Leybold

Fundamentals of leak detection

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Preface

Leybold, a member of the globally active industrial Atlas Copco Group of companies has developed into the world market leader in the area of vacuum technology. In this leading position, we recognize that our customers around the world count on Leybold to deliver technical superiority and maximum value for all our products and services.

This brochure is meant to provide an easy to read overview covering the entire range of vacuum technology and is independent of the current Leybold product portfolio. The presented product diagrams and data are provided to help promote a more comprehensive understanding of vacuum technology and are not offered as an implied warranty.

To us, partnership-like customer relationships are a fundamental component of our corporate culture as well as the continued investments we are making in research and development for our next generation of innovative vacuum technology products.

In the course of our over 165 year-long corporate history, Leybold developed a comprehensive understanding of process and application know-how in the field of vacuum technology. Jointly with our partners and customers, we plan to continue our efforts to open up further markets, implement new ideas and develop pioneering products.

Leybold GmbH

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Introduction

In addition to the actual vacuum systems and their individual components (vacuum vessel, lines, valves, measuring devices, etc.) there are numerous other systems and products in the fields industry and research with high requirements regarding tightness or so-called "hermetic sealing". These include, in particular, assemblies for the automotive and refrigeration industry.

Generalized statements often made, such as "no detectable leaks" or "leak rate zero", do not represent an adequate basis for acceptance testing. Every experienced engineer knows that properly formulated acceptance specifications will indicate a certain leak rate under defined conditions. Which leak rate is acceptable is also determined by the application itself.

1 Types of leaks

The simplest **definition for the term "leak"** is:

A leak is an "opening" in a (separating) wall or barrier through which solids, liquids or gases can <u>undesirably</u> enter or exit.

Depending on the type of material or joining fault, the following **leak types** are differentiated:

- **Leaks in detachable connections:**
  Flanges, ground mating surfaces, covers

- **Leaks in permanent connections:**
  Solder and welding seams, glued joints

- **Leaks due to porosity:**
  particularly following mechanical deformation (bending!) or thermal processing of polycrystalline materials and cast components

- **Thermal leaks:**
  opening up at extreme temperature loading (heat/ cold), above all at solder joints

- **Apparent (virtual) leaks:**
  leaks: quantities of gas will be liberated from hollows and cavities inside cast parts, blind holes and joints (also due to the evaporation of liquids).

- **Indirect leaks:**
  leaking supply lines in vacuum systems or furnaces (water, compressed air, brine)

- **"Serial leaks":**
  this is the leak at the end of several "spaces connected in series", e.g. a leak in the oil-filled section of the oil pan in a rotary vane pump

- **"One-way leaks":**
  these will allow gas to pass in one direction but are tight in the other direction (very seldom)

An area which is not gas-tight but which is not leaky in the sense that a defect is present would be the

- **Permeation**
  naturally permeability of gas through materials such as rubber hoses, elastomer seals, etc. (unless these parts have become brittle and thus "leaky").

2 Leak rate, leak size (gas) mass flow

No vacuum device or system can ever be absolutely vacuum-tight and it does not actually need to be. The simple essential is that the leak rate must be low enough that the required operating pressure, gas balance and ultimate pressure in the vacuum container are not influenced. It follows that the **requirements in regard to the gas-tightness of an apparatus are the more stringent** the **lower the required pressure level is.**

In order to be able to register leaks quantitatively, the **concept of the "leak rate"** with the **symbol q_L** and the **unit mbar l/s** was introduced.

A leak rate of q_L = 1 mbar·l/s is present when in an enclosed, evacuated vessel with a volume of 1 l the pressure rises by 1 mbar per second or, where there is positive pressure in the container, pressure drops by 1 mbar.

The leak rate of a vessel indicates the amount of gas flow which escapes through the walls of the vessel. **It must be noted, however, that the leak rate for a leak depends on the type of gas.**

If the gas temperature T and the molar mass M of a gas G is known, the gas mass flow can be calculated from the leak rate q_L suing the equation of state for ideal gases via the relationship

(1) $\Delta m/\Delta t = (q_L \cdot M)/(R \cdot T)$ Unit: g/s

with

R = 83.14 (mbar·l)/(mol·K)

T = Gas temperature in K   M = Molar mass in g/mol

Δm = Mass in g Δt = Time span in s

The relationship (1) is used to

a) to determine the mass flow
$\Delta m/\Delta t$ at a known leak rate of q_L

(in this context, see example at 4.1)

or

b) to determine the leak rate q_L at a known gas mass flow
$\Delta m/\Delta t$

(see example below).

Example for b):
A refrigeration system using the refrigerant R134a (= Freon) exhibits a refrigerant loss of 1 g per year at 25 °C.
How large is the Freon leak rate q_L(Freon)?
With T = (273 + 25) K = 298 K and M(R134a) = 102.03 g/mol, the Freon leak rate is q_L(Freon) = 6.5·10⁻⁶ mbar·l/s in accordance with (1).

For high-vacuum systems, the following rule of thumb applies:

q_L(air) < 10⁻⁶ mbar·l/s = System is "very tight"

q_L(air) < 10⁻⁵ mbar·l/s = System is "sufficiently tight"

q_L(air) > 10⁻⁴ mbar·l/s = System is "leaky"

A leak can in fact be compensated by a vacuum pump of sufficient capacity since the following applies to the reachable ultimate (operating) pressure p_{ult}:

(2) $p_{ult} = q_L/S_{eff}$

with

q_L = Leak rate in mbar l/s

S_{eff} = Effective pumping speed of the vacuum pump at the vacuum vessel in l/s

If S_{eff} is increased sufficiently, it is therefore always possible to reach a specified ultimate (operating) pressure p_{ult} independent of the leak rate q_L.

In practice, however, a desired increase of S_{eff} may not be realizable due to economic and design reasons (high investment costs, high space requirement).

If the desired ultimate pressure is not reached in a vacuum system, there are usually two causes for this:

1. the presence of leaks

and/or

2. the gas liberation from the vessel walls and seal outgassing.

In order to differentiate between the two causes, a partial-pressure analysis with a mass spectrometer or the time-related pressure rise test may be used. Since it is only possible to determine the existence of a leak and not its position in the system when using the pressure rise test, it is recommended to use a helium leak detector with which the leaks may also be localized significantly faster.

In order to achieve an overview of the correlation between the geometric size of the hole and the associated leak rate it is possible to operate on the basis of the following, rough estimate:

A circular hole with a diameter D = 1 cm in the wall of a vacuum vessel is closed with a valve. Atmospheric pressure (p = 1013 mbar) prevails outside, a vacuum inside. When the valve is opened, the air flows at the speed of sound (v_S = 330 m/s) through the opening cross section of A = $\pi \cdot (D^2/4) \approx 0.79$ cm² into the vessel. The air quantity flowing into the vessel amounts to q_L(air) = $p \cdot v_S \cdot A \approx 2.6 \cdot 10^4$ mbar·l/s.

If all other conditions are kept identical and helium is allowed to flow into the hole at its speed of sound of 970 m/s, then the helium leak rate q_L (helium) is $\approx 7.7 \cdot 10^4$ mbar·l/s, so the leak rate is significantly higher.

This greater "sensitivity" for helium is used in leak detection and has resulted in the development and mass production of highly sensitive helium-based leak detectors (see Section 5.2).

Shown in **Fig. 1** is the **correlation between the hole size** and leak rate for air, with the approximate value of q_L (air) = 10^4 mbar·l/s for the "1 cm hole".

The table shows that when the hole diameter D is reduced to 1 μm = 0.001 mm (= reduction of D by the factor 10000) the leak rate will amount to $1.0 \cdot 10^{-4}$ mbar·l/s, a value which in vacuum technology already represents a major leak (see the rule of thumb above). A leak rate of $1.0 \cdot 10^{-12}$ mbar·l/s corresponds to hole diameter of 1 angstrom (Å); this is the lower detection limit for modern helium leak detectors. Since the grid constants for many solids amount to several Å and the diameter of smaller molecules (H_2, He) are about 1 Å, inherent permeation through solids can be registered metrologically using helium leak detectors. This has led to the development of calibrated test leaks with very small leak rates. This is a measurable "lack of tightness" but not a "leak" in the sense of being a defect in the material or joint.

Correlation between hole diameter and leak rate, estimation for air

Δp = 1013 mbar, hole diameter d = 1 cm

Gas speed = speed of sound in air = 330 $\dfrac{m}{s}$

Volume/second: $330 \dfrac{m}{s} \cdot \dfrac{1^2 \cdot \pi}{4} \cdot cm^2 = 26 \cdot 10^3 \dfrac{cm^3}{s} = 26 \dfrac{\ell}{s}$

Quantity/second: $1013 \text{ mbar} \cdot 26 \dfrac{\ell}{s} = 2{,}6 \cdot 10^4 \dfrac{mbar \cdot \ell}{s} \approx 10^4 \dfrac{mbar \cdot \ell}{s}$

Diameter	Leak rate in $\dfrac{mbar \cdot \ell}{s}$	
10^{-2} m = 1,0 cm	10^4	
10^{-3} m = 1,0 mm	10^2	
10^{-4} m = 0,1 mm	10^0	(= 1)
10^{-5} m = 0,01 mm	10^{-2}	
10^{-6} m = 1,0 μm	10^{-4}	
10^{-7} m = 0,1 μm	10^{-6}	
10^{-8} m = 0,01 μm	10^{-8}	
10^{-9} m = 1,0 nm	10^{-10}	
10^{-10} m = 1,0 Angström	10^{-12}	(Detection limit of helium leak detectors)

Fig. 1: *Correlation between hole diameter and leak rate, estimation for air*

Estimates or measurements of the sizes of atoms, molecules, viruses, bacteria, etc. have often given rise to everyday terms such as "watertight" or "bacteria-tight" (see **Table 1**).

Concept / criterion	Comment	q_L (mbar · l/s)	Relevant particle size
Water-tight*)	Droplets	$< 10^{-2}$	
Vapor-tight	"Sweating"	$< 10^{-3}$	
Bacteria-tight*) (cocci) (rod-shaped)		$< 10^{-4}$	$\varnothing \approx 1\ \mu m$ $\varnothing \approx 0.5 - 1\ \mu m, 2 - 10\ \mu m$ long
Oil-tight		$< 10^{-5}$	
Virus-tight*) (vaccines e. g. pox) (smallest viruses, bacteriophages) (viroids, RNA)		$< 10^{-6}$ $< 10^{-8}$ $< 10^{-10}$	
Gas-tight		$< 10^{-7}$	
"Absolutely tight"	Technical	$< 10^{-10}$	

*) As opposed to vapor, it is necessary to differentiate between hydrophilic and hydrophobic solids. This also applies to bacteria and viruses since they are transported primarily in solutions.

Table 1: Correlation between tightness criteria and leak rates q_L

Compiled **in Fig. 2** are **the nature and detection limits of frequently used leak detection methods**.
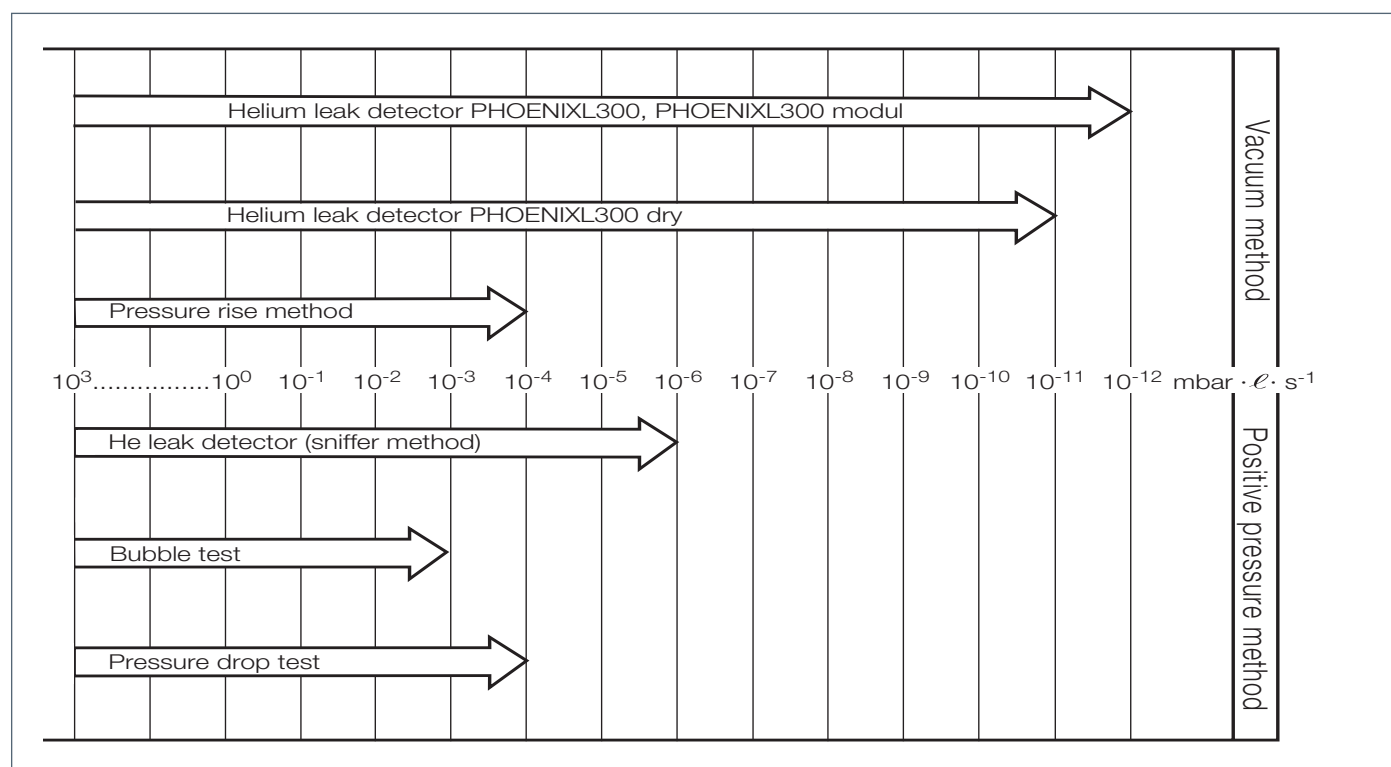
Fig. 2: Nature and detection limits of frequently used leak detection methods

2.1 Helium standard leakrate

Required for unequivocal definition of a leak are the pressures prevailing on either side of the (vessel) wall and the nature of the medium passing through that wall (viscosity, molar mass). For the case where the test is carried out with **helium[4] at a pressure difference of 1 bar from the atmosphere pressure (external) to the vacuum**

(p < 1 mbar, internal), which is frequently found in practice, the designation **"helium standard leak rate"** has been introduced in the standard DIN EN 1330-8.

In order to indicate the rejection rate for a test using helium under standard helium conditions it is necessary first to convert the real test conditions of use to helium standard conditions (see 2.2). Some examples of such conversions are shown in **Fig. 3**.

Leak	Quantity of substance per time unit through hole	Standard helium conditions: $p_1 = 1$ bar, $p_2 < 1$ mbar ($\Delta p = 1$ bar) Test gas = Helium
$\downarrow$	$\downarrow$	$\downarrow$
Known leaks:	**Leaking quantity of substance:**	**Standard helium leak rate:**
Water faucet dripping	$34 \frac{mg}{s}$ Water $\left(= 6{,}45 \frac{mbar \cdot \ell}{s} \text{ Air} \right)$	$0{,}17 \frac{mbar \cdot \ell}{s}$ He Std
4 mm ø, 1 Hz, $\Delta p = 4$ bar		
Hair lies on seal	$10^{-2} \frac{mbar \cdot \ell}{s}$ Air	$0{,}9 \cdot 10^{-2} \frac{mbar \cdot \ell}{s}$ He Std
Bicycle tube in water (bubble test) 2 mm ø, 1 Hz, $\Delta p = 0{,}1$ bar	$4{,}19 \cdot 10^{-3} \frac{Ncm^3}{s} \left(= 4{,}24 \cdot 10^{-3} \frac{mbar \cdot \ell}{s} \text{ Air} \right)$	$1{,}88 \cdot 10^{-2} \frac{mbar \cdot \ell}{s}$ He Std
Car tire looses air 25 l, 6 Mo: 1,8 --> 1,6 bar	$3{,}18 \cdot 10^{-4} \frac{mbar \cdot \ell}{s}$ Air	$4{,}3 \cdot 10^{-5} \frac{mbar \cdot \ell}{s}$ He Std

Fig. 3:
Examples for the conversion of leak rates to helium standard leak rates

2.2 Conversion formulas

Regarding the **conversion of pressure and gas type** (viscosity, molar mass), it must be noted that **different formulas apply to laminar viscous and molecular flow**. The boundary between these areas is very difficult to determine. As a guideline, the following can be assumed: at leak rates

$q_L > 10^{-4}$ mbar·l/s   laminar viscous flow

and at leak rates

$q_L < 10^{-6}$ mbar·l/s   molecular flow

In the intermediate range the manufacturer (who is liable under the guarantee terms) must assume values on the safe side.

The equations are listed in **Table 2**.
Here indices "I" and "II" refer to the one or the other pressure ratio and indices "1" and "2" reference the inside and outside of the leak point, respectively. For a sensible use of the formulas, the pressure p_1 must always be the higher pressure ($p_1 > p_2$).

Flow	Laminar viscous	Molecular
Pressure	$q_I \cdot (p_1^2 - p_2^2)_{II} = q_{II} \cdot (p_1^2 - p_2^2)_I$	$q_I \cdot (p_1 - p_2)_{II} = q_{II} \cdot (p_1 - p_2)_I$
Gas type	$q_{GasA} \cdot \eta_{GasA} = q_{GasB} \cdot \eta_{GasB}$	$= \dfrac{q_{GasA} \cdot (M_{GasA})^{1/2}}{q_{GasB} \cdot (M_{GasB})^{1/2}}$

Table 2:
Formulae for the conversion of pressure and gas type, p = pressure, q = gas flow (leak rate), η = viscosity, M = molar mass

3 Terms and definitions

When searching for leaks one will generally have to distinguish between two tasks:

1. locating leaks and
2. measuring the leak rate

In addition, we distinguish, based on the direction of flow for the fluid, between the

a. vacuum method
(sometimes known as an "outside-in leak"), where the direction of flow is into the test object; the pressure inside the test object is less than ambient pressure

and the

b. positive pressure method
(often referred to as the "inside-out leak"), where the flow takes place from inside the test object outward; the pressure inside the test object is higher than the ambient pressure.

The test objects should wherever possible be examined in a configuration corresponding to their later application, i.e. components for vacuum applications using the vacuum method and using the positive pressure method for parts which will be pressurized on the inside.

When measuring leak rates, we differentiate between registering
a. individual leaks (local measurement), Fig. 4b and 4d,
and registering
b. the total of all leaks in the test object (integral measurement) Fig. 4a and 4c.

The smallest leak rate which is no longer tolerable in accordance with the acceptance specifications is known as the **rejection rate**. Its calculation is based on the condition that the test object may not fail during its planned utilization period due to faults caused by leaks, and this to a certain degree of certainty.

Often it is not the leak rate for the test object under normal operating conditions which is determined, but rather the throughput rate of a test gas under similar conditions. The achieved measuring values have to be converted to correspond to the actual application

situation in regard to the pressures inside and outside the test object and the type of gas (or liquid) being handled.

Where a vacuum is present inside the test object (p < 1 mbar), atmospheric pressure outside, and helium[4] is used at the test gas, one refers to **standard helium conditions**. Standard helium conditions are always present during helium leak detection for a vacuum system when the system is connected to a leak detector, if the system is pumped down to p less than 1 mbar and if it is sprayed with helium[4] **(spray technique)** (see Fig. 4b).

If the test object is evacuated solely by the leak detector, then one would say that the leak detector is operating in the **direct-flow mode of the leak detector (LD)**.
If the test object is itself a complete vacuum system with its own vacuum pump and if the leak detector is operated in parallel to the system's pumps, then one refers to **partial-flow mode of the leak detector**. One also refers to partial-flow mode when a separate auxiliary pump is used parallel to the leak detector.

When using the positive pressure method it is sometimes either impractical or in fact impossible to measure the leakage rate directly while it could certainly be sensed in an envelope which encloses the test specimen. The measurement can be made by connecting that envelope to the leak detector or by **accumulation** (= increasing the concentration) of the test gas inside the envelope (see Fig. 4c). The **bombing test** is a special version of the accumulation test (see 7.4).

In the so-called **sniffer technique**, another variation of the of the positive pressure technique, the (test) gas issuing from leaks is collected (extracted) by a special apparatus and fed to the leak detector (see Fig. 4d). This procedure can be carried out using either helium or refrigerants or SF_6 as the test gas.
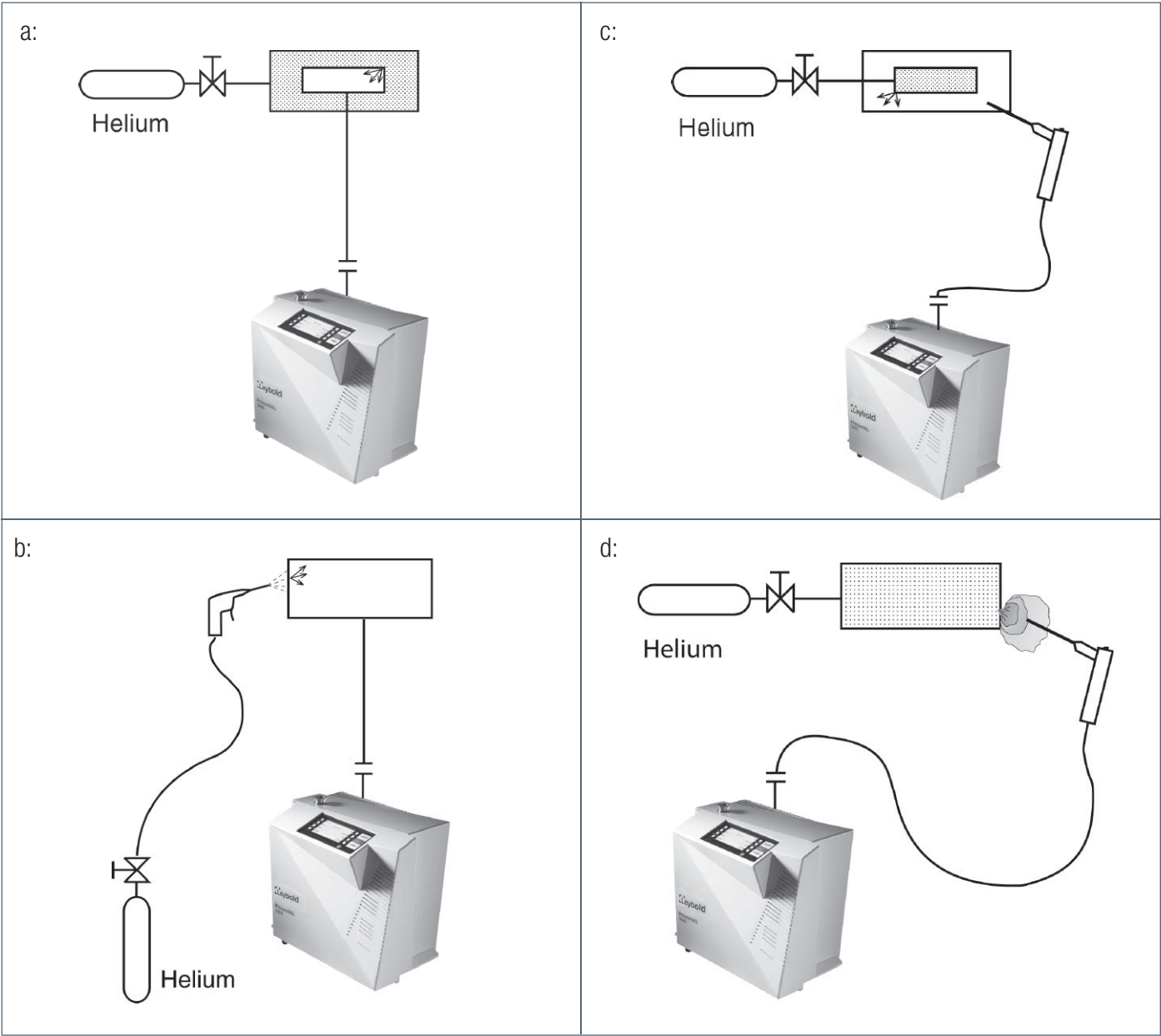
Fig. 4:
Usage options for a vacuum leak detector based on the vacuum method (a, b) and based on the positive pressure method (c, d)

Vacuum method	Positive pressure method
= Vacuum inside specimen	= Pressurized test gas inside specimen
a: Enclosure test (integral leak detection)	c: Enclosure test (integral leak detection)
b: Spray technique (local leak detection)	d: Sniffer technique (local leak detection)

4 Leak detection methods without leak detector

The most sensible differentiation between the test methods used is the differentiation as to whether or not special leak detection equipment is used.

In the simplest case a leak can be determined qualitatively and, when using certain test techniques, quantitatively as well (this being the leak rate) without the assistance of a special leak detector.
For example, the quantity of water dripping from a leaking water faucet over a certain period of time can be determined by collecting the water with a measuring vessel. In this case, however, one would hardly refer to this as a leak detector.

In those cases where the leak rate can be determined during leak detection without using a leak detector, this leak rate will often be converted to the helium standard leak rate (see 2.1). The helium standard leak rate is often required for issuing acceptance certificates but can also be of service when comparing leak rate values determined via helium leak detector devices.

In spite of careful inspection of the individual engineering components, leaks may also be present in an apparatus following its assembly – be it due to poorly seated seals or damaged sealing surfaces. The processes used to examine an apparatus depend on the size of the leaks and on the desired degree of tightness as well as on whether the apparatus is made of metal, glass or other materials.

Below, you will find the description of a few leak detection methods. These methods are used in accordance with the particular application situations while economic factors often play an important part as well.

4.1 Pressure rise test

This leak testing method capitalizes on the fact that a leak allows a quantity of gas – remaining uniform through a period of time – to enter a sufficiently evacuated device. In contrast, the quantity of gas liberated from the walls and from the seals declines over time.

The valve at the pump end of the evacuated vacuum vessel is closed in preparation for pressure rise measurements. Then the time Δt is measured during which the pressure rises by a certain amount Δp (by one power of ten, for example). The valve is opened again and the pump is run again for some time, following which measurement of the pressure rise will be repeated. If the time Δt for the amount of pressure rise Δp remains

constant, then a leak is present, assuming that the waiting period between the two pressure rise measurements was long enough. The appropriate length of the waiting period depends on the nature and size of the device. If the time for the pressure rise Δp increases, this effect is most likely caused by a reduced gas liberation on the inside of the apparatus.

One may also attempt to differentiate between leaks and contamination by interpreting the curve depicting the rise in pressure (= pressure as a function of time).

Plotted on a graph with linear scales, the curve for the rise in pressure must be a straight line where a leak is present, even at higher pressures.

If the pressure rise is due to gas being liberated from the walls, then the pressure rise will gradually taper off and will approach a final and stable value. In most cases both phenomena will occur simultaneously so that separating the two causes is often difficult if not impossible.

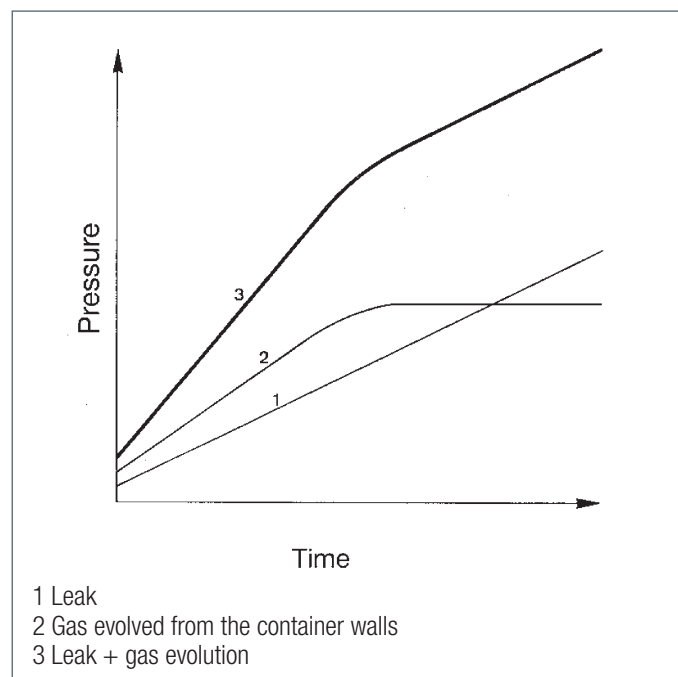These relationships are shown schematically in **Fig. 5.**

1 Leak
2 Gas evolved from the container walls
3 Leak + gas evolution

Fig. 5:
Pressure rise in a vacuum container as a function of the time after turning off the vacuum pump

Once it has become clear that the rise in pressure is due solely to a real leak, then the leak rate can be determined quantitatively from the pressure rise, plotted against time, in accordance with the following equation:

(3) $q_L = V \cdot (\Delta p / \Delta t)$

with

q_L =   Leak rate in mbar l/s

V =   Volume of the vacuum reservoir in l

$\Delta p / \Delta t$ = Pressure rise in the vacuum reservoir Δp divided by the measuring time Δt in mbar/s

Example:

After closing the pump-end valve, the pressure p in a vacuum vessel with the volume **V = 20 l** rises from $1 \cdot 10^{-4}$ mbar to $1 \cdot 10^{-3}$ mbar in **Δt = 300 s** Thus, **Δp = ($1 \cdot 10^{-3}$ – $1 \cdot 10^{-4}$) mbar = $9 \cdot 10^{-4}$ mbar** and the leak (leak rate) for air in accordance with relation (3) **q_L(air) = V ($\Delta p / \Delta t$) = $6 \cdot 10^{-5}$ mbar·l/s**.

Via relation (1), one obtains the gas mass flow $\Delta m / \Delta t$ through
the leak by means of the leak rate $q_L = 6 \cdot 10^{-5}$ mbar·l/s:

$\Delta m / \Delta t$ = $7 \cdot 10^{-8}$ g/s
(temperature T = 293 K, molar mass for air M $\simeq$ 29 g/mol)

If the container is evacuated with a TURBOVAC 50 turbo-molecular pump, for example (pumping speed S = 50 l/s), which is attached to the vacuum vessel by means of a shut-off valve, then one may expect an effective pumping speed of approximately **S_{eff} = 30 l/s**. Thus the ultimate pressure will be

$p_{ult} = q_L / S_{eff}$ = ($6 \cdot 10^{-5}$ mbar·l/s)/(30 l/s) = $2 \cdot 10^{-6}$ mbar

Naturally it is possible to improve this ultimate pressure, should it be insufficient, by using a larger-capacity pump (e.g. the TURBOVAC 151) and at the same time reduce the pump-down time required to reach ultimate pressure.

4.2 Pressure drop test

The thinking here is analogous to that for the pressure rise method. The pressure drop test is, however, only rarely used to check for leaks in vacuum systems. If this is done, however, then gauge pressure should not exceed 1 bar since the flange connectors used in vacuum technology will as not tolerate higher pressures. On the other hand, the pressure drop test is a technique commonly employed in tank engineering. When dealing with large containers and the consequentially long measuring periods required for the pressure drop, it may under certain circumstances be necessary to consider the effects of temperature changes. As a consequence it may happen, for example, that the system cools to below the saturation pressure for water vapor, causing water to condense so that the measurement is distorted.

4.3 Leak test using vacuum gauges which are sensitive to the type of gas

The fact that the pressure reading at vacuum gauges is sensitive to the type of gas involved can, to a certain extent, be utilized for leak detection purposes. Thus it is possible to brush or spray suspected leaks with alcohol. The alcohol vapor which flows into the device changes the pressure reading of the vacuum gauge since the thermal conductivity and ionizability of alcohol vapor vary greatly from the same properties for air. The availability of more precise, easy-to-use helium leak detectors has, however, rendered this method almost completely obsolete.

4.4 Bubble immersion test

The pressurized test specimen is submerged in a liquid bath. Rising gas bubbles indicate the leaks.

Leak detection depends on the awareness of the inspecting person to a significant extend and induces the desire to increase the "sensitivity" by using increasingly higher pressures. Sometimes, however, this results in safety instructions not being observed. In case of small leak rates, this method is very time consuming (see table 3). **Table 3** refers to the leak test of refrigeration systems which are operated with the refrigerant R134a. In case of these systems, the leak rate is indicated as grams of refrigerant lost per year (g/a). Water or petroleum-based oils are used as a test liquid (which may be heated or to which a surfactant may be added) The surface tension should not exceed 75 dyn/cm (1 dyn = 10^{-5} N).

4.5 Foam-spray test

In many cases pressurized containers or gas lines (including the gas supply lines for vacuum systems) can be checked quite conveniently for leaks by brushing or spraying a surfactant solution on them. Corresponding leak detection sprays are also available commercially. Escaping gas forms soap bubbles at the leak points. Here, again, the detection of smaller leaks is time-consuming and will depend greatly on the attentiveness of the inspector.

The hydrogen gas refrigeration systems used in power plant generators represent a special case. These are indeed sometimes tested in the fashion described above but they can be examined much better and at much higher sensitivity by sniffing the hydrogen escaping at leaks using a helium leak detector which has been adjusted to respond to (H_2).

4.6 Vacuum box check bubble

As a variation on the spray test mentioned above, in which the escaping gas causes the bubbles, it is possible to place a so-called "vacuum box" with a seal (something like a diver's goggles) on the surface being examined once it has been sprayed with a soap solution. This box is then evacuated with a vacuum pump. Air entering through leaks will cause bubbles inside the box, which can be observed through a glass window in the box. In this way it is also possible, for example, to examine flat sheet metal plates for leaks. Vacuum boxes are available for a variety of applications, made to suit a wide range of surface contours.

4.7 Krypton 85 test

When dealing with small, hermetically sealed parts where the enclosure is leaky, krypton 85, a gaseous, radioactive isotope, can first be forced into the device by applying pressure from the outside. Once an exactly measured holding period has elapsed the pressure will be relieved, the component flushed and the activity of the gas charge will be measured.

In the same way it is also possible to use helium as the test gas.

4.8 High-frequency vacuum test

The so-called high-frequency vacuum tester can be used not only to check the pressure in glass equipment but also to locate porous areas in plastic or paint coatings on metals. This comprises a hand-held unit with a brush-like high-frequency electrode and a power pack. The shape and color of the electrical gas discharge can serve as a rough indicator for the pressure prevailing inside glass equipment.

In the case of the vacuum tester - which comprises primarily a tesla transformer (which delivers a high-voltage, high-frequency AC current) - the corona electrode approaching the apparatus will trigger an electrode-free discharge inside the apparatus. The intensity and color of this discharge will depend on the pressure and the type of gas. The luminous discharge phenomenon allows us to draw conclusions regarding the approximate value for the pressure prevailing inside the apparatus. The discharge luminosity will disappear at high and low pressures.

When searching for leaks in glass equipment the suspect sections will be scanned or traced with the high-frequency vacuum tester electrode. Where there is a leak an arc will strike through to the pore in the glass wall, tracing a brightly lit discharge trail. Small pores can be enlarged by these sparks. The corona discharge of the vacuum tester can also penetrate thin areas in the glass particularly at weld points and transitional areas between intermediate components. Equipment which was originally leak-free can become leaky in this fashion! In contrast to the actual leak detector units, the high-frequency vacuum tester is highly limited in its functioning.

4.9 Test with chemical reactions and dye penetration

Occasionally leaks can also be located or detected by means of chemical reactions which result in a discoloration or by penetration of a dye solution into fine openings.

In the past, the discoloration of a flame due to halogen gas escaping through leaks was used to locate leaks in solder joints for refrigeration units.

An example of a dye penetration test is the inspection of the tightness of rubber plugs or plungers in glass tubes, used for example in testing materials suitability for disposable syringes or pharmaceutical packages.

When evaluating tiny leaks for liquids it will be necessary to consider the wetability of the surface of the solid and the capillary action.

Some widely used leak detection methods are shown – together with the test gas, application range and their **particular features – in Table 4.**

Loss of refrigerant R134a per year	Equivalent R134a leak rate at 25 °C	Time for 10 gas bubbles, Ø 2 mm	Detection time using helium leak detector
g/a	mbar · ℓ/s	s	s
430	$3,32 \cdot 10^{-3}$	3.2	a few seconds
86	$6,63 \cdot 10^{-4}$	15.8	a few seconds
21,5	$1,66 \cdot 10^{-4}$	63.1	a few seconds
17,2	$1,33 \cdot 10^{-4}$	1 min 48 s	a few seconds
4,3	$3,32 \cdot 10^{-5}$	5 min 15 s	a few seconds
0,86	$6,63 \cdot 10^{-6}$	26 min 19 s	a few seconds
0,1 *)	$7,70 \cdot 10^{-7}$	3 h 46 min	a few seconds
*) This leak rate represents the detection limit for good halogen leak detectors ($\approx$ 0.1 g/a).			

Table 3: Comparison of bubble immersion test with helium leak detector

Method	Test gas	Smallest detectable leak rate		Pressure range	Quantitative measurement
		mbar · ℓ/s	g/a R 134 a		
Foaming liquids	Air and other gases	10^{-4}	$7 \cdot 10^{-1}$	Positive pressure	No
Ultrasound microphone	Air and other gases	10^{-2}	70	Positive pressure	No
Thermal conductivity leak detector	Other gases except air	$10^{-3} - 10^{-5}$	$7 - 10^{-1}$	Positive pressure and vacuum	No
Halogen leak detection	Substances containing halogens	10^{-6} (10^{-5})	10^{-1} (10^{-1})	Positive pressure (Vacuum)	With restrictions
Universal sniffer leak detection	Refrigerant Helium and other gases	10^{-6}	10^{-1}	Positive pressure	Yes
Helium leak detection	Helium	10^{-12} 10^{-7}	$7 \cdot 10^{-9}$ $7 \cdot 10^{-4}$	Vacuum Positive pressure	Yes
Bubble test	Air and other gases	10^{-3}	7	Positive pressure	No
Water pressure test	Water	10^{-2}	70	Positive pressure	No
Pressure drop test	Air and other gases	10^{-4}	$7 \cdot 10^{-1}$	Positive pressure	Yes
Pressure rise test	Air	10^{-4}	$7 \cdot 10^{-1}$	Vacuum	Yes

Table 4: Comparison of the most important leak detection methods

5 Leak detectors and how they work

Most leak testing today is carried out using special leak detection devices. These can detect far lower leak rates than methods which do not use special equipment.

The function of most leak detectors is based on the fact that testing is conducted with a special test gas, i.e. with a medium <u>other than the one</u> used in normal operation.

Helium[4] which is detected using a mass spectrometer is frequently used as test gas for leak detection. So, for example, the tested object may be a cardiac pacemaker whose interior components are to be protected against the ingress of bodily fluids during normal operation. This example alone makes it clear that the varying flow properties of the test and the working media need to be taken into consideration.

5.1 Halogen leak detectors
5.1.1 Halogen diode principle

Gaseous chemical compounds whose molecules contain chlorine and/or fluorine - such as refrigerants R12, R22 and R134a - will influence the emissions of alkali ions from a surface impregnated with a mixture of KOH and Iron (III) hydroxide and maintained at 800 °C to 900 °C by an external Pt heater. The released ions flow to a cathode where the ion current is measured and then amplified (halogen diode principle). This effect is so significant that partial pressures for halogens can be measured down to $1 \cdot 10^{-7}$ mbar.

Whereas such devices were used in the past for leak testing in accordance with the vacuum method, today – because of the problems associated with the CFCs – more sniffer units are being built. The attainable detection limit is about $1 \cdot 10^{-6}$ mbar·l/s for all the devices.

Equipment operating in accordance with the halogen diode principle can also detect SF_6. Consequently these sniffer units are used to determine whether refrigerants are escaping from a refrigeration unit or from an SF_6 type switch box (filled with arc suppression gas).

5.1.2 Infrared principle (HLD 5000)

The HLD 5000 uses the physical property of molecules being able to absorb infrared radiation. The test gas, which is taken in by the sniffer line, flows through a cuvette which is exposed to infrared radiation. The infrared-active gases (refrigerant) inside the test gas absorb a part of the infrared radiation and thus modify the primary infrared signal. The modified infrared signal is detected by a sensor, processed, and then displayed. The detection limit lies at around $5 \cdot 10^{-5}$ mbar·l/s. Due to continuous measuring of the ambient air, the background level of the test gas is automatically taken into account during the calculation of the measuring value.

5.2 Leak detectors with mass spectrometers (MS)

The detection of a test gas using mass spectrometers is far and away the most sensitive leak detection method and the one most widely used in industry. The MS leak detectors developed for this purpose make possible quantitative measurement of leak rates in a range extending across many powers of ten (see Chapter 2). The lower limit lies around $1 \cdot 10^{-12}$ mbar·l/s. This even allows for the quantitative measurement of the inherent gas flow through solids (permeation).

In principle, it is possible to detect all gases using mass spectrometry. Of all the available options, the use of helium[4] as a test gas has proved to be especially practical. **Helium[4] is**

- **unequivocally detectable with a mass spectrometer,**
- **chemically inert,**
- **non-explosive,**
- **non-toxic,**
- **present in normal air in a concentration of only 5 ppm (= $5 \cdot 10^{-4}$ volume %)**

and quite economical.

Two types of mass spectrometer are used in commercially available MSLD's:

a) the quadrupole mass spectrometer and preferably

b) 180° sector field mass spectrometer (due to its simple design).

Every mass spectrometer consists of three fundamental assemblies:

- **ion source,**
- **separation system** and
- **ion trap.**

The ions must be able to travel along the path from the ion source and through the separation system to the ion trap, to the greatest possible extent without colliding with gas molecules. This path amounts to about 15 cm for all types of spectrometers and thus requires a medium free path length of at least 60 cm, corresponding to pressure of about $1\cdot10^{-4}$ mbar; in other words, a mass spectrometer will operate only in high vacuum. In modern leak detectors, turbomolecular pumps are used to create the high vacuum.

Associated with the individual component groups are the required electrical and electronic supply systems and software which, via a microprocessor, allow for the greatest possible degree of automation in the operating sequence, including all adjustment and calibration routines and measured value display.

5.2.1 The operating principle of a leak detector with mass spectrometer

Fig. 6 is provided to explain the operating principle of a leak detector with mass spectrometer: This sketch shows the most commonly found configuration for leak detection using the test gas spray method (see Chapter 7.1) at a vacuum component (= test object).

If gas enters the component through a leak, it is pumped thorough the interior of the leak detector to the outlet, where it leaves the detector again. Assuming, that the leak detector is properly sealed, the gas flow q is always the same at any point between the inlet and the outlet of the leak detector. The following applies directly at the pumping port of the vacuum pump:

(4) $\quad$ **q = p·S** with

p = $\quad$ Inlet pressure directly at the pumping port of the vacuum pump in mbar

S = $\quad$ Pumping speed of the vacuum pump directly at the pumping port of the vacuum pump in l/s

At any other position x, the following applies while taking the line losses into account:

(4a) $\quad$ $\mathbf{q_x = q = p_x \cdot S_x}$ $\quad$ with

p_x = $\quad$ pressure at position x in mbar

S_x = $\quad$ pumping speed of the vacuum pump at position x in l/s ($S_x < S$!)

Equation (4a) applies to all gases which are pumped by the vacuum pump and thus also for the test gas TG (e.g. TG = helium [4]). At the mass spectrometer (x = MS), the following applies:

(4b) $\quad$ $\mathbf{q_{MS,\ TG} = q_{TG} = p_{MS,\ TG} \cdot S_{MS,\ TG} = q_L}$ $\quad$ with

$p_{MS,\ TG}$ = $\quad$ partial test gas pressure at mass spectrometer in mbar

$S_{MS,\ TG}$ = $\quad$ pumping speed of the vacuum pump for the test gas at mass spectrometer in l/s

In this case, the test gas flow q_{TG} equals the lake rate q_L being sought. It must be noted that, in case of equation (4b), the partial test gas pressure $p_{MS,\ TG}$ is present at the mass spectrometer. The measuring value for $p_{MS,\ TG}$ is provided by the mass spectrometer which must be set to the mass M of the test gas (e.g. M = 4 for TG = helium[4]). The value of $S_{MS,\ TG}$ is an experimentally determined constant for each leak detector.

The value for $p_{MS,\ TG}$ provided by the mass spectrometer is multiplied by the value $S_{MS,\ TG}$ which is stored in the microprocessor of the leak detector. The result of this multiplication is then displayed as leak rate q_L.
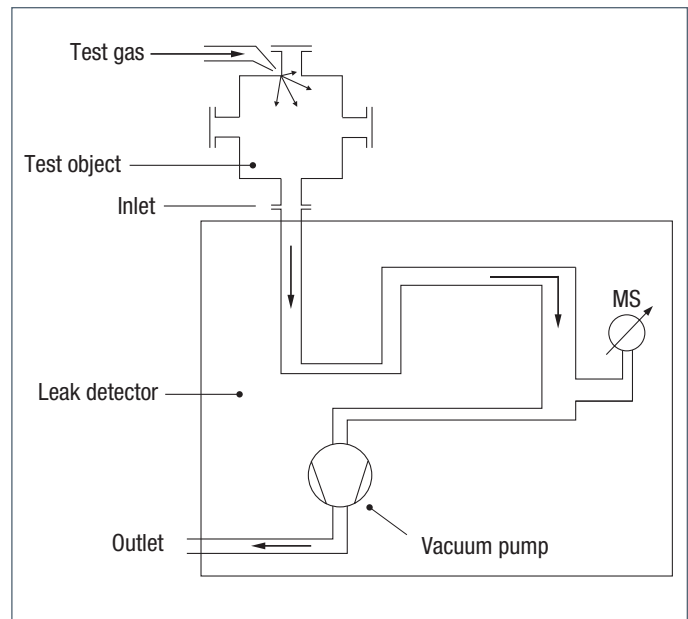

Fig. 6: Operating principle of a leak detector with mass spectrometer (main flow leak detector)

5.2.2 Detection limit, background, gas storage in oil (gas ballast), floating zero-point suppression

The **smallest detectable leak rate** is dictated by the natural background level for the test gas to be detected.

Even with the inlet at the leak detector closed, test gas will enter the mass spectrometer and will be detected there if the electronic means are adequate to do so.

The background signal generated in the mass spectrometer determines the **detection level of the leak detector**.

The high-vacuum pump system used to evacuate the mass spectrometer will normally comprise a turbomolecular pump and an oil-sealed rotary vane pump. Like every liquid, the oil in the rotary vane pump possesses the capability of dissolving gases until equilibrium is reached between the gas dissolved in the oil and the gas outside the oil.

When the pump is warmed up, this equilibrium state represents the detection limit for the leak detector.

However, it is possible for test gas to enter the leak detector not only via the inlet. Improper installation or inept handling of the test gas can allow test gas to enter the interior of the leak detector via the airing and/or gas ballast valve.

This inevitably results in a higher test gas concentration in the oil and the elastomer seals and thus to an increased background signal.

Conclusion: The more test gas is present in the oil the higher the background signal of the leak detector will be.

In case of the nowadays common installation of the leak detector (see **Fig. 7**), gas ballast valve and airing valve are connected to fresh air. The outlet of the leak detector should - if possible - be routed to outside the room where the leak test takes place. An increased background signal can be lowered again by opening the gas ballast valve and introducing gas which is free of the test gas (e.g. fresh air). The helium which is stored in the oil will be flushed out, so to speak. Since the effect always affects only the part of the oil present in the pump body, the flushing procedure will have to be continued until the entire oil supply of the pump has been recirculated several times. This period of time will usually be 20 to 30 minutes.
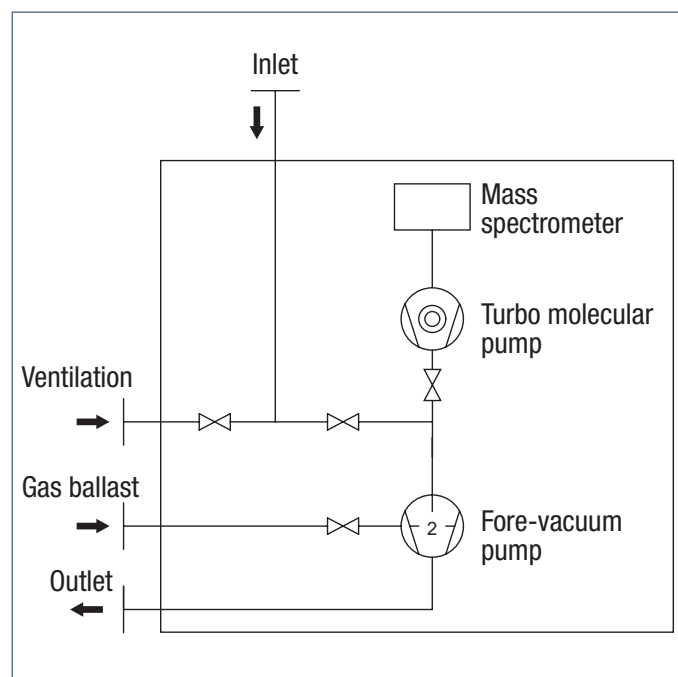
Fig. 7: Vacuum diagram of a counterflow leak detector

In case of so-called **"dry leak detectors"**, which are leak detectors without oil-sealed vacuum pumps, the problem of gas storage in the oil does not exist. However, dry leak detectors must still be flushed with gas which is free of test gas since, over time, test gas will accumulate in these devices as well.

In order to spare the user the trouble of always having to keep an eye on the background level and simplify the operation of the leak detector, the so-called **floating zero-point suppression** has been integrated into the automatic operating concepts of all Leybold leak detectors (see Chapter 5.2.5). Here the background level measured after the inlet valve has been closed is stored and then automatically deducted from subsequent measurements when the valve is then opened again. Only at a relatively high threshold level will the display panel show a corresponding warning.

Independent of the floating zero-point suppression, Leybold leak detectors offer the capability for **manual zero point shifting**. Here the display for the leak detector at the particular moment will be reset to zero so that only rises in the leak rate from that point on will be shown. This serves only to facilitate the evaluation of a display but can, of course, not influence its accuracy.

Equipment background level:	$< 2 \cdot 10^{-10}$	$1 \cdot 10^{-8}$	$1 \cdot 10^{-10}$ (suppressed)
Leak:	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
Display:	$2 \cdot 10^{-8}$	$3 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
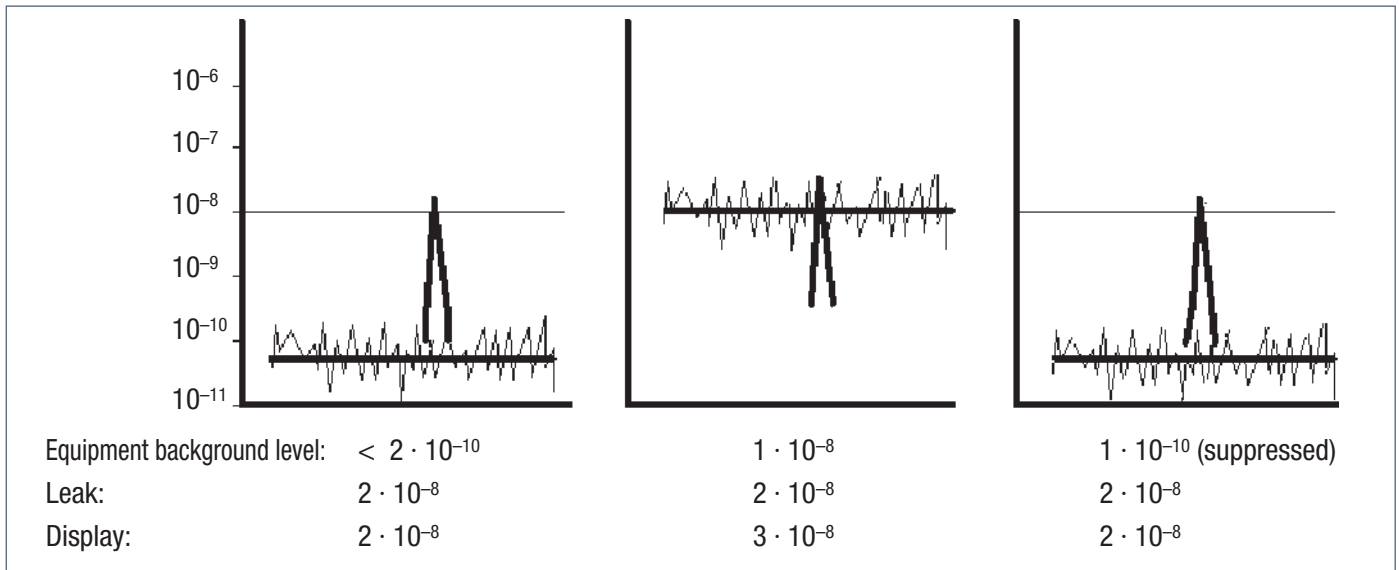
Fig. 8: Example of zero-point suppression

Fig. 8 is provided to illustrate the zero-point suppression:

Chart on the left: The signal is clearly larger than the background.

Center chart: The background has risen considerably; the signal can hardly be discerned.

Chart on the right: The background is suppressed electrically; the signal can be clearly identified again.

5.2.3 Calibrating leak detectors; calibration leaks

The **calibration of a leak detector** is to be understood as the adjustment of the display at a leak detector, to which a **calibration leak** (or **test leak**) is attached. A calibration leak is a leak whose leak rate at a certain temperature and under specific pressure conditions is known precisely. This leak rate is provided on the calibration certificate of the calibration leak or documented on a label which is attached to the calibration leak.

In vacuum operations (spray technique, see Chapter 7.1) one must differentiate between two types of calibration:

a) internal calibration and

b) external calibration.

Internal calibration of a leak detector uses a calibration leak which is permanently built into the leak detector. Using this **"internal calibration leak"**, only the leak detector, in which the calibration leak is built in, itself may be calibrated.

All Leybold leak detectors are equipped with an internal calibration leak. Via the automatically operated calibration routine, each leak detector may be "internally calibrated" within just a few seconds.

External calibration of a leak detector uses a calibration leak which is installed at the inlet of the leak detector. Using this **"external calibration leak"**, the leak detector may be calibrated in just a few minutes.

Furthermore, the external calibration leak may be used to check the proper functioning and operation of the internal calibration leak. In particular, external calibration leaks are always used if complete leak detector systems or partial flow arrangements must be calibrated.

Sniffer devices and sniffer arrangements must also usually be calibrated with external calibration leaks. In this case, it must be ensured that on the one hand the entire test gas from the calibration leak reaches the sniffer tip and on the other hand the gas flow through the sniffer unit is not hindered by the calibration process (see **Fig. 9**).

When making measurements using the sniffer technique (see Chapter 7.2) it is also necessary to take into account the distance from the probe tip to the surface of the specimen and the scanning speed; these must be included as a part of the calibration. In the special case where helium[4]
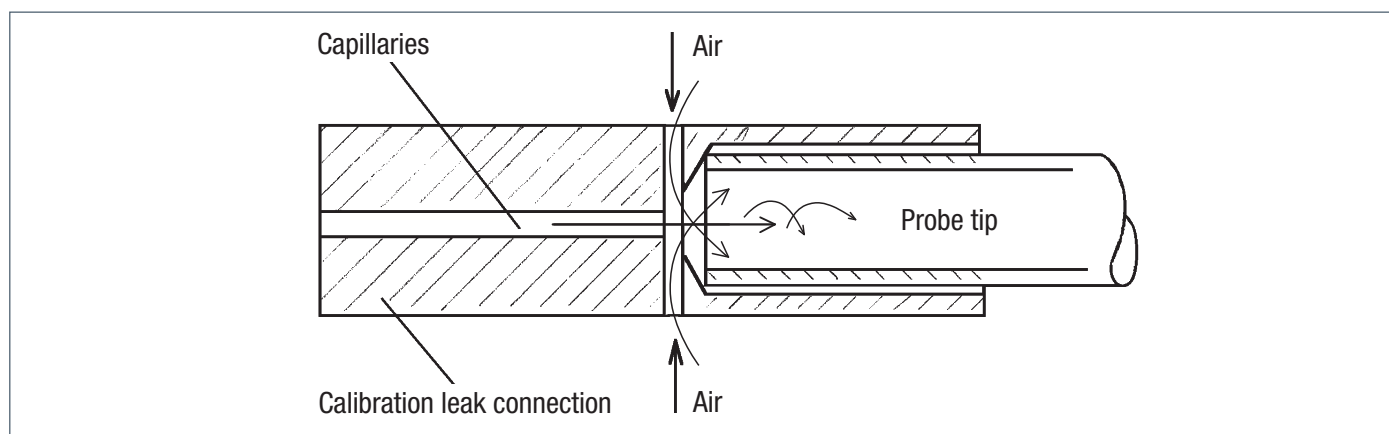
Fig. 9: Calibration connection of a sniffer calibration leak

concentration is being measured, calibration can be made using the helium content in the air, which is a uniform 5 ppm worldwide. **Calibration leaks** normally comprise a gas supply, a choke with a defined conductance value, and a valve. The configuration will be in accordance with the leak rate required.

Fig. 10 shows different helium calibration leaks. Permeation leaks are usually used in case of leak rates of 10^{-10} to 10^{-7} mbar·l/s. Capillaries are usually used for leak rates between 10^{-7} to 10^{-4} mbar·l/s and, for very large leak rates in a range from 10 to 1000 mbar·l/s, pipe sections or orifice plates with exactly defined conductance values.

Calibration leaks used with a refrigerant charge represent a special situation since the refrigerants are liquid at room temperature and usually feature a vapor pressure between 4 bar and 10 bar. One technological problem which is difficult to solve is the risk of clogging of the capillaries. All refrigerants are also very good solvents for oil and grease and thus are often seriously contaminated so that it is difficult to fill the calibration leaks with pure refrigerant. Decisive here is not only the chemical composition but above all dissolved particles which can repeatedly clog the fine capillaries.
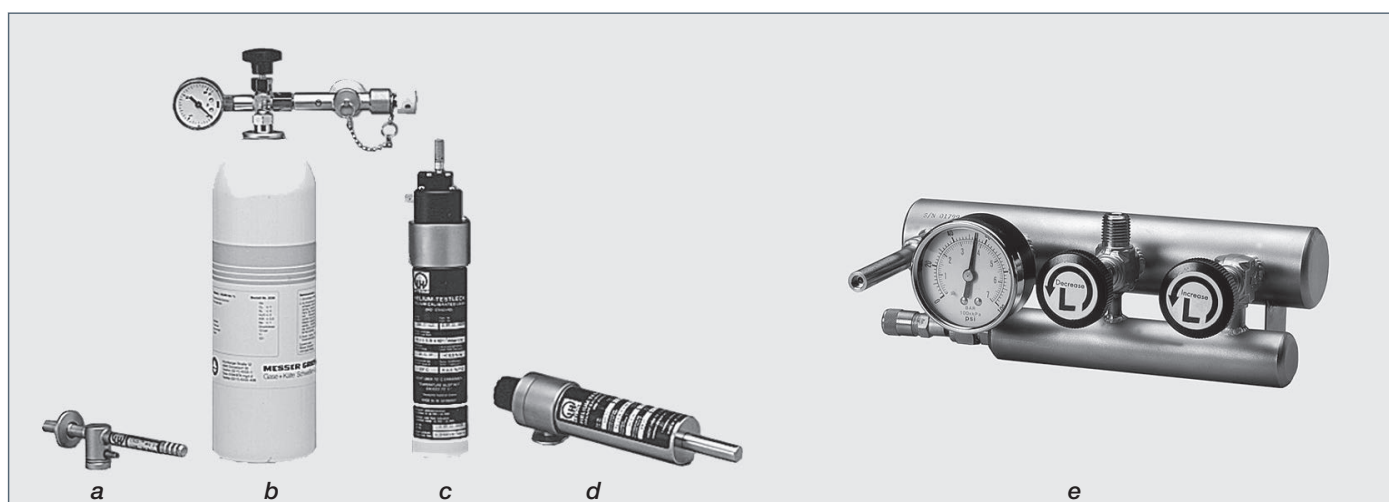
Fig. 10:
Examples for the composition of calibration leaks
a Calibration leak without gas supply TL4, TL6
b Calibration leak for sniffer and vacuum applications TL4-6
c (Internal) capillary calibration leak TL7
d Permeation calibration leak (also called "diffusion calibration leak") TL8, TL9
e Refrigerant calibration leak

Fig. 11:
Calibration leak for sniffing method with pressure regulator

5.2.4 Leak detectors with quadrupole mass spectrometer

Leak detectors with quadrupole mass spectrometers (QMS) are mostly build to detect masses greater than helium[4]. Apart from special cases, these will be refrigerants or lamp filling gases. Therefore, leak detectors with QMS are mostly used to inspect refrigeration units for leaks.

Fig. 12 shows the vacuum diagram of a leak detector with QMS. One may recognize the twofold gas inlet system which consists of the (direct flow) inlet for refrigerant via flow divider 1 and the (counter flow) inlet for helium into the turbomolecular pump via flow divider 2. This way, the device may be used to sniff for refrigerants as well as for helium.

Another special feature is the use of a two-stage diaphragm vacuum pump for evacuation of the QMS as well as for delivery of the sniffer gas flow (1st stage of the diaphragm vacuum pump).

5.2.5 Leak detectors with 180° sector field mass spectrometer

Helium leak detectors with 180° sector field mass spectrometer are the most sensitive and reliable leak detection devices. There is no other leak detection method with which one can, with greater reliability and better stability, locate leaks and measure them quantitatively. Therefore, helium leak detectors – even though the purchase price is relatively high – are very economical in the long run since the required for the leak detection procedure itself is very short.

A helium leak detector with 180° sector field mass spectrometer basically consists of three assemblies:
1. the mass spectrometer
2. the high-vacuum pump system
3. the roughing pump system.

The **mass spectrometer** (see **Fig. 13**) consists of the **ion source** (1–4), the **separation system** (5–10), and the **ion trap** (11–14). The ion beam is extracted through the orifice (5). The ions always enter the magnetic field (10) at a certain speed. Inside this magnetic field the ions move
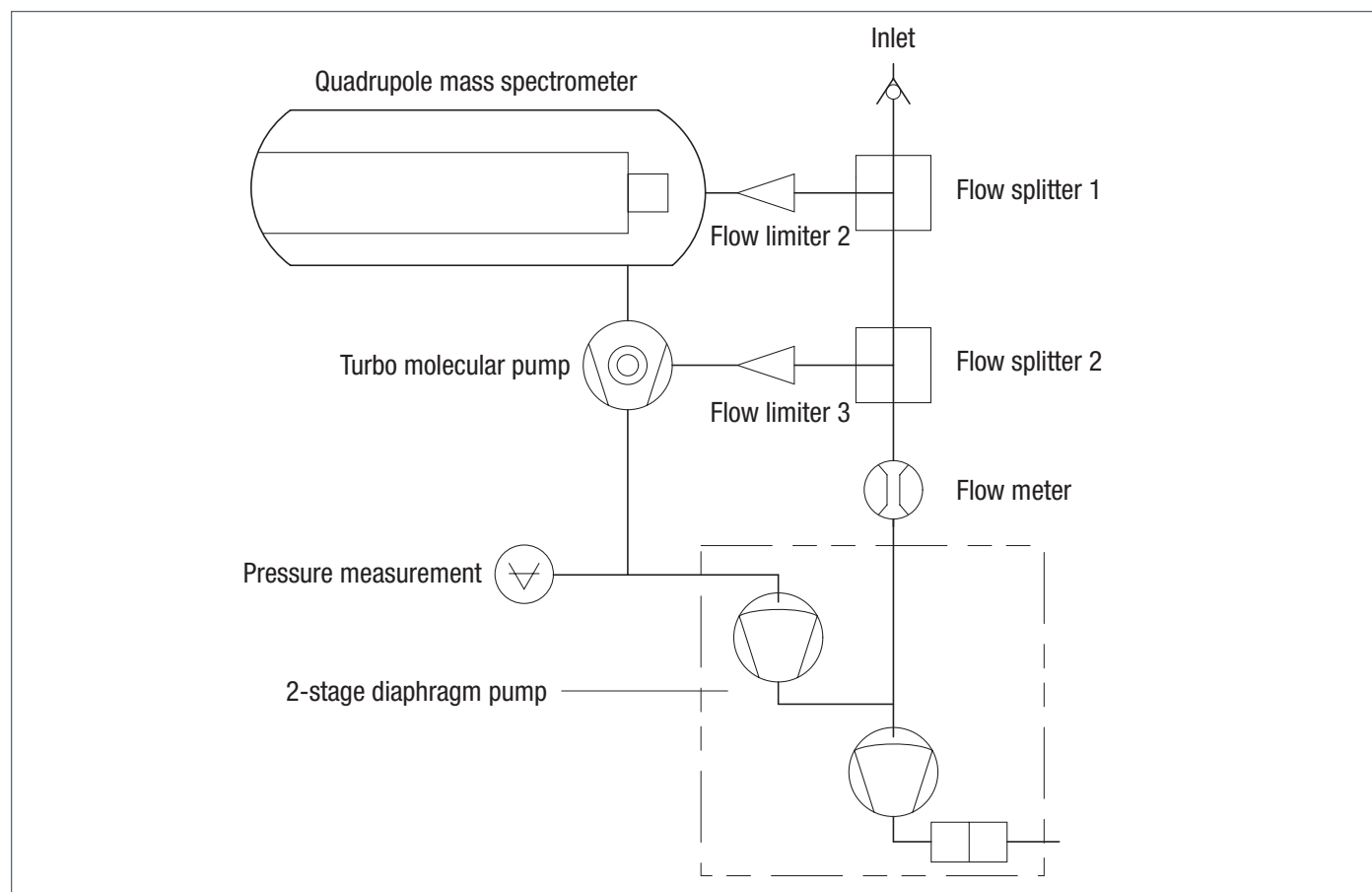
Fig. 12: Vacuum diagram of the Ecotec II

along circular paths whereby the radius for low masses is smaller than that for higher masses. With the correct setting of the acceleration voltage during tuning one can achieve a situation in which the helium[4] ions move exactly on the circular arc which is required for them to pass through the intermediate orifice plate (9). They way, the helium[4] ions reach the ion trap (13).

The ion source features a simple and rugged design. It can be replaced without much effort. During operation, the ion source is permanently heated and therefore unsusceptible to contamination.

The two selectable yttrium oxide coated iridium cathodes have a long service life. These cathodes are largely in-sensitive to air ingress, i.e. the quick-acting safety cut-out will keep them from burning out even if air enters. However, as for any annealed metals, prolonged use of the ion source may eventually lead to cathode embrittlement and can cause the cathode to splinter if exposed to vibrations or shock.

5.2.6 Direct-flow and counter-flow leak detectors

Depending on the way in which the gas from the test object is supplied to the mass spectrometer, one can differentiate between two types of helium leak detectors:

1. The direct-flow leak detector

2. The counter-flow leak detector

Fig. 14 shows the vacuum diagrams for the two leak detector types. In both cases, the mass spectrometer is evacuated by a high-vacuum pump system.

In case of the **direct flow leak detector** (left diagram), the gas to be inspected is supplied to the mass spectro-meter via a cold trap. The cold trap is cooled with liquid nitrogen (LN_2) and is basically a cryopump in which all the vapors and other contaminants condense. In case of the diffusion pump, which was usually used in the past, the LN_2-cooled cold trap was therefore an effective protection for the mass spectrometer against the oil vapors discharged from the diffusion pump.

1 Ion source flange
2 Cathode (2 cathodes: $Ir + Yt_2O_3$)
3 Anode
4 Shielding of the ion source with discharge orifice
5 Orifice
6 Ion traces for $M > 4$
7 Ion traces for $M = 4$
8 Intermediate orifice plate
9 Magnetic field
10 Suppressor
11 Shielding of the ion trap
12 Ion trap
13 Flange for ion trap with preamplifier
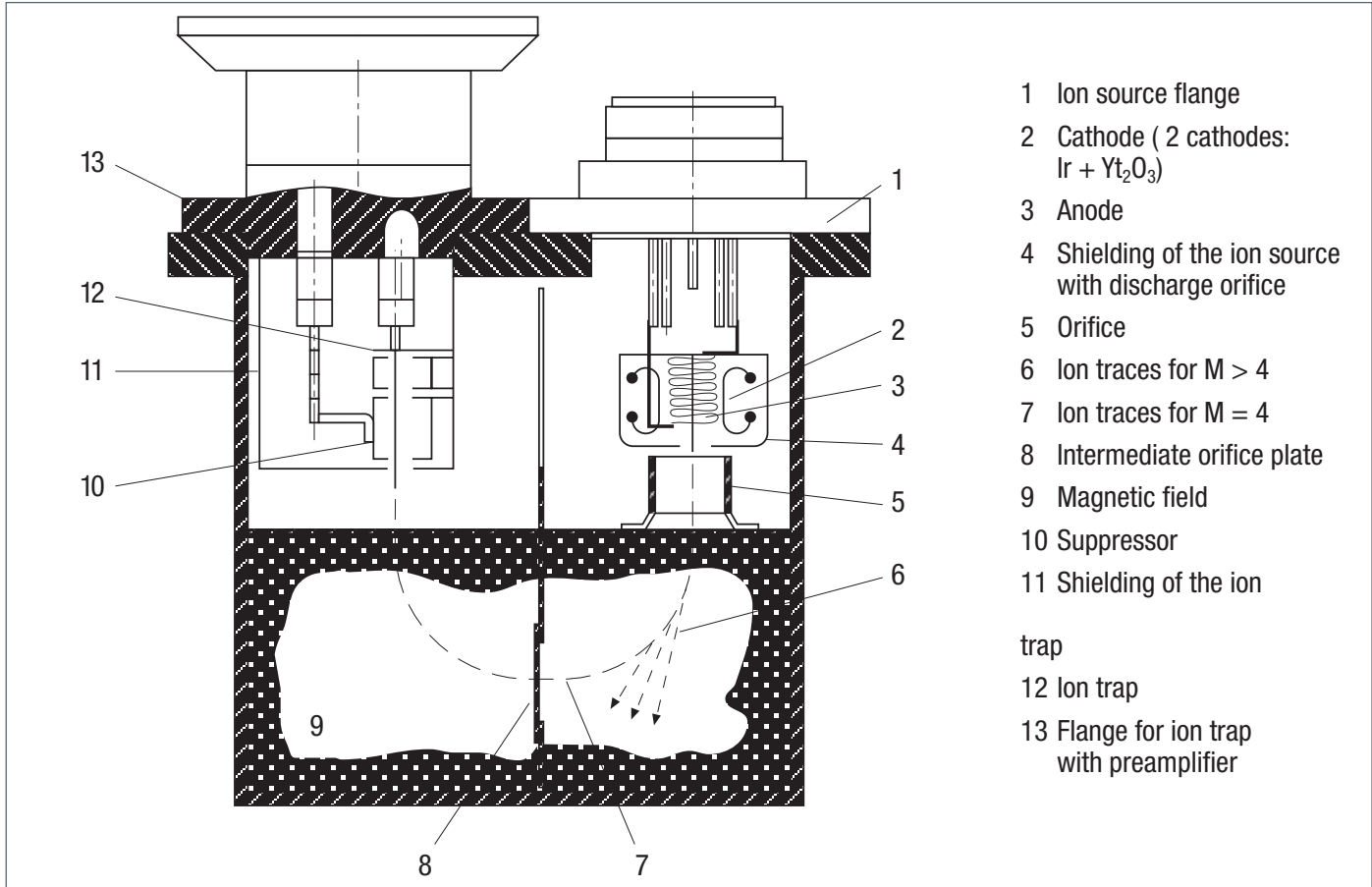
Fig. 13: Structure of a 180° sector field mass spectrometer

The auxiliary pump serves for pre-evacuation of the test object and the required connection lines. In order to be able to connect the high-vacuum side of the running high-vacuum pump with the test object, the auxiliary pump must evacuate the test object to a pressure below $5 \cdot 10^{-2}$ mbar. Only then it is possible to open the valve between auxiliary pump and cold trap. The high-vacuum pump must not evacuate the test object, the required connection lines and the mass spectrometer to a pressure below $2 \cdot 10^{-4}$ mbar. Afterwards, the mass spectrometer may start operating in order to detect leaks.

Depending on the size of the leak in the test object and the pumping performance of the vacuum pumps used, pumping times may be very long. In case of a very large leak, the abovementioned pressure values may not even be reached at all.

The right part of **Fig. 14** shows the diagram for the **counter-flow leak detector**. One immediately recognizes the substantial difference to the diagram of the direct-flow leak detector: Here, the high-vacuum pump only evacuates the mass spectrometer (smaller volume, very small leak rate) and not the test object (large volume, large leak rate in general).

In should be noted that, in case of the counter-flow leak detector, the supply of the gas to be inspected is carried out between the roughing pump and the high-vacuum pump. This means that the roughing pump and the auxiliary pump must bring the test object to a pressure at which the roughing side of the running high-vacuum pump can be connected to the test object. In case of today's counter-flow leak detectors, this so-called **start pressure** amounts to several millibars (Leybold counter-flow leak detector PHOENIX L300: start pressure = 15 mbar). If the start pressure at the inlet of the leak detector is reached, it immediately switches over to the measuring mode.

The partial test gas pressure $p_{FV, TG}$ between roughing pump and high-vacuum pump is increased by the test gas TG (TG = helium[4] or hydrogen) which flows into the leak detector. When the high-vacuum pump is running, the partial test gas pressure ($p_{HV, TG}$) on the high-vacuum side of the pump is significantly smaller than on the fore-vacuum side of the pump ($p_{FV, TG}$). Therefore, a certain amount of the test gas flows – against the delivery direction of the high-vacuum pump – from the fore-vacuum side to the high-vacuum side of the high-vacuum pump. This phenomenon is the reason why this kind of leak detector

Solution 1: Main flow leak detector

M S

PMS $< 2 \cdot 10^{-4}$ mbar

He

LN_2

High vacuum pump:
Turbo
(Diff)

Fore-vacuum pump   Auxiliary pump

Solution 2: Counterflow leak detector

M S

PMS $< 2 \cdot 10^{-4}$ mbar

He

High vacuum pump:
Turbo

Fore-vacuum pump   Auxiliary pump

Fig. 14: Comparison between main flow leak detector (left) and counterflow leak detector (right)

is referred to as "counter-flow leak detector".

In equilibrium, the following partial test gas pressure will be present on the high-vacuum side, i.e. between high-vacuum pump and mass spectrometer:

(5) $p_{HV, TG} = p_{FV, TG}/C_{0, TG}$

ein. In this case, $C_{0, TG}$ refers to the compression of the high-vacuum pump for the test gas TG at a test gas flow of zero (the net gas flow of the test gas through the high-vacuum pump is zero).

Nowadays, the high-vacuum pump in counter-flow leak detectors is always a turbomolecular pump with compound stage. This high-vacuum pump type features a high fore-vacuum consistency (e few millibars) and therefore allows for the abovementioned high start pressures in the millibar range. Therefore, the leak detection process can be carried out much faster than with a leak detector with oil diffusion pump (fore-vacuum consistency of an oil diffusion pump $\simeq 5 \cdot 10^{-1}$ mbar).

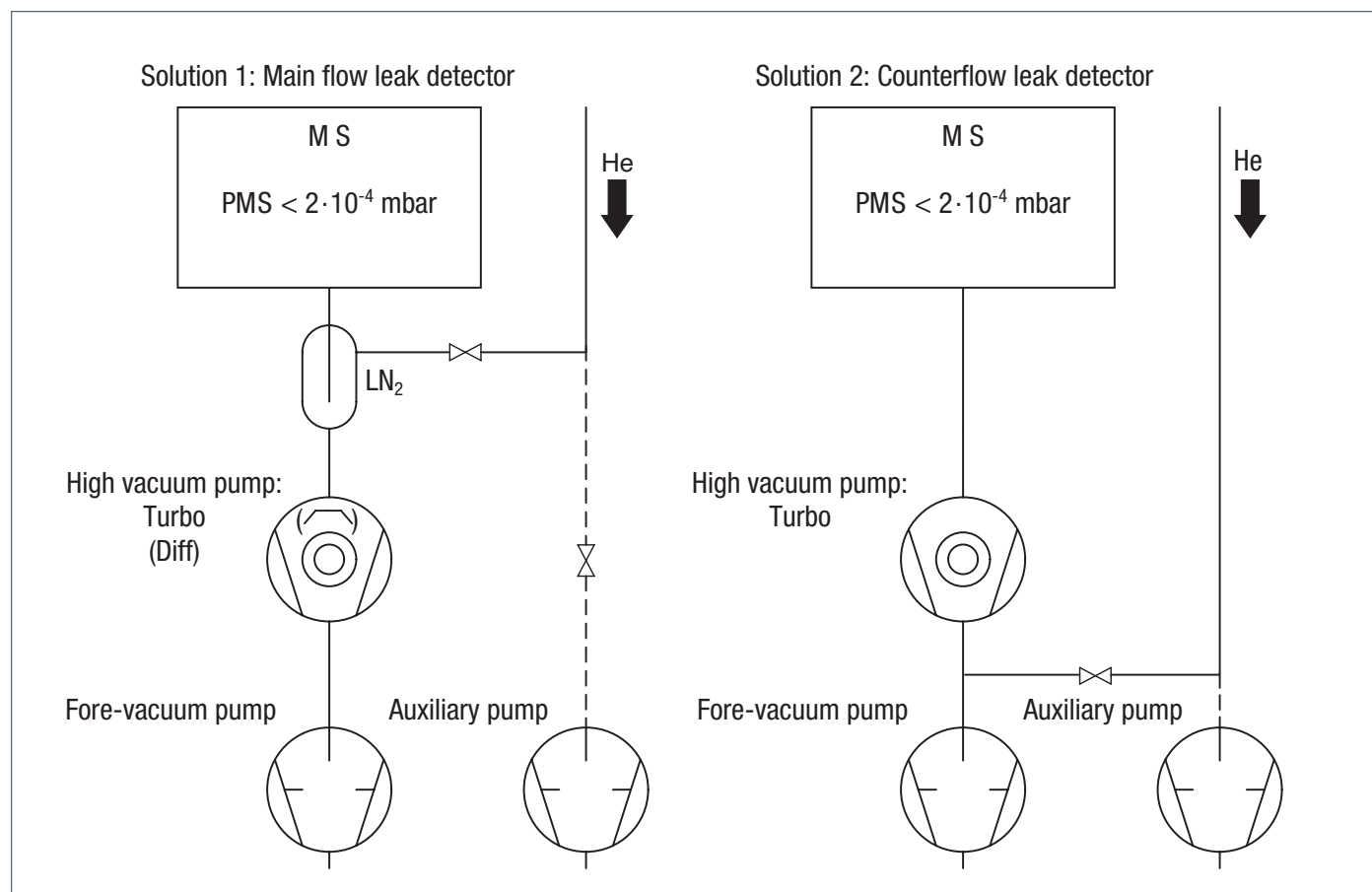Turbomolecular pumps feature a very high compression for heavy gases (hydrocarbon, oil vapors). Therefore, the following applies: In contrast to light test gases such as helium and hydrogen, heavy gas particles basically cannot reach the mass spectrometer. The turbomolecular pump is thus an optimal protection for the mass spectrometer and renders a liquid nitrogen-cooled cold trap obsolete.

5.2.7 Counter-flow leak detector in partial-flow operation

If evacuating the test object to the required start pressure is impossible or takes too long due to the size of the test object or the leak, an auxiliary pump (auxiliary pump system) must be used in addition to the leak detector. The leak detector will then be operated in a so-called partial-flow configuration (see **Fig. 14**). Since the auxiliary pump usually as a higher performance than the roughing pump integrated into the leak detector, the larger amount of the test gas will flow through the auxiliary pump and only a small amount of the test gas will flow through the roughing pump.

However, the partial test gas pressure at the inlet of the roughing pump and at the inlet of the auxiliary pump $p_{FV, TG}$ will be identical. Therefore, the total test gas flow from the test object amounts to

(6) $q_L = p_{FV, TG} \cdot (S_{RP, TG} + S_{AP, TG})$

with

$S_{RP, TG}$ = pumping speed of the roughing pump integrated into the leak detector for the test gas in l/s

$S_{AP, TG}$ = pumping speed of the auxiliary pump for the test gas in l/s

This is the true leak rate which the leak detector is supposed to display. The electronic system of the leak detector, however, generates the following display

(7) $q_{L, display} = p_{FV, TG} \cdot S_{RP, TG}$

The following results from (6) and (7):

The leak rate $q_{L, display}$ which is displayed by the leak detector equals the product of the true leak rate q_L and the partial flow ratio γ:

(7a) $q_{L, display} = q_L \cdot \gamma$

(8) $\gamma = S_{RP, TG}/(S_{RP, TG} + S_{AP, TG})$
        (partial-flow ratio)

The partial-flow ratio is calculated by means of relation (8). In practice, it often makes sense to determine the partial-flow ratio experimentally. To do this, one installs a calibration leak with the leak rate q_L directly at the leak detector (operation without auxiliary pump). The leak detector will then indicate the true leak rate q_L of the leak detector on the display. The value q_L must be recorded. Now, one installs the same calibration leak at the test object, puts the auxiliary pump in operation and records the indication on the display of the leak detector. The leak detector now indicates $q_{L, display}$. The partial-flow ratio γ being sought will then result from the quotient of $q_{L, display}$ and q_L:

(8a) $\gamma = q_{L, display}/q_L$ **(partial-flow ratio)**

5.2.8 Connection to vacuum systems

The connection of a leak detector to vacuum systems with multi-stage vacuum pump sets is usually carried out by means of the partial-flow method. When considering where to best make the connection, it must be kept in mind that the leak detector is usually a small, portable unit which has only a low pumping speed at the connection flange (typically with $S_{RP, TG} \simeq 2$ m³/h). This makes it all the more important to estimate - based on the partial flow ratio to be expected vis à vis a diffusion pump with pumping speed of $S_{AP, TG} = 10,000$ l/s = 36,000 m³/h for example - which leak rates can be detected at all.

In systems with high vacuum and Roots pumps, the surest option is to connect the leak detector between the rotary vane pump and the roots pump or between the roots pump and the high-vacuum pump. If the pressure there is greater than the permissible inlet pressure for the leak detector, then the leak detector will have to be connected by way of a metering (variable leak) valve. Naturally one will have to have a suitable connector flange available. It is also advisable to install a valve at this point from the outset so that, when needed, the leak detector can quickly be connected (with the system running) and leak detection can commence immediately after opening the

valve. In order to avoid this valve being opened inadvertently, it should be sealed off with a blank flange during normal vacuum system operation.

Another method for connecting a leak detector to lager vacuum systems is to insert a sniffer into the atmosphere-side outlet of the system. One then sniffs the increase in the test gas concentration in the exhaust.

$S_{LD} = S_{R, He}$ = pumping speed of the roughing pump built into the leak detector for helium in l/s at the branching point

$S_{AP} = S_{AP, He}$ = pumping speed of the auxiliary pump for helium in l/s at the branching point

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Example for usage of a leak detector with partial flow principle

Vacuum reservoir with leak

$V_{ch} = 150$ l

Helium leak rate
$q_L(He) = 3 \cdot 10^{-1}$ mbar · l/s

Branching point

Helium leak detector
$S_{LD}(He) = 8$ l/s

Auxiliary pump
$S_{AP}(He) = 60$ m³/h $\simeq 17$ l/s
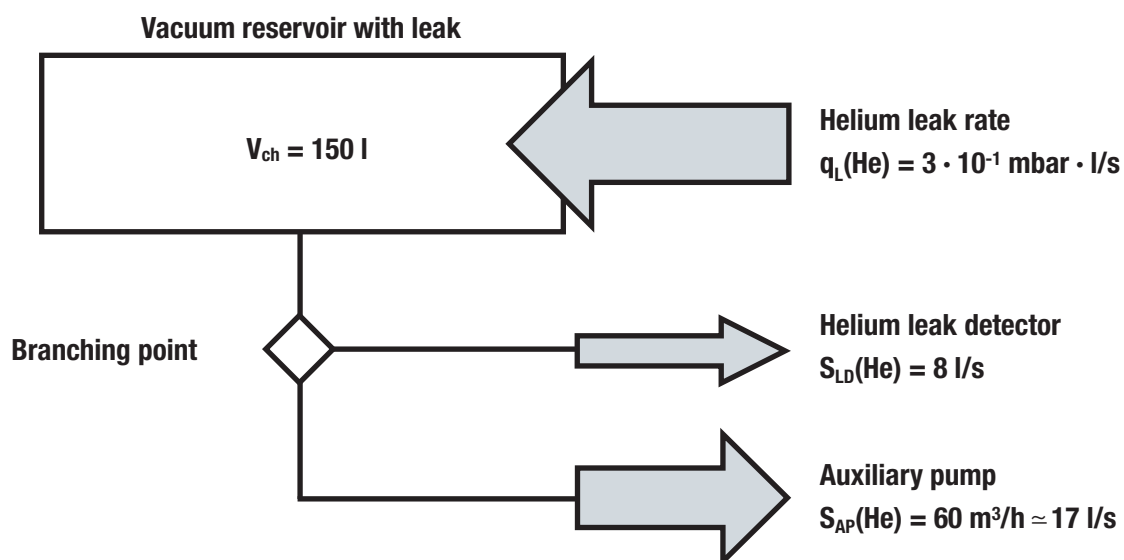
At the branching point, the helium flow q_L which is discharged from the vacuum reservoir is divided into a helium flow $q_{L, display}$ towards the leak detector and a helium flow q_{AP} towards the auxiliary pump.

Helium flow towards leak detector:
The leak rate $q_{L, display}$ which is displayed by the leak detector equals the product of the true leak rate q_L and the partial flow ratio γ !

The calculation shows $\gamma = S_{LD}/(S_{LD} + S_{AP}) \simeq (8 \text{ l/s})/(8 \text{ l/s} + 17 \text{ l/s}) = 0.32$ and

$q_{L,\_display} = q_L \cdot \gamma = (3.0 \cdot 10^{-1} \text{ mbar·l/s}) \cdot 0.32 = 9.6 \cdot 10^{-2}$ mbar·l/s

Conclusion: The leak detector shows a leak rate which is smaller than the true leak rate by a factor of $1/\gamma = 1/0.32 \simeq 3.1$!

Response time $= 3 \tau = 3 \cdot V_{ch}/S_{eff} = 3 \cdot V_{ch}/(S_{LD} + S_{AP}) \simeq (3 \cdot 150 \text{ l})/(8 \text{ l/s} + 17 \text{ l/s}) = 18$ s

Fig. 15: Example for usage of a leak detector with partial flow principle

5.2.9 Time constant

The **time constant** of a vacuum system is provided by

(9) $\tau = V_{ch}/S_{eff}$ with

V_{ch} = volume of the vessel in l
S_{eff} = effective pumping speed for the test gas at the vessel in l/s

Fig. 16 shows the course of the signal after spraying a leak in a test object attached to a leak detector, for three different configurations:

1. Center: The test object (volume V_{ch}) is directly connected to the leak detector LD (effective pumping speed for the test gas = S_{LD}).

2. Left: In addition to 1, an auxiliary pump (= partial-flow pump) with the same effective pumping speed $S_{AP} = S_{LD}$ is connected to the test object.

3. Right: Same as 1, however, S_{LD} is throttled down to 0.5 S_{LD}.
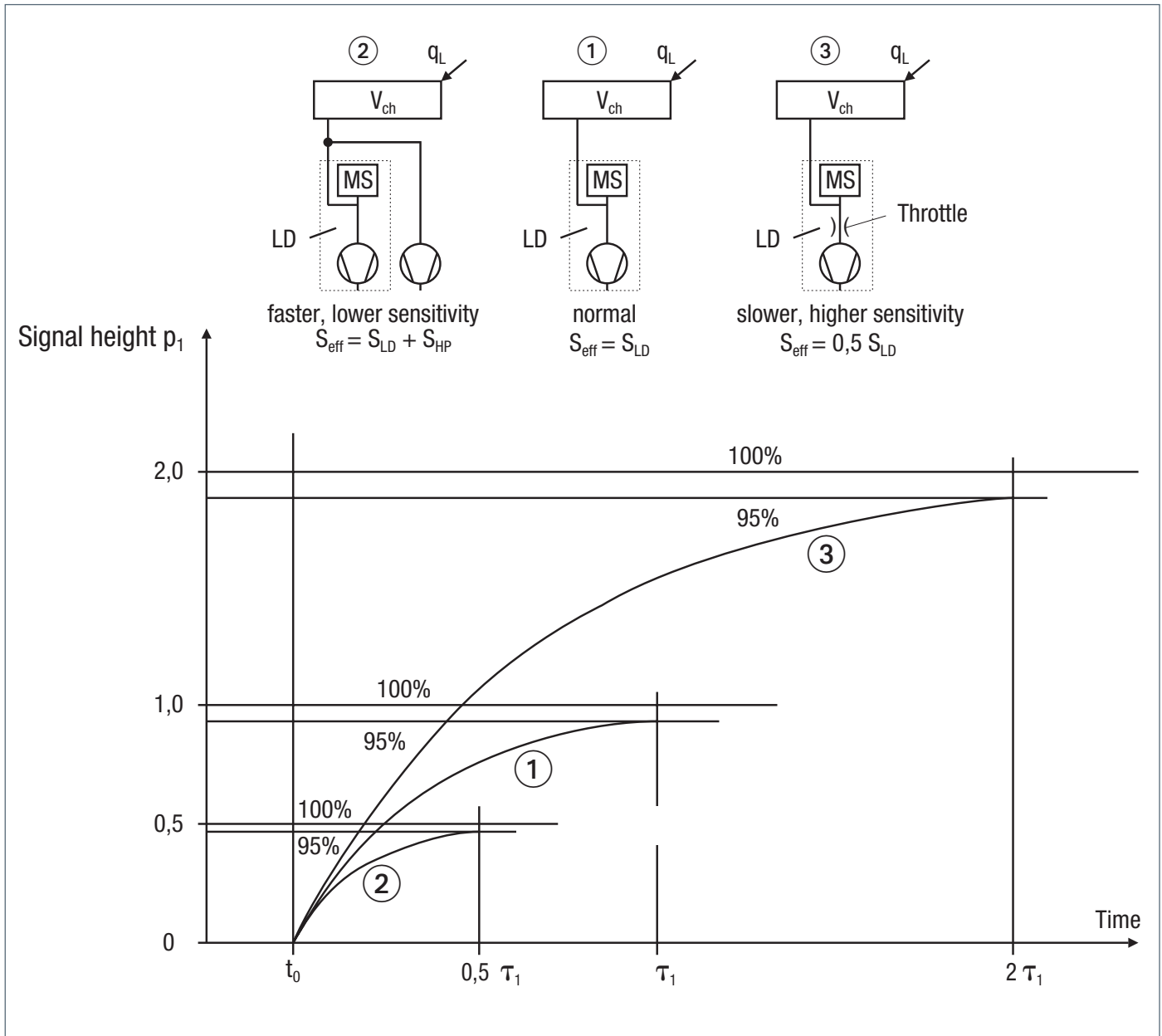
Fig. 16: Example for usage of a leak detector with partial flow principle
   $p_1 = q_L/S_{eff}$, $\tau_1 = 3\ V_{ch}/S_{eff}$

The three corresponding signal curves are shown below:

Curve 1: After a **"dead time" t_0** the signal proportional to **the partial test gas pressure p_{TG}** increases over **time t** according to the relation

(10) $\qquad p_{TG} = (q_L/S_{eff}) \cdot \{\, 1 - \exp[\,-(t - t_0)/\tau\,]\,\}$

After a certain period of time, the signal reaches a portion of its ultimate value

$t - t_0 = 1\,\tau$	**63.3 % of ultimate value**
$t - t_0 = 3\,\tau$	**95.0 % of ultimate value**
$t - t_0 = 6\,\tau$	**99.8 % of ultimate value**

The **ultimate value of the signal is proportional to** $p_{TG} = q_L/S_{eff}$ since the exponential term in (10) will disappear for $t - t_0 \gg \tau$. The time span $t - t_0$ which is required to reach 95 % of the ultimate value is referred to as **response time**. This is given by **$3\,\tau$**.

This provides the following result for **curve 1**:
The ultimate value of the signal is proportional to
$p_{TG} = q_L/S_{eff} = q_L/S_{LD} = p_1$
Response time = $3\,\tau = 3\,V_{ch}/S_{eff} = 3\,V_{ch}/S_{LD} = \tau_1$

The following applies for **curve 2 (= partial-flow operation)**:
The ultimate value of the signal is proportional to
$p_{TG} = q_L/S_{eff} = q_L/(S_{LD} + S_{AP}) = 0.5 \cdot p_1$
**Response time** $= 3\,\tau = 3\,V_{ch}/S_{eff} = 3\,V_{ch}/(S_{LD} + S_{AP}) = 0.5 \cdot \tau_1$

Due to the installation of an auxiliary pump (= partial-flow pump), the **response time** will always be **shortened** and the **ultimate value of the signal** will always be **decreased**. In the above example, the response time is halved but the ultimate value of the signal is halved as well.

A short response time means a quick change and display of the signal. This provides that advantage that the expenditure of time required for leak detection can be significantly reduced. The consequential downside that the ultimate value of the signal is smaller does, in most cases, not result in any severe problems due to the very high sensitivity of today's leak detectors.

Conclusion: Partial-flow operation reduces the expenditure of time for leak detection!

Accordingly, the following applies to **curve 3**:
Ultimate value of the signal is proportional to
$p_{TG} = q_L/S_{eff} = q_L/(0.5 \cdot S_{LD}) = 2 \cdot p_1$
Response time = $3\,\tau = 3\,V_{ch}/S_{eff} = 3\,V_{ch}/(0.5 \cdot S_{LD}) = 2 \cdot \tau_1$

Due to the throttling of the pumping speed, the **response time** will always be **prolonged** and the **ultimate value of the signal** will always be **increased**. In the above example, the response time is doubled but the ultimate value of the signal is doubled as well. A reduction of the pumping speed is always associated with a higher expenditure of time and thus by no means always an advantage.

An estimate of the overall time constants for several volumes connected one behind to another and to the associated pumps can be made in an initial approximation by adding the individual time constants.

6 Limit values / specifications for the leak detector

1. The smallest detectable leak rate ($q_{L,\,min}$)

2. The effective pumping speed for the test gas at the inlet ($S_{eff,\,TG}$)

2a. The effective pumping speed for air at the inlet (S_{eff})

3. The maximum permissible pressure inside the test object (p_{max})
(= the maximum permissible inlet pressure)
The maximum permissible inlet pressure p_{max} is about 10^{-1} mbar for leak detectors with classic turbomolecular pump and 2 to 15 mbar for leak detectors with compound turbomolecular pump.

4. The maximum permissible gas flow for air (q_{max})

The product of the maximum permissible inlet pressure p_{max} and the effective pumping speed for air at the inlet S_{eff} equals the maximum permissible gas flow for air q_{max}. If a gas flow which is greater than q_{max} enters the leak detector due to one large or several small leaks, the device is inoperable.

7 Leak detection techniques using vacuum leak detectors

7.1 Vacuum method – spray technique (local leak test)

The test object connected to the vacuum leak detector is traced with a very fine stream of test gas from the spray pistol at likely leakage points (flange connections, welding seams, etc,) in an appropriately slow manner. The appropriate speed for this process is determined by the response time of the system (see Chapter 5.2.9). The test gas amount sprayed must be adjusted to suit the leak rate to be detected as well as the size and accessibility of the object being tested.

Although the test gas (hydrogen, helium) is lighter than air and will therefore accumulate beneath the ceiling of the room, it will be so well distributed by drafts and turbulence induced by movements within the room that one need not assume that test gas will be found primarily (or only) at the top of the room during search for leaks. In spite of this, it is advisable – particularly when dealing with larger components – to start the search for leaks at the top.

In order to avoid a surge of test gas when the spray pistol is opened, it is advisable to install a choke valve to adjust the test gas flow directly before or after the spray pistol (see **Fig. 17**). The easiest way to set the desired test gas flow is to submerge the spray pistol in a water container and determine the setting based on the rising test gas bubbles.

With helium leak detectors, it is also easy to detect the natural amount of helium[4] in the atmosphere.

The natural amount of helium[4] in the atmosphere amounts to $5 \cdot 10^{-4}$ volume percent (= 5 ppm). If air enters the test object through a very large leak, the leak detector will therefore already detect helium[4] gas flowing through the leak. The leak rate is then:

(11)   Display (helium[4] from spray pistol) / 100 % = Display (helium[4] from atmosphere) / $5 \cdot 10^{-4}$ %

or

(11a)   Display (helium[4] from spray pistol) = $2 \cdot 10^5 \cdot$ Display (helium[4] from atmosphere)
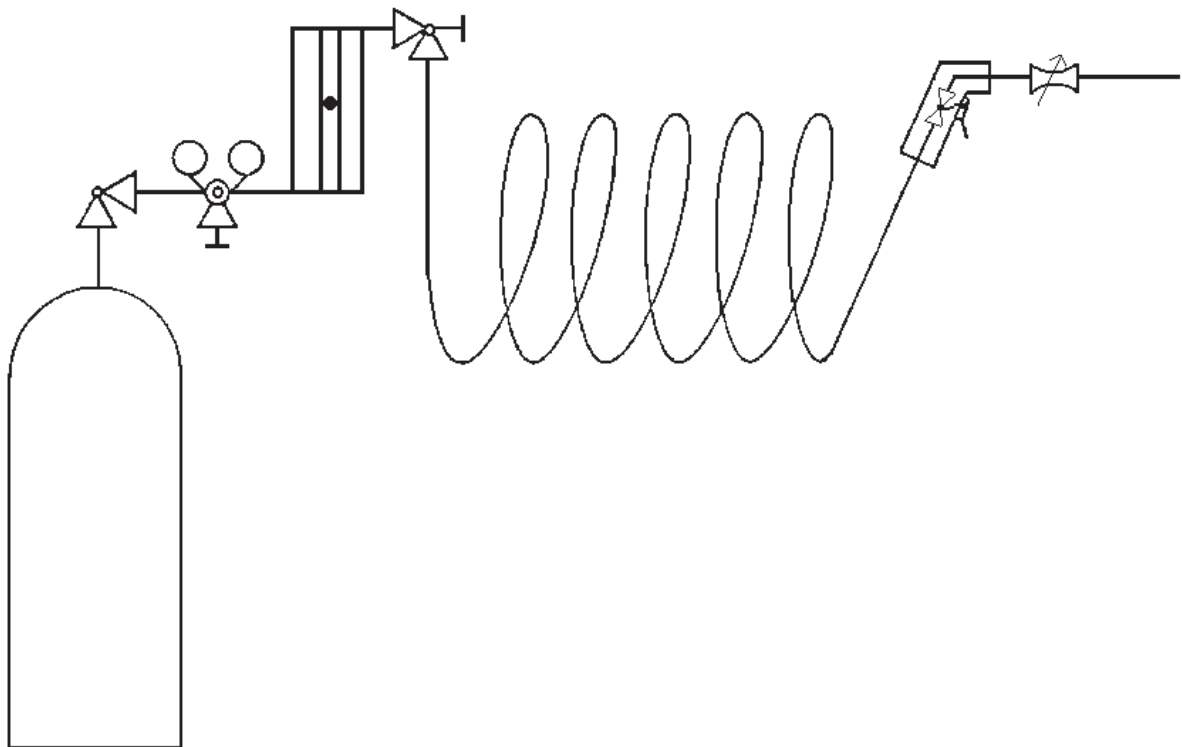
Avoiding the "helium surge" when the spray-pistol valve is opened by means of throttle valve at the spray-pistol tip

Minimum helium flow for correct display:
Changes on the throttle valve setting must not affect the indication

Simplest way to check the helium flow:
Bubble test in a glass of water

Fig. 17: Handling information for using test gases (e.g. helium)

7.2 Positive pressure method – sniffer technique (local leak test)

In case of this method, the test object is filled with test gas to an extend so that the partial test gas pressure in the test object is significantly larger than that around the test object. If possible, the test object should be evacuated prior to filling it with test gas.

The likely leak positions of the test object are traced with a sniffer tip in an appropriately slow manner. A typical tracing speed is 1 cm/s.

The sniffer tip is connected to the roughing pump (see Fig. 4d) via a long, thin line (length ≃ 1 m, diameter≃ 1 mm). Test gas which enters the sniffer tip is delivered to the leak detector by the roughing pump and then detected there by the mass spectrometer.

Vacuum detectors by Leybold are able to "sniff" helium[4] or hydrogen.
The sensitivity of the method and the accuracy of the localization of leaks depend on

a) **the type of sniffer unit used (sniffer tip + line),**
b) **the response time of the leak detector used,**
c) **the tracing speed**
   and
d) **the distance of the sniffer tip from the surface of the test object.**

The many parameters which play a part here make it more difficult to determine the leak rates quantitatively. Using sniffer processes, it is possible to detect leak rates of more than $1 \cdot 10^{-7}$ mbar·l/s. The limitation regarding the sensitivity for detecting helium[4] is due primarily to the natural amount of helium[4] in the atmosphere. For quantitative measurements, the leak detector and sniffer unit will have to be calibrated together. In this case, the distance of the sniffer tip from the outlet of the calibration leak will be included in the calibration as well.

7.3 Envelope test (integral leak test)

An envelope test is an integral leak test using helium[4] as test gas. In case of this method, the test object is enclosed in a rigid (usually metal) enclosure or in a light plastic envelope. The helium[4] which flows through the leaks of the test object is detected using a helium leak detector.

Envelope tests are carried out according to the vacuum method (test object under vacuum, Fig 4a) as well as the positive pressure method (test object under positive pressure, Fig. 4c). In both cases it might be necessary to carry out the conversion to the helium standard leak rate.

7.3.1 Envelope test according to the positive pressure method

a) **Envelope test with concentration measurement and subsequent leak rate calculation**

In order to determine the overall leakage of the test object, it is enclosed with an envelope which may be rigid or flexible. The helium[4] which flows through the leaks of the test object accumulates in the envelope so that the helium concentration in the envelop increases. After an accumulation time (operating period) to be determined, the change in concentration inside the envelope will be measured with a sniffer connected to the helium leak detector (Fig. 4c). The overall leak rate (= integral leak rate) can be calculated following the calibration of the test configuration with a known concentration, e.g. atmospheric air (5 ppm).

This method makes it possible to detect even the smallest overall leakage and is suitable in particular for automated industrial leak testing. Due to gas accumulation, the limits for normal sniffer techniques are shifted toward lower leak rates and the ambient conditions such as temperature, air flow and sniffer tracing speed lose influence. When using plastic envelopes it is necessary to take into account helium permeation through the plastic envelope during long enrichment periods.

b) **Direct measurement of the leak rate with the leak detector (rigid envelope)**

When the test object, pressurized with helium, is placed in a rigid vacuum vessel which is connected to a helium leak detector, the integral leak rate can be read directly at the leak detector.

7.3.2 Envelope test according to the vacuum method

a) Envelope = "plastic tent"

The evacuated test object which is connected to the leak detector is enclosed with a flexible, light (plastic) envelope. Before the envelope is filled with helium, one presses it against the test object, in order to remove as much of the existing atmosphere air as possible.

The entire outer surface of the test object has contact with the test gas (helium). If test gas enters the test object through the leaks, the integral leak rate is measured without knowing the exact number of leaks.

In case of repeated tests in closed rooms, it must be noted that the helium concentration in the room will increase rather rapidly after removing the envelope. Using plastic bags is therefore more advisable for "one-time testing" of large systems.

b) Rigid envelope

Rigid envelops should be used in case of test series for determining integral leak rates. Furthermore, this has the advantage that the helium can be recovered after the test has been carried out.

7.4 "Bombing" test, "storage under pressure"

The "bombing test" is used to check the tightness of components which are already hermetically sealed and which exhibit a gas-filled, internal cavity. The components to be examined – e.g. IC housings, transistors, laser diodes, reed contacts, quartz oscillators – are placed in a pressure vessel which is filled with helium. Operating with the test gas at relatively high pressure (5 to 10 bar) and leaving the system standing over several hours the test gas will accumulate inside leaking test objects. This process is called "bombing".

For the leak test, the test objects are placed in a vacuum chamber (= rigid envelope) after the "bombing" and – as described for the envelope test according to the vacuum method – tested for their integral leak rate. Test objects with large leaks, however, already lose most of their test gas during evacuation of the vacuum chamber to the required test pressure so that no leaks are detected during the leak test using a leak detector.

Therefore, another test for detection of large leaks must be carried out prior to the leak test inside the vacuum chamber.

8 Industrial leak test.

Industrial leak testing using helium as the test gas is characterized above all by the fact that the leak detection equipment can be fully integrated into the manufacturing line. The design and construction of such test units will naturally take into account the task to be carried out in each case (e.g. leak testing of car rims for tubeless tires and fuel tanks or leak testing of components for refrigeration and air conditioning technology or leak testing of metal drums), where mass-produced, standardized component modules will be used wherever possible.

The parts to be examined are fed to the leak testing system (envelope test with rigid envelope), where the leak test is carried out, by way of a conveyor system. Parts which have a leak can be detected and sorted out very quickly.

Since costs always play an important role in case of industrial leak testing, the helium consumption must be kept as low as possible. This is achieved e.g. by using a mixture of helium and air as test gas instead of 100 % helium.

The helium concentration c(He) is determined by the partial helium pressure p(He) (= pressure of the helium in the mixture) in relation to the total pressure p (= pressure of the helium/air gas mixture):

$$c(He) = p(He) \ / \ p = p(He) \ / \ [\ p(He) + p(air) \ ]$$

The leak rate $q_{L, display}$ is proportional to c(He) and proportional to the "true leak rate" q_L which would be measured at c(He) = 1.

Therefore, the following applies:

$$q_{L, display} = c(He) \cdot q_L$$

Regarding this method for the reduction of helium consume, however, it is always important to check whether the "reduced leak rate" $c(He) \cdot q_L$ is still within the permissible operating range of the leak detector and whether it may therefore be displayed correctly.

The **advantages of industrial leak testing using helium as test gas** can be summarized as follows:

- The detectable leak rates are significantly lower than the leak rates which must be detected in practice.

- The integral leak test also allows for detection of microscopic and sponge-like distributed leaks.

- Testing procedure and testing sequence can be automated.

- The cyclical, automatic test system check ensures great testing reliability.

- Helium is non-toxic and non-hazardous.

- The quantitative result of the test can be documented quickly and easily along with all process parameters.

The industrial leak test using helium as test gas results in a significant time advantage (cycle times of only a few seconds) and a significant increase in test reliability. Therefore, traditional industrial test methods such as "water bath" and "soap bubble test" have already been largely abandoned.

9 Formulary for leak detection technique

9.1 Pressure of a gas and pressure units

The **pressure of a gas on a limiting wall** is the surface-related normal component of the force which the gas exerts on the wall (DIN 28 400):

Pressure (p) = normal component of the force (F_N) per surface (A)

$$p = F_N / A$$

The SI unit of pressure (formula symbol: **p**) is **Pascal** (unit symbol: **Pa**). The unit **Bar** (unit symbol: **bar**) is also legally approved. The common pressure unit in vacuum technology is **millibars** (unit symbol: **mbar**).

$$1\ Pa = 1\ N/m^2$$

$$1\ bar = 1000\ mbar = 10^5\ Pa = 10^5\ N/m^2$$

$$1\ mbar = 100\ Pa = 1\ hPa$$

Unit of force: 1 N(ewton) = 1 kg·m/s²

Unit of surface: 1 m², 1 cm² (1 m² = 10,000 cm² = 10⁴ cm²)

9.1.1 Partial pressure – total pressure

Example for gas mixture: air

Normal pressure	p_n	=	1013.25 mbar
Normal temperature	T_n	=	273.15 K
Molar gas constant	R	=	83.145 (mbar·l) / (mol·K)
Molar volume of an ideal gas	$V_{M,n}$ = $\dfrac{R \cdot T_n}{p_n}$		22.414 l/mol
	V	=	100.00 l

Dry air at p_n; T_n; V = 100 l

Component	Composition (concentration)	Mass	Molar mass	Molar composition	Partial pressure
i	$c_i = \gamma_i/\gamma$ Volume percent (sea level)	$m_i = (M_i/V_{M,n}) \cdot V \cdot c_i$ g	M_i g/mol	$\gamma_i = m_i/M_i$ mol	mbar
1 N_2	78.10 %	97.609	28.013	3.484	791.87
2 O_2	20.90 %	29.837	31.999	0.932	211.91
3 Ar	0.90 %	1.604	39.948	0.040	9.13
4 CO_2	0.03 %	0.065	44.010	0.001	0.33
5 H_2	$< 1.0 \cdot 10^{-3}$ %	0.000	2.016	0.000	$1.0 \cdot 10^{-2}$
6 He	$5.0 \cdot 10^{-4}$ %	0.000	4.003	0.000	$5.1 \cdot 10^{-3}$
7 Rest	0.07 %				
Total	100.00 %	129.116	28.959	4.459	1013.25
		$m = \Sigma_i m_i$	$M = m/\gamma$	$\gamma = \Sigma_i \gamma_i$	$p_{total} = \Sigma_i p_i$

9.2   Gas quantity

Gas quantity   = pressure x volume

             = p·V

             = pV - value

Unit   **mbar·l**

9.2.1   Equation of state for ideal gases

p·V = (m/M)·(R·T)

Legend   **p** = The pressure with which the gas has been pressurized

                     (gas pressure) in **mbar**

                V = The volume which the gas occupies

                     (gas volume) in **l**

                m = The mass of the gas

                     (gas mass) in **g**

                M = The molar mass of the gas

                     (formerly: molecular weight) in **g/mol**

                T = The temperature of the gas

                     (gas temperature) in **K**

                R = The molar gas constant

                     = 83.145 **(mbar·l)/(mol·K)**

9.3   Gas flow

Gas flow Q

= Change of a gas quantity over time

= Δ(p·V)/Δt

Unit   **mbar·l/s**

Legend   **Δt** = time period in **s**

9.3.1   (Gas) mass flow

Q = Δ(p·V)/Δt = (Δm/Δt)·(R·T)/M

therefore

Δm/Δt = (Q·M)(R·T)

Unit   **g/s**

9.4 Pumping speed

Pumping speed S of a vacuum pump in case of inlet pressure p_P

= Gas flow/inlet pressure

= Q/p_P

= $S(p_P)$

Unit   **l/s, m³/h**

Conversion l/s <=> m³/h:

1 l/s   =   3.6 m³/h

1 m³/h   =   (1/3.6) l/s =   0.28 l/s

Legend   **Q** = The gas flow through the vacuum pump
                           in **mbar·l/s**

                     p_P = The pressure at the inlet of the vacuum pump
                           in **mbar**

9.5 Leak rate

Leak rate q_L

= Gas flow through an existing leak

Unit   **mbar·l/s**

9.5.1 Leak rate for pressure rise/pressure drop measurement

Leak rate q_L

= $\Delta(p \cdot V)/\Delta t = V \cdot (\Delta p/\Delta t)$

V is independent of the time!

Unit   **mbar·l/s**

Legend   **V** = The volume of the test object
                           in **l**

                     Δp = The pressure rise/pressure drop inside the test object after expiration of the time **Δt**
                           in **mbar**

                     Δt = The measuring time
                           in **s**

9.6 Concentration of the test gas

Concentration of the test gas c_{TG}

= Partial test gas pressure/total pressure

$$c_{TG} \text{ [volume \%]} = \frac{p_{iTG}}{p_T} \cdot 100$$

9.6.1 Leak rate in case of decreased test gas concentration

Leak rate $q_{L, display}$ displayed by the leak detector

= Test gas concentration x true leak rate q_L

$$q_{L, display} = c_{TG} \cdot q_L$$

Legend c_{TG} = Test gas concentration

p_{iTG} = Partial test gas pressure

in **mbar**

p_T = Total pressure

in **mbar**

$q_{L, display}$ = The leak rate displayed by the leak detector

in **mbar·l/s**

q_L = The true leak rate ($c_{TG} = 1$)

in **mbar·l/s**

9.7 "Temperature adjustment" (test temperature conversion)

Laminar viscous flow

$$q_L(T_2) \cdot (T_2)^{1/2} = q_L(T_1) \cdot (T_1)^{1/2}$$

Molecular flow

$$q_L(T_2) \cdot (T_1)^{1/2} = q_L(T_1) \cdot (T_2)^{1/2}$$

Legend $q_L(T_1)$ = The leak rate measured at the temperature T_1

in **mbar·l/s**

$q_L(T_2)$ = The leak rate measured at the temperature T_2

in **mbar·l/s**

T_1 = Temperature T_1

in **K**

T_2 = Temperature T_2

in **K**

9.8 "Pressure adjustment" (test pressure conversion)

Laminar viscous flow

$q_L = q_N \cdot (p_B^2 - p_A^2)$ Vacuum technique

$q_L = q_N \cdot (p_A^2 - p_B^2)$ Positive-pressure technique

Molecular flow

$q_L = q_N \cdot (p_B - p_A)$ Vacuum technique

$q_L = q_N \cdot (p_B - p_A)$ Positive-pressure technique

Legend q_L =   Leak rate in **mbar·l/s**

The test gas flows through the leak due to a difference between the partial test gas pressures p_A and p_B.

q_N =   The "standard leak rate" in **mbar·l/s**

The test gas flows from 1 bar absolute partial test gas pressure to 0 bar absolute partial test gas pressure.

q_A =   Partial test gas pressure inside test object in **bar absolute**

q_B =   Partial test gas pressure outside the test object in **bar absolute**

9.9 Change of gas type

Laminar viscous flow

$q_{L, \text{gas A}} \cdot \eta_{\text{gas A}} = q_{L, \text{gas B}} \cdot \eta_{\text{gas B}}$

Molecular flow

$q_{L, \text{gas A}} \cdot (M_{\text{gas A}})^{1/2} = q_{L, \text{gas B}} \cdot (M_{\text{gas B}})^{1/2}$

Molar mass and viscosity of gases

Gas type	Chemical symbol	Molar mass M [g/mol]	Viscosity at 25 °C η_V(25 °C) [10^{-6} Pa·s]
Hydrogen	H_2	2.0	8.9
Helium	He	4.0	19.7
Methane	CH_4	16.0	11.2
Ammonia	NH_3	17.0	10.0
Water vapor	H_2O	18.0	9.5
Neon	Ne	20.2	31.6
Carbon monoxide	CO	28.0	17.7
Nitrogen	N_2	28.0	17.9
Air		29.0	18.3
Oxygen	O_2	32.0	20.5
Hydrogen chloride	HCl	36.5	14.6
Argon	Ar	40.0	22.8
Carbon dioxide	CO_2	44.0	14.8
R 23	CHF_3	70.0	14.8
Chlorine	Cl_2	70.9	13.6
R 14	CF_4	80.0	17.4
Krypton	Kr	83.8	25.5
R 22	$CHClF_2$	86.5	12.8
Phosgene	$COCl_2$	98.9	11.0
R 134a	CH_2FCF_3	102.0	14.1
R 13	$CClF_3$	104.5	14.5
R 502	$CHClF_2 / CClF_2 - CF_3$	111.6	12.8
R 12	CCl_2F_2	120.9	12.7
Xenon	Xe	131.3	23.2
R 11	CCl_3F	137,4	11,0
Sulfur hexafluoride	SF_6	146.1	15.7
R 13 B 1	$CBrF_3$	148.9	14.4

Gase-Handbuch Messer-Griesheim, 1989

9.10 Conversion of liquid leak rate to gas leak rate

$$q_{L, gas} = c \cdot q_{L, LI} \cdot (p_1 + p_2)/2$$

Legend $q_{L, gas}$ = Gas leak rate
in **mbar·l/s**

$q_{L, LI}$ = Liquid leak rate
in **cm³/s**

c = η_{LI}/η_{gas} matter constant

p_1, p_2 = Pressure in the liquid on both sides of the leak
in **bar absolute**

9.10.1 Matter constant c

Material	Density ρ(20 °C) in g/cm³	Formula	c (air)	c (helium)
Water	0.9982	H_2O	55	50
Carbon tetrachloride	1.5950	CCl_4	101	93
Ethanol	0.7893	CH_3CH_2OH	55	61
Benzene	0.8990	C_6H_6	90	83
Hydrochloric acid, 36%	1.1791	HCl	109	101
Sulfuric acid, 60%	1.4987	H_2SO_4	323	298
Acetone, 10%	0.9849	CH_3COCH_3	68	63
Ammonia, 10%	0.9575	NH_3	62	57
Glycerin, 15%	1.2600		81	75
Glycerin, H_2O-free	1.2611	$CH_2OHCHOHCH_2OH$	$9.62 \cdot 10^4$	$8.86 \cdot 10^4$
Methanol	0.7917	CH_3OH	32	30
Ethylene glycol	1.0765	CH_2OHCH_2OH	275	253
Mercury	13.5500	Hg	87	81
Castor oil	0.9610		$53 \cdot 10^3$	$49 \cdot 10^3$

CRC Handbook of Chemistry and Physics, 56th Ed. 1975/76

9.11   Partial-flow ratio

The partial-flow ratio γ indicates which fraction of the test gas flow reaches the leak detector through the leak.

$$\gamma = \frac{S_{LD}}{S_{LD} + S_{PF}} = \frac{q_{L, display}}{q_L}$$

$$q_{L, display} = \gamma \cdot q_L$$

Legend S_{LD} = The pumping speed of the leak detector
in **l/s**

S_{PF} = The pumping speed of the partial-flow pump
in **l/s**

$q_{L, display}$ = The leak rate displayed by the leak detector
in **mbar·l/s**

q_L = The true leak rate
in **mbar·l/s**

9.11.1 Response time

After expiration of the response time t_R

$$t_{R\ 95\%} = 3 \cdot \frac{V}{S_{eff}}$$

95% of the total signal is displayed.

After expiration of the time

$$t_{R\ 87\%} = 2 \cdot \frac{V}{S_{eff}}$$

87% of the total signal is displayed.

After expiration of the time

$$t_{R\ 63\%} = 1 \cdot \frac{V}{S_{eff}}$$

63% of the total signal is displayed.

Legend   **V**   = The volume of the test object in **l**

         S_{eff}   = The effective pumping speed at the test object in **l/s**

9.12   Pump-down time

The provided formula for the pump-down time $t(p_{start} \Rightarrow p_{target})$ only applies if p_{target} is greater than 0.01 mbar
and
$S_{eff}(p)$ for $p_{target} \le p \le p_{start}$ constant is $[S_{eff}(p) = S_{eff}]$.

$$t(p_{start} \Rightarrow p_{target}) = \frac{V}{S_{eff}} \cdot 2.3 \cdot \log\left(\frac{p_{start}}{p_{target}}\right)$$

$$t(p_{start} \Rightarrow p_{target}) = \frac{V}{S_{eff}} \cdot \ln\left(\frac{p_{start}}{p_{target}}\right)$$

Legend   **V**   = The volume of the test object in **l**

         S_{eff}   = The effective pumping speed at the test object in **l/s**

         p_{start}   = The start pressure inside the test object in **mbar**

         p_{target}   = The target to be reached in the test object in **mbar**

9.12.1 Required pumping speed

The provided formula for the pumping speed S_{eff} only applies if

p_{target} is greater than 0.01 mbar

and

$S_{eff}(p)$ for $p_{target} \leq p \leq p_{start}$ constant is [$S_{eff}(p) = S_{eff}$].

$$S_{eff} = \frac{V}{t} \cdot 2.3 \cdot \log\left(\frac{p_{start}}{p_{target}}\right)$$

$$S_{eff} = \frac{V}{t} \cdot \ln\left(\frac{p_{start}}{p_{target}}\right)$$

Legend	**V**	=	The volume of the test object in **l**
	t	=	The pump-down time in **s**
	p_{start}	=	The start pressure inside the test object in **mbar**
	p_{target}	=	The target to be reached in the test object in **mbar**

9.13 Conversion of pressure units

1⇓ = .. ⇒	mbar	Pa (N/m²)	dyn·cm⁻² (µbar)	atm (phys.)	Torr (mm Hg)	inch Hg	Micron (µ)	cm H₂O	kp·cm⁻²	lb·in⁻² (at tech.)	lb·ft⁻² (psi)
mbar	1	10^2	10^3	$9.87 \cdot 10^{-4}$	0.75	$2.953 \cdot 10^{-2}$	$7.5 \cdot 10^2$	1.02	$1.02 \cdot 10^{-3}$	$1.45 \cdot 10^{-2}$	2.089
Pa	10^{-2}	1	10	$9.87 \cdot 10^{-6}$	$7.5 \cdot 10^{-3}$	$2.953 \cdot 10^{-4}$	7.5	$1.02 \cdot 10^{-2}$	$1.02 \cdot 10^{-5}$	$1.45 \cdot 10^{-4}$	$2.089 \cdot 10^{-2}$
µbar	10^{-3}	0.1	1	$9.87 \cdot 10^{-7}$	$7.5 \cdot 10^{-4}$	$2.953 \cdot 10^{-5}$	$7.5 \cdot 10^{-1}$	$1.02 \cdot 10^{-3}$	$1.02 \cdot 10^{-6}$	$1.45 \cdot 10^{-5}$	$2.089 \cdot 10^{-3}$
atm	1013	$1.01 \cdot 10^5$	$1.01 \cdot 10^6$	1	760	29.92	$7.6 \cdot 10^5$	$1.03 \cdot 10^3$	1.033	14.697	2116.4
Torr	1.33	$1.33 \cdot 10^2$	$1.33 \cdot 10^3$	$1.316 \cdot 10^{-3}$	1	$3.937 \cdot 10^{-2}$	103	1.3595	$1.36 \cdot 10^{-3}$	$1.934 \cdot 10^{-2}$	2.7847
in Hg	33.86	$33.9 \cdot 10^2$	$33.9 \cdot 10^3$	$3.342 \cdot 10^{-2}$	25.4	1	$2.54 \cdot 10^4$	34.53	$3.453 \cdot 10^{-2}$	0.48115	70.731
µ	$1.33 \cdot 10^{-3}$	$1.33 \cdot 10^{-1}$	1.333	$1.316 \cdot 10^{-6}$	10^{-3}	$3.937 \cdot 10^{-5}$	1	$1.36 \cdot 10^{-3}$	$1.36 \cdot 10^{-6}$	$1.934 \cdot 10^{-5}$	$2.785 \cdot 10^{-3}$
cm H₂O	0.9807	98.07	980.7	$9.678 \cdot 10^{-4}$	0.7356	$2.896 \cdot 10^{-2}$	$7.36 \cdot 10^2$	1	10^{-3}	$1.422 \cdot 10^{-2}$	2.0483
at	$9.81 \cdot 10^2$	$9.81 \cdot 10^4$	$9.81 \cdot 10^5$	0.968	$7.36 \cdot 10^2$	28.96	$7.36 \cdot 10^5$	103	1	14.22	2048.3
psi	68.95	$68.95 \cdot 10^2$	$68.95 \cdot 10^3$	$6.804 \cdot 10^{-2}$	51.71	2.036	$51.71 \cdot 10^3$	70.31	$7.03 \cdot 10^{-2}$	1	$1.44 \cdot 10^2$
lb · ft⁻²	0.4788	47.88	478.8	$4.725 \cdot 10^{-4}$	0.3591	$1.414 \cdot 10^{-2}$	359.1	0.488	$4.88 \cdot 10^{-4}$	$6.94 \cdot 10^{-3}$	1

Normal conditions: 0 °C and sea level, therefore p = 1013.25 mbar = 760 mm Hg = 760 Torr = 1 atm

in Hg = inch of mercury;   1 mTorr (millitorr) = 10^{-3} Torr = 1 µ (Micron ... µm Hg column)

Pound per square inch = lb · in⁻² = lb/sqin = psi;   (psig = psi gauge ... positive pressure, pressure gauge reading; psia = psi absolute ... absolute pressure)

Pound per square foot = lb/sqft = lb · ft⁻²;   kgf/sqcm² = kg force per square cm = kp · cm⁻² = at;   also analogous to this: lbf/sqin = psi

1 dyn · cm⁻² (cgs) = 1 µbar (microbar) = 1 barye;   1 bar = 0.1 MPa;   1 cm WS (cm water column = g/cm² at 4 °C) = 1 Ger (Geryk)

atm ... physical atmosphere   at ... technical atmosphere;   100 – (x mbar / 10.13) = y % vacuum

9.14 Conversion of gas flow/leak rate units

1 ⇓ = .. ⇒ (20 °C)	mbar·l/s (0 °C)	kg · h⁻¹ (NTP)	kg · h⁻¹ (NTP)	cm³/h	cm³/s (R12, 20 °C)	Torr · l/s (F134, 20 °C)	g/a	g/a	μ · cfm	lusec	Pa · l/s	slpm
mbar·l/s	1	$4{,}28 \cdot 10^{-3}$	$4{,}59 \cdot 10^{-3}$	3554	0,987	0,75	$1{,}56 \cdot 10^{5}$	$1{,}54 \cdot 10^{5}$	1593	$7{,}52 \cdot 10^{2}$	100	$59{,}2 \cdot 10^{-3}$
kg · h⁻¹ (20 °C)	234	1	1,073	$8{,}31 \cdot 10^{5}$	231	175	–	–	$37{,}2 \cdot 10^{4}$	$1{,}75 \cdot 10^{5}$	$23{,}4 \cdot 10^{3}$	13,86
kg · h⁻¹ (0 °C)	218	0,932	1	$7{,}74 \cdot 10^{5}$	215	163	–	–	$34{,}6 \cdot 10^{4}$	$1{,}63 \cdot 10^{5}$	$21{,}8 \cdot 10^{3}$	12,91
cm³/h (NTP)	$2{,}81 \cdot 10^{-4}$	$1{,}20 \cdot 10^{-6}$	$1{,}29 \cdot 10^{-6}$	1	$2{,}78 \cdot 10^{-4}$	$2{,}11 \cdot 10^{-4}$	44	–	$44{,}7 \cdot 10^{-2}$	$2{,}11 \cdot 10^{-1}$	$2{,}81 \cdot 10^{-2}$	$1{,}66 \cdot 10^{-5}$
cm³/s (NTP)	1.013	$4{,}33 \cdot 10^{-3}$	$4{,}65 \cdot 10^{-3}$	3600	1	0,760	$1{,}58 \cdot 10^{5}$	–	1611	760	101	$6 \cdot 10^{-2}$
Torr · l/s	1.33	$5{,}70 \cdot 10^{-3}$	$6{,}12 \cdot 10^{-3}$	4727	1,32	1	$2{,}08 \cdot 10^{5}$	$2{,}05 \cdot 10^{5}$	2119	$1 \cdot 10^{3}$	133	$78{,}8 \cdot 10^{-3}$
g/a (R12, 20 °C)	$6{,}39 \cdot 10^{-6}$	–	–	$2{,}27 \cdot 10^{-2}$	$6{,}31 \cdot 10^{-6}$	$4{,}80 \cdot 10^{-6}$	1	–	$10{,}2 \cdot 10^{-3}$	$4{,}8 \cdot 10^{-3}$	$6{,}39 \cdot 10^{-4}$	$37{,}9 \cdot 10^{-8}$
g/a (F134, 20 °C)	$6{,}50 \cdot 10^{-6}$	–	–	–	–	$4{,}88 \cdot 10^{-6}$	–	1	$10{,}4 \cdot 10^{-3}$	$4{,}89 \cdot 10^{-3}$	$6{,}5 \cdot 10^{-4}$	$38{,}5 \cdot 10^{-8}$
μ · cfm	$6{,}28 \cdot 10^{-4}$	$2{,}69 \cdot 10^{-6}$	$2{,}89 \cdot 10^{-6}$	2.24	$6{,}21 \cdot 10^{-4}$	$4{,}72 \cdot 10^{-4}$	98,16	96,58	1	0,472	$6{,}28 \cdot 10^{-2}$	$37{,}2 \cdot 10^{-6}$
lusec	$1{,}33 \cdot 10^{-3}$	$5{,}70 \cdot 10^{-6}$	$6{,}12 \cdot 10^{-6}$	4.737	$1{,}32 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	208	205	2,12	1	$13{,}3 \cdot 10^{-2}$	$78{,}8 \cdot 10^{-6}$
Pa · l/s	$1 \cdot 10^{-2}$	$4{,}28 \cdot 10^{-5}$	$4.59 \cdot 10^{-5}$	35.54	$9{,}87 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$	$1{,}56 \cdot 10^{3}$	$1.54 \cdot 10^{3}$	15.93	7.50	1	$59.2 \cdot 10^{-5}$
slpm	16,88	$72.15 \cdot 10^{-3}$	$77.45 \cdot 10^{-3}$	$60.08 \cdot 10^{3}$	16.67	12.69	$2.64 \cdot 10^{6}$	$2.60 \cdot 10^{6}$	$26.9 \cdot 10^{3}$	$12.7 \cdot 10^{3}$	$16.9 \cdot 10^{2}$	1

1 cm³ (NTP) = 1 cm³ under normal conditions (T = 273.15 K; p = 1013.25 mbar)

NTP = normal temperature and pressure (1 atm; 0 °C); R = 83.14 mbar · l · mol⁻¹ · K⁻¹

1 cm³ (NTP) · h⁻¹ = 1 atm · cm³ · h⁻¹ = 1 Ncm³ · h⁻¹ = 1 std cch

1 sccm = 10⁻³ slpm = 10⁻³ N · l · min⁻¹ = 60 sccs

SI system coherent: 1 Pa · m³ · s⁻¹ = 10 mbar · l · s⁻¹; R = 8.314 Pa · m³ · mol⁻¹ · K⁻¹; M in kg/mol

1 cm³ (NTP) · s⁻¹ = 1 sccs = 60 cm³ (NTP) · min⁻¹ 60 sccm = 60 std ccm = 60 Ncm³ · min⁻¹

1 lusec = 1 l · μ · s⁻¹ 1 · μ = 1 micron = 10⁻³ Torr 1 lusec = 10⁻³ Torr · l · s⁻¹

Freon F 12 (CCl₂F₂) M = 120.92 g · mol⁻¹; air M = 28.96 g · mol⁻¹

Caution: Abbreviations of Anglo-American units are inconsistent! Example: Standard cubic centimeter per minute -> sccm = sccpm = std ccm = std ccpm

9.15 Conversion of Anglo-American units

1 ⇓ = ... ⇒	mbar·l/s	cm³/s **)	Torr·l/s	Pa·m³/s	g/a *)	oz/yr *)	lb/yr *)	atm·ft³/min	m·l/s	m·ft³/h	m·ft³/min
mbar·l/s	1	0,987	0,75	10^{-1}	$1,56 \cdot 10^5$	$5,5 \cdot 10^3$	$3,4 \cdot 10^2$	$2,10 \cdot 10^{-3}$	$7,52 \cdot 10^2$	$9,56 \cdot 10^4$	1593
cm³/s **)	1,013	1	0,76	$1,01 \cdot 10^{-1}$	$1,58 \cdot 10^5$	$5,6 \cdot 10^3$	$3,44 \cdot 10^2$	$2,12 \cdot 10^{-3}$	760	$96,6 \cdot 10^3$	1614
Torr·l/s	1,33	1,32	1	$1,33 \cdot 10^{-1}$	$2,08 \cdot 10^5$	$7,3 \cdot 10^3$	$4,52 \cdot 10^2$	$2,79 \cdot 10^{-3}$	103	$1,27 \cdot 10^5$	2119
Pa·m³/s	10	9,9	7,5	1	$1,56 \cdot 10^6$	$5,51 \cdot 10^4$	$3,4 \cdot 10^3$	$2,09 \cdot 10^{-2}$	$7,5 \cdot 10^3$	$9,54 \cdot 10^5$	$15,9 \cdot 10^3$
g/a *)	$6,39 \cdot 10^{-6}$	$6,31 \cdot 10^{-6}$	$4,80 \cdot 10^{-6}$	$6,41 \cdot 10^{-7}$	1	$3,5 \cdot 10^{-2}$	$2,17 \cdot 10^{-3}$	$1,34 \cdot 10^{-8}$	$4,8 \cdot 10^{-3}$	0,612	$10,2 \cdot 10^{-3}$
oz/yr *)	$1,82 \cdot 10^{-4}$	$1,79 \cdot 10^{-4}$	$1,36 \cdot 10^{-4}$	$1,82 \cdot 10^{-5}$	28.33	1	$6,18 \cdot 10^{-2}$	$3,80 \cdot 10^{-7}$	0,136	17,34	0,289
lb/yr *)	$2,94 \cdot 10^{-3}$	$2,86 \cdot 10^{-3}$	$2,17 \cdot 10^{-3}$	$2,94 \cdot 10^{-4}$	$4.57 \cdot 10^2$	16	1	$6,17 \cdot 10^{-6}$	2,18	280	4,68
atm·ft³/min	$4,77 \cdot 10^2$	$4,72 \cdot 10^2$	$3.58 \cdot 10^2$	47.7	$7,46 \cdot 10^7$	$2,63 \cdot 10^6$	$1,62 \cdot 10^5$	1	$3,58 \cdot 10^5$	$4,55 \cdot 10^7$	$7,60 \cdot 10^5$
m·l/s	$1,33 \cdot 10^{-3}$	$1,32 \cdot 10^{-3}$	10^{-3}	$1,33 \cdot 10^{-4}$	208	7.34	$4,52 \cdot 10^{-1}$	$2,79 \cdot 10^{-6}$	1	127	2.12
m·ft³/h	$1,05 \cdot 10^{-5}$	$1,04 \cdot 10^{-5}$	$7.87 \cdot 10^{-6}$	$1,05 \cdot 10^{-6}$	1.63	$5,77 \cdot 10^{-2}$	$3,57 \cdot 10^{-3}$	$2,20 \cdot 10^{-8}$	$7,86 \cdot 10^{-3}$	1	$1,67 \cdot 10^{-2}$
m·ft³/min	$6,28 \cdot 10^{-4}$	$6,20 \cdot 10^{-4}$	$4.72 \cdot 10^{-4}$	$6,28 \cdot 10^{-5}$	98	3.46	$2.14 \cdot 10^{-1}$	$1,32 \cdot 10^{-6}$	0.472	60	1

1 · m · ft³ · h⁻¹ = 1.04 · 10⁻⁵ stsd cc per second

1 kg = 2.2046 pounds (lb)

1 cm³ · s⁻¹ (NTP) = 1 atm · cm³ · s⁻¹ = 1 scc · s⁻¹ = 1 sccss

1 cubic foot (cfut, cf) = 28.3168 dm³

1 atm · ft³ · min⁻¹ = 1 cfm (NTP)

1 Pa · m³/s = 1 Pa · m³/s (Anglo-American) = 103 Pa·l/s

1 lusec = 1 m · l · s⁻¹

1 std cc/sec = 760 m · l · s⁻¹

1 micron cubic foot per hour = 0.0079 micron liter per second

1 lb = 16 ounces (oz)

1 micron liter per second = 0.0013 std cc per second = 1 lusec

1 micron cubic foot per minute = 1 m · ft³ · min⁻¹ = 1 m · cuft · min⁻¹ = 1m · cfm

1 standard cc per second = 96.600 micron cubic feet per hour

1 m · l · s⁻¹ = 127 m · ft³ · h⁻¹ = 0.0013 std cc per second = 1 lusec

*) F12 (20 °C) CCl₂F₂ M = 120.92 g · mol

**) (NTP) normal temperature and pressure 1 atm and 0 °C

9.16   Conversion of temperature units

Conversions to

Units/symbol 1 = ..	Kelvin K	Celsius °C	Fahrenheit °F	Rankine °Ra	Reaumur °Re
Kelvin K	1	K - 273.15	9/5 · (K-273.15) + 32	9/5 · K	(K-273.15) · 8/10
Celsius °C	°C + 273.15	1	9/5 · °C + 32	9/5 · °C + 32	°C · 8/10
Fahrenheit °F	5/9 · (°F - 32) + 273.15	5/9 · (°F - 32)	1	°F + 459.67	5/9 · (°F - 32) · 8/10
Rankine °Ra	5/9 · °Ra	5/9 · °Ra - 273.15	°Ra - 459.67	1	5/9 · (°Ra - 273.15) · 8/10
Reaumur °Re	5/4 · °Re + 273.15	5/4 · °Re	9/4 · (°Re + 32)	9/4 · (°Re + 32) + 459.67	1

9.17   Temperature comparison (rounded to integers)

	Kelvin	Celsius	Reaumur	Fahrenheit	Rankine
Boiling point H_2O	373	100	80	212	672
Body temperature 37 °C	310	37	30	99	559
Room temperature	293	20	16	68	527
Ice point H_2O	273	0	0	32	492
NaCl/H_2O 50:50	255	-18	-14	0	460
Ice point Hg	34	-39	-31	-39	422
CO_2 (dry ice)	195	-78	-63	-109	352
Boiling point LN_2	77	-196	-157	-321	170
Absolute zero	0	-273	-219	-460	0

9.18 Compilation of the most important gas laws (continuum theory)

$p \cdot V = \text{const.}$ for T = consstanta (isothermal)   **Boyle–Mariotte law,**

$V = V_0(1+\beta_1 \cdot \Theta \,^{*)})$ for p = constant (isobaric)   **Gay-Lussac's law**

$p = p_0(1+\beta_2 \cdot \Theta \,^{*)})$ for V = constant (isochoric)   **Amonton's law**

$\Sigma_i \, p_i = p_{total}$ **Dalton's law**

$p \cdot V^{\kappa \,**)} = \text{const.}$ (adiabatic)   **Poisson's law**

$\dfrac{m_1}{V_1} : \dfrac{m_2}{V_2} = M_1 : M_2$ **Avogadro's law**

$p \cdot V = \dfrac{m}{M} \cdot R \cdot T$ **General gas equation**

also: Equation of state for ideal gases

(from the continuum theory)

$(p + \dfrac{a}{V_M^2}) \cdot (V_M - b) = R \cdot T$ **Van der Waals equation**

a, b = constants (cohesion pressure, co-volume)

V_M = molar volume

also: Equation of state for real gases

$L = T \cdot \dfrac{dp}{dT} \cdot (V_{M,\,S} - V_{M,\,Ll})$ **Clausius-Clapeyron equation**

L = Evaporation heat

T = Evaporation temperature

$V_{M,\,S}$; $V_{M,\,Ll}$ = Molar volume of steam or liquid

*) Θ = Temperature in °C

**) κ = Adiabats exponent

Notes

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