greer and J. Nightengale, *Adv. Vac. Sci. Technol.*, 2, E. Thomas, Ed., Pergamon Press, 1960, p. 473;

^e D. J. Santeler, *Trans. 5th Symp. Vac. Tech. (1958)*, Pergamon Press, New York, 1959, p. 1;

^f B. D. Power and D. J. Crawley, *Adv. Vac. Sci. Technol.*, 1, E. Thomas, Ed., Pergamon Press, New York, 1960, p. 207;

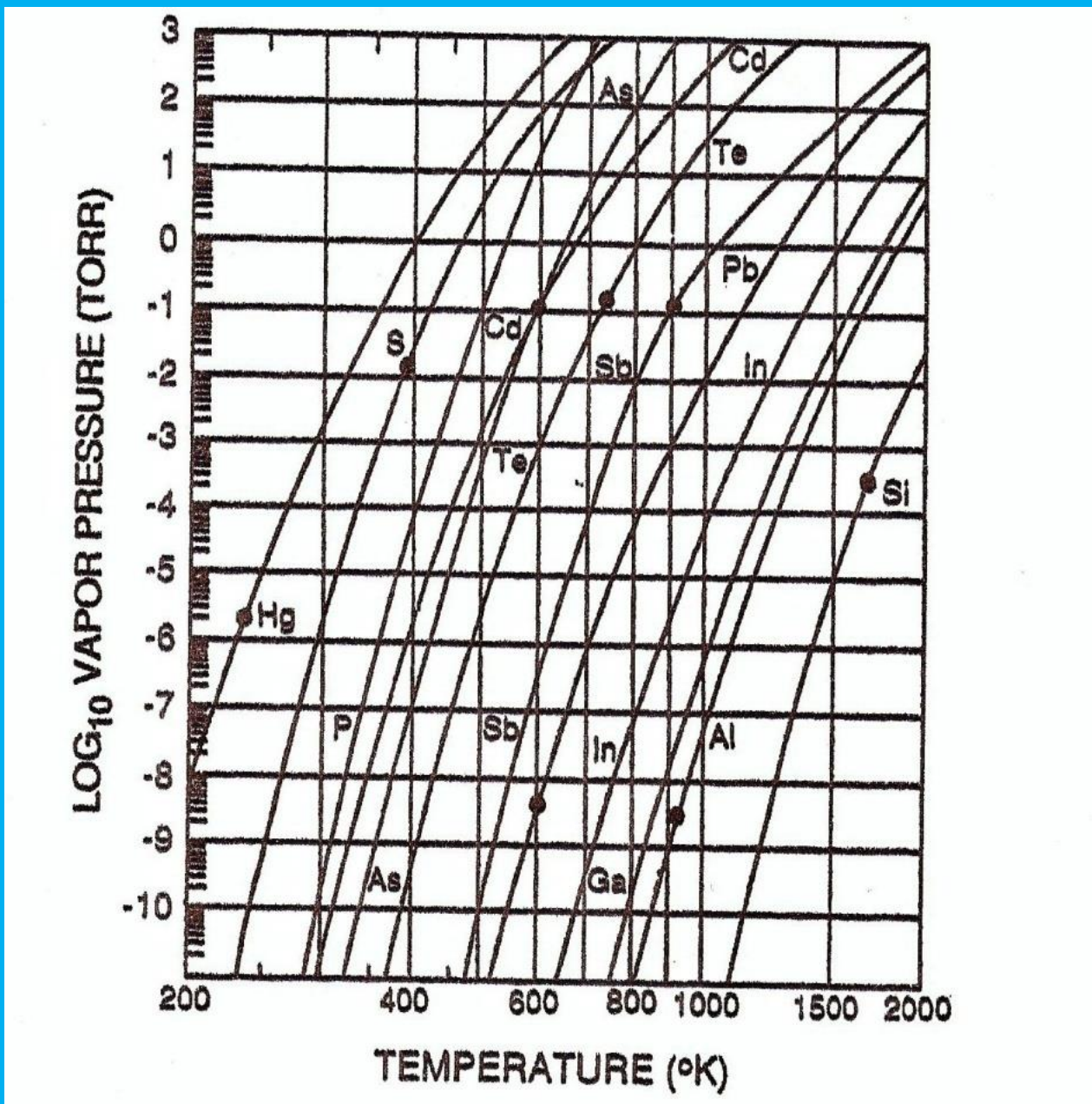
^g G. Thieme, *Vacuum*, 13, 55 (1963);

^h B. B. Dayton, *Trans. 6th Nat. Vac. Symp. Vac. Technol. (1959)*, Pergamon Press, New York, 1960, p.101.

Table 3-11 Gassing Rates at Room Temperature in Torr Liters/cm² sec

<i>Material</i>	<i>After a few hours of pumping</i>	<i>After a 24-hr bake</i>	<i>Bakeout temp., °C</i>	<i>Ref.</i>
Nylon 51	2×10^{-8} (51 hr)	4×10^{-11}	120	(59)
Araldite CT200 + HT901	5×10^{-8} (51 hr)	10^{-10}	100	(59)
Neoprene	10^{-6}			(57)
Viton A	7×10^{-8} (52 hr)	1.3×10^{-9}	200	(60)
Teflon	10^{-8} - 10^{-7}	Low	250	(57),(61)
Glass	10^{-9} - 10^{-8}	10^{-15} - 10^{-14}	400	(62)
Ceramic	10^{-9} - 10^{-8}	10^{-15} - 10^{-14}	400	(57),(62)
Metal	10^{-9} - 10^{-8} (10^{-10} after 50-100 hr)	10^{-15} - 10^{-14}	400	(62),(63)

Pressão de Vapor em função da Temperatura



Modelos de Fontes de Gases em um Sistema de Vácuo

Fonte de gás	Característica	Comentário
Volume	$P = P_o e^{-\frac{S}{V}t}$	Pressão cai exponencialmente dependendo de S e V
Vazamento Real	$P_{res} = \frac{Q_{vr}}{S}; Q_{vr} \approx C_{vr} P_{atm}$	Fluxo constante. Utilizar detector de vazamentos. Deve ser eliminado
Vazamento Virtual	$Q_{vv} = \frac{C_v}{S} P_o e^{-\frac{C_v}{V_c}t}$	$C_v \ll S b$ Queda da pressão depende de C_v e V_c . Evitar no projeto
Difusão	$Q(t) = c_o \frac{\sqrt{D}}{\sqrt{\pi t}}$	$Q(t)$ é proporcional a $\frac{1}{\sqrt{t}}$
Permeação	$Q = \frac{K(P_e^n - P_i^n)}{d}$	$N=1$ para não metais; $n=1/2$ para moléculas diatômicas em metais. Constante de permeação $K(T)$ é proporcional a $10^3/T$
Evaporação	$W = 0.058 P_v \sqrt{\frac{M}{T}} \frac{g}{cm^2 s}$ $Q = WA$ (g/s) $Q = \frac{\Delta N}{\Delta t} kT \frac{Torrl}{s}$	Crescimento de P_v em função da temperatura é exponencial e por isso mais rápido do que $\frac{1}{\sqrt{T}}$
Desorção Térmica (desgaseificação)	Primeira ordem: $\frac{dc}{dt} = c_o k_1 e^{-\frac{t}{\tau_{res}}}$ $\frac{1}{k_1} = \tau_{res} = \tau_o e^{\frac{E_d}{N k T}}$	Rápido $\tau_{res} = 10^{-12} s$
Temperatura (cozimento)	Segunda ordem: $\frac{dc}{dt} = \frac{-k_2 C_o^2}{(1 + C_o K_2 t)^2}$	Cai lentamente A molécula de H_2 se dissocia na adsorção e recombina na desorção
Superfícies Reais	$q_n = \frac{q}{t^\alpha}$ $0.7 \leq \alpha \leq 2$	Fórmula geral $q_n = q t^{-1}$ Adsorção química Adsorção física

4.6 PRESSURE LIMITS

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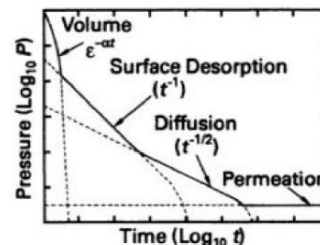


Fig. 4.10 Rate limiting steps during the pumping of a vacuum chamber.

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Nilberto H. Medina
Universidade de São Paulo
Instituto de Física

