HANDBOOK OF VACUUM PHYSICS

VOLUME 1
GASES AND VACUA

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Part 1

B. B. DAYTON—Vacuum Technology as applied to Continuously Pumped Systems

Part 2

T. E. LUCAS—Properties of High Vacuum Pumps and Design of Vacuum Pumping Systems

Part 3

A. H. TURNBULL—Leak Detection and Detectors

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PREFACE

EVERY worker who uses vacuum apparatus or works on the diverse applications of high-vacuum technology in research or industry has, at one time or another, experienced the need for a source in which he could find the essentials of all the many different scientific disciplines involved. The range of information required is very wide indeed, ranging from material on the quantum theoretical aspects of the complex semi-conductors used for thermionic and photo-electric emission on the one hand to data on the performance of commercially available pumps, gauges and high-vacuum materials, on the other. It has long been clear that the range is so great that it is beyond the powers of any individual or even of two or three authors, to produce a book which would adequately cover more than a limited part of the required matter. The *Handbook of Vacuum Physics* sets out to satisfy this need by presenting a series of long articles, each prepared by an expert, giving an up-to-date survey of his subject.

The Handbook was originally conceived as a set of three volumes, Vol. I on " Gases and Vacua " Vol. II on " Physical Electronics " and Vol. III on " Vacuum Technology ". Owing to the many demands on their time some of the writers originally approached have not been able to prepare their articles, while others have been able to keep to their schedules. Therefore, so as not to delay the presentation of the large amount of valuable material which has been prepared it was decided to prepare a series of much smaller paperback volumes, each containing either two or three separate contributions to the Handbook and forming a coherent part of the whole project. Then, at a time when the whole of the material had been published, it would be possible to issue binders which would enable the paperbacks to be assembled into the volumes as originally set out. The present work constitutes Parts 1–3 of Volume I of the Handbook.

In preparing the Handbook great care has been taken to ensure that enough theoretical material has been included so that the theory which underlies the various formulae is understood. This

is very necessary in a field where the blind application of rules of thumb is unlikely to produce acceptable results. However, it would be unrealistic to include all the basic theory. The criterion used to exclude elementary matter was that theory would be included unless it might fairly be assumed that it would be covered by any ordinary course of higher education in engineering or physics. This has meant that more background material is included than would be expected of most handbooks.

On the practical side, especial emphasis has been placed on the provision of accurate modern tables of physical constants, properties of materials, laboratory techniques and, most important of all, properties of commercial pumps, gauges and leak detectors. It is hoped that users of the Handbook will be able to avoid or, at least, materially shorten the protracted literature searches often necessary at the moment.

In view of the international composition of the panel of authors it would have been impractical to attempt to create the impression of a uniform style so the authors have been left to speak for themselves. The Editor would, however, be grateful to hear of any errors or misprints which users may find, and to receive suggestions for the coverage of fields which it may be felt should have been included.

In conclusion the Editor would like to express on behalf of all the contributors their thanks to the Editorial and Production staff of Pergamon Press for the continuous help and care which have gone into the publication of this work.

CONTENTS

PART 1

VACUUM TECHNOLOGY AS APPLIED TO CONTINUOUSLY PUMPED SYSTEMS

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PART 1

VACUUM TECHNOLOGY AS APPLIED TO CONTINUOUSLY PUMPED SYSTEMS

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1. DEFINITIONS OF SYMBOLS

a_{nm} = velocity constant for permeation in cm^3 (STP) sec^{-1} cm^{-2} for a pressure gradient of 1 torr mm^{-1} for the nth gas through the mth material.

A = total surface area in cm^2 inside the chamber.

A_m = area in cm^2 of the mth surface assumed to be a plane.

C_a = net speed of the roughing pump (or fore pump) in l. per sec.

C_{ij} = conductance for combined gases flowing between two points (i and j) in a given conduit, expressed in torr l. sec^{-1} $torr^{-1}$.

D_a = value of diffusion coefficient, D_{nm}, at ambient temperature, T_a, in cm^2 sec^{-1}.

D_b = value of diffusion coefficient, D_{nm}, at the bake-out temperature, T_b, in cm^2 sec^{-1}.

e_{nm} = sorption coefficient representing the fraction of n-type molecules striking the mth surface which are sorbed.

e'_{nm} = ultimate value of e_{nm} when the pumping time is very large.

E = total net speed of exhaust for all gases in l. sec^{-1}.

E_n = net speed of exhaust for the nth gas in l. sec^{-1}.

E_{nm} = activation energy for permeation in cal $mole^{-1}$ for the nth gas through the mth material.

F_b = limiting or tolerable forepressure for high vacuum pumping stage.

f_n = effusion law factor in l. sec^{-1} cm^{-2}.

H_{nm} = activation energy for diffusion in cal $mole^{-1}$ for the nth gas through the mth material.

j = dissociation number representing the number of adsorbed particles formed when a molecule of type n is sorbed by the mth surface.

K_h = measured total outgassing rate in torr l. sec^{-1} cm^{-2} of mth material using air calibration factor for measurement of p and S_a.

K_i = value of K_{nm} at time t_i.

K_1 = value of $K_{nm}-K_u$ when $t_h = 1$ hr.

K_{nm} = free outgassing rate in torr l. sec^{-1} cm^{-2} for the nth gas from the mth surface.

K'_{nm} = ultimate value of K_{nm} when pumping time is very large.

K_u = ultimate free outgassing rate when pumping time is very large, or steady state free outgassing rate due to permeation and leaks.

L_a = total leak rate for air.

M_n = molecular weight of the nth gas.

N_a = Avogadro's number ($N_a = 6.02 \times 10^{23}$).

p = $\Sigma_n p_n$ = total pressure in the vacuum chamber in torr.

p_i = total pressure at inlet to pump in torr.

p_n = partial pressure in torr of nth gas at the temperature T °K.

p_u = ultimate pressure in the vacuum chamber in torr.

p_{up} = ultimate pressure of pumping system alone in torr.

P_n = partial pressure of the nth gas outside the chamber at the temperature T °K.

Q = total throughput for all gases in torr l. sec^{-1}.

Q_n = throughput of nth gas in torr l. sec^{-1}.

R = molar gas constant in cal $°K^{-1}$ ($R = 1.986$).

R_o = molar gas constant in c.g.s. units ($R_o = 8.31 \times 10^7$).

P_v = molar gas constant in vacuum engineering units (R_v = 62.36 torr l. per °K per mole).

S = net pumping speed in l. sec^{-1} for combined gases in chamber at pressure p.

S_a = value of S_n for air.

S_i = speed of the pump in l. sec^{-1} for combined gases at the total pressure, p_i.

S_n = net pumping speed in l. sec^{-1} for the nth gas.

S_p = average value of S_n for those gases which permeate the walls.

S_{ni} = speed of the pump in l. sec^{-1} for the nth gas.

t = time in sec from the beginning of pump down or evacuation.

t_b = value of t_h when bake-out begins.

t_c = value of t_h when cooling begins.

t_d = time to pump down from atmospheric pressure to 0.75 torr (roughing time).

t_h = time in hr from the beginning of evacuation.

t_m = time in hr at which α begins to increase rapidly.

T = absolute temperature of the gas phase in the chamber.

T_a = ambient temperature in °K.

T_b = bake-out temperature in °K.

T_m = absolute temperature of the mth material.

U_{nm} = permeability coefficient in cm^3 at standard temperature (0°C) and pressure (760 torr) sec^{-1} cm^{-2} for a pressure gradient of 1 torr mm^{-1} for the nth gas through the mth material.

V = volume in litres of the vacuum chamber.

w_m = thickness in mm of the mth material assumed in the form of a flat sheet.

α = exponent of the time t (or t_h) governing the rate of decay of outgassing.

α_1 = value of α when $t = 3600$ sec or $t_h = 1$ hr.

2. NOMENCLATURE

Vacuum systems comprise four basic types of components (see Fig. 1) : (1) an enclosure or chamber within which a process or

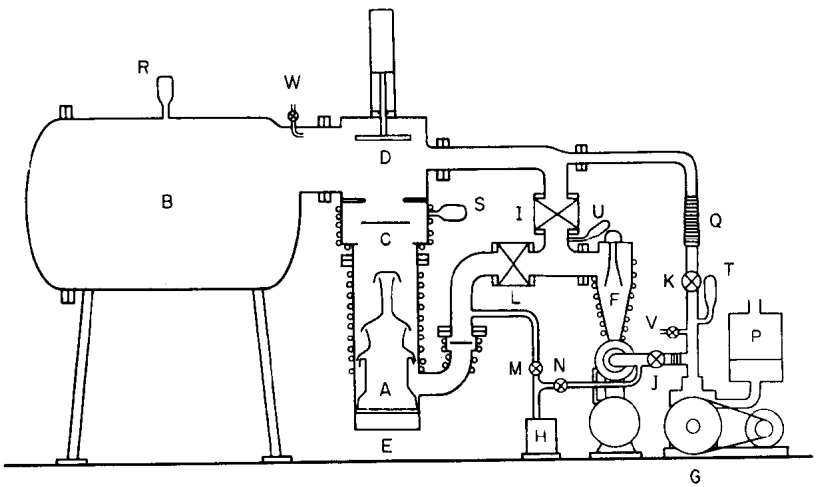

FIG. 1. Typical continuously pumped system.

storage occurs, (2) pumping or gettering devices, (3) vacuum gauges, and (4) vacuum " plumbing " such as valves, baffles, conduits, manifolds, etc. *Continuously pumped systems* are distinguished from systems which are sealed-off after pumping in that the pumps continue to remove gas* from the chamber during the process cycle. However, the residual gases in sealed-off devices may also continue to be removed by sorption in getters or by electrical clean-up within the chamber. Getter-ion pumps are available which permit large sealed-off devices to be pumped continuously or intermittently as required.

Demountable vacuum systems are constructed with joints and seals which are easily disconnected, and may employ gaskets, vacuum waxes, or vacuum grease between the surfaces to be joined. When gaskets of rubber or synthetic elastomers are used, or when waxes, greases, and non-metallic sealants are used, the outgassing rate is usually high and correspondingly large pumping rates must be

* For simplicity the term *gas* will be understood to include any vapours in the vacuum system as well as the non-condensable gases.

employed. Such systems are sometimes called *dynamic* or *kinetic* systems (Strong[42]). When metal gaskets are used, or when the system is constructed mainly of glass and metal parts fused or welded together, the outgassing rate is normally low and relatively small pumps or gettering surfaces are sufficient for maintaining pressures in the 10^{-3} to 10^{-7} torr range. Such systems have been referred to as " static systems " (Strong[42]), but the terms *dynamic*, *kinetic*, and *static* are not recommended because all vacuum systems involve continuous gas evolution and pumping or gettering of gas (British Standards Institution[8]).

In a *bakable system* the walls of the chamber can be baked to accelerate the outgassing rate so that on cooling the desired operating pressure is quickly obtained. An *ultra-high vacuum system* may be defined as any system capable of reaching a pressure less than 10^{-9} torr. Ultra-high vacuum systems are usually bakable and constructed entirely from materials, such as metal and glass, having a low outgassing rate (Alpert[2]). However, large high-speed pumps may still be required to reach pressures below 10^{-9} torr in a short time. By exposing large surfaces cooled to 20°K or less (cryopumps) within the chamber, pressures less than 10^{-9} torr may be achieved even in the presence of high rates of gas evolution (Richman and Hood[39] and Santeler [40]).

Throughput, Q, is defined as the quantity of gas in pressure–volume units at a specified temperature flowing per unit time across a specified open cross section, such as the mouth of a pump or the inlet of a pumping system. The *pump speed*, S_i, is defined as the volume of gas that flows into the pump in unit time at a constant pressure, p_i, measured near the pump inlet by a gauge having a tubulation attached to the system so that the plane of the entrance of the tubulation is parallel to the direction of flow of the gas into the pump. When Q is the throughput across the pump inlet,

$$S_i = Q/p_i. \tag{1}$$

In the following paragraphs *pressure* will be expressed in torr, *throughput* in torr l. sec^{-1} and *speed* in l. sec^{-1}.

Speed of exhaust, E, is the magnitude of the rate of reduction of pressure in a chamber multiplied by the volume, V, and divided by the pressure, p, in the chamber :

$$E = -(V/p)\, dp/dt. \tag{2}$$

Conductance, C_{ij}, is defined as the throughput under steady-state conservative flow conditions divided by the difference in static pressure, $p_j - p_i$, between two specified cross-sections in a conduit :

$$C_{ij} = Q/(p_j - p_i). \tag{3}$$

Net speed, S_j, is defined as the throughput across a section remote from the pump inlet divided by the static pressure, p_j, at that section :

$$S_j = Q/p_j. \tag{4}$$

Ultimate pressure, p_u, is defined as the limiting pressure in a vacuum chamber after sufficient pumping time to establish that further reduction in pressure will be negligible.

3. THE FLOW OF GAS BETWEEN CHAMBER AND PUMP

Under steady-state conservative flow conditions the throughput, Q, at a specified temperature, T, will be a constant across any section of the conduit, or conducting passage, between the exit of the chamber and the inlet of the pump. Then from (1), (3) and (4)

$$Q = S_i p_i = S_j p_j = C_{ij}(p_j - p_i) = Sp, \tag{5}$$

where S is the net pumping speed at the chamber and p is the pressure in the chamber (which is assumed to have a length not much greater than the mean diameter so that the pressure gradient inside the chamber is negligibly small). From (5) it follows that

$$1/S = (1/S_i) + (1/C_i), \tag{6}$$

where S is the net speed in the chamber, S_i the speed at the pump inlet, and C_i the conductance of the conduit between the chamber and the pump inlet.

When vapours are condensed on traps within the conduit between chamber and pump, equations (5) and (6) cannot be applied. However, similar relations hold for each non-condensable gas, or for the sum of the non-condensable gases. The trap can be considered as a pump for the vapour, and equations similar to (5) and (6) can be applied for the flow of vapour through that section of the conduit between the chamber and the trap.

Letting p_n represent the partial pressure of the nth gas in the chamber, Q_n the throughput and S_n the net pumping speed for this gas, then

$$Q_n = S_n p_n = S_{ni} p_{ni}, \tag{7}$$

where S_{ni} is the speed of the pump for the nth gas as measured at the static pressure p_{ni} near the inlet of the pump. Corresponding to (6) we have

$$1/S_n = (1/S_{ni}) + (1/C_{ni}), \tag{8}$$

where C_{ni} is the conductance for the nth gas of the conduit between chamber and pump. Several types of mass spectrometers are commercially available for measuring partial pressures of the common gases in vacuum systems (Della Porta[36] and Preuss[37]).

The methods of calculating the conductance of conduits will be given elsewhere in Volume 7 of this series. Care must be exercised to avoid using so-called " entrance corrections " or " short tube " conductance formulas when the latter do not apply because of the direct coupling of components of the same cross section and the measurement of pressure as static rather than dynamic or impact pressure.

While as a general rule the conduit should be as short as possible and have a cross section equal to or greater than that of the pump inlet, in practice it is difficult to achieve an economical conduit design which yields a net speed at the chamber much more than 70 per cent of the speed of the pump (without baffle). A well designed conduit containing an " optically tight " water-cooled baffle, an " optically tight " (refrigerated or zeolite sorption) trap, and a valve may reduce the net pumping speed to 15–20 per cent of the pump speed.

4. SOURCES OF GAS WITHIN THE CHAMBER

There are four principal sources of gas within the chamber: (1) the residual gas molecules of the initial atmosphere enclosed in the chamber, (2) outgassing from the exposed surfaces within the chamber, (3) gas (including vapours) migrating from the pumping system into the chamber, (4) leaks. In the following mathematical formulae leaks will be treated as a special case of outgassing from the surface represented by the exit of the capillary opening through

which gas escapes into the chamber. Evaporation of liquids within the chamber and gases evolved by chemical decomposition may also be treated as special cases of outgassing from the surfaces involved. Then, assuming that there are n different volatile constituents (hereafter referred to as " gases ") and m different outgassing surfaces, the principle of material balance requires that the net throughput of each of the n gases across the inlet to the pumping system be equal to the net throughput of that gas with respect to the combined exposed surfaces plus the rate of reduction of the quantity (in pressure-volume units) of that gas in the free space bounded by these surfaces.

When the partial pressure in torr of the nth gas is p_n at the temperature T °K in the gas phase inside the vacuum chamber, the rate at which n-type molecules strike a plane surface of area A_m cm^2 in the throughput units of torr l. sec^{-1} at the temperature T is

$$G_n = f_n A_m p_n, \tag{9}$$

where f_n is the " effusion law " factor in l. sec^{-1} cm^{-2} as given by :

$$f_n = (R_o T/2\pi M_n)^{1/2} \cdot 10^{-3} \tag{10}$$

in which R_o is the molar gas constant in c.g.s. units ($R_o = 8.31 \times 10^7$) and M_n is the molecular weight of the nth gas. If e_{nm} is the fraction of these molecules which are sorbed (the word sorbed including both adsorption and absorption processes), then the rate of sorption for the exposed surface is

$$G_{nm} = f_n e_{nm} A_m p_n. \tag{11}$$

At any instant of time during pump down, n-type molecules will be escaping from the mth surface at a rate depending on the temperature, T_m, of the surface and the concentration of these molecules at the surface. The rate of desorption from and through the surface of area A_m is :

$$G'_{nm} = K_{nm} A_m, \tag{12}$$

where K_{nm} is defined as the " free outgassing rate " in torr l. sec^{-1} cm^{-2} for the nth gas from the mth surface as measured at the temperature T of the gas phase within the chamber. The " free outgassing rate " of the mth material for all volatile matter is defined by :

$$K_m = \sum_n K_{nm}. \tag{13}$$

The net throughput of n-type molecules with respect to the mth surface is then :

$$Q_{nm} = G'_{nm} - G_{nm} = A_m(K_{nm} - f_n e_{nm} p_n). \tag{14}$$

The outgassing rate in torr l. $\sec^{-1}$ cm^{-2} for the nth gas from the mth surface is given by :

$$k_{nm} = Q_{nm}/A_m, \tag{15}$$

or using (14)

$$k_{nm} = K_{nm} - f_n e_{nm} p_n. \tag{16}$$

5. RELATION BETWEEN PRESSURE, SPEED AND OUTGASSING RATE

The net throughput of the nth gas across the inlet to a pumping system having net speed S_n for this gas will be

$$Q_n = S_n p_n. \tag{17}$$

The principle of material balance then gives

$$Q_n = \sum_m Q_{nm} - V(\mathrm{d}p_n/\mathrm{d}t), \tag{18}$$

where V is the volume of the vacuum chamber in litres.

From (14), (17) and (18) the partial pressure, p_n, in torr is given by

$$p_n = \frac{\sum_m K_{nm} A_m - V(\mathrm{d}p_n/\mathrm{d}t)}{\sum_m f_n e_{nm} A_m + S_n} \tag{19}$$

The total pressure, p, in the vacuum chamber is given by

$$p = \sum_n p_n, \tag{20}$$

and the total throughput of the pumping system at the pressure p is

$$Q = \sum_n S_n p_n. \tag{21}$$

6. THE ULTIMATE PRESSURE

The ultimate pressure, p_u, in the chamber is defined as the limiting pressure after sufficiently long pumping so that the rate of pressure decrease, $\mathrm{d}p/\mathrm{d}t$, is negligibly small. From (20) we have as the

necessary condition for p to be equal to the ultimate value, p_u, that

$$dp_n/dt \doteq 0 \tag{22}$$

for all values of n. Then from (19) and (20) the ultimate pressure is given by

$$p_u = \sum_n \frac{\sum_m K'_{nm} A_m}{\sum_m f_n e'_{nm} A_m + S_n}, \tag{23}$$

where K'_{nm} and e'_{nm} are the limiting or ultimate values of K_{nm} and e_{nm}. Equation (23) is a generalization of a formula for the ultimate pressure first published by Burch and Sykes in 1935[6] in an article on continuously pumped radio tubes (valves).

The true ultimate pressure after a sufficiently long pumping time would be limited only by permeation and leaks through the walls and joints of the vacuum system, and by the vapour pressure inside the chamber of the remaining solid phases, and by the net speed of the high vacuum pump for the various gases involved (taking into consideration the effect of back diffusion through vapour pumps, operational release of gas in getter-ion pumps, etc.). In other words, at the true ultimate pressure all of the sorbed and occluded gas will have been removed except that which can remain in equilibrium at the ultimate pressure determined by permeation and the other factors listed above. In practice, the pumping is seldom continued long enough to produce the true ultimate pressure, but some criterion is established as to when the rate of decrease in pressure is negligible, and the pressure at that time is regarded as the "ultimate pressure". In this case the ultimate pressure also depends to some extent on the outgassing rate of the exposed materials after the pumping time which has elapsed.

The sorption coefficient, e'_{nm}, associated with permeability is usually so small that $f_n e'_{nm} A_m$ can be neglected in comparison to S_n. Therefore the terms in equation (23) arising from permeation can be written

$$[p_u]_{\text{perm.}} = \sum_{nm}\sum K'_{nm} A_m / S_n, \tag{24}$$

where

$$K'_{nm} = (760/273) \cdot 10^{-3}\, T\, (U_{nm}/w_m) P_n^{l/j}, \tag{25}$$