

VACUUM TECHNOLOGY

Second, revised edition

A. ROTH

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A. ROTH

*Deputy Director, Former Head of
Department of Vacuum Technology,
Soreq Nuclear Research Centre,
Israel*



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Preface

"The Aristotelians and Cartesians have said that there is no vacuum at all in the tube of Torricellius since glass has small pores, which the beams of light, the effluvia of the loadstone, and other very thin fluids may go through." *Third Paper of Leibnitz to Clarke.*

Although the phenomena are not precisely those assumed by the early investigators, the "horror vacuum" exists, at least here on the earth, where the surrounding exerts its "opposition" to our attempts at isolating a part of the space and completely evacuating its gas content. This is—in fact—just a particular case of the general tendency to oppose any disturbance of the equilibrium. In outer space, where the equilibrium pressure is in the vacuum range, no efforts are required to evacuate our vessel; on the contrary, many difficulties are encountered in keeping it at atmospheric pressure.

The "horror vacuum" appears to the vacuum technologist as the combined effect of conductance, leak rate, desorption, permeation, vapour pressure, diffusion, etc., and Vacuum Technology comprises to date the knowledge developed to avoid or to use these phenomena in order to achieve, measure and maintain lower and lower pressures.

This book is a result of the Postgraduate Course given by the author at the Faculty of Engineering of the Tel-Aviv University. It attempts to cover vacuum technology from the low vacuum up to the ultra-high vacuum as it is known today.

The material presented in the book was selected with a double aim:

- to give enough detailed explanations on principles and phenomena that the author considered as fundamental for any worker in the field, and
- to give the reader the necessary connections to the literature on those topics which are not treated in detail. The book includes numerical examples, tabulated and plotted data, as well as a collection of nomograms which may provide the answers to most of the questions which occur to workers in this field.

It is hoped that the book will provide a useful background for graduates and undergraduates in Universities and Technical Colleges, and serve as a "handbook" for scientists and engineers having to cope with problems of vacuum technology in R & D work or in industry.

To the many authors cited as reference throughout the book is due the credit for their publications, and to them I acknowledge my indebtedness. I wish to express my thanks to the authors and to the publishers for their kind permission to reproduce material from their publications.

I am very grateful to my daughter, Miss Michaela Roth, B.Sc., for preparing and drawing the figures for this book, and to Mrs. Rebeca Kuznetz for typing the manuscript.

I also wish to express my indebtedness to the Management and Staff of North-Holland Publishing Company, for their cooperation.

Alexander ROTH

Commonly used symbols

- A – area (also depth of grooves on sealing surfaces)
- a – distance (also radius)
- a, b – sides of rectangle
- B – circumference, perimeter
- C – conductance
- C_r – compression ratio
- c_p – specific heat (constant pressure)
- c_v – specific heat (constant volume)
- D – diameter
- D_{12} – coefficient of diffusion
- E – energy
- e – charge of the electron
- F – force
- f – molecular sticking coefficient
- h – height (also thickness)
- i, I – current
- J – mechanical equivalent of heat (also factor defining molecular-viscous flow)
- K – heat conductivity (also correction factor molecular flow)
- k – Boltzmann's constant
- L – length
- L_T, L_0 – latent heat of evaporation
- m – mass (of molecule)
- M – molecular weight
- n – molecular density
- N – total number (of molecules)
- N_A – number of molecules per mole
- P – pressure
- $\bar{P}$ – average pressure
- P_u – ultimate pressure
- P_v – vapour pressure
- P_r – probability factor
- q – gas flow (molecules per second)

- q_l – specific leak rate
 q_o – specific outgassing rate
 q_p – specific permeation rate
 Q – throughput
 r, R – radius
 R – sealing factor
 R_o – gas constant (per mole)
 R_e – Reynold's number
 S – pumping speed
 S_p – pumping speed at pump inlet
 t – time
 t_c – temperature ($^{\circ}\text{C}$)
 T – temperature ($^{\circ}\text{K}$)
 V – volume
 v – velocity
 w – width (of seals)
 W – mass or specific mass (per sec, per cm^2)
 Y – correction factor (viscous flow)
 α (alpha) – accommodation coefficient
 γ (gamma) – ratio c_p/c_v (also surface tension)
 δ (delta) – molecular-viscous flow ratio
 ϵ (epsilon) – slip coefficient
 η (eta) – viscosity
 λ (lambda) – mean free path
 Λ (lambda) – free molecular heat conductivity
 ξ (xi) – molecular diameter
 ρ (rho) – density, mass per unit volume
 τ (tau) – period (time)
 ϕ (phi) – molecular incidence rate
 ψ (psi) – correction factor (viscous flow)

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CHAPTER 1

Introduction

1.1. The vacuum

Although the Latin word *vacuum* means "empty", the object of vacuum techniques is far from being spaces without matter. At the lowest pressures which can be obtained by modern pumping methods there are still hundreds of molecules in each cm^3 of evacuated space.

According to the definition of the American Vacuum Society (1958) the term "vacuum" refers to a given space filled with gas at pressures below atmospheric, i.e. having a density of molecules less than about 2.5×10^{19} molecules/ cm^3 .

The general term "vacuum" includes nowadays about 19 orders of magnitude of pressures (or densities) below that corresponding to the standard atmosphere. The lower limit of the range is continuously decreasing, as the vacuum technology improves its pumping and measuring techniques.

1.1.1. Artificial vacuum

Here on the earth vacuum is achieved by pumping on a vessel, the degree of vacuum increasing as the pressure exerted by the residual gas decreases below atmospheric. Measuring a system's absolute pressure is the traditional way to classify the degree of vacuum. Thus, we speak of low, medium, high and ultra-high vacuum corresponding to regions of lower and lower pressures (fig. 1.1).

At first approach the limits of these various ranges may look as arbitrary, since for each range there are specific kinds of pumps and measuring instruments. In fact, each of these various vacuum ranges corresponds to a different physical situation. In order to describe these situations it is useful to utilize the concepts of *molecular density*, *mean free path*, and *the time constant to form a monolayer*, concepts which are related to the pressure, as well as to the kind of gas and its temperature.

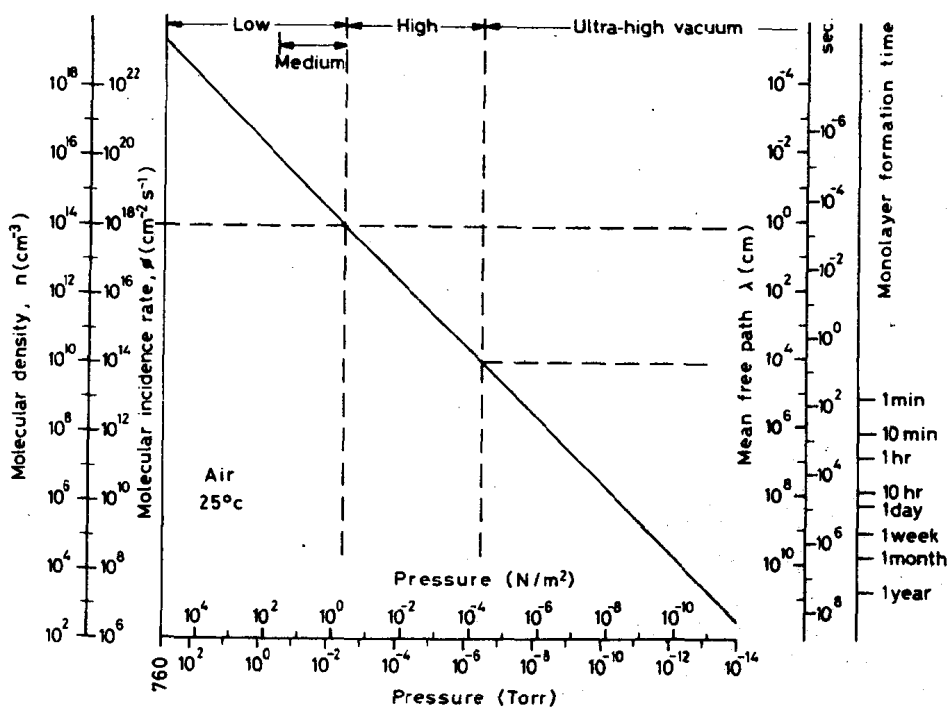


Fig. 1.1 Relationship of several concepts defining the degree of vacuum.

These terms will be mathematically analyzed in further chapters. For the sake of this introduction, they can be defined as:

- *Molecular density* is the average number of molecules per unit volume.
- *Mean free path* is the average distance that a molecule travels in a gas between two successive collisions with other molecules of that gas.
- *Time to form a monolayer* is the time required for a freshly cleaved surface to be covered by a layer of the gas of one molecule thickness. This time is given by the ratio between the number of molecules required to form a compact monolayer (about 8×10^{14} molec/cm²) and the molecular incidence rate (at which molecules strike a surface).

Tables 1.1 and 1.2 list values of these terms, and fig. 1.1 shows their relationship.

By analysing the ranges shown on fig. 1.1 and the values of the terms listed in

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Table 1.1.

Values of molecular density n , molecular incidence rate ϕ , mean free path λ , and time to form a monolayer τ , as a function of pressure P , for air at 25°C.

P Torr	n molec/cm ³	ϕ molec/cm ² ·sec	λ cm	τ sec
760	2.46×10^{19}	2.88×10^{23}	6.7×10^{-6}	2.9×10^{-9}
1	3.25×10^{16}	3.78×10^{20}	5.1×10^{-3}	2.2×10^{-6}
10^{-3}	3.25×10^{13}	3.78×10^{17}	5.1	2.2×10^{-3}
10^{-6}	3.25×10^{10}	3.78×10^{14}	5.1×10^3	2.2
10^{-9}	3.25×10^7	3.78×10^{11}	5.1×10^6	2.2×10^3
10^{-12}	3.25×10^4	3.78×10^8	5.1×10^9	2.2×10^6
10^{-15}	3.25×10	3.78×10^5	5.1×10^{12}	2.2×10^9

Table 1.2.

Values* of ϕ , λ and τ for various gases at 25°C and 10^{-3} Torr.

Gas	ϕ molec/cm ² ·sec	λ cm	τ sec
H ₂	14.4×10^{17}	9.3	1×10^{-3}
He	10.4×10^{17}	14.7	2.3×10^{-3}
N ₂	3.85×10^{17}	5.0	2.1×10^{-3}
O ₂	3.60×10^{17}	5.4	2.4×10^{-3}
A	3.22×10^{17}	5.3	2.6×10^{-3}
Air	3.78×10^{17}	5.1	2.2×10^{-3}
H ₂ O	4.80×10^{17}	3.4	1.1×10^{-3}
CO ₂	3.07×10^{17}	3.3	1.7×10^{-3}

*Notations as in table 1.1.

tables 1.1 and 1.2, it results that the physical situations characterizing the various vacuum ranges are :

Low (and medium) vacuum – the number of molecules of the gas phase is large compared to that covering the surfaces, thus in this range the pumping is directed toward rarefying the existing gas phase. The range extends from atmospheric pressure to about 10^{-2} Torr.

High vacuum – the gas molecules in the system are located principally on surfaces, and the mean free path equals or is greater than the pertinent dimensions of the enclosure. Therefore the pumping consists in evacuating or capturing the molecules leaving the surfaces and individually reaching (molecular flow) the pump.

This is the range where particles can travel in the vacuum enclosure without colliding with other particles. The range extends from about 10^{-3} to 10^{-7} Torr.

Ultra-high vacuum – the time to form a monolayer is equal or longer than the usual time for laboratory measurements, thus “clean” surfaces can be prepared and their properties can be determined before the adsorbed gas layer is formed. This vacuum range extends from about 10^{-7} to 10^{-16} Torr (lower limit decreasing with the progress of the technology). Hobson (1973) calculated that a pressure of 10^{-33} Torr can be achieved (theoretically) by cryopumping.

Composition of the gas – While the total pressure in a vacuum chamber decreases, the composition of the gas phase changes as well. In the *low vacuum* range the composition of the gas mainly resembles that of the atmosphere (table 1.3). In the *high vacuum* range the composition changes continuously, toward one which contains 70–90 percent water vapour. The water molecules come from the surfaces. As pumping is continued and heating is applied, the carbon monoxide content increases. In the *ultra-high vacuum* range hydrogen is the dominant component (table 1.3), coming mostly from the bulk of the materials (permeation).

Table 1.3.
Gas compositions.

Component	Atmosphere ⁽¹⁾		Ultra-high vacuum	
	Percent by volume	Partial pressure Torr	Partial pressure Torr	
			(2)	(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^{-12}
CH ₄	2×10^{-4}	1.5×10^{-3}	7.1×10^{-11}	3×10^{-12}
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.