1. Physical Quantities, their Symbols, Units and Definitions
(as per DIN 28 400, part 1 — 1979 — and DIN 28 402 — 1976)

1.1. Fundamental quantities

Pressure $p$ (mbar)$^1$ of fluids (gases, liquids) (quantity: pressure, symbol $p$; unit: millibar; symbol for unit: mbar).

According to DIN 1314 the pressure $p$ is defined as the quotient of the perpendicular force on a surface and the area of this surface (unit of force per unit surface area).

Even if the pressure unit “torr” has been discarded (see chapter 8), it should be briefly mentioned as it is clear and descriptive. 1 torr is understood as that gas pressure which is able to balance at 0 °C a mercury column of 1 mm in height. The normal atmospheric pressure amounts to 760 torr or 760 mm Hg.

The difference between mbar and torr is often insignificant, especially at very low pressures, e.g. in high and ultra-high vacuum and is, therefore, negligible in most cases. For this reason the conversion from torr to mbar should not give rise to any difficulty or error.

The pressure may be more specified adding an index to the symbol $p$.

**Absolute pressure $p_{abs}$**:

In vacuum technology pressures are given as absolute pressures, so virtually in all cases the index “abs” can be omitted.

**Total pressure $p_{tot}$**:

The total pressure in a container is equal to the sum of the partial pressures of all the gases and vapours within it. In all cases, however, where a differentiation between total pressure and partial pressure is insignificant, the symbol $p$ without an index stands for total pressure.

**Partial pressure $p_{part}$**:

The partial pressure of a given gas or vapour is that pressure that this gas or vapour would have if it were present alone in the container. The partial pressure may be even more specified by using for instance a chemical formula as the index: $p_{H_2O}$, $p_O$, indicating the partial pressure of water vapour and oxygen respectively.

**Saturation vapour pressure $p_v$**:

The pressure of the saturated vapour is called the saturation vapour pressure $p_v$.

For a given material, $p_v$ is a function of the temperature.

**Vapour pressure $p_v$**

**Normal atmospheric pressure $p_n$**:

The normal atmospheric pressure $p_n$ is taken (according to DIN 1343) as the pressure $p_n = 1.01325$ mbar.

**Ultimate pressure $p_{ult}$**:

The lowest attainable pressure in a vacuum container, the so-called ultimate pressure $p_{ult}$, will not be determined only by the pumping speed of the pump, but also by the vapour pressure $p_v$ of the lubricating and sealing material and pump fluid used in the pumps. If, for example, a container is evacuated by an oil-sealed positive displacement pump alone, the attainable ultimate pressure will be determined primarily by the vapour pressure of the pump oil used, and — depending on the cleanliness of the container — moreover by the vapours given off by the walls of the container.

**Ambient pressure $p_{amb}$**

**Overpressure $p_o$**

Note: By international agreement the index “e” stands for “excessive”. $p_o$ can attain positive and negative values!

**Working pressure $p_w$**:

This is the gas and/or vapour pressure prevailing in a vacuum vessel during a process that takes place in this vessel. $p_w$ is usually not very constant in time but its average value or its band width serves as a useful quantity in many vacuum applications.

**Gas — vapour**

During evacuation of a container or vessel, gases and/or vapours are removed in order to produce a low pressure. By a gas we mean material in the gaseous state which is not condensable at the operating temperature. Vapour is likewise material in the gaseous state which, however, is condensable at the ambient temperature. Finally, saturated vapour is material which, at ambient temperature, is gas in equilibrium with the liquid or solid phase of the same material.

A clear distinction is made between gases and vapours in the following text only when it is required for understanding.

**Number density of molecules $n$** (cm$^{-3}$)

The number $n$ of gas particles (e.g. within a cubic centimetre) is related to the gas pressure $p$ and the thermodynamic (Kelvin) temperature $T$ by laws of the kinetic theory of gases:

$$n = \frac{p}{k T} \quad (k = \text{Boltzmann constant})$$

Hence at a given temperature the pressure of a gas depends only on the number density of molecules (number of particles per unit volume) and not on the nature of the gas. The nature of a gas particle is, amongst other things, characterized by its mass $m$.

**Gas density $\rho$** (kg m$^{-3}$ g cm$^{-3}$)

The product of the number density of molecules $n$ and the particle mass $m$ is the gas density $\rho$:

$$\rho = n m \quad \text{(2)}$$

**The ideal gas law**

The relation between the mass $m$ of a gas particle and the molar mass $M$ of this gas is given by:

$$M = N A m \quad \text{(3)}$$

The Avogadro constant $N_A$ specifies how many gas particles are contained in 1 mol of a gas. It, therefore, provides a simple relationship between the molar gas constant $R$ and the Boltzmann constant $k$:

$$R = N_A k \quad \text{(4)}$$

From the above equations (1) to (4) there follows directly the relationship between the gas pressure $p$ and the gas density $\rho$ of an ideal gas:

$$p = \rho RT \quad \text{(5)}$$

In practice, one is frequently concerned with a given closed volume $V$, in which the gas is under a definite pressure $p$. If $G$ is the mass of the gas which is contained within a volume $V$, then

$$\rho = \frac{G}{M} \quad \text{(6)}$$

From equation (5) follows therefore the Clapeyron equation for ideal gases:

$$p V = \frac{G}{M} RT \quad \text{(7)}$$

or for 1 mol:

$$p V = RT \quad \text{(7a)}$$

$G/M$ is the number of moles contained in the volume $V$.

The following numerical example, making use of the numerical values on page 78, may illustrate the relationship between mass of the gas and pressure for gases with different molar masses.

Suppose that a 10 litre volume at 20 °C contains (a) 1 g of helium, (b) 1 g of nitrogen. Application of equation (7) gives on substituting

$$V = 10 \text{ ltr}, \ G = 1 \text{ g}$$

$$R = 83 \text{ mbar ltr mol}^{-1} \text{ K}^{-1}$$

$$T = 293 \text{ K}$$

**case (a):**

$$M = 4 \text{ g mol}^{-1} \text{ (monatomic gas):}$$

$$p = \frac{1 \times 83 \times 293}{10 \times 4 \times \text{litr mol}^{-1} \text{ K}^{-1} K} \times 605 \text{ mbar}$$

**case (b):**

$$M = 28 \text{ g mol}^{-1} \text{ (two-atomic gas):}$$

$$p = \frac{1 \times 83 \times 293}{10 \times 28 \times \text{litr mol}^{-1} \text{ K}^{-1} K} \times 86.5 \text{ mbar}$$

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1) The unit in brackets is the most commonly used unit in vacuum technology for the corresponding quantity.
From this the paradoxical result appears to arise, that for a given mass of a light gas, a higher pressure is exerted than for the same mass of a heavier gas. Considering, however, that for the same gas density (see equation 2) more particles of a light gas (large n, small m) are present than for the heavy gas (small n, large m), the result is understandable, because, for establishing a given pressure at the same temperature (equation 1) only the number density of molecules n is involved.

The chief object of vacuum technology is to reduce number density of molecules n in a given volume V. At constant temperature, this is always equivalent to a reduction of the gas pressure. It must at this point be emphasized, however, that a pressure decrease (keeping the volume constant) is attained not only by a reduction of the number density of molecules n but (equation 5) also by a reduction of the temperature T of the same gas. This important fact must always be taken into account, if the same temperature does not prevail throughout the volume.

Further quantities that play an important part in vacuum technology are:

**Volume V** (lit, m³, cm³)

This indicates:

a) The purely geometric, usually the given measured volume of a vacuum container or of a whole vacuum system including the space occupied by tubulation and junctions.

b) The pressure-dependent volume of a gas or vapour which, for instance, is transferred by a vacuum pump or cleaned-up by sorption materials or by condensation.

**Volume flow rate qᵥ**

(litr s⁻¹, m³ h⁻¹, cm³ s⁻¹)

The volume of gas, at specified pressure and temperature at a given time, which flows in unit time through a conducting tube element. It must be made clear that, depending on the pressure and temperature, the number of the particles concerned is different for the same volume flow rate.

**Pumping speed S**

(pump volume flow rate of flow)

(litr s⁻¹, m³ h⁻¹, cm³ s⁻¹)

The pumping speed S of a pump is the volume rate of flow through the intake aperture of the pump

\[ S = \frac{dV}{dt} \]  

(8)

If S is constant during the pumping process, instead of the differential expression the difference quotient

\[ \frac{\Delta V}{\Delta t} \]  

(8a)

applies.

A table for the conversion of the various units of pumping speed is given in chapter 7, Table 6).

**Quantity of gas** (pressure-volume units)

The quantity of gas can be specified in terms of its mass or its weight in the usual units of mass or weight. In vacuum practice, however, the product pV is in many cases of much greater interest than the mass or weight of a quantity of gas. The pV unit has the dimension of energy and is given in millibar litre (mbar litr). Knowing the nature of the gas and the temperature, the mass G can be readily calculated from the product pV by using equation 7:

\[ G = \frac{pV}{RT} \]  

(7b)

In practice, one mostly speaks, not quite correctly, of the "gas quantity" pV for a given kind of gas, whereby it is tacitly assumed that a gas at room temperature (approx. 300 K) is involved. This, however, is by no means always the case, so when using the notation (pV) its dependence on temperature — see eq. (7) — should always be borne in mind!

**Examples:**

100 mbar litr of N₂ corresponds to 0.11 g of N₂ (at 300 K).

This follows from eq. (7b):

\[ G = \frac{100 \text{ mbar litr} \times 28 \text{ g mol}^{-1}}{83 \text{ mbar litr} \text{ mol}^{-1} \text{ K}^{-1} \times 300 \text{ K}} = \frac{2800}{300 \times 83} = 0.113 \text{ g N}_2 \]

In analogy:

1 mbar litr of O₂ corresponds to 1.28 x 10⁻³ g O₂
70 mbar litr of Ar corresponds to 1.13 x 10⁻³ g Ar

The quantity of gas which flows in unit time through a conducting element can correspond to the two concepts for gas quantities described above — be given in two kinds of way, in fact as:

**Mass flow rate qₘ** (kg h⁻¹, g s⁻¹)

That is the mass of a gas which flows in unit time through a conducting tube element,

\[ q_m = \frac{G}{t} \]

or as:

**Throughput qᵥ** (mbar litr s⁻¹)

The throughput is the product of the pressure and the volume of gas which flows through a conducting element divided by the time:

\[ qᵥ = \frac{pV}{t} \]

Throughput of a pump qᵥ

The throughput of a pump is either equal to the mass flow rate through the intake aperture of the pump, given by

\[ qᵥ = \frac{G}{t} \]  

(9)

or equal to the throughput through the intake aperture of the pump, given by

\[ qᵥ = \frac{pV}{t} \]  

(10)

In most cases indicated in mbar litr s⁻¹, p is the pressure at the intake side of the pump.

If p and V are constant at the intake size of the pump, the throughput of this pump is given by the simple relationship

\[ qᵥ = pS \]  

(10a)

where S is the pumping speed of this pump at the intake pressure p.

The concept of pump throughput is of great importance in practice and ought not to be confused with the pumping speed. The quantity of gas pumped is, for example, important in the determination of the size of a backing pump in relation to the size of a high vacuum pump (see chapter 2.3.2).

**Conductance C** (litr s⁻¹)

The throughput of the gas through any conducting element, e.g. tube or hose connections, valves, nozzles, apertures in a wall between two containers etc. is given by

\[ qᵥ = C (p_1 - p_2) \]  

(11)

Here (p₁ — p₂) is the difference between the pressures at the entrance and exit of the conducting element. The constant of proportionality C is called the conductance. It is decided by the geometry of the conducting element and is calculable in some cases of simple arrangements (see chapter 2.3.6).

In the region of high and ultra-high vacua, C is a constant; in the region of rough and medium vacua, however, its magnitude depends on the pressure. Consequently, the calculation of C for the conducting element must be separately undertaken in the specific pressure regions. (For details see chapter 2.38). Conversely from the definition of volume flow rate, one can also say, the conductance C is the volume flow rate through a conducting element. From equation (11) one can also speak of "Ohm's law of vacuum technology", because qᵥ corresponds to the current, Δp to the voltage and C to the electrical conductance. In analogy with Ohm's law in electricity, the flow resistance R = 1/C is introduced as the reciprocal of the flow conductance. Equation (11) can then be written:

\[ qᵥ = \frac{1}{R} \Delta p \]  

(12)
From this follows directly for series connection:

$$R_{\text{tot}} = R_1 + R_2 + R_3 + \ldots \quad (13)$$

For parallel connection:

$$\frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \quad (13a)$$

**Leak (flow) rate \( q \) (mbar ltr s\(^{-1}\))**

From the previous definitions, it is understandable, without further explanation, that the amount of flow of gas through leaks, i.e., undesired conducting elements, is also given in mbar ltr s\(^{-1}\). Generally, a leak rate is measured or quoted under the condition that atmospheric pressure prevails on one side of the leak.

**Outgassing (mbar ltr)**

By outgassing is meant the evolution of gases and vapours from the walls of a vacuum container or other components or parts in the interior of a vacuum plant. This quantity of gas is designated by the product \( pV \), where \( V \) is the volume of the container in which the gas is evolved, and \( p \), preferably \( \Delta p \), is the increase of pressure which the evolved gases cause in this volume.

**Outgassing rate (mbar ltr s\(^{-1}\))**

The outgassing rate in mbar ltr s\(^{-1}\) is the quantity of gas evolved in unit time.

**Mean free path \( \bar{l} \) (cm)**

**Collision rate \( z \) (s\(^{-1}\))**

The postulate that a gas consists of a large number of discrete particles between which no forces are acting, has led to a series of theoretical considerations, which today are collected together within the designation "kinetic theory of gases". One of the first and, at the same time, most important results of this theory was the calculation of the gas pressure \( p \) as a function of the gas density \( \rho \) and the mean square velocity \( \bar{c}^2 \) of the gas molecules each of mass \( m \):  

$$p = \frac{1}{3} \rho \bar{c}^2 = \frac{1}{3} \frac{n}{m} \bar{c}^2 \quad (14)$$

whereby  

$$\bar{c}^2 = 3 \frac{kT}{m} \quad (15)$$

The molecules travel with all possible velocities in straight lines and collide with the container walls and also collide (elastically) with one another. This motion of the molecules is described numerically with the aid of the kinetic theory of gases. The average number of collisions per second between the particles, the so-called collision rate \( z \) and the path which each gas particle makes on the average between two collisions with other particles, the so-called mean free path \( \bar{l} \), are given as functions of the mean particle velocity \( \bar{c} \), the particle diameter \( 2r \) and the number density of molecules \( n \) — to a very good approximation — by the equations:

$$z = \frac{\bar{c}}{1} \quad (16)$$

$$\bar{c} = \sqrt{\frac{8 kT}{\pi m}} \quad (17)$$

$$\bar{l} = \frac{1}{n} \bar{c} (2 r)^2 \quad (18)$$

It follows that the mean free path is inversely proportional to the number density of molecules \( n \) and therefore, according to equation (1) to the gas pressure \( p \). At constant temperature \( T \) for every gas

$$\bar{l} = \text{const.} \quad (19)$$

Table 3 as well as Fig. 82.2 in chapter 7 are useful in the calculation of the mean free paths \( \bar{l} \) for any pressure of various gases. In the same place are compiled the most important formules of the kinetic theory of gases for vacuum technology (Table 4).

**Impingement rate \( Z_\text{i} \) Monolayer time \( t \) (cm\(^2\) s\(^{-1}\))**

To designate the state of the pressure in the ultra-high vacuum region, it is frequently the practice to quote the time required for the formation of a monomolecular or monatomic layer on a gas-free surface, with the assumption that every particle arriving at this surface remains bonded to the surface. This monolayer time \( t \) is strictly related to the so-called impingement rate \( Z_\text{i} \). For a gas in the static state, the impingement rate gives the number of particles which are incident upon unit surface area per unit time:

$$Z_\text{i} = \frac{n \bar{c}}{4} \quad (20)$$

If \( a \) is the number of free places per unit of surface area within a given gas, the monolayer time is

$$t = \frac{a}{Z_\text{i}} = \frac{4a}{n \bar{c}^2} \quad (21)$$

**Volume collision rate \( Z_\text{v} \) (cm\(^3\) s\(^{-1}\))**

This is the product of the collision rate \( z \) and half of the number density of molecules \( n \), because the collision of two particles accounts for one impingement; hence:

$$Z_\text{v} = \frac{n \bar{c}}{2} \quad (21a)$$

**1.3. The Pressure Regions of Vacuum Technology and their Characteristics**

(In this connection, see also Table 9 in chapter 7). In vacuum technology, it is customary to divide into single, smaller regions the large pressure region which today covers more than 16 orders of magnitude. In general, the subdivisions are:

- Rough vacuum (RV) 1,000 to 1 mbar
- Medium vacuum (MV) 1 to 10\(^{-3}\) mbar
- High vacuum (HV) 10\(^{-3}\) to 10\(^{-7}\) mbar
- Ultra-high vacuum (UHV) 10\(^{-7}\) mbar and below

These divisions are naturally somewhat arbitrary. Thus, the chemist frequently refers to the region between 100 and 1 mbar, in which he is chiefly interested, as an intermediate vacuum, and many a technician refers to the total pressure region not as vacuum but as low pressure (below atmospheric). The pressure regions presented above are clearly distinguished from the point of view of the relationship in the kinetic theory of gases and according to the kind of gas flow. Moreover, the
practical technology in the different regions is distinguishable. There are in vacuum technology essentially three types of gas flow:

1. **Viscous flow**, which prevails almost exclusively in a rough vacuum. The mutual interactions of the particles with one another determine the character of this flow. Therefore inner friction, the viscosity of the streaming material, plays a dominant role. If vortex motion appears in the streaming process, one speaks of turbulent flow; and if the various layers of the streaming medium slide over one another, the flow is called laminar. In cylindrical tubes, laminar flow with a parabolic velocity profile is called Poiseuille flow. This special case appears especially frequently in vacuum technology. The criterion of viscous flow is: the mean free path of the particles is smaller than the diameter of the conducting tube (\( l < d \)). A characteristic quantity for the condition of viscous flow is the Reynolds number Re, Re is a dimensionless quantity; namely — for the flow of a gas through a cylindrical tube — the product of the tube diameter, the flow velocity, the density and the reciprocal of the viscosity of the streaming gas.

For \( Re > 2200 \), the flow is turbulent; for \( Re < 2200 \), laminar.

2. **Molecular flow** is dominant in high and ultra-high vacuum. In these regions, the particles can move freely, virtually without mutual hindrance. The criterion is: the mean free path of a particle is greater than the diameter of the conducting tube (\( l > d \)).

3. **Knudsen flow**, at which there is a transition from viscous flow to molecular flow. It predominates above all in the medium vacuum region (\( l \sim d \)). The product of the pressure \( p \) and the tube diameter \( d \) for a given gas at a given temperature can serve as a characteristic quantity for the transition between the different types of gas flow. For air at \( 20^\circ \text{C} \), making use of the numerical values in Table 3 in chapter 7, the following equivalent relationships are obtained:

| Rough vacuum | Viscous flow | \( p \cdot d > 6 \times 10^{-1} \text{ mbar cm} \) | \( l < \frac{d}{100} \) |
| Medium vacuum | Knudsen flow | \( 6 \times 10^{-1} > p \cdot d > 1.3 \times 10^{-2} \text{ mbar cm} \) | \( \frac{d}{100} < l < \frac{d}{2} \) |

**High and ultra-high vacuum**

**Molecular flow**

\[
p \cdot d < 1.3 \times 10^{-2} \text{ mbar cm} \\
\frac{l}{d} > \frac{1}{2}
\]

In the region of viscous flow, the preferred direction of all the gas molecules is the same as the macroscopic direction of the streaming gas. A corresponding alignment is thereby enforced, in that the particles forming the gas are densely packed and collide with one another much more frequently than with the boundary walls of the apparatus. In the region of molecular flow, on the other hand, the collisions of the particles with the walls predominate. As a result of elastic reflection, but also through desorption after a certain sojourn time on the container walls, a gas particle in the high vacuum region can have any direction at random: one can no longer speak of streaming in the macroscopic sense. It would be of little significance to determine the vacuum pressure region by its dependence on the actual geometric operating conditions. The boundaries between the various pressure regions (see Table 9) are chosen so that, with laboratory plants of normal dimensions, in a rough vacuum the collisions of gas particles with one another predominate, whereas in high and ultra-high vacuum, on the other hand, the collisions of the gas particles with the walls of the container predominate.

In the high and ultra-high vacuum regions the nature of the walls of a vacuum container is of decisive significance, because, below \( 10^{-3} \text{ mbar} \), there are more gas molecules on the surfaces than in the gas space itself. Assuming that a monomolecular layer is adsorbed on the inner wall of an evacuated sphere of 1 ltr volume, the ratio of the number of the adsorbed particles to the number of free particles in the space is

<table>
<thead>
<tr>
<th>Pressure (mbar)</th>
<th>( 10^{-2} )</th>
<th>( 10^4 )</th>
<th>( 10^9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 1 mbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at ( 10^{-6} \text{ mbar} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at ( 10^{-11} \text{ mbar} )</td>
<td></td>
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</tbody>
</table>

On this basis, the characteristic which serves to decide the boundary between the ultra-high vacuum region and the high vacuum region is the monolayer formation time (see chapter 1.1). This monolayer formation time amounts to only fractions of a second in a high vacuum, in an ultra-high vacuum, on the other hand, to minutes and hours. Gas-free surfaces can therefore only be produced and maintained for long periods of time under ultra-high vacuum conditions.

Further physical properties alter with change of pressure. Amongst others, the thermal conductivity and the viscosity of gases are very strongly dependent on the pressure in the medium vacuum region. On the other hand, in the rough and high vacuum regions, these two properties are almost independent of the pressure.

It is understandable, therefore, that the pumps needed for the production of pressures in the various pressure regions are different. Likewise, the vacuum gauges which are applicable to the measurement of the pressures.

A clear classification of the pumps and measuring apparatus for the pressure regions concerned is presented in Fig. 92.2 and 3 in chapter 7.
2. The Production of Vacuum

2.1. Vacuum Pumps

2.11. A survey of the various types of vacuum pumps

In order to reduce the gas density and thereby the gas pressure (see equation (5) in chapter 1.1) in a given gas-filled volume, gas particles must be removed from the volume; this is the purpose of vacuum pumps.

Fundamentally, distinction can be made between two groups of vacuum pumps:

a) Those which remove the gas particles from the pumped volume and convey them to the atmosphere in one or more stages of compression (compression pumps, also called gas transfer pumps), and

b) Vacuum pumps which condense or in some other manner (e.g. chemically) bind the particles to be removed at a solid wall, which is often a part of the boundary of the volume being pumped.

In present day technology and practical applications, the following types of pump are listed, in which the first three groups are classed as compression pumps or as gas transfer pumps, and the remaining two groups as entrapment pumps, i.e. as condensation and getter pumps:

1. Pumps which operate by creating periodically increasing and decreasing chamber volumes (all gas ballast pumps, therefore rotary vane and rotary piston pumps).

2. Pumps which transport gas from the low pressure to the high pressure side in which the pump chamber volume is constant (Roots pumps and turbomolecular pumps).

3. Pumps in which the pumping action is essentially due to diffusion of gases in a gas-free stream of high velocity (vapour pumps).

4. Pumps which pump vapours by condensation (condensers); in addition, pumps which remove permanent gases by condensation at very low temperatures (cryopumps).
5. Pumps which bind or embed gases at extensive gas-free surfaces by adsorption or absorption (sorption pumps).

A survey of these classes of vacuum pumps is given in the diagram (as per DIN 28 400, part 2, issue 1979).

2.12. Rotary Pumps (positive displacement pumps)

Rotary vacuum pumps belong to the group of positive displacement pumps (see diagram under 2.11).

A positive displacement pump is understood to be a mechanical vacuum pump which transports the gas with the aid of pistons, rotors, vanes, valves and other levers, compresses it and expels it. Here are so-called oil-sealed and so-called "dry" rotary pumps. Oil sealing of the moving parts allows compression ratios up to 10^6 in one stage. Without oil sealing as in the case of a "dry" pump the internal leakage is much higher, consequently the compression ratio obtainable much lower, about 10.

As shown in the diagram in chapter 2.11, reciprocating piston and rotary pumps are positive displacement pumps. Reciprocating piston pumps are not produced by LEYBOLD-HERAEUS. Of the various kinds of rotary pumps, in which the pumping process takes place due to the rotary motion of the rotor inside the pump, LEYBOLD-HERAEUS manufacture rotary vane, rotary piston and Roots pumps in one- and two-stage models, as well as single-stage trochoid pumps. These various types of pumps — with the exception of Roots pumps — are equipped with the gas ballast device as invented by Gaede in 1935 (for further description see chapter 2.124). The gas ballast arrangement enables — within given technical limits — vapours to be pumped (especially water vapour), without condensation in the pump during the compression process.

2.121. Rotary vane pumps

Rotary vane pumps (see Fig. 9.1) consist of a cylindrical housing (stator) (1) in which rotates in the direction of the arrow an eccentrically mounted, slotted rotor (2). The rotor contains vanes (16) which are forced apart usually by centrifugal force, and in some models by springs. These vanes slide along the stator walls and thereby push forward the air drawn in at the inlet (4) to eject it finally through the oil above the outlet discharge valve (12). The oil charge of the rotary vane pump, but also of other types of oil-sealed positive displacement pumps, serves as lubrication and sealing medium, fills the dead space and any gaps and adds to the cooling effect. The lowest working pressure is about at the lower limit of the medium vacuum pressure range (see chapter 1.3).

Note: Supply of very little oil or no oil at all to the "vacuum" stage (stage 1) in order to achieve an even lower ultimate pressure can lead in actual practice to great difficulties and affects the reliability of operation of such pumps considerably.

2.122. Rotary plunger pumps

Fig. 10.1 shows a cross-section through a rotary plunger pump or monoblock design. In it a piston (2), which is rotated in the direction of the arrow on an eccentric rotor (3), slides along the wall of the housing. The intake gas streams through the inlet port (11) in the pump and is transported through the pumping channel in the slide valve (12) into the pump chamber (14). The slide valve forms a unit with the piston and slides to and fro within the hinge bar (13). The pumped gas finally reaches the compression region (4). On rotation the piston compresses this gas until it is forced through the oil-sealed discharge outlet valve (5). The supply of oil above the valves serves, as in the rotary vane pump as a lubricant, as a sealing medium, to fill up the dead space beneath the valve and to assist the cooling of the pump.

As the pump chamber volume is divided into two parts by the rotating piston, a working cycle is completed each revolution. See the operating cycle in Fig. 10.2. Rotary piston pumps are also supplied in single- and two-stage models.

For different vacuum processes, the combination of a Roots pump with a single-stage rotary piston pump can be preferable to a two-stage rotary piston pump. If such a combination or a two-stage rotary pump alone should be inadequate for the process it is frequently recommended to use a Roots pump in combination with a two-stage rotary piston pump.
Motor power

The motors supplied for rotary vane and rotary piston pumps are so rated that they are suitable for the maximum drive power (at about 400 mbar) at an ambient temperature of 12 °C and using our special oils. In the actual working region of the pump the motor of the pump when running warm requires only about a third of the rated power (see Fig. 10.3). This applies also to the trochoid pumps described in the following chapter.

2.123. Trochoid pumps

Trochoid pumps are single-stage, oil-sealed positive displacement pumps operating on a principle comparable to that of the rotary piston combustion engine. The centre of gravity of the piston moves on a circular path around the axis of rotation. This is why trochoid pumps, contrary for instance to ordinary rotary piston or plunger pumps, can be completely dynamically balanced. This has the advantage that even very large pumps are vibration-free and that mounting on a foundation is not necessary. In addition, trochoid pumps can run with faster rotational speeds than ordinary rotary piston pumps (see below). The trochoid pump is a rotary piston pump with outward rolling motion (see Fig. 10.4) whereby the radius \( r \) of the stationary circle is half of the radius \( R \) of the rolling circle (so-called 2:1 machine).

In this outward rolling motion at an integral ratio \( \frac{R}{r} \) every point on the rolling circle describes a closed curve which turns out to be an epitrochoid. In the special case of \( \frac{R}{r} = 2 \) this epitrochoid is an ellipse, and hence the piston of the trochoid pump has an elliptical cross-section. The shape of the pump chamber is determined by the envelope curve described by the eccentric rotation of the piston. It appears from the

Fig. 10.4 Principle of outward rolling motion: the circle of radius \( r \) is stationary, the circle of radius \( R \) rolls about it.

Fig. 10.5 Principle of inward rolling motion: the circle of radius \( R \) is stationary, the circle of radius \( r \) rolls within it.
geometry of the design that there is a fixed point P of the chamber which remains in permanent positive contact with the piston in any position of its rotation (see Fig. 11.1). The sealing strip fitted at this point ensures hermetic separation of the intake port from the discharge port of the pump chamber. Fig. 11.2 shows a schematic drawing of the trochoid pump and Fig. 11.3 the operational diagram.

Fig. 11.3 shows the working principle. Every piston revolution includes a complete working cycle consisting of suction, compression and discharge of the gas. The swept volume per revolution related to the pump chamber volume of trochoid pumps is about twice that of ordinary rotary piston pumps. Large size rotary piston pumps operate at a rotational speed of 500 r.p.m., while in trochoid pumps of comparable size 1000 r.p.m. are admissible. A trochoid pump is, therefore, four times smaller in size than a conventional rotary piston (plunger) pump of comparable pumping speed, and it runs virtually free of vibration.
Cooling of fluid entrainment pumps

The heater power which is continuously supplied for vaporizing the pump fluid, must be conveyed away again by efficient cooling; the energy required for pumping the gases and vapours is minimal. The walls of the mercury diffusion pumps are almost always cooled with water, because a low wall temperature is decisive for the efficiency of these pumps. Also, the oil diffusion pumps are mostly cooled with water; smaller types can, however, also be cooled with an air stream, because a low wall temperature is not so decisive as for mercury diffusion pumps. (Oil diffusion pumps can operate well with wall temperatures of 30 °C, whereas the walls of mercury diffusion pumps must be cooled to 15 °C). Mercury vapour ejector pumps can also be operated at the cooling water temperature of oil diffusion pumps.

In order to protect the pumps from the danger of failure of the cooling water — insofar as the cooling-water coil is not controlled by thermally operated protective switching — a water circulation monitor should be installed in the cooling water circuit. By this means evaporation of the pump fluid from the pump walls is avoided.

2.141. Oil diffusion pumps

These pumps consist basically (see Fig. 20.1) of a pump body (3) with cooled wall (4) and a three- or four-stage nozzle system (A — D). The oil serving as pump fluid is in the boiler (2) and is vaporized from here by electrical heating (1). The pump fluid vapour streams through the chimneys and emerges with supersonic speed from the ring-shaped nozzles (A — D). The so formed jet widens thereafter like an umbrella, reaches the wall where condensation of the pump fluid takes place. The liquid condensate flows as a thin film along the wall downwards and returns finally into the boiler.

Because of this spreading of the jet, the vapour density is relatively low. The diffusion of air or any pumped gases (or vapours) into the jet is so fast that the jet in spite of its high velocity becomes virtually completely saturated with the pumped medium.

Diffusion pumps have, therefore, over a wide pressure range, a high pumping speed. This is practically constant over the whole working region of the diffusion pump (< 10⁻³ mbar), because the air at these low pressures cannot influence the jet, so that its course remains undisturbed. At higher inlet pressures, the course of the jet is altered. As a result, the pumping speed decreases until, at about 10⁻¹ mbar, it becomes immeasurably small.

The forevacuum pressure also influences the vapour jet and becomes detrimental if its value exceeds a certain critical limit. This limit is called maximum backing pressure (ISO) or critical forepressure. The "capacity" of the chosen backing pump has to be such that the amount of gas discharged from the diffusion pump is pumped off without building up a backing pressure that is near the maximum backing pressure or even exceeding it. The attainable ultimate pressure depends on the construction of the pump, the vapour pressure of the pump fluid used, the maximum possible condensation of the pump fluid and on the cleanliness of the vessel; moreover, backstreaming of the pump fluid into the vessel should be reduced as far as possible by suitable baffles or cold traps (see chapter 2.146 for further details).

Degassing of the pump oil

In oil diffusion pumps it is necessary for the pump fluid to be degassed before its return to the boiler. On heating of the pump oil, decomposition products can arise in the pump; contamination from the vessel can get into the pump or be contained in the pump in the first place. These constituents of the pump fluid can significantly worsen the ultimate pressure attainable by a diffusion pump, if they are not kept away from the vessel. The pump fluid must therefore be freed of these impurities and from absorbed gases.

This is the function of the degassing section, which the circulating oil passes through shortly before re-entry into the boiler. In the degassing section, the most volatile impurities escape. Degassing is obtained by the carefully controlled temperature distribution in the pump. The
condensed pump fluid, which runs down the cooled walls as a thin film, is raised to a temperature of about 130° below the lowest diffusion stage, so that the volatile components evaporate and are removed by the backing pump. The re-evaporating pump fluid consists, therefore, of only the less volatile components.

High NO factor

The magnitude of the specific pumping speed $S$ of a diffusion pump, i.e., the pumping speed per unit area of the active inlets, depends on several parameters, e.g., on the position and dimensions of the high vacuum stage, on the velocity of the pump fluid vapour and the mean molecular velocity $\bar{v}$ of the gas being pumped (see formula (17) in chapter 1.1).

With the aid of the kinetic theory of gases, the maximum attainable specific pumping speed at room temperature of pumping air is calculated to be

$$ S_{\text{max}} = 11.6 \text{ ltr s}^{-1} \text{ cm}^{2} $$

This is the specific (molecular) flow conductance of the intake area of the pump, resembling an aperture of the same surface area (see chapter 2.351).

Quite generally, diffusion pumps have a higher pumping speed for lighter gases than for heavier.

To characterize the effectiveness of a diffusion pump, the so-called NO factor is defined; this is the ratio of the actually obtained specific pumping speed to the theoretical maximum possible specific pumping speed. For the diffusion pumps supplied by LEYBOLD-HERAEUS it reaches optimum values (0.3 for the smallest pump up to 0.55 for the large pumps).

The various oil diffusion pumps supplied by LEYBOLD-HERAEUS are distinguished from one another by the following constructional differences (see Fig. 21.1 a and b).

1) LEYBODIFF models

Pumps of this type have a fractionating device: The various constituents of the pump fluid are so selected that the high vacuum nozzle is only supplied by the fraction of the pump fluid which has the lowest vapour pressure. This assures a very low ultimate pressure. Fractionating occurs because the degassed oil first enters the outer part of the boiler, which serves the nozzle on the backing vacuum side. Here a part of the more volatile constituents evaporates. In this way, the already purified pump fluid reaches then the intermediate part of the boiler, which serves the intermediate nozzle. Here evaporate the lighter constituents in greater quantities than the heavier. When the oil enters the central region of the boiler, which serves the high vacuum nozzle, it is freed of the light volatile constituents.

b) DI models

In these pumps a burst-free evaporation of the pump fluid and so a pumping speed constant with time is obtained by an unusual heater construction.

The heating is arranged by an internal heater and consists of heater cartridges which are slid into tubes with brazed-on heat conducting fins. The stainless steel tubes are welded horizontally in the pump body and lie above the oil surface. The heat conducting fins of copper dip partly into the pump fluid. The part of the heat conducting fins which projects into the pump fluid is so chosen that an intensive but smooth evaporation of the pump fluid is obtained. The pump fluid receives additional energy from the parts of the conducting fins which are above the surface.

On the basis of the special construction of this heater arrangements, changing of the heater cartridges is also possible with the pump still hot.

2.142. Mercury diffusion pumps

In the history of vacuum technology, diffusion pumps using mercury as a pump fluid were the first pumps of this type. They were conceived and developed (1915) by Gaede, Langmuir and Volmer. The very first diffusion pumps were entirely made of glass. But very soon diffusion pumps made entirely of metal became generally available and were widely used by industry. The pumping mechanism is basically the same as for oil diffusion pumps, but it must be taken into account that the va-
3. Low Pressure Measurement

Today, the pressures measured in vacuum technology cover the range from 10^13 mbar to 10^{-12} mbar, thus over 16 orders of magnitude. For measurement in this wide pressure region, measuring instruments are used which are known as vacuum gauges. Since it is impossible on fundamental physical grounds to build a vacuum gauge which can give quantitative measurements in the whole vacuum region, a series of vacuum gauges are available. Each has a characteristic measuring range, which mostly extends over a few orders of magnitude (see Figure 3-1). The measuring range of an individual vacuum gauge is limited at both ends of the range by physical phenomena.

3.1. Fundamentals of low pressure measurement

Vacuum gauges are devices for the measurement of gas pressures below atmospheric pressure (DIN 28 400, part 3, issue 1979). In several cases the pressure indication depends on the nature of the gas. With compression vacuum gauges it should be noted that — depending on the nature of the vapor present — condensation can occur on compression, falsifying the pressure indication. Compression vacuum gauges measure the sum of the partial pressures of all gas components that do not condense in the gauge during the measurement procedure.

The exact measurement of the partial pressures of specific gases or vapors is undertaken with the aid of partial pressure measuring instruments which operate on the mass spectrometer principle.

Dependence of the pressure indication on the nature of the gas it is only with a direct (or absolute) pressure measurement that the reading of the measuring instrument is independent of the type of gas. By it the pressure will be measured in accordance with its definition as the force which acts on unit area (mechanical manometer). According to the kinetic theory of gases, this force depends only on the number of gas molecules per unit volume (number density of molecules) and their temperature, but not on their molar mass (see Equation (1)).

In all indirect pressure measurements, the pressure is determined as a function of a pressure-dependent property of the gas (thermal conductivity, ionization probability, electrical conductivity). These properties are dependent on the molar mass as well as on the pressure. Consequently, the pressure reading of the measuring instruments, which determines the pressure indi-

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**Legend**

- Instrument with Digital Display
- Instrument with Direct Indication
- Instrument with Remote Electrical Indication
- Instrument with Pressure-Sensitive Switch
- Instrument to which a Pressure Switch can be Connected
- Corrosion-Resistant

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Figure 3-1. Pressure operating ranges of vacuum gauges.
rectly depends on the nature of the gas. Their scales refer always to air or nitrogen as the test gas. For other gases or vapors correction factors (mostly related to air or nitrogen) must be given (see Table on page 55). It follows that for exact pressure measurement with electrical vacuum gauges, which determine the number density of the gas by introducing electrical energy (indirect pressure measurement) it is important to know the gas composition.

In practice, this is only known to a rough approximation. On the other hand, it is often sufficient to know whether the gas mixture, of which the pressure is to be measured, light or heavy molecules predominate (e.g., hydrogen or pump fluid molecules).

**Example:** If, with an ionization gauge, the pressure is measured of a gas which consists solely of pump fluid molecules, then the measured value (valid for air or N₂) is too high by a factor of about 10.

The measurement of pressures in the rough vacuum region may be undertaken relatively exactly by vacuum gauges with direct pressure measurement. The measurement of lower pressures, on the other hand, is almost always affected by a series of principle errors. This limits the accuracy of measurement, so that the accuracy cannot be compared with that usually found in other measurement techniques. To undertake a pressure measurement in the medium and high vacuum regions, which have an error of less than 5%, requires increased care of the experimenter.

Pressure measurements, which are to be accurate to a few percent, require a great deal of effort and, in general, the use of special measuring instruments. This is particularly the case for all pressure measurements in ultra-high vacuum (p<10⁻⁷ mbar.)

If one wants to make a statement about a pressure recorded by a vacuum gauge, one must first take into account at which location and in what manner the gauge head is connected. In all pressure regions in which laminar flow prevails (p>10⁻⁴ mbar), the pressure must be taken of pressure gradients due to pumping. Immediately before the pump (as seen from the vessel) a lower pressure is created than in the vessel. Also components of small conductance can introduce pressure gradients. Finally, the conductance of the connection line between the vacuum system and the measuring system should not be too small, otherwise, this will be evacuated too slowly in the pressure region of laminar flow, so that too high a pressure is recorded.

In high and ultra-high vacuum, the relationship is more complicated. Here, depending on the actual geometry of the installation, outgassing of the walls of the vacuum gauge or inadequate degassing of the gauge may cause too high a pressure. Also, gauges degassed too thoroughly may cause too low a pressure to be recorded. In the regions of high and ultra-high vacuum the equalizing of the pressure between the vacuum system and the vacuum gauges can, therefore, take a very long time. If possible, so-called nude gauges are used. These are inserted, without an envelope and usually flange-mounted, directly in the vacuum system without a connection tube.

Special consideration should always be given to the influence of the gauge mechanism proper on the gaseous environment, and thus on the pressure measurement. For compression vacuum gauges with very high compression ratios (e.g., McLeod gauges), a part of any condensable vapors present can become liquified. The pressure indication depends, therefore, not only on the total pressure and on the vapor fraction but also on the compression ratio. In ionization vacuum gauges which work with hot cathodes, gas particles, especially of the higher hydrocarbons, can become thermally decomposed. As a result, the gas composition changes. This kind of effect plays a marked role in pressure measurement in ultra-high vacuum. The same is true for gas clean-up arising in the ionization gauges and Penning gauges; this applies for pressures 10⁻¹ and 10⁻² mbar. Contamination of the vacuum gauge, interfering electric and magnetic fields and inadmissibly high environmental temperatures falsify the pressure measurement. The consequences of such mostly avoidable faults and the necessary remedies are discussed in the following sections, dealing with the individual gauge systems.

**Choice of a suitable vacuum gauge**

In the choice of a suitable gauge for pressure measurement it is not only the required pressure range that is decisive; the operating conditions under which the apparatus works also play a significant role. If measurements are to be made under difficult operating conditions (i.e., there is a high risk of contamination, vibrations of the gauge tube cannot be eliminated, air bursts are to be expected, etc.), then the measuring instrument must be robust. For industrial plants, therefore, capacitance manometers, diaphragm vacuum gauges, Pirani and combined Penning-Pirani vacuum gauges are recommended. Exact measuring instruments are frequently sensitive to adverse operating conditions; they can then only be used successfully if the above sources of error are excluded as much as possible and attention is paid to the operating instructions.

**3.2. Usable vacuum gauges when calibration is independent of the nature of the gas (mechanical vacuum gauges)**

Mechanical vacuum gauges measure pressure directly by registering the force which the particles (molecules and atoms) in a gas-filled space exert on a surface by virtue of their thermal velocities.

**3.2.1. Diaphragm vacuum gauges**

**3.2.1.1. The capsule vacuum gauge**

The capsule vacuum gauge contains a hermetically sealed, evacuated, thin-walled diaphragm capsule made from a copper-beryllium alloy. As the pressure is reduced, the capsule diaphragm expands outwards. This movement is conveyed to a pointer by a lever system. The capsule vacuum gauge indicates the pressure on a linearly divided scale independently of the external atmospheric pressure.

Capsule vacuum gauges measure the pressure to ±10 mbar fairly accurately (due to linear scale, they are least accurate at the low pressure end of the range). If only pressures below about 30 mbar are to be measured, the DIAVAC is recommended, the reading of which is essentially more accurate. For the highest accuracy demands of all, the capacitance manometer vacuum gauge should be used.

**3.2.1.2. DIAVAC diaphragm vacuum gauge**

Frequently as accurate as possible pressure reading is required below 50 mbar. At this range, another diaphragm vacuum gauge, the DIAVAC, is suitable, the pressure scale of which is considerably extended between 1 and 100 mbar.

![Figure 3-2: Section of a diaphragm vacuum gauge](image-url)

The whole part of the inner space, in which the lever system (10) of the gauge head is located (see Figure 3-2), is evacuated to a constant reference pressure of below 10⁻³ mbar. The closure against the vessel is in the form of a corrugated diaphragm (9) made of a copper-beryllium alloy. As long as the vessel is not evacuated, this diaphragm is pressed firmly against a wall. With increasing evacuation, the difference between the pressure to be measured and the reference pressure becomes smaller. The diaphragm bends weakly at first, but below 100 mbar more strongly. The diaphragm deflection is conveyed to a pointer (5). In this way, the measuring region, especially between 1 and 20 mbar, is considerably extended and, therefore, can be read quite accurately (to about 0.3 mbar).

The sensitivity to vibration of this instrument is somewhat greater than for the capsule vacuum gauge. All mechanical vacuum gauges are sensitive to vibration to some extent; on the other hand, small vibrations (e.g., as arise on direct connection with a backing pump) are generally not detrimental.

3.213. Capacitance manometer gauges
A capacitance manometer sensor measures absolute pressures by sensing very small deflections of a metal diaphragm. The reference side of the sensor, which is fixed to a high vacuum and permanently sealed off, contains two capacitance electrodes. One electrode is fixed; the other, a thin metal diaphragm, deflects when pressures are applied to it. The change in capacitance that results from this movement is measured and converted to a pressure reading. These sensors provide highly accurate measurements that are independent of the type of gas.

3.22. Liquid-filled (mercury) manometers

3.221. U-tube manometers
The U-tube manometers filled with mercury are the simplest and most exact means of measuring pressure in the rough vacuum region (10⁻¹ to a few mbar). Unfortunately, their use in technical applications is limited because of their size and vulnerability to breakage.

In the evacuated limb of the U-tube manometer a constant pressure is maintained equal to the vapor pressure of the mercury at room temperature, about 10⁻³ mbar. The other limb is connected to the vacuum vessel (Figure 3-3). Due to the action of the external air pressure, on evacuation the end of the tube is deflected and the attached pointer mechanism is actuated. The scale is linear. As the pressure reading is dependent on the external atmospheric pressure, the reading is only accurate to about +/−10 mbar if any change of the ambient atmospheric pressure is not corrected.

3.222. McLeod gauges
Another gauge that should be mentioned is the McLeod gauge, a compression gauge developed by McLeod in 1874. The McLeod gauge has few present day industrial applications due to its use of mercury, awkward operating procedures, and non-continuous measurement of pressure. It was extensively used in laboratories in the past as a calibration or reference instrument for medium and some high vacuum gauges and units may still be found in many of these laboratories. Depending on the pressure range and other system characteristics, spinning rotor gauges (see section 3.34) or capacitance manometers are now more often used.

The pressure measurement of McLeod gauges is based on Boyle's Law and results from the compression of a quantity of gas into a smaller volume by the raising of a mercury level. The increased pressure can be measured, as in the U-tube manometer, and from it the original pressure can be calculated. Compression gauges, such as the McLeod gauge, give an exact reading of the sum of all the partial pressures of the permanent gases, assuming that no vapors are present that condense during the compression process. The accuracy of these gauges depends strongly on the procedure followed and the reading of the measurement. The McLeod gauge does not provide a continuous pressure reading. For every reading, the mercury must be raised into the gauge again.

These gauges can give very accurate pressure readings under strictly controlled conditions, and there are some high accuracy laboratory models still on the market.

3.23. Bourdon gauges
The Bourdon gauge is another instrument that should be mentioned due to its frequent use in the past. The interior of a tube bent into a circle (so-called Bourdon tube) is connected to the evacuated vessel (Figure 3-3). Due to the action of the external air pressure, on evacuation the end of the tube is deflected and the attached pointer mechanism is actuated. The scale is linear. As the pressure reading is dependent on the external atmospheric pressure, the reading is only accurate to about +/−10 mbar if any change of the ambient atmospheric pressure is not corrected.

3.3. Usable vacuum gauges that are dependent on the nature of the gas (electrical vacuum gauges)
Electrical vacuum gauges measure the pressure indirectly in terms of the number density of molecules. Since the measurement of this density depends on the nature of the particles, the pressure measurement with electrical vacuum gauges is a gas-dependent, indirect pressure measurement. Within electrical vacuum gauges are included thermal conductivity gauges and all gauges in which the gas is ionized. The apparatus consists of the actual gauge head and the required control unit for its operation. The pressure scales of these instruments usually refer to nitrogen pressures; the pressure reading is denoted as the "nitrogen equivalent pressure." If the presence of a gas or vapor other than nitrogen is to be determined the "nitrogen equivalent" value must be multiplied by a factor characteristic for this gas.

Some digital gauges such as the IG3 and CC3 allow the user to enter a factor into the software of the gauge, eliminating the need for a manual calculation. For ionization gauges, these factors are (under other similar conditions) practically independent of the pressure, so long as measurements are made in the usual pressure measuring range of the instrument. On the other hand, for thermal conductivity vacuum gauges these factors are mostly pressure-dependent. For the most important gases, corresponding correction curves are provided by the manufacturer.
(also to the supports at the filament ends.)

In rough vacuum the thermal transfer due to convection is almost independent of the pressure (see Figure 3-4). If, however, at a few mbar, the mean free path of the gas is of the same order of magnitude as the filament diameter, heat transfer through the gas surrounding the filament becomes dependent of pressure. This continues to be so until at still lower pressures of about 10^-3 mbar the mean free path becomes comparable with the inner diameter of the gauge head (see Table 3 in section 17). Now heat transfer through the gas by conduction virtually ceases. Heat transfer is now by radiation only and independent of pressure. The sensing filament in the gauge head forms one branch of a Wheatstone bridge.

In a thermal conductivity gauge of constant resistance (e.g. THERMOVAC & PG3 series) the sensing filament in the gauge head is also a branch of a Wheatstone bridge. The voltage for the THERMOVAC (or current in the case of the PG3 Pirani sensor) applied to this bridge is regulated so the resistance (and therefore the temperature) of the filament remains constant independent of the heat loss. This means that the bridge is always balanced. This mode of regulation has a time constant of a few milliseconds, so the apparatus reacts very quickly to pressure changes. Since the heat transfer from the filament to the gas increases with increasing pressure, the voltage for the THERMOVAC (or current in the case of the PG3 Pirani sensor) applied to the bridge is thus a measure of the pressure. The voltage or current measurement is corrected by electronic methods such that an approximately logarithmic scale is obtained over the whole measuring range.

Whereas the thermal conductivity gauge of variable resistance (thermocouple gauges) will only cope with pressures between 10^-3 and 10 mbar, the thermal conductivity gauges of constant resistance have a large measuring range from 10^-9 to 1013 mbar. Due to the very short response time, they are particularly suitable for control and pressure monitoring (see section 4). The accuracy of measurement is different in the different pressure regions depending on the kind of vacuum gauge concerned. For THERMOVAC the maximum error at full-scale deflection amounts to about ±1 to 2%. This corresponds to the most sensitive region, between 10^-2 and 1 mbar, to about ±10% of the pressure reading.

For THERMOVAC Pirani gauges, the scales given on the meter are for nitrogen and for air. Within the limits of error, the pressures of gases with similar molecular masses, i.e. O_2, CO and others, can be read directly. For the Inficon digital controllers, the user can select between nitrogen and argon pressure measurements. Calibration curves for a series of gases are given in Figure 3-5. If oil and other organic vapors are predominate, too large a value will be indicated at low pressures. Especially below 10^-2 mbar, the pressure measurement can be subject to considerable errors in the presence of oil vapors.

3.32. Ionization vacuum gauges

Ionization vacuum gauges measure — like all electrical vacuum gauges — the pressure in terms of the number density of molecules. In them a portion of the molecules or atoms within the gas space are ionized by electron impact. The ions produced give up their positive charge to a measuring electrode of the system. The resulting ion current is a measure of the pressure. The formation of the ions is a consequence of either a discharge at high electric field strengths (so-called cold or self-sustaining discharge) or the impact of electrons which are emitted from a hot cathode.

3.321. The cold-cathode ionization gauge

Ionization gauges which operate with a cold discharge are called cold-cathode or
Penning vacuum gauges. The discharge process in the gauge tube is in principle the same as in the electrode system of a sputter-ion pump (see section 2.163). A common feature of all types of cold-cathode ionization gauges is that they simply contain two unheated electrodes—a cathode and an anode—between which the so-called cold discharge is excited by means of a dc voltage (of about 2 kV) and maintained so that the discharge still continues at very low pressures. This is attained by the use of a magnetic field to make the paths of the electrons so long that their collision probability with gas molecules is sufficiently large to maintain the discharge on the formation of the required number of charge carriers. The magnetic field is so arranged (see Figure 3-6) that the magnetic field lines of force cross the electric field lines. In this way the electrons are confined to a spiral path and oscillate between the two cathode plates. The positive and negative charge carriers produced by collision move to the corresponding electrodes and form the pressure-dependent discharge current, which is indicated on the meter. The reading is dependent on the nature of the gas. For further details see section 3.33. The upper limit of the measuring region is decided by the fact that slightly above 10⁻² mbar the Penning discharge changes to a glow discharge with intense light output in which the current— at constant voltage—depends only to a small extent on the pressure and is, therefore, not suitable for measurement purposes.

In all Penning gauges there is considerable higher gas sorption than in the ionization vacuum gauge which operates with a hot cathode. A Penning gauge tube, therefore, pumps gases similarly to a sputter-ion pump (S = 10⁻² ltr s⁻¹). The ions produced in the discharge are accelerated to the cathode where they are partly retained and partly cause sputtering of the cathode material. The sputtered cathode material forms a gettering surface film at the walls of the gauge tube. Despite these disadvantages, which bring about a relatively highly inaccurate pressure reading (up to ±50% for the PM310 and ±30% for the CC3), the cold-cathode ionization gauge has two especially outstanding advantages. The first is that the gauge head is insensitive to the inrush of air and vibrations, and the second is that it is less susceptible to harm from contaminants. It is therefore recommended for dirty and industrial environments.

3.322. The hot-cathode ionization gauge

Within this category are included measuring systems which consist of three electrodes (cathode, anode and ion collector) where the cathode is a hot cathode. Ionization gauges of this kind work with low voltages and without an external magnetic field. The hot cathode is a very abundant source of electrons. The electrons are accelerated in the electric field (see Figure 3-7) and receive sufficient energy from the field to ionize the gas in which the electrode system is located. The positive gas ions formed are transported to the ion collector which is negative with respect to the cathode, and give up their charge. The ion current thereby produced is a measure of the gas density and so of the gas pressure. If i is the electron current emitted by the hot cathode, the pressure-proportional ion current i⁺ produced in the gauge head is given by:

\[ i^+ = C i \cdot p \]  \hspace{1cm} (58)

and

\[ p = \frac{i^+}{i C} \]  \hspace{1cm} (58a)

The quantity C is the "relative sensitivity" of the gauge. It amounts generally to about 10 mbar⁻¹ for nitrogen. (The dependence of the pressure reading on the nature of the gas is discussed in section 3.33.) For a constant electron current, the "absolute sensitivity" of a gauge head is given as the quotient of the ion current and the pressure. For an electron current of 1 mA
and with \( C = 10 \text{ mbar}^{-1} \), the absolute sensitivity \( E \) of the gauge head amounts, therefore, to:

\[
E = \frac{l}{p} = Cl = 10 \text{ mbar}^{-1} \text{ mA} = 10 \text{ mbar}^{-1} \times 10^3 \text{ A mbar}^{-1}
\]

Hot-cathode ionization gauges also exhibit gas sorption (pumping action) which, indeed, is considerably smaller than for Penning gauges and amounts to a few \( 10^{-3} \text{ l/s} \). Essentially, this gas sorption takes place at the glass wall of the gauge head, and to a smaller extent at the ion collector. Here, use is made of the node gauge, which is easily arranged because an external magnet is not needed. The upper limit of the measuring range of the hot-cathode ionization gauge is about \( 10^2 \text{ mbar} \) except for gauge heads of special design as discussed in b) of this section. It is essentially determined by the fact that, at higher pressures, uncontrollable glow or arc discharges can form between the electrodes in the gauge. At low pressures, the measuring range is limited by two effects: by the x-ray and by the ion desorption effect. These phenomena result in loss of the strict proportionality between the pressure and the ion current and produce a low pressure limit which apparently cannot be traversed (see Fig. 3-8).

The x-ray effect (see Fig. 3-9)
The electrons emitted from the cathode impinge on the anode and photons are released. These photons release further electrons from surfaces which they encounter. The photoelectrons released from the ion collector are transported to the anode, i.e., the ion collector emits an electron current, which is indicated in the same manner as the positive ion current flowing to the ion collector. This photocurrent simulates a pressure. This effect is called the positive x-ray effect. It depends on the anode voltage and on the size of the surface of the ion collector.

There is also, however, under certain circumstances, a negative x-ray effect. Photons which impinge on the surrounding walls in the gauge head release photoelectrons there, which likewise flow in the direction of the anode and — since the anode is a grid construction — also into the space within the anode. If the surrounding wall is at the same potential as the ion collector, e.g., at earth potential, a portion of the electrons released at the wall can reach the ion collector. This results in the flow of an electron current to the ion collector, i.e., a negative current flows which can compensate the positive ion current. This negative x-ray effect depends on the potential which is assumed by the outer wall of the gauge head.

The ion desorption effect
Adsorbed gases can become desorbed from a surface by electron impact. For an ionization gauge, this means that, if a layer of adsorbed gas is present on the anode, this gas is partly desorbed as ions by the impinging electrons; the ions reach the ion collector and lead to a pressure indication, which is largely independent of the pressure but increases with increase of the electron current. If such a small electron current is used so that the number of electrons incident at the surface is small compared with the number of adsorbed gas particles, every electron will be able to desorb positive ions. If the electron current is then increased, the desorption will increase in the first place, because more electrons impinge on the surface. This leads finally to a reduction of adsorbed gas particles at the surface, the reading will fall again and generally reach values which can lie considerably below the pressure reading, which is observed with a small electron current. In practice, this effect has the consequence that one must ascertain whether the pressure reading has been influenced by a desorption current. This can be done by temporarily altering the electron current by a factor of 10 or 100. The more exact pressure value corresponds to the reading for the larger electron current.

In addition to the conventional ionization gauge of which the electrode structure is very much like that of the usual triode, there are various ionization gauges. In particular there is the Bayard-Alpert gauge and the extractor gauge which, according to the kind of construction, more or less suppress the two effects and, therefore, are used for measurement in the ultra-high vacuum region.

a) The conventional ionization gauge
As a gauge head a triode of conventional construction (see Fig. 3-10, a) with tungsten cathode is used, but slightly modified in that the outer electrode serves as the ion collector, the grid within it as the anode. With this arrangement, the electrons follow very long paths (oscillating about the grid wires of the anode) so that the probability of ionizing collisions and the sensitivity of the gauge are relatively high. Because the triode system can generally be used only in high vacuum on account of its strong x-ray effect, the gas sorption (pumping) effect and the gas content of the electrode system have only a small influence on the pressure measurement.

b) The "high pressure" ionization gauge (up to 1 mbar)
The electrode system is again a triode (see Fig.3-10, b), but this time of unmodified conventional construction. As the gauge is designed to allow pressure measurement up to 1 mbar, the cathode must be resistant against relatively high oxygen pressure. It is, therefore, designed as a non-burnout cathode, consisting of a thoria-coated ribbon. To obtain a rectilinear characteristic (ion current as a linear function of the pressure) up to pressures of 1 mbar, a high-ohmic resistor \( R \) of several
Megohms is included into the anode circuit (see Fig. 3-11).

c) Bayard-Alpert ionization gauge

To ensure linearity between the gas pressure and the ion current over a large pressure region as possible, the x-ray effect must be suppressed as much as possible. This is brought about in the electrode arrangement (developed by Bayard and Alpert) as the hot tungsten cathode lies outside the anode and the ion collector is a thin wire which forms the axis of the electrode system (see Fig. 3-10, c). The x-ray effect is reduced by two to three orders of magnitude because of the great reduction of the surface area of the ion collector.

In the measurement of pressures in the ultra-high vacuum region, the inner surfaces of the gauge head envelope and the connections to the vessel influence the pressure reading. The various effects of adhesion, desorption, disassociation and flow phenomena cannot be discussed here, within the context of this publication. The use of the Bayard-Alpert gauge in its nude form, which is placed directly in the vessel, avoids to a large extent errors in measurement due to the above effects.

d) Extractor ionization gauge

The disturbing effects influencing low pressure measurement can be largely eliminated by an ion-optical arrangement first suggested by Redhead. With this extractor system (Fig. 3-10, d) the ions from the anode cylinder are focused on a very thin and short ion collector. The ion collector is set up in a region close to a wall, which is maintained at the anode potential so that it cannot be reached by ions which arise from the gas space. Due to the geometry of the system as well as the potentials on the individual electrodes, the disturbing effect on the x-ray and ion desorption are almost completely excluded, and so is the necessity for a modulator. The extractor gauge measures pressures between $10^{-4}$ and $10^{-10}$ mbar. A further advantage is that the structure can be made as a nude gauge with a diameter of only 35 mm, which can be inserted into small apparatus.

3.33. Gas type dependency of ionization gauges

For ionization gauges with cold cathodes (Penning gauges) as well as those with hot cathodes, the pressure reading depends on the nature of the gas. The various ionization probabilities of the individual gases are responsible for this. The pressure indicated by a vacuum gauge with a gas dependent pressure reading is strictly valid for nitrogen and for air. Gases which consist of relatively small atoms or molecules (He, Ne, H₂) have naturally a smaller ionization probability than those with larger molecules. (A, Kr, CO₂, hydrocarbons).

The electrode systems as well as the recommended currents of most Leybold ionization gauges are so arranged that the pressure in so-called nitrogen equivalents is shown on the scale of the instrument concerned. This means that the indicated pressure corresponds to the pressure of a pure nitrogen atmosphere in the vessel.

Unfortunately, the factors from which the sensitivity of an ionization gauge can be calculated for a gas from the known sensitivity for another gas are also dependent on the geometry; practically each type of gauge must be calibrated for each gas pressure measured. For a rough estimation, an average value is given for the various models of ionization gauges (see table below). If other gases are predominant in the vessel, the pressure reading has to be multiplied by the following factors in order to be able to ascertain the correct pressure in the vessel. The Inficon IG3 allows a sensitivity factor for different gas types to be entered into the gauge.

3.34. Calibration of ionization gauges

Ionization gauges are not absolute vacuum measuring instruments. They do not measure pressure directly in accordance with its definition (see section 1.1) as a force acting on a surface, but in terms of a pressure-dependent or, more precisely, density-dependent physical quantity (for the relationship between pressure and density, see section 1.1). The physical process, on which pressure measurement with ionization gauges is based, is electrical conduction in gases.

Such a measuring instrument can only be used if the exact relationship between the pressure and the pressure-dependent current is known, i.e. if the quantity C is determined in Equation (58)

\[ i = C \cdot p \]

This quantity must be determined by calibration. This calibration involves fundamentally three exercises:

1. Determination of the gas pressure
   a) by measurement of a gas pressure with a reference standard vacuum gauge
   b) by the production of a known pressure

2. Measurement of the pressure-dependent process

3. The maintenance of constant conditions of all steps which influence the experimental procedure.

1a) Measurement of the pressure with a reference standard

The working range of most ionization gauges lies in the high or the ultra-high vacuum areas. The capacitance manometer gauge operates chiefly in the rough or medium vacuum region, or in the upper part of the high vacuum range; therefore, for pressure measurement intended for calibration, there is only a relatively small range available in which the measuring ranges of the two kinds of vacuum gauges overlap. With a capacitance manometer and carefully executed measurements, pressures down to $10^{-4}$ mbar may be measured with considerable accuracy for calibration purposes. Since it is known from other considerations that the relative sensitivity C is a constant under equilibrium conditions (for certain reservations see section 3.32), the value measured in the region between $10^{-4}$ and $10^{-6}$ mbar can be regarded as correct at lower pressures.

The Spinning Rotor Gauge can also be used as a reference standard and often is by standards institutions worldwide. The measuring system consists of a microprocessor control unit, gauge tube and sensing head. Synchronous a.c. voltage applied to the sensing head causes a small steel ball suspended in the gauge tube to rise and rotate to a preset frequency of 425 Hz. In the automatic drive mode, the ball is accelerated when rotational speed falls below 405 Hz. Once stabilized, ball flotation is sustained while the rotational drive voltage is removed, permitting the ball to decelerate in the presence of the gaseous media.
whose pressure is to be determined.

Due to the viscosity of the gas, the rate of deceleration is dependent upon the gas pressure.

Pressure is measured by determining the time required for one complete revolution of the ball. As uncertainty in the measurement of time for one ball revolution is large, the determination requires a multiple of measurements. By suitable statistical processing of measured values, reduction in the ball rotational speed is thus determined with significantly less uncertainty. The absolute uncertainty of differential pressure depends only on this measuring time.

The measuring range is 1 x 10^-7 to 1 mbar, overlapping a large portion of the range of an ionization gauge.

1b) Production of a known pressure: static expansion method

Proceeding from a definite quantity of gas, for which the quantities p, V and T are known exactly — p lies in the measuring range of a capacitance manometer — an accurately known low pressure is obtained in the working range of the ionization gauge by expansion in several stages.

If the gas quantity of volume $V_1$ is expanded to a volume $(V_1 + V_2)$ from $V_1$ to $(V_1 + V_2)$ etc., after n stages of expansion, there is obtained:

$$p_n = p_0 \frac{V_1 V_2}{V_1 + V_2} \frac{V_2 + V_3}{V_2 + V_3} \cdots \frac{V_n + V_1}{V_n + V_1} \quad (62)$$

$p_0$ = initial pressure directly measured in mbar, e.g. by means of a U-tube manometer

$p_n$ = calibration pressure

For this, the volumes must be known as accurately as possible and the temperature must remain constant.

This method requires great cleanliness of the apparatus and reaches its limit in the pressure regions in which the quantity of the gas can be altered by desorption or adsorption effects beyond the permissible limits of error. Experience shows that this limit lies at about 5 x 10^-7 mbar. The method is called the static expansion method, because the pressure and volume of the quantities of gas at rest are the decisive quantities.

1c) Dynamic expansion method

(Figure 3-12)

In this procedure, the calibration pressure $p$ is produced by admitting gas at a constant throughput $Q$ into a vacuum chamber while simultaneously gas is pumped out of the chamber by a pump arrangement with a constant pumping speed $S$. At equilibrium, according to Equation (10a):

$$p = \frac{Q}{S}$$

Q is obtained either from the quantity of gas which flows into the calibration chamber from a supply reservoir in which a constant pressure prevails or from the quantity of gas at a measured pressure which flows through a known conductance into the calibration chamber. The pressure before the inlet valve must be high enough so that it can be measured with an absolute vacuum gauge. The inlet openings to the valve (narrow capillary, sintered body) must be so small that the condition $d \ll l$ is fulfilled so that molecular flow and hence constant conductance of the inlet valve is obtained (see section 1.3). The quantity of gas is then determined from $p \times C_1$.

$P_1$ = pressure before the inlet valve

$C_1$ = conductance of the valve

(3 in Figure 3-11)

The pumping system consists of an exactly measured aperture with conductance $C_2$ in a wall which is as thin as possible and a pump with pumping speed $S_p$. Hence:

$$S = \frac{C_2 S_p}{C_2 + S_p} = \frac{C_2}{1 + C_2 S_p} \quad (63)$$

The method has the advantage that, after obtaining an equilibrium state, sorption effects can be ignored and, therefore, this procedure can be used for calibrating gauges at very low pressures.

2. Measurement of the pressure-dependent process

Applying present-day metrology allows the accurate measurement of all electric currents that are found in ionization gauges, hence the measurement of pressure-dependent vacuum processes should not entail any difficulties. For carrying out such measurements one needs a constant dc voltage supply unit, means for keeping constant the electron emission current and a sensitive standard dc amplifier.

3. Establishment of constant experimental conditions

In order to be able to carry out in principle the relatively simple calibration methods, a considerable technical procedure is required. For example, calibration at low pressures requires a UHV system in order to reach ultimate pressures which are at least two orders of magnitude below the lowest calibration pressure, so that the calibration gas is not contaminated by the residual gas atmosphere in the apparatus. Furthermore, care must be taken that the following parameters are kept constant: temperature, geometry of the gauge head, condition of the electrode surfaces, electrode potentials, magnitude of the ionizing electron current, magnitude and direction of the magnetic field, composition of the calibration gas, etc. At low pressures, where the calibration apparatus is connected by tubing, it is necessary to ensure that the connections remain unaltered when the gauge is connected to another piece of apparatus.

The calibration of vacuum gauges is undertaken by the National Institute of Standards and Technology (formerly NBS). In Germany it is performed by the National Standards Institution, the PTB, and the PTB's German calibration service (OKD) housed at Leybold in Cologne.