

A USER'S GUIDE TO VACUUM TECHNOLOGY

JOHN F. O'HANLON

Preface

This book is intended for the vacuum system user—the university student, technician, engineer, manager, or scientist—who wishes a fundamental understanding of modern vacuum technology and a user's perspective of current vacuum practice.

Vacuum technology is largely secondary in that it is a part of other technologies that are central to analysis, research, development, and manufacturing. It is used to provide a process environment. Many advances in vacuum technique have resulted from the demands of other technologies, although scientists and engineers have studied vacuum for its own sake. The average user is process-oriented and becomes immersed in vacuum technique only when problems develop with a process or new equipment purchases become necessary.

A User's Guide to Vacuum Technology focuses on the understanding, operation and selection of equipment for processes used in semiconductor, optics, and related technologies. It emphasizes subjects not adequately covered elsewhere while avoiding in-depth treatments of topics interesting only to the designer or curator. Residual gas analysis is an important topic whose treatment here goes beyond the usual explanation of mass filter theory. New components such as turbomolecular and helium gas refrigerator cryogenic pumps are widely used but not so well understood as diffusion pumps. New processes for film deposition and removal require the use of toxic, corrosive, or explosive gases. Special precautions need to be taken for safe use of these gases. The discussion of gauges, pumps, and materials is a prelude to the central discussion of the total system. Systems are grouped according to their common vacuum requirements of speed, working pressure, and gas throughput. The suitability of each pump is examined for several classes of systems, and basic operational procedures are given for each.

high vacuum pumping system. The economic analysis discusses the costs of purchasing, maintaining, and operating vacuum equipment and describes ways in which operating costs can be significantly reduced.

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J. F. O'Hanlon

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Its Basis

An understanding of how vacuum components and systems function begins with an understanding of the behavior of gases at low pressures. Chapter 1 discusses the nature of vacuum technology. Chapter 2 reviews basic gas kinetics and the flow properties of gases at reduced pressures which form the foundation of vacuum technology.

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CHAPTER 1

Vacuum Technology

Galileo was the first person to create a partial vacuum. He did so with a piston. This seventeenth-century discovery was followed in 1643 by the invention of the mercury barometer by Torricelli and in 1650 the first pump by von Guericke. Interest in the properties of gases at reduced pressures remained at a low level for more than 200 years, when a period of rapid discovery began with the invention of the compression gauge by McLeod. In 1905 Gaede, a prolific inventor, designed a rotary pump sealed with mercury. These developments, in addition to the thermal conductivity gauge, the diffusion pump, the ion gauge and pump, the liquefaction of helium, and the refinement of organic pumping fluids, formed the nucleus of a technology that has made possible everything from light bulbs to the simulation of outer space.

Vacuum technology is the systematic study of scientific ideas and the application of these principles to the production of practical, reduced-pressure environments. It has drawn on discoveries from many fields such as chemistry, physics, mathematics, ceramics, materials and surface science, and engineering. It has also made fundamental contributions in its own right.

A vacuum is a space from which air or other gas has been removed. In practice we know that all the gas can never be removed and we sometimes wish to remove only a particular fraction of that gas. Air is the most important gas to be pumped because it is in every system. It contains at least a dozen constituents, the concentrations of which are given in Table 1.1. It is useful to be aware of the content of air in

Table 1.1 Components of Dry Atmospheric Air

Constituent	Content		Pressure (Pa)
	(vol %)	Ppm	
N ₂	78.084±0.004		79,117
O ₂	20.946±0.002		21,223
CO ₂	0.033±0.001		33.437
Ar	0.934±0.001		946.357
Ne		18.18±0.04	1.842
He		5.24±0.004	0.51
Kr		1.14±0.01	0.116
Xe		0.087±0.001	0.009
H ₂		0.5	0.051
CH ₄		2.	0.203
N ₂ O		0.5±0.1	0.051

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order to predict the responses of pumps and gauges. The concentrations listed in Table 1.1 are those of dry atmospheric air at sea level [total pressure 101,323.2 Pa (760 torr)]. The partial pressure of water vapor is not given in this table because it is constantly changing. At 20°C a relative humidity of 50% is equivalent to a partial pressure of 1165 Pa (8.75 Torr) which makes it the third largest constituent of air. The total pressure changes rapidly with altitude, as shown in Fig. 1.1, its proportions, slowly but significantly. In outer space the atmosphere is thought to be mainly hydrogen with some helium [1].

For convenience it is customary to divide the pressure scale below atmospheric into several ranges and to relate phenomena and processes to them. Table 1.2 lists the ranges currently in use. Epitaxial growth of semiconductor films [2,3] takes place in the low vacuum range. Sputtering [4,5], plasma etching, plasma deposition [5], and low-pressure chemical vapor deposition [5-7] are examples of processes performed in the medium vacuum range. Pressures in the very high vacuum range are required for most thin-film preparation [5,8],

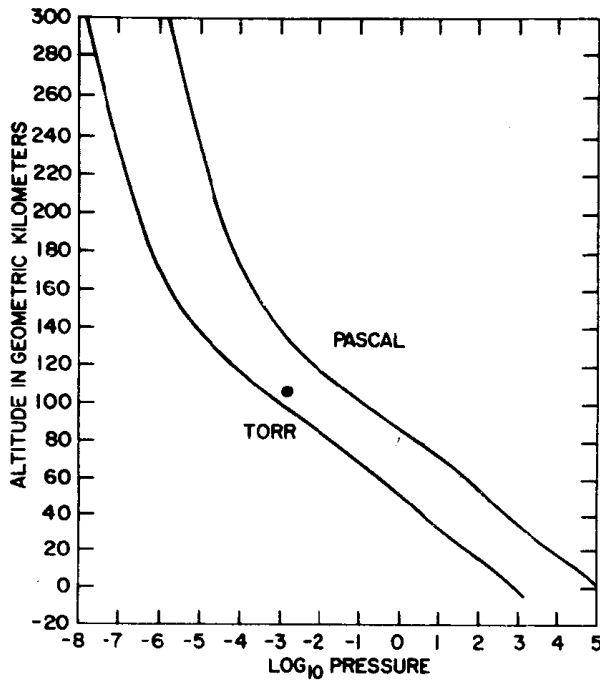


Fig. 1.1 Relation between the atmospheric pressure and the geometric altitude. Reprinted with permission from *The Handbook of Chemistry and Physics*, 59th ed., R. C. Weast, Ed. Copyright 1978, The Chemical Rubber Publishing Co., CRC Press, Inc., West Palm Beach, FL 33409.

electron microscopy [9], mass spectroscopy [10], crystal growth [11], x-ray and electron beam lithography [12,13], and the production of cathode ray and other vacuum tubes [14]. For ease of reading, we call the very high vacuum region *high vacuum* and the pumps, *high vacuum pumps*. Pressures in the ultrahigh vacuum range are necessary for surface and material studies [15].

SI units are used with few exceptions. Pumping speeds are given in L/s (high vacuum pumps and conductances) and in m³/h (mechanical pumps) instead of m³/s. Diffusion pumps, whose nomenclature is not well standardized, are referred to by the inch size of the top flange. This often bears little relation to their performance. Unless otherwise indicated, all formulas are given in the basic SI units.

Table 1.2 Vacuum Ranges.

Degree of Vacuum	Pressure Range (Pa)
Low	$10^5 > P > 3.3 \times 10^3$
Medium	$3.3 \times 10^3 \geq P > 10^{-1}$
High	$10^{-1} \geq P > 10^{-4}$
Veryhigh	$10^{-4} \geq P > 10^{-7}$
Ultrahigh	$10^{-7} \geq P > 10^{-10}$
Extreme Ultrahigh	$10^{-10} > P$

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CHAPTER 2

Gas Properties

Phrases like *vacuum pump* and *vacuum system* are not particularly descriptive. In reality, a vacuum pump is a gas pump designed to operate at lower than atmospheric pressures. A vacuum system consists of pumps and a chamber connected by piping and ductwork. The low pressure in the chamber is maintained by the continued flow of gases from the chamber to the pumps, where they are entrained or expelled into the atmosphere. This chapter discusses static and dynamic gas properties and the flow of gases at reduced pressures.

2.1 THE KINETIC PICTURE OF A GAS

The kinetic picture of a gas is based on several assumptions. The volume of gas under consideration contains a large number of molecules. A cubic meter of gas at a pressure of 10^5 Pa and a temperature of 22°C contains 2.5×10^{25} molecules, whereas at a pressure of 10^{-7} Pa, a very high vacuum, it contains 2.5×10^{13} molecules. Indeed, any volume and pressure normally used in the laboratory will contain molecules in large numbers. Adjacent molecules are separated by distances that are large compared with their individual diameters. If we could stop all molecules instantaneously and place them on the coordinates of a grid, the average spacing between them would be about 3.4×10^{-9} m at atmospheric pressure (10^5 Pa). The diameter of most molecules is in the 2×10^{-10} to 6×10^{-10} m range and distances of about 6 to 15 times their diameter at atmospheric pressures separate