



**VTECH LEAK DETECTION**  
**Leak Detection Theory and Practise**  
**Comparison among leak testing techniques**

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## 1. INTRODUCTION

Leak detection procedures are becoming popular in many areas of industrial production, playing key roles in all processes where components or equipment must be leak-free to prevent external air penetration or internal gas loss. Applications include vacuum chambers and pressure vessels, pumps, cathode ray tubes production, refrigeration and HVAC systems, vacuum thermal isolation (e.g. dewars), automotive manufacturing, chemical production, aerosol containers, electronic and semiconductor industries, beverage cans, electron microscopes, pacemakers, etc. Enclosures with greater or smaller tightness have to assure a satisfactory isolation between external atmosphere and inside over or under-pressure. The words "leak" and "leakage" appear in the field of hermetically sealed units and do not involve only vacuum technologists but also engineers working with high pressures. In some industries, such as pharmaceutical, medical and food industries, the term "package integrity" or "seal integrity" are used instead of leak. A leak can be defined as an unintended crack, hole or porosity in an enveloping wall or joint which must contain or exclude different fluids and gases, allowing the escape or penetration of an undesired medium. Critical leak spots in closed systems are usually connections, gaskets, welded and brazed joints, defects in material, etc.

In spite of modern technologies, it is practically impossible to manufacture a sealed enclosure or system that can be guaranteed to be leak-proof without first being tested. It is sufficed to say there are no products without some leakage; they only have leaks smaller than a specified value. A leak test procedure is usually a quality control step to assure device integrity, and should preferably be a one-time non-destructive test, without impact on the environment and operators. Regarding quality demands in different production processes, production engineers very often encounter specific standards for tightness testing. The basic functions of leak detection are:

- determining if there is leakage or not
- measurement of leak rate
- leakage location

For solving the aforementioned problems, different treatments and techniques are known but among them there is no universal method. Each test is suitable only for a selected leak rate or for fixed forms and technologies.

In the most common uses of leak detection, explicit leak rate measurement is not required, but the system must be able to recognize if the leak rate is above or below a specified level, so as to meet the required tightness. To establish this reference limit, it is necessary to determine what the maximum acceptable leak rate is consistent with the reasonable performance life of the product. This acceptance level is the main parameter to be considered when selecting the proper testing method or combination of methods. In this selection, several other factors have to be taken into account. In particular, system costs, complexities, environmental impact, reliability, influence of external conditions, operator dependence and user friendliness. Leak testing is a challenge. On one hand products must meet stricter leak rate standard while, on the other, leak testing processes should be less costly and less dependent on operator skill. To meet this dilemma, all aspects of the leak testing process have to be well understood. A lot of documentation about leak detection, leak testing methods is available in industry literature. This article presents leak types, their sizes and various leak detection techniques with a comparison of their performance with particular attention to refrigerant leakages.

## 2. LEAK TYPES

Different types of leak sources can be determined.

1. Leaks caused by defects in the enclosure or materials permitting gas diffusion and permeation through the wall. For example, a thin wall of a plastic bottle becomes cracked microscopically at high enough pressure difference, or in the canning industry if the score mark is too deep in the ring on a pull-tab can top or a porous cast in a machine housing metallurgy, etc.
2. Leaks in newly manufactured products are most commonly due to imperfect joints, fixed or demountable, or seals among the various assembled parts. The most commonly used junctions are welded, brazed and soldered joints, glass-to-metal and ceramic-to-metal seals, O-rings and other gaskets.
3. Leaks caused by internal sources of gas or vapor creating an internal pressure rise. In this case they are not really leaks and are known as out-gassing or as a virtual leak in vacuum technology. This is due to surface phenomenon on the chamber walls or materials inside the enclosure, dirty materials, or presence of low vapor pressure so that substances, such as water and oils permeate inside the chamber.

## 3. LEAKAGE MEASUREMENT UNIT

The main measurable effect of a leak is the flow of a medium through it, so the generally accepted method to define a leak is the quantifying of this gas or fluid flow in specified conditions of temperature and pressure difference. Consequently, leak rates can be defined in terms of flow, that is:

- mass in a specified time at reference condition of pressure and temperature, e.g. grams of a refrigerant in years at reference pressure (3 g/y R134a at 500 kPa);
- number of bubbles of a specified diameter in a certain time period and pressure (5 bubbles of 2 mm per second at 400 kPa);
- volume in a specified time at standard condition of pressure (atmospheric pressure) and temperature (0 °C), e.g. standard cubic meter or centimeter per second (std cm<sup>3</sup>/s or std cc/s);
- pressure variation in a specified time period, e.g. 200 Pa pressure increment in 1 hour;
- referring to vacuum leak detection method, e.g.:  $3 \cdot 10^{-7}$  Pa · m<sup>3</sup>/s helium (using He-detection method), or  $3 \cdot 10^{-6}$  mbar · l/s.

Clearly, all these different ways to identify a leak rate are equivalent and related to the kinetic theory of gases. For convenience, a conversion table for the most commonly used units are reported in Annex A.

## 4. LEAK SIZES

Since the shapes of leaks (cracks, fissures, porosity, damages, etc) are very different, unknown and non-uniform, it is impossible to measure their sizes with any geometrical dimension. Exceptions are very big leakages and ideal or artificial leaks, as those used for calibration.

The leak rate does not only depend on the geometric dimensions (diameter, length) of the leak but also on the physical properties of the gas (or the liquid), such as viscosity, relative molecular mass and the pressure difference. For example, in the same environmental conditions helium flows through orifices 2.7 times faster than air. Measuring the same leak by various medium implies getting different results, so it must always be specified which testing procedure was used in leakage definition. This procedure may be implicitly defined considering the specific application, for refrigerating purposes it is the grams/year of refrigerant at the plant working conditions. For industrial applications, the acceptable leak rates are

generally in the range  $10^{-9} \div 1 \cdot \text{mbar l/s}$ , while the majority of products require less stringent specifications, usually  $10^{-6} \div 1 \cdot \text{mbar l/s}$ . Only few products, such as very long life systems and high-quality units, and/or safety constraints, such as in hazardous substance containment, require high sensitivity leak test, up to or better than  $10^{-9} \text{mbar} \cdot \text{l/s}$ . The maximum acceptable leak rate for a given product depends on the nature of product. Since the cost of leak detection (and manufacturing hermetic envelopes) increases in inverse proportion to the leak rate, it follows that testing for unnecessary small leaks causes unnecessary rise in production costs. Some examples of acceptable leaks in different elements and systems are reported in the following table.

System	Max. permissible leakage	Remark
chemical process equipment	$10^{-1} \div 1 \text{mbar} \cdot \text{l/s}$	great process flows
automotive components (i.e. steering system)	$10^{-3} \div 10^{-4} \text{mbar} \cdot \text{l/s}$	liquid containment
beverage can bottom	$10^{-5} \div 10^{-6} \text{mbar} \cdot \text{l/s}$	retention of $\text{CO}_2$
refrigerating application	$10^{-4} \div 10^{-7} \text{mbar} \cdot \text{l/s}$	HVACR plant life and environment impact rules
dynamic pumped vacuum system	$10^{-5} \div 10^{-7} \text{mbar} \cdot \text{l/s}$	permanent pumping
IC-package	$10^{-7} \div 10^{-8} \text{mbar} \cdot \text{l/s}$	
pacemaker	$10^{-9} \text{mbar} \cdot \text{l/s}$	long time implanted in body
closed vacuum elements	$10^{-8} \div 10^{-10} \text{mbar} \cdot \text{l/s}$	e.g. TV and X-ray tubes

Table 1 - Leak rate specification for various systems

A statistical analysis of leaking units, considering leakage size, frequency, leak types, is available in industry literature. The following figure shows the typical distribution of leakage probability against the size as observed in industrial products.

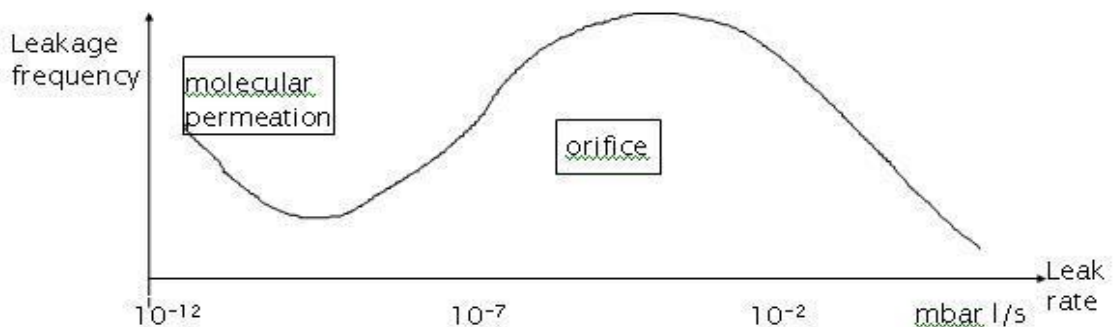


Fig. 1 - Typical distribution of leaks in industrial products

The two relative maximums shown in this curve refer to the two different leak modes: permeation or orifice flow. It is not unusual that a part has more small leakages rather than a large one.

## 5. SOME USEFUL FORMULAE

Before investigating the leak detection issue, it is worthwhile to recall some basic principles of the kinetic theory of gas. The basic concepts are well known. The measurement units are expressed in the international metric system (SI).

### 5.1 Ideal Gas Law and Real Gases

The pressure, volume and temperature of a perfect gas are related by the universal gas law:

$$p \cdot V = n \cdot R \cdot T$$

where  $p$  is the gas pressure (Pa or  $\text{N/m}^2$ ),  $V$  is the volume occupied by the gas ( $\text{m}^3$ ),  $T$  is the gas absolute temperature (K),  $n$  is the gas quantity in number of moles, and  $R$  is the universal gas constant:

$$R = 8.314472 \text{ J / (mol} \cdot \text{K)}$$

Real gases can behave in a different way from that expected for an ideal gas. The state equation, i.e. the pressure, volume, temperature relationship, for a non-ideal gas can be written as:

$$p \cdot V = Z \cdot n \cdot R \cdot T$$

Where  $Z$ , the gas compressibility factor, describes the difference between ideal and actual behavior of a gas. It should be written as  $Z(p, T)$ , as it is a function of both pressure and temperature:

$$Z = \frac{p \cdot V}{n \cdot R \cdot T} = \frac{V}{V - n \cdot b} - \frac{a \cdot n}{R \cdot T \cdot V} = \frac{1}{1 - n \cdot \frac{b}{V}} - \frac{a \cdot n}{R \cdot T \cdot V}$$

$Z$  is always one for ideal gases and, in general, can be either greater or less than unity, depending on the effect of either the size of the molecules (repulsive forces), modeled by parameter  $b$ , or the attractive forces, modeled by parameter  $a$ . While this equation (being linear) is very simple to use, obtaining values of  $Z$  is not. There are several models to compute  $Z$  factor, the most known are the Redlich-Kwong equation and the Peng-Robinson equation; refer to Annex C for more details. For pressures close to atmospheric, it is common to use a value of  $Z$  set to 1.0, and similarly, when the pressure is controlled very close to a design set-point, it is usually adequate to use the fixed design compressibility. If, however, the pressure and temperature can vary during normal operating conditions, then there can be a significant variation in the compressibility factor for a gas. The following plot shows the compressibility factor of some gases typically used, varying with pressure for a number of different temperatures.

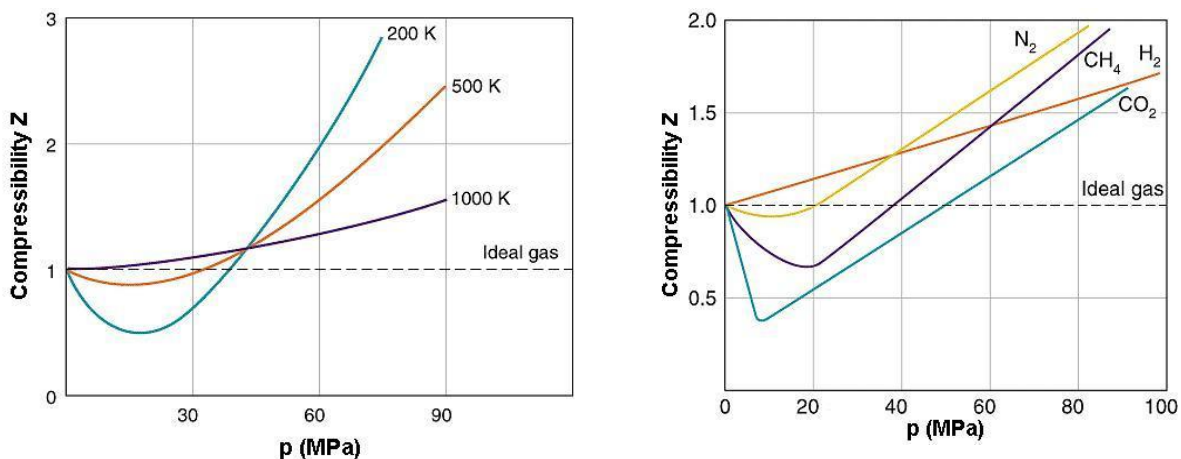


Fig. 2 - Nitrogen and other gas compressibility factor typical behavior

The deviation from ideal gas behavior tends to become particularly significant (or, equivalently, the compressibility factor strays far from unity) near the critical point, or in the case of high pressure or low temperature.

## 5.2 Gas Flow and Leak Rate

The flow of a gas through pipes, holes or orifices depends on gas properties, container wall's characteristics and pressure. When the particles in the gas are very close each other, typically at pressure above 2 Pa, they collide more frequently with each other than with the container walls. If pressure difference is established, gas flows like a fluid in the direction of the pressure gradient. This condition is known as viscous flow and a distinction in two different kinds of flow, turbulent flow and laminar flow, is usually carried out. When the gas particles are less close, each particle travels independently of other molecules. They collide more frequently with the walls than with each other. The mean free path is larger than the geometric dimension of the container. This flow condition is known as molecular flow. There is not an abrupt transition from the laminar flow to the molecular flow, but there is an intermediate situation, identified with transitional flow, where gradually the flow passes to the molecular condition. These flow considerations can be applied also to leak analysis. However, in leak detection technology, in most cases it is not possible to determine accurately the kind of flow. It must be estimated using formulae for calculating it in various conditions of pressure, pipes, etc. All these formulae contain geometry factors (length, diameters, etc.) but with leaks, in normal practice, these factors are unknown. A commonly reported table in industry literature that may help in immediate flow identification is:

Flow type	Leak rate (Pa · m <sup>3</sup> /s)
Turbulent flow	$> 10^{-3}$
Laminar flow	$10^{-2} \div 10^{-7}$
Transitional flow	$10^{-5} \div 10^{-8}$
Molecular flow	$< 10^{-8}$

Table 2 - Leak rate and type of flow

The most common leaks are in the turbulent and laminar flow range, while small leaks are characterized by a transitional flow. Molecular flow signifies only very small leaks.

### 5.2.1 Turbulent flow

Turbulent flow occurs only in larger leaks and at higher pressure differences. Due to the high speed of gas, leaks with turbulent flow emit a sound (whistle) and these can be detected and located by ultrasonic leak detectors.



Fig. 3 - Typical velocity profile of a particle in turbulent flow



The formula for the leak rate at turbulent flow is not given here since leaks with turbulent flow are so large and can be readily located and repaired. There is seldom a need for calculation. In general, in turbulent flow increasing the internal pressure will increase the volumetric flow rate until the gas flow velocity reaches the speed of sound and the flow becomes “choked”. From that point, increasing the pressure does not increase the volumetric flow rate, but the gas density will increase.

### 5.2.2 Laminar flow

Laminar flow is defined as a parallel flow of molecules in a pipe, whereby the transverse distribution of the speed of the molecules is parabolic, as sketched in the following picture.

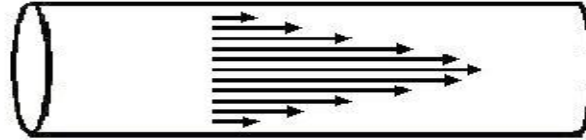


Fig. 4 - Typical velocity profile of a particle in laminar flow

The speed of the molecules in the centre of the pipe is at a maximum value and it decreases towards the walls of the pipe. Laminar flow through a straight pipe with circular cross-section is described by the well known Poiseuille formula.

Considering a leak like a cylindrical path (virtual leak), the leak rate can be expressed as:

$$Q = \frac{\pi \cdot r^4}{16 \cdot \nu \cdot l} \cdot (p_i^2 - p_o^2)$$

Where:

$\nu$  is the dynamic viscosity of the gas (Pa · s) (e.g.  $1.8 \cdot 10^{-5}$  Pa · s for air  $2.0 \cdot 10^{-5}$  Pa · s for He)

$l$  is the length of the round tube, that is the virtual leak path (m)

$r$  is the radius of the pipe, that is the virtual leak radius (m)

$p_i$  is the absolute internal pressure (Pa)

$p_o$  is the absolute external pressure (Pa)

$Q$  is the flow rate, i.e. the leak rate (Pa · m<sup>3</sup>/s)

From this equation the main property of the laminar flow emerges. The volumetric leak flow rate does not depend on gas molecular weight, but on gas viscosity. Therefore, it is not true that helium leaks four times more than nitrogen, from a given defect at a given pressure, since it is four times lighter than nitrogen. Instead, since helium viscosity is about ten percent higher than nitrogen at room temperature, a product with a fixed defect and differential pressure will leak less if filled with helium rather than nitrogen.

Furthermore, if the pressure difference across a leak changes, the leak rate changes with the square of the pressure. Assuming that the geometrical dimensions of the leak do not change during the measurement period, the following relation can be written:

$$\frac{Q_A}{(p_{Ai}^2 - p_{Ao}^2)} = \frac{Q_B}{(p_{Bi}^2 - p_{Bo}^2)}$$

Where:

$p_{Ai}$  and  $p_{Bi}$  are the absolute internal pressure (Pa)

$p_{Ao}$  and  $p_{Bo}$  are the absolute external pressure (Pa)

$Q_A$  and  $Q_B$  are the corresponding leak rate ( $\text{Pa} \cdot \text{m}^3/\text{s}$ ) in the two cases

From this equation it can be stated that a drastic increase of sensitivity test can be achieved by increasing the internal pressure of the object under test. In large containers filled with a tracer gas (e.g. helium) for a sniffer-test, cost reduction can be achieved by increasing the inner total pressure, but reducing the concentration of the test gas. Of course the safety conditions for filling containers with pressurized gas must be followed. The Poiseuille equation can be rearranged so to express the leak as mass flow rate:

$$M = \frac{\pi \cdot r^4}{16 \cdot \nu \cdot l \cdot k_B \cdot T} \cdot m \cdot (p_i^2 - p_o^2)$$

Where:

$\nu$  is the dynamic viscosity of the gas ( $\text{Pa} \cdot \text{s}$ ) (e.g.  $1.8 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$  for air  $2.0 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$  for He)

$l$  is the length of the round tube, that is the virtual leak path (m)

$k_B$  is the Boltzmann constant ( $1.38 \cdot 10^{-23} \text{ J}/(\text{molecules} \cdot \text{K})$ )

$T$  is the absolute temperature (K)

$r$  is the radius of the pipe, that is the virtual leak radius (m)

$m$  is the mass of one molecule (kg) (e.g.  $4.78 \cdot 10^{-26} \text{ kg}$  for air,  $6.6 \cdot 10^{-27} \text{ kg}$  for He)

$p_i$  is the absolute internal pressure (Pa)

$p_o$  is the absolute external pressure (Pa)

$M$  is the total mass flow ( $\text{kg}/\text{s}$ )

To convert mass flow to volumetric flow ( $\text{m}^3/\text{s}$ ) the previous equation must be divided by the density of the gas (e.g.  $1.16 \text{ kg}/\text{m}^3$  for air  $0.17 \text{ kg}/\text{m}^3$  for He).

### 5.2.3 Molecular flow

Molecular flow exists in small leaks (cf. Table 2) and at low pressures. In a molecular flow condition each molecule travels independently of other molecules. The mean free path is larger than the diameter of the leak capillary. Therefore it is possible for a single molecule to travel against the general flow direction, because molecules do not collide with each other, but only with the walls. Despite this fact, the general flow is in the direction of the pressure gradient.

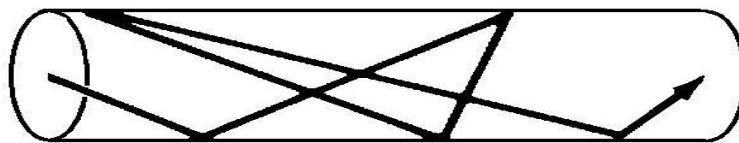


Fig. 5 - Typical velocity profile of a particle in molecular flow

Molecular flow through a straight pipe with circular cross-section is described by the Knudsen formula. Considering a leak like a cylindrical path (virtual leak), the leak rate can be expressed as:

$$Q = \frac{\sqrt{2\pi}}{6} \cdot \sqrt{\frac{R \cdot T}{M}} \cdot \frac{d^3}{l} \cdot (p_i - p_o)$$

Where:

$R$  is universal gas constant ( $8.314472 \text{ J}/(\text{mol} \cdot \text{K})$ )

$T$  is absolute temperature (K)

$M$  is relative mass of molecule

$d$  is the diameter of the pipe, that is the virtual leak diameter (m)

$l$  is the length of the round tube, that is the virtual leak path (m)

$p_i$  is the absolute internal pressure (Pa)  
 $p_o$  is the absolute external pressure (Pa)  
 $Q$  is the flow rate, i.e. the leak rate ( $\text{Pa} \cdot \text{m}^3/\text{s}$ )

From the previous formula one can see that, to the contrary of the laminar flow, leak rate follows linear proportion to pressure difference. To calculate a leak rate after a pressure change, the following formula is valid:

$$\frac{Q_A}{(p_{Ai} - p_{Ao})} = \frac{Q_B}{(p_{Bi} - p_{BAo})}$$

Where:

$p_{Ai}$  and  $p_{Bi}$  are the absolute internal pressure (Pa)  
 $p_{Ao}$  and  $p_{Bo}$  are the absolute external pressure (Pa)  
 $Q_A$  and  $Q_B$  are the corresponding leak rate ( $\text{Pa} \cdot \text{m}^3/\text{s}$ ) in the two cases

### 5.2.4 Transitional flow

There is a gradual transition from laminar to molecular flow, which can be interpreted as both flows are present simultaneously or as a change of condition long the path, i.e. the flow, laminar at the entrance of the leak, gradually changes to molecular at the end of the leak.

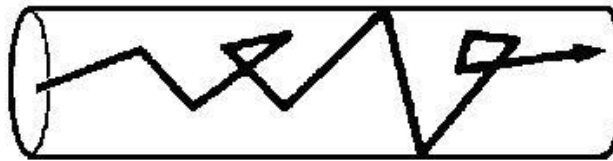


Fig. 6 - Typical velocity profile of a particle in molecular flow

The mathematical description of this flow condition is difficult. There are some formulae available, but all of them have some restrictions. The simplest formula, from Burrow, combines the laminar and molecular flow:

$$Q = \frac{\pi \cdot r^4}{16 \cdot \nu \cdot l} \cdot (p_i^2 - p_o^2) + \frac{\sqrt{2\pi}}{6} \cdot \sqrt{\frac{R \cdot T}{M}} \cdot \frac{d^3}{l} \cdot (p_i - p_o)$$

Where:

$\nu$  is the dynamic viscosity of the gas ( $\text{Pa} \cdot \text{s}$ ) (e.g.  $1.8 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$  for air  $2.0 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$  for He)  
 $R$  is universal gas constant ( $8.314472 \text{ J}/(\text{mol} \cdot \text{K})$ )  
 $T$  is absolute temperature (K)  
 $M$  is relative mass of molecule  
 $l$  is the length of the round tube, that is the virtual leak path (m)  
 $r$  is the radius of the pipe, that is the virtual leak radius (m)  
 $d$  is the diameter of the pipe ( $d = 2 \cdot r$ ) (m)  
 $p_i$  is the absolute internal pressure (Pa)  
 $p_o$  is the absolute external pressure (Pa)  
 $Q$  is the flow rate, i.e. the leak rate ( $\text{Pa} \cdot \text{m}^3/\text{s}$ )

This formula can be used for rough calculations. For practical use it is preferable to estimate if the laminar or molecular flow predominates and utilize the correspondent Poiseuille or Knudsen formula to calculate the dimension of the idealized leak.

### 5.3 Gas Dependency

In the previous paragraphs, starting from the relations describing gas flow throughout leaks, the effects of pressure are reported. The dependencies of leak rates on the gas properties are analyzed in the following.

#### 5.3.1 Laminar flow

Recalling the Poiseuille equation:

$$Q = \frac{\pi \cdot r^4}{16 \cdot \nu \cdot l} \cdot (p_i^2 - p_o^2)$$

One can see that the gas flow rate is inversely proportional to its dynamical viscosity. So changing the type of gas, in the same pressure condition, it can be written:

$$\frac{Q_A}{Q_B} = \frac{\nu_B}{\nu_A}$$

Where  $\nu_A$  and  $\nu_B$  are the dynamic viscosities (Pa · s) of the two gases and  $Q_A$  and  $Q_B$  are the leak rate (Pa · m<sup>3</sup>/s) in the two cases.

Annex B reports a table of the viscosities of some gases. Since the viscosity values for most gases are very closed each other (they have all the same order of magnitude), little variation in flow rates result changing the test medium. In Annex B is reported also a conversion table of leak rates.

#### 5.3.2 Molecular flow

From the Knudsen equation, given here again for convenience:

$$Q = \frac{\sqrt{2\pi}}{6} \cdot \sqrt{\frac{R \cdot T}{M}} \cdot \frac{d^3}{l} \cdot (p_i - p_o)$$

One can see that the gas flow rate is inversely proportional to the square root of its molecular relative mass. So changing the type of gas, in the same pressure condition, it can be written:

$$\frac{Q_A}{Q_B} = \frac{\sqrt{M_B}}{\sqrt{M_A}}$$

Differently from the laminar flow, in the molecular flow condition, a change of gas can make larger differences in leak rate (at constant pressure difference). In annex B, the molar masses and the leak correction factors for some gases are reported.

### 5.4 Conversion from Mass Leak Rate to Volume Leak Rate

In vacuum technology, the leak rate in general is described as a volume leak rate (Pa · m<sup>3</sup>/s or mbar · l/s). In many industrial applications, e.g. the refrigeration industry, it is common to define the leak rate in loss of mass of a specified material per year, for example grams of refrigerant per year (g/y). Clearly the two

indications are related and a conversion is possible using the kinetic theory of gas. Assuming a simplifying hypothesis of ideal gas and known flow condition, laminar or molecular, this conversion is easy, as well as determining the behavior of different gases. In this condition it can be written:

$$Q = \frac{F_s}{M} \cdot \frac{V_M}{T_0} \cdot T$$

Where:

T is the ambient absolute temperature (K)

M is molar mass of the gas (kg/mol)

T<sub>0</sub> is the absolute temperature in standard condition (273.16 K)

V<sub>M</sub> is the molar volume in standard condition (22.414 · 10<sup>-3</sup> m<sup>3</sup>/mol)

F<sub>s</sub> is the mass leak rate (kg/s)

Q is the flow rate, i.e. the leak rate (Pa · m<sup>3</sup>/s)

Knowing the internal pressure and the type of leak flow, using the equation previously discussed the equivalent flow rate of different gases or at different pressures can be computed.

### 5.5 Diffusion of Gases

Diffusion is the phenomenon of the spreading of one gas into another. Diffusion happens also with liquid, but in leak detection only diffusion of gases are important. Under equal conditions, light gases diffuse faster than heavy gases. The diffusion of gases is inversely proportional to their relative molecular mass. The diffusion law, known also as Graham Law, is:

$$\frac{D_1}{D_2} = \frac{M_2}{M_1}$$

Where D is the diffusion coefficient and M is the molecular mass. In Annex B the diffusion coefficient for the most commonly used gases are reported.

The diffusion of one gas into another at atmospheric pressure is relatively slow. This requires special attention when test pieces are filled with tracer gas for a sniffer test. With long tubes with closed ends, the tracer gas cannot bypass the air which is in the test piece as far as the end of the tube. This air cushion can remain there for some time, before it is mixed with the other gases by diffusion. A leak, which happens to be at this end of the tube, may not be detected by the sensor, which is only sensitive of the tracer gas.

To avoid this problem, test objects should be evacuated prior to filling with tracer gas. Diffusion speed increases with decreasing pressure since at low pressure the mean free path increases and, therefore, the collisions among gas particles decrease. If a complete filling with tracer gas is desired, an evacuation down to a pressure of 10 to 50 Pa is sufficient.

### 5.6 Permeation

Permeation is the passage of a fluid into, through and out of a solid barrier having no holes. The process involves diffusion through a solid and may involve many phenomena such as adsorption, dissociation, migration and desorption.

Permeation can have negative effects on a helium leak test, especially when the leak rate specification is low and the test time long. Some materials, e.g. PTFE, require special attention because helium is highly permeable. Accurate results are almost impossible to get from Helium leak tests on pieces containing seals of such materials. The following figure shows the permeation characteristics of some elastomers.

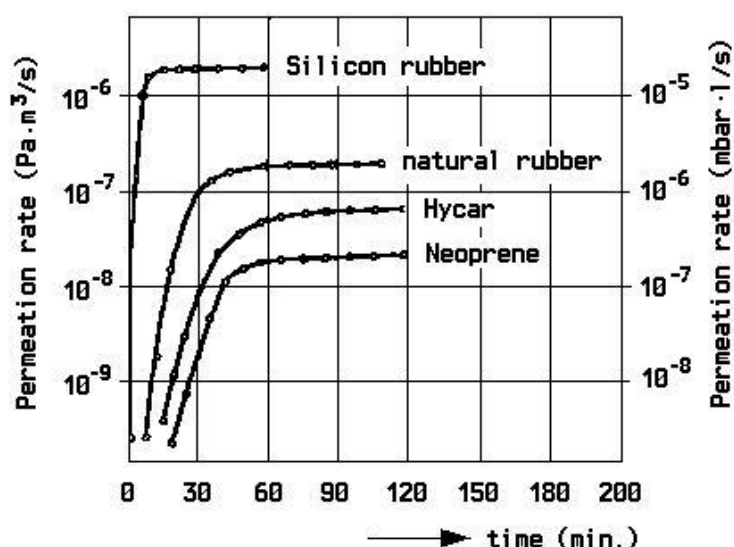


Fig. 7 - Permeation

Permeation does not affect routine leak tests, when the measurement occurs in times too short to permit permeation to take effect.

## 6. LEAK TESTING IN REFRIGERATION INDUSTRY

In the refrigeration industry, components and system must be leak tested to ensure that refrigerant leakages are below specified limits. These reference limits may depend either on the maximum acceptable leak rate, consistent with the reasonable working life expectation for final products, and, especially in certain countries, either on rule and regulation constraints. The basic functions of leak testing are determining if there is leakage or not (detection), measurement of leak rate and leakage location. There are many methods and many types of test equipment but to approach these problems but unfortunately there is no universal solution – no one method fits every situation. Each testing method is suitable only for a specific leak rate or for fixed forms and technologies. In the common use of leak detection, explicit leak rate measurement is not required, but the system must be able to recognize if the leak rate is above or below a specified level, in order to meet the required tightness. Usually the acceptable leak rate, depending on refrigerant type and application, spans from 15 g/y of refrigerant, as for some big air conditioning system and/or automotive application, to 0.5 g/y, as for some domestic refrigerators.

This acceptance level is the main parameter to be considered when selecting the proper testing method or combination of methods. Several other factors have to be taken into account for a correct choice. In particular, system costs, complexities, environmental impact, reliability, influence of external conditions, operator dependence and user friendliness.

A lot of documentation about leak-testing, leak detection and leak location methods is available in industry literature. Some references are reported in Annex E. This section presents some leak detection techniques and comparison of their performance with particular regard to refrigerant leakages.

## 7. LEAK TESTING METHODS

A leak can be defined as an unintended crack, hole or porosity in an enveloping wall or joint which must contain or exclude different fluids and gases, allowing the escape of closed medium. Critical leak spots in

closed systems are usually connections, gaskets, welded and brazed joints, defects in material, etc. A leak test procedure is usually a quality control step to assure device integrity, and should preferably be a one-time non-destructive test, without impact on the environment and operators. Several leak-testing techniques are available, spanning from very simple approaches to systems that are more complex. The most commonly used non-destructive leak test methods are the underwater bubble test, bubble soap paint, pressure and vacuum decay and tracer gas detection (halogen, helium and hydrogen). The first three techniques, due to their characteristics and sensitivity, can be used only for gross leak detection, 300 g/y or more refrigerant leakages. Tracer gas leak testing methods are much more responsive than the previous group but, in many cases, their theoretical sensitivity is more than required. In the practical use, however, this is limited by environmental and working conditions.

In the following, each method is briefly described and its advantages and drawbacks are reported. In annex A, a conversion chart for the most commonly used vacuum and leak rate measurement units is provided.

In the diagram below, the performance of various leak-test techniques are summarized:

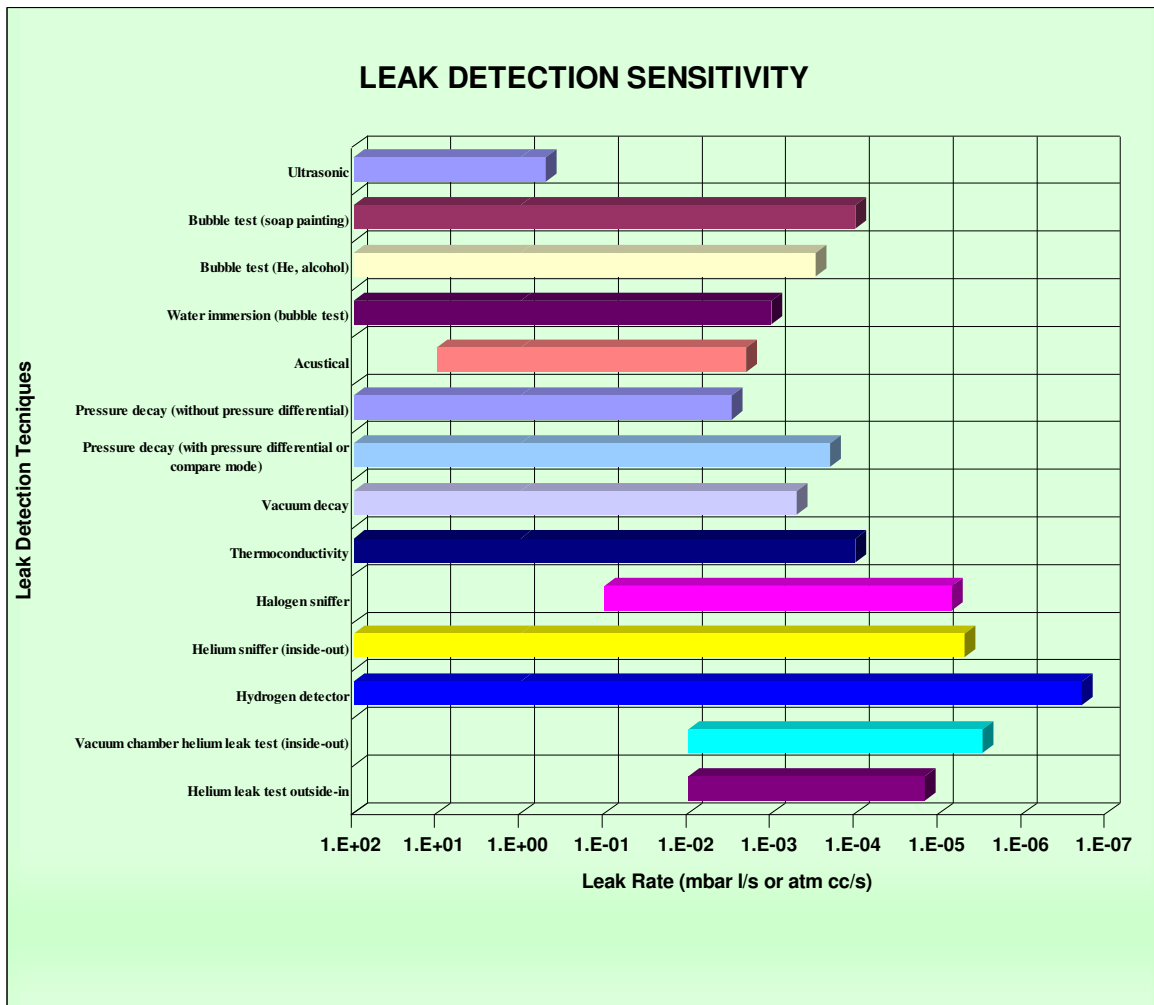


Fig. 8 - Leak detection sensitivity of some techniques



It is important to note that a leak test would not be possible if the leak test personnel could not control the test permanently against failures.

In the following, each leak detection method is analyzed in detail.

### 7.1 *Ultrasonic Leak Detector*

Acoustical leak detection uses the sonic or ultrasonic energy generated by gas as it expands through an orifice. Pressurized gas proceeds from a tested system through leaks which are detected outside by a sensitive microphone (typically about 40 000 Hz). Acoustical leak detection is widely used in testing high pressure lines, ductworks etc. It requires modest instrumentation; it is simple and fast but is limited to about  $10^{-3}$  mbar l/s. This procedure can be very successful if, and only if, the area in which you're trying to detect the leak in is absolutely quiet area. This is usually impossible, which imposes great limits on the ultrasonic leak detector. The higher the pressure in the system, the greater is the chance of finding or even hearing the leak.

### 7.2 *Water Immersion Bubble Test Method*

The water immersion bubble test, called also "bubble testing" or "dunking" is a traditional and a relatively primitive technique of leak detection. It consists in immersing a charged or pressurized part, usually with high pressure dry air or nitrogen, in a water tank and watching for bubbles to escape from the eventual leaks. The larger and more frequent the bubbles, the bigger the leak is. Small leaks are possible to detect, but very difficult. The main limit of this method is sensitivity, that is, the minimum detectable leak rate. Considering a spherical bubble of radius R, its internal volume V will be:

$$V = 4/3 \cdot \pi \cdot R^3$$

Let p the pressure inside the bubble and t the time required to form the first bubble, the leak rate Q will be:

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

The two key parameters determining the sensitivity of this method are the smallest bubble detectable by the operator and the waiting time for bubble generation. This time must be compatible with the production rate and with operator attention.

It is reasonable to consider that the smallest bubble an operator could detect has 1 mm radius and that the waiting time is 30 seconds. Assuming that the pressure inside the bubble is the atmospheric pressure, from the previous equations, it can be stated that the bubble volume is  $V = 4.2 \cdot 10^{-3} \text{ cm}^3$  and then minimum detectable leak rate is:

$$Q = (p \cdot V) / t = 1000 * 4.2 \cdot 10^{-6} / 30 = 1 \cdot 10^{-4} \text{ mbar} \cdot \text{l/s}$$

This is a theoretical value. The real sensitivity is strongly affected by many external factors, such illumination conditions, water turbidity, unit location and placement and water movement. All these issues, together with operator dependency, limit the useful sensitivity to  $5 \cdot 10^{-4} \text{ mbar} \cdot \text{l/s}$ , but usually  $1 \cdot 10^{-3} \text{ mbar} \cdot \text{l/s}$  is considered. The following picture exploits the dependency of bubble formation time and leak rate at several internal test pressures.



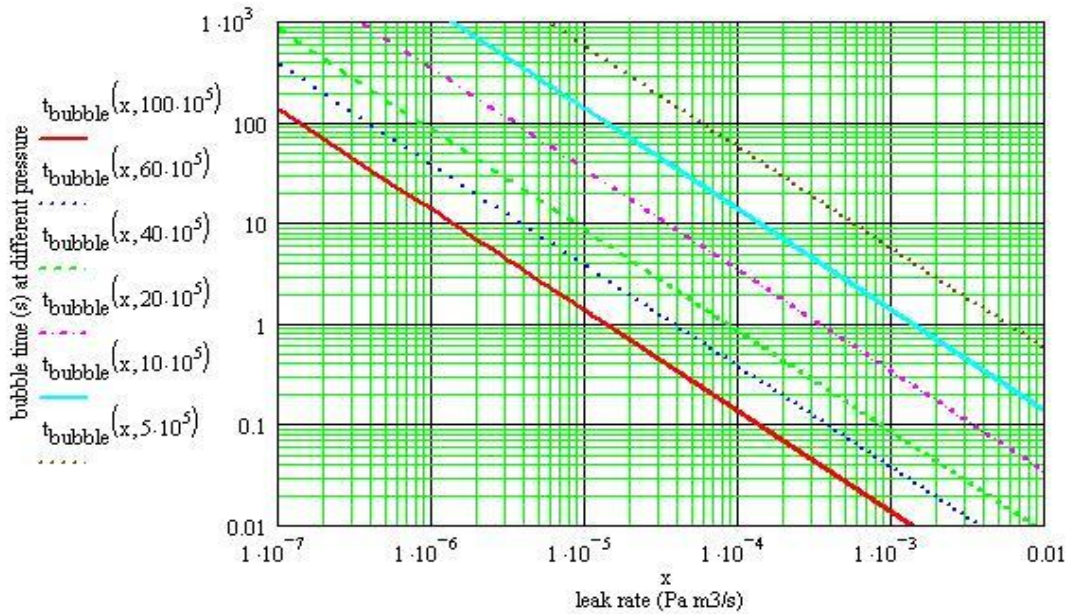


Fig. 9 – Bubble formation time and leak rate at different internal test pressure

In the following picture, mass leakage of refrigerant (R134a) is related to the bubble formation time.

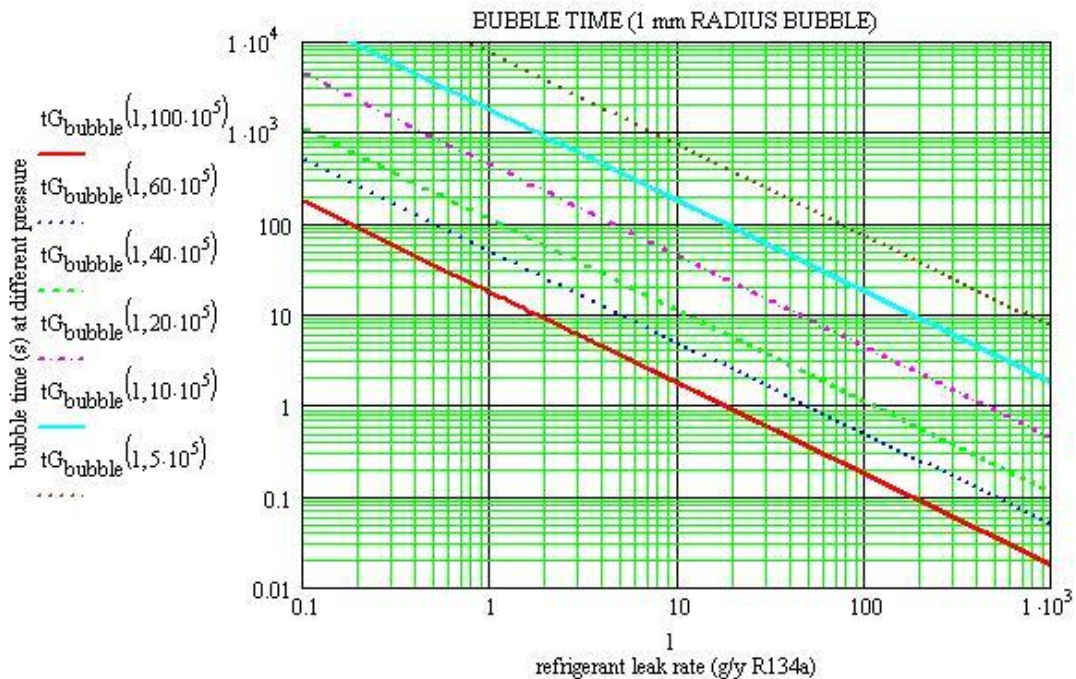


Fig. 10 – Bubble formation time and mass leak rate at different internal test pressure

Some tricks can be introduced to get some improvements to this method. For instance, an incremental increase in the internal pressure may yield more a probable and less time consuming leak pinpointing. A detergent can be added to the water to decrease surface tension, which helps to prevent the leaking gas from clinging to the side of the component. Using different gases (e.g. helium) and/or liquid may give some advantage in system performance, at a cost disadvantage. Hot water in the tank sometimes helps to increase the pressure inside the component or piping system. If dry nitrogen is used, this does not help because nitrogen does not increase its pressure significantly. If refrigerant is contained in the system or component, it may help considerably to increase the pressure and, therefore, increase the chance of finding the leak.

It can be concluded that this technique features accuracy in the  $10^{-3}$  mbar · l/s range in high volume production applications, but it is not recommended. Immersion is a very economical leak testing method. It allows leak detection and, in most cases, also leak location. However, disadvantages range from a relatively low sensitivity, high operator dependency, and possible part contamination, to fluid waste and the possibility of having to dry parts after testing. Moreover, in particular for big coils, the unit handling, to put parts in and out from tanks, may be complex and a source of part damages. Some costs may be hidden. This approach, in fact, implies using large space and can produce a certain amount of waste - water. Especially for big units, like in large heat exchangers, the tank could have great dimensions and require a lot of water. The dryers are not costless machines; they require as much care and maintenance as any in the plant.

### **7.3 Soap Solution Bubble Test**

Instead of submersing the part, the pressurized unit to be tested can be painted with a soap solution and again the operator can see the bubbles escaping where the leak is. Soap solutions are available in many different types. Some have a brush applicator and others have a dabber (an absorbent ball attached to a stiff wire inside of the cap). Some brands may even have a spray applicator to quickly cover large areas of tubing in a short amount of time. This is an advantage but is also messy and time consuming to clean up. Some soap solutions even have an antifreeze base to prevent them from freezing in the winter time. Others may have a lower density to make them even more sensitive to very tiny leaks.

This method has a higher sensitivity than the water immersion. It enables detecting the leakage up to  $10^{-5}$  mbar · l/s and is suitable for very large systems. This method is particularly useful if the soap solution can be applied in the approximate area where a leak may be known to exist. In this case the soap solution can be used in that area to test for and pinpoint a leak. It is the simplest and least expensive (material wise) method known today. However, it may also be more expensive to use, because of labor costs, if the operator does not have any idea where the leak could be. Increasing the gas pressure makes it more a probable and less time-consuming way of pinpointing the leak. However, for operator safety, the pressure must be limited to low values, up to 1700 kPa (250 psi). The use of the soap solution bubble test is limited by some drawbacks. The surface area to be painted should be simple and easily accessible. Otherwise, as for finned pipes or the bottom part of a large heat exchanger, it could be a hard, if not impossible, for the operator to “paint” the part and watch for a bubble. Moreover, the application is not well suited for high productivity lines.

### **7.4 Pressure Decay Test**

This method consists of pressurizing the system with a high pressure gas, usually air or dry nitrogen. Then the part is isolated from the gas supply and, after a stabilizing time, its internal pressure is controlled over time. The pressure drop  $\Delta p$  is measured in the time  $\Delta t$ . If the pressure in the system drops fast, there is a large leak present in that component or section of the system. If the system’s pressure drops slowly, there is a small leak present. If the pressure remains the same, that component does not leak. The leak rate  $Q$  can easily be computed considering the volume  $V$  of the component. That is:

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

Leak detection sensitivity is related to the testing time, the pressure transducer resolution and the volume. The most advanced system measures a pressure variation even less than 70 Pa (0.010 psig) at test pressure. Depending on the volume of the units to be tested, the leak detection cycle can be as short as 30 seconds and guarantees high resolution. Considering  $V = 1.5 \text{ dm}^3$  (0.4 gal) internal volume component with a  $\Delta p = 70 \text{ Pa}$  (0.010 psig) of pressure decay at 3450 kPa (500 psig) test pressure in  $\Delta t = 60$  seconds, the leak rate is:

$$Q = (\Delta p \cdot V) / \Delta t = 0.7 \cdot 1.5/60 = 1.7 \cdot 10^{-2} \text{ mbar} \cdot \text{l/s}$$

Several external factors, such as temperature variations and mechanical deformations, affect this test. The internal pressure, in fact, depends on temperature, and thermal fluctuations may cause changes in pressure altering the results. Fortunately, dry nitrogen experiences very little pressure changes when it is exposed to small temperature changes.

The sensitivity of this testing technique depends on pressure measurement resolution, test time and pressure values. The following picture shows the typical test sensitivity related to internal test pressure and leak rate, for a reference volume (1 litre or 0.26 gal) and a fixed pressure difference (100 Pa or 0.014 psi).

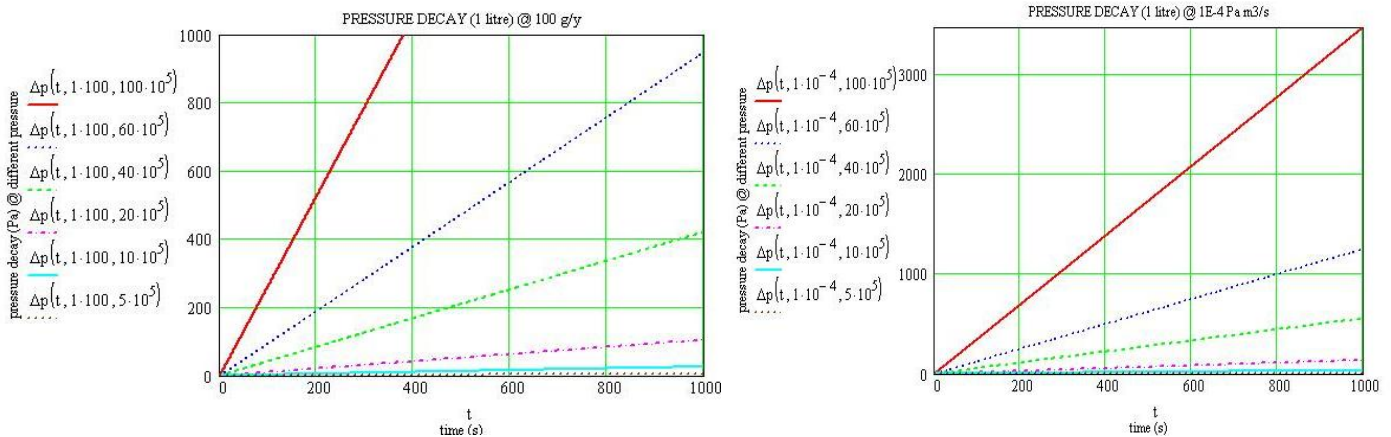


Fig. 11 – Computed pressure test decay sensitivity

Long test times allow a more sensitive check but, in this way, the test can be very time-consuming because some low-level leaks may require a very long holding period, even some hours. The unit volume also affects test sensitivity. In fact, the same pressure variation will correspond to a larger leak if the volume is bigger, and therefore the sensitivity will be less. The higher the pressure, the faster you can determine if a leak is present. However, operator safety concerns limit the maximum admissible pressure value. Components can be leak tested at low pressures, less than 2 MPa (290 psig) without protection, higher pressures, e.g. 7 MPa (1000 psig), may be used adopting safety interlocked protection hoods. Using the proper pressure, this test method also allows compliance with technical specifications, such as American Underwriters Laboratory (UL) Burst test and the European EN378 rules. Burst test is designed to test the mechanical strength of the refrigeration tubing circuit, i.e. ruptured tubing, bad brazed joints with material separation. Pressure ranges for the test vary depending on if the test unit is a component of the refrigeration circuit, or if it is a complete refrigeration circuit with a compressor.

The testing performance can be improved using a pressure differential. In this mode, the test unit is pressurized together with a reference volume and the two pressure trends are compared. For this reason this method is known also as compare mode.



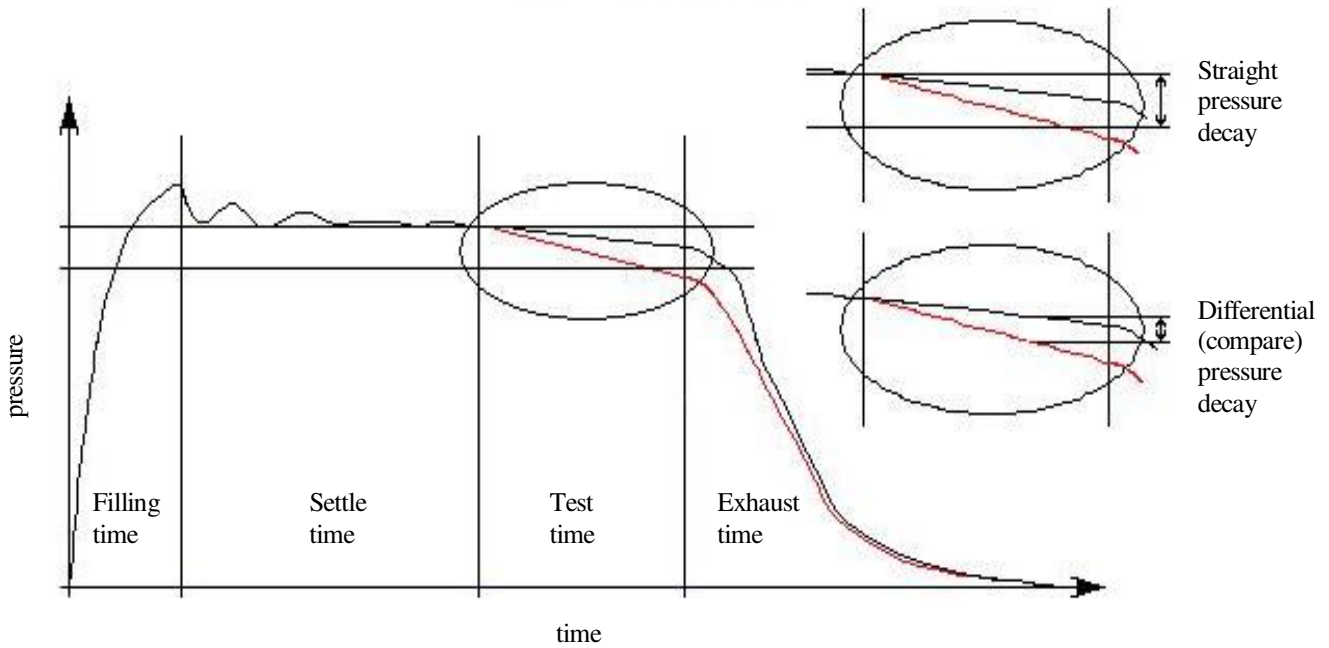


Fig. 12 – Typical pressure behavior in pressure decay test

Pressure decay proof is a go-no go test. It detects the leakage, but leak location requires using other techniques, such as soap paint, or better, tracer gas detection. Usually, the limit is in range  $10^{-3}$  mbar · l/s for pressure decay test without pressure differential and  $10^{-4}$  mbar · l/s for pressure decay test with compare mode (pressure differential).

This leak testing technique has some advantages; this method will positively identify whether or not a leak exists by monitoring pressure drop. If any pressure drop occurs, it means a leak is definitely present. Furthermore this method can be realized completely automatic, so as to avoid operator errors. This procedure is a preliminary leak test, which detects large leaks before the final automatic leak test operation using tracer gas, e.g. helium. This test will detect over 90%, up to even 98%, of the defective parts, especially those not brazed correctly. If the test unit has a large leak, i.e. an over looked brazed joint, without doing the pressure decay test first, large quantities of helium, would leak out of the test unit.

The helium, at this much volume and concentration, would render the system inoperable for hours. Another advantage of the nitrogen filling, besides the mechanical stress and leakage test, is the purging of the circuit to be tested, lowering its humidity. On a successful completion of the pressure decay test, the component is ready for final test.

The disadvantage is that this method does not identify where the location of the leak, only if a leak is or is not present.

### 7.5 Vacuum Decay Test or Pressure Rise Test

Vacuum decay test or pressure rise test works in the opposite way of the pressure decay test. This method involves evacuating the part to suitably low pressure and, after stabilizing the pressure, measuring the increase in pressure caused by test media entering the part. Only parts that are able to withstand external pressure can be tested in this way (e.g. thin walled plastic parts cannot be tested due to the danger of collapsing).

Even if in a vacuum decay test is not possible to get more than one atmosphere of pressure difference from inside to outside, using some solvents (i.e. alcohol, acetone or similar) exalts the pressure increment due to solvent entering into the leak. This approach, however, has some shortcomings, such as the possibility of solvent freezing causing temporary stuffing of leak, or elastomer gaskets becoming damaged by solvents. Like the pressure decay test, the accuracy of this method is related to the volume of the part to be tested; the bigger the volume the smaller the sensitivity will be. Respective of the pressure decay test, however, this technique has some advantages. It is less sensitive to temperature changes since the pressure inside the part is lower than atmospheric pressure. Furthermore, vacuum-meters usually are very sensitive to small pressure changes, so the theoretical sensitivity might be very high, up to  $1 \cdot 10^{-5}$  mbar · l/s.

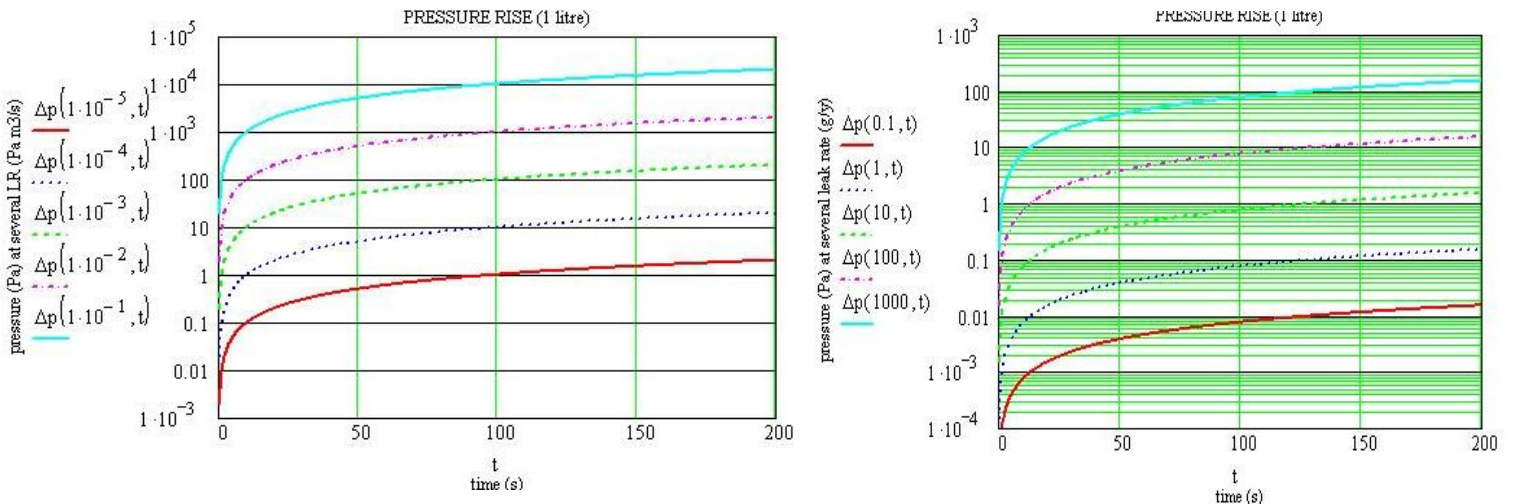


Fig. 13 – Theoretical pressure rise behavior in vacuum decay test

However, surface out-gassing and liquid evaporation affect and limit the real sensitivity. For instance, small quantities of water, even a few grams, start evaporating at 2 kPa (0.3 psia) and at 1 Pa (7.5 μm Hg) the water vapor content is so high that the consequent pressure increase is comparable to a leakage. In refrigeration circuits, where the out-gassing from oil is so significant that could be mistaken for a leak, the sensitivity is limited to  $1 \cdot 10^{-3}$  mbar · l/s

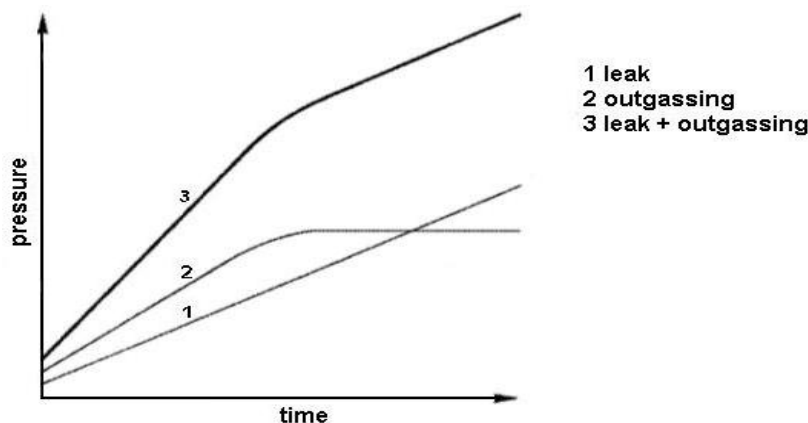


Fig. 14 – Pressure rise due to leak and out-gassing exemplification

Vacuum decay method can be realized in a fully automatic procedure and, in this way, it is independent of an operator. This technique is a “pass-no pass” test. It detects the total system leak and more than one leak can exist, but leak location requires other techniques. In vacuum decay test, the unit to be tested is evacuated and its internal pressure is lower than atmospheric pressure. Therefore, this leak testing method will stress the part in the opposite way, if the working condition requires an internal pressure.

## **7.6 Tracer Gas Leak Testing**

The words “tracer gas leak testing” point out a group of several test methods characterized to detect and measure a tracer gas flowing through a leak. These techniques differ for the tracer gas used and for the realization technology.

The most commonly used tracer gases are halogen gas, just CFC, HCFC and HFC refrigerant, helium and a mixture of nitrogen 95% hydrogen 5%. Despite the simplicity of their detectors, electronic devices, halogens are losing their appeal as tracer gas, due to environmental protection rules following Montreal and/or Kyoto protocols. On the other hand, helium and especially hydrogen/nitrogen mixture are gaining ever more interest.

Helium has been used as tracer gas for long time and this success is due to its physical properties. It is neither toxic nor flammable. It is an inert gas and does not react with other compounds. Helium has low viscosity and relative molecular mass, so it easily passes through cracks. In the same environmental conditions, it may flow through orifices 2.7 times faster than air. Since its concentration in air is low (5 ppm), it is easy to detect an increment of helium concentration. However, there are some shortcomings. Helium slowly disperses into the atmosphere so, in case of big leaks, its concentration will only return to a value suitable to continue leak testing in a long time, even hours. It is not cheap, even if less expensive than halogen gases. The most appropriate helium detector is based on mass spectrometer, which is an expensive and delicate apparatus requiring care and maintenance, more suitable for a laboratory than for a manufacturing industry.

The mixture of nitrogen 95% and hydrogen 5% is a relatively new tracer gas. Hydrogen has a number of properties that make it an excellent trace gas for leak testing, even in production environments. It is the lightest element, with higher molecular speed and lower viscosity than any other gas, so it is easy to fill, evacuate and dissipate, it finds and passes through a leak faster, is easier to flush out and vent away and its molecules do not stick to surfaces as easily as helium atoms. It is environmentally friendly and renewable. More importantly, it has the highest leak rate of any gas. Moreover, the normal background concentration of hydrogen (0.5 ppm) is ten times less than helium. Detectors use a semiconductor sensor, have no moving parts, making it completely maintenance free. These devices are not affected by the presence of other gases. Pure hydrogen should never be used as trace gas, but a standard industrial grade mix of 5% hydrogen in nitrogen is inexpensive, non-flammable (as for ISO10156 specification), easily available from industrial gases suppliers.

It is important to remember that background concentration in air is a limiting factor for any tracer gas detector. There are two ways to carry out leak testing with tracer gas: external detection of tracer gas escaping from leaks of a filled unit (inside-out method), and internal detection of tracer gas entering from leaks (outside-in method). For each of these two methods there are two realization techniques. The inside-out methods can be executed with atmospheric sniffing or with vacuum chamber detection, while the outside-in method is generally implemented putting the unit to be tested in a room containing the tracer gas or, very rarely, spraying the tracer gas on the unit surface. In the following sections, each of these methods is described.

### 7.6.1 Sniffing

This is the simplest realization of an “inside-out” testing. The sniffing technique of leak detection utilizes a detector probe, or sniffer, to sense leaks from a unit previously filled and pressurized with the tracer gas. Before filling the unit with the tracer gas, it must be evacuated, so a pumping group, even a small one, is required. This method is very operator dependent. In fact, the probe (or wand) is moved over the part and detects the leak as it passes over that leak. The speed, distance from the part and the probe sensitivity determine the accuracy of leak detection. However, sniffing will locate a leak on a part, unlike the other methods described, and has the ability to sense leaks as small as  $10^{-7}$  mbar · l/s, depending on the tracer gas. Sniffing is not recommended in a high volume production environment, other than for locating leaks for repair. Depending on the tracer gas, sniffing may involve a relatively low tooling cost investment, representing an economical method of leak detection. Besides, the cost of the tracer gas may be significant and, in case of a particularly expensive gas, the used of a suitable gas recovery and reclaim system should be considered, further increasing the overall costs. Disadvantages include a high chance of missing leaks due to operator dependency, fragile equipment in rugged environments, rejecting good parts (because of the inability to quantify the leak) and it is not a good overall leak detection technique. Some sniffers and the relevant detectors require a periodic maintenance to assure proper functioning, since they are complex system composed of vacuum pumps, mass spectrometer and vacuum fittings. Electronic detectors, without moving parts, are very profitable. Some detectors are sensitive to gases other than the tracer gas used. Therefore, using these sensors, attention to the chemical environmental conditions is required.

The minimum leak rate measurable by sniffer is the concentration of the tracer gas in the working area, the value known as background level. This level may change during the production cycle and increase in the case of leaking units. Relating to the tracer gas used, in case of big leak in the part under test, a lot of tracer gas escapes from it and may remain for long time in the working area strongly affecting the following tests, causing rejection of good parts. It is good practice to use a preliminary leak testing system to reject parts with gross leakages. It is possible to integrate this preliminary test, i.e. a pressure decay test, in the tracer gas-filling machine, so as to simplify the system.

It is important to note that sniffing techniques are local methods, allowing the testing of single points. Each of the tested points can have a leak below the sniffing sensitivity, but the overall leakage may be above the acceptance limit. As result, the test is successful, but the part is defective. Global tests, such as vacuum chamber inside-out and outside-in methods, solve this problem.

### 7.6.2 Accumulation leak testing

This method is a variation of sniffer leak testing. The part to be tested is enclosed in a closed containment box, and then it is pressurized with the tracer gas. The sniffer is connected to this hood where the leaked tracer gas is accumulated during the test time. When accumulated, the tracer gas is more readily sensed by the detector. The gas sensor will measure the total or global leak.

In addition to the characteristic limitations of the sniffer testing method, this technique has other drawbacks. The larger the accumulation volume, the longer the time needed to detect the leakage. Leak rate and sensibility depend on the residual volume and the test time. The tracer gas partial pressure increment  $\Delta p$ , the tracer gas flow  $Q$ , residual volume  $V$  and the test time  $\Delta t$  can be expressed with a sample equation:

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

This method is used in very special applications, e.g. very small components to be tested for tiny leaks.

### 7.6.3 Vacuum chamber inside-out leak testing

Vacuum chamber inside-out leak testing is the most complex system for leak detection, but it is theoretically suitable to find very small leaks, using a proper tracer gas. The equipment is composed of one or more vacuum chambers, large enough to house the unit to be tested. The chamber is connected to a vacuum pumping group equipped with the tracer gas detector, for chamber evacuation and gas detection. A second vacuum group is required to evacuate the unit under test before filling it with gas. A tracer gas-filling device completes the testing apparatus. The unit to be tested is put into the vacuum chamber and connected to service hoses. Then the vacuum chamber and the unit are evacuated. During chamber evacuation, the part is pressurized with the tracer gas and, after a stabilization time, the detector is linked to the vacuum line, so to detect the tracer gas flown through a leak and sucked by the pumping group. In this way, the leakage is detected. It is a “go-no go” test and to locate the leak requires other techniques.

This method has some advantages. This technique is fully automatic, so it is not very operator dependent. Its sensitivity, depending to tracer gas and test time, can reach  $10^{-10}$  mbar · l/s, even if in a practical application in the refrigeration industry the limit is  $10^{-6}$  mbar · l/s.

There are also some drawbacks. Depending on the vacuum chamber dimensions, the evacuation group can have a high pumping speed. Some gas detectors require a periodic maintenance to ensure proper functioning, since they are complex system composed of vacuum pumps, mass spectrometer and vacuum fittings. Besides, the cost of the tracer gas may be significant and, in case of a particularly expensive gas, the used of a suitable gas recovery and reclaim system should be considered, further increasing the overall costs and the system complexity. Concerning the tracer gas used, in case of big leak in the part under test, a lot of tracer gas escapes from the leak. A long pumping time could be required to lower the tracer gas in the detector to an acceptable level compatible with system function. The system is unusable during this time. It is good practice to use a preliminary leak testing system to reject parts with gross leakages. It is possible to integrate this preliminary test, i.e. a pressure decay test with the vacuum chamber test, so to simplify the system.

Another disadvantage is that this method does not identify where the leak exists, only if a leak is or is not present. It detects the total system leak and more than one leak can exist. Leak location requires other techniques.

### 7.6.4 Outside-in leak testing

In this testing technique, the unit to be tested is put into a containment hood containing the tracer gas. The part is connected to a vacuum group and evacuated. A tracer gas detector is placed in the vacuum line to detect the tracer gas flow in a leak and sucked in by the pumping group.

This method has some advantages. This technique is fully automatic, so it is not very operator dependent. The sensitivity, depending on the tracer gas and test time, can reach  $10^{-6}$  mbar · l/s. The containment hood can be designed to prevent dispersion in order to reduce working area pollution and tracer gas consumption, saving money and avoiding the need for a recovery system.

There are also some drawbacks. The difference from inner and outer pressure is limited to values slightly above the atmospheric pressure. Concerning to the tracer gas used, in case of big leak in the part under test, a lot of tracer gas escapes from the leak. A long pumping time could be required to lower the tracer gas in the detector to an acceptable level compatible with system function. The system is unusable during this time. It is good practice to use a preliminary leak testing system to reject parts with gross leakages. It is possible to integrate this preliminary test, i.e. a pressure decay test, in the tracer gas-detecting machine, so to simplify the system.



Another disadvantage is that this method does not identify where the leak is, only if a leak is or is not present. It detects the total system leak and more than one leak can exist. Leak location requires other techniques.

In the following sections, the main applications of the previously reported methods are described.

### 7.6.5 Halogen leak detectors

The working principle of the halogen detector is based on the measure of a positive ions emission due to the halide presence inside an electronic cell. This ion current is related to the halogenated gas concentration and, therefore, to the leak size. Less sensitive detectors are based on infrared light absorption by halogenated gas. The main application for halogen detectors is for inside-out systems, while their use for outside-in methods is very limited.

In the inside-out method, halogen leak detectors are used in the detector-probe mode, requiring that the system be pressurized with a tracer gas containing an organic halide, such as CFC, HCFC and HFC. The exterior of the system is then scanned with a sniffer probe sensitive to traces of the halogen-bearing gas. The achievable sensitivity can be  $10^{-5}$  mbar · l/s.

In outside-in mode, an evacuated vessel is connected to a halogen detecting instrument and is sprayed by halogenated gas. In this manner, its performance is up to  $5 \cdot 10^{-7}$  mbar · l/s and is used in rough, medium and high vacuum. This method is quite complex and has high environmental impact, so it is rarely used. Halogen leak detectors have a wide spread usage in refrigeration and air conditioning maintenance to locate leaks in refrigerant charged system due to their high sensitivity. In manufacturing industry, however, their use is limited because of several disadvantages and drawbacks. Refrigerant has a higher specific volume than air; therefore refrigerants will fall when exposed to atmospheric pressures. This means leak detecting on the bottom sides of the piping or components will be more effective in detecting a leak.

Since electronic halogen detectors are sensitive to many gases, included non-halogenated ones, such as carbon monoxide and alcohol, their sensitivity is strongly determined by the tracer gas type and environmental conditions. The best performance is achievable if used in a controlled atmosphere room.

If a unit previously charged with refrigerant has to be evacuated and re-charged, the pre-evacuation phase is difficult and very time consuming. Halogenated gases are costly, more expensive than other tracer gases, like helium and nitrogen-hydrogen mixture. Halogen gases have a high environmental impact and their dispersion in the atmosphere is severely regulated, if not forbidden, in many countries.

### 7.6.6 Inside-out helium sniffer detectors

A Helium sniffer is a detector probe and an ancillary accessory of leak detectors. A vacuum pump inside the leak detector maintains the helium spectrometer in high vacuum (up to  $1 \cdot 10^{-2}$  Pa or  $7.5 \cdot 10^{-2}$   $\mu$ m Hg). One side of the sniffer is connected to this vacuum group, while its detection probe, provided with a calibrated orifice, is opened to the atmosphere. Air, with helium, flows through this hole into the mass spectrometer, where the helium concentration is measured and the leak rate is computed.

In inside-out techniques, the unit to be tested is evacuated and then pressurized with helium. An operator moves the sniffer over the part and tests with the probe around suspected leak sites. The orifice dimension establishes the probe flow and then the detection performance. Flow,  $Q_{He}$ , pumping speed,  $S_{He}$ , and partial pressure,  $P_{He}$ , are related as:

$$Q_{He} = P_{He} \cdot S_{He}$$

The minimum leak rate measurable by a helium sniffer is the concentration of helium in the working area. In the ideal case, the atmospheric concentration of helium is 5 ppm, so its partial pressure is 0.5 Pa (3.7  $\mu\text{m Hg}$ ). Then, considering a standard pumping speed of 1  $\text{cm}^3/\text{s}$ , the sensitivity is:

$$Q_{\text{He}} = P_{\text{He}} \cdot S_{\text{He}} = 0.5 \cdot 1 \cdot 10^{-6} \text{ Pa} \cdot \text{m}^3/\text{s} = 5 \cdot 10^{-6} \text{ mbar} \cdot \text{l/s}$$

The slower the pumping speed, the higher the sensitivity will be, but the slower the helium will arrive at the spectrometer and longer the delay time to get the measurement. The most commonly used pumping speed, a trade-off between sensitivity and response time, is 1  $\text{cm}^3/\text{s}$  that, with a pipe 5 m (16.4 ft) length, provides a delay time of about one second. As a consequence of this delay time, the sniffer's moving speed and its distance from the part to be tested are critical points. The nearer the probe is, the higher the helium concentration entering the mass spectrometer and better the test quality. On the other hand, the faster the detector movement, the smaller the pumped helium quantity is. Furthermore, the sensitivity of this method is strongly limited by the background helium level and is not as good as that achievable with others techniques based on mass spectrometers.

The helium sniffer leak testing method has the big advantage of determining leak location but, as shown before, has some drawbacks. Helium sniffer leak detection implies manual operation, strongly operator dependant, and the operator's experience is a determining factor in the outcome of the testing procedure. Helium disperses slowly into the atmosphere, so in the case of leaks, the background level increases limiting the successive tests. In case of a big leak, the working area may become unusable for long time. It is good practice to use a preliminary leak test, such as a pressure decay test, to detect gross leakages. This test may be integrated in the same helium inside-out machine.

Leak detection sensitivity is related to the internal pressure, as shown in the following diagram. However, the maximum usable pressure is limited by operator safety concerns. Unless using a robotized arm, sniffing inside a protective hood is not feasible.

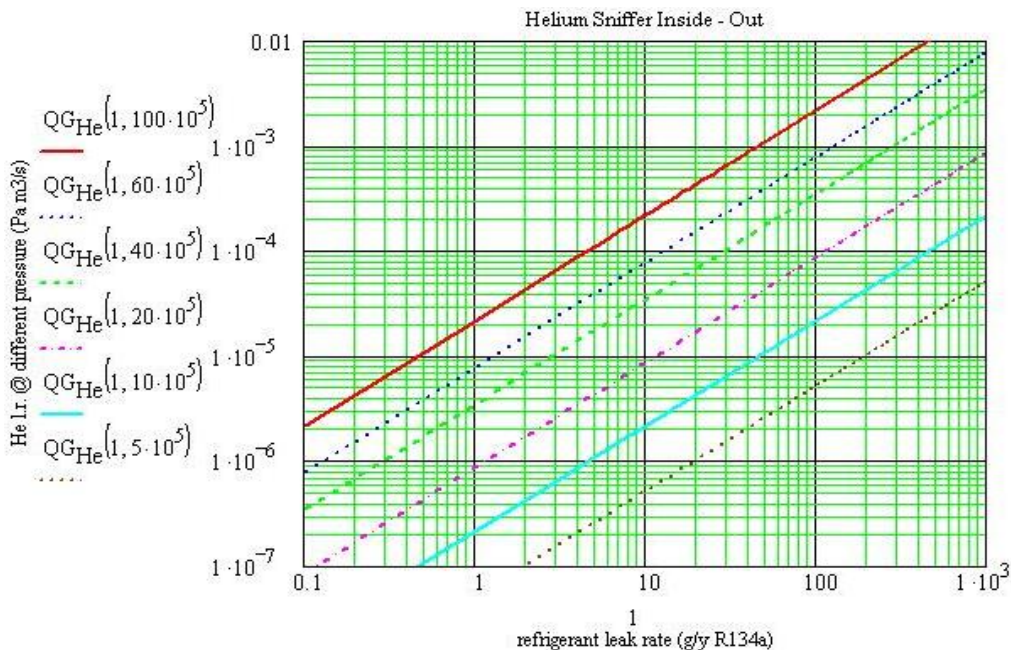


Fig. 15 – Inside – out helium sniffer dependency on internal pressure



Helium is quite an expensive gas, and, as stated before, it is not convenient to spread it into the working area, so is good practice to use helium recovery/reclaim stations to empty the unit at the end of leak testing. The recovered helium can be reutilized for successive tests. Nevertheless, even using a recovery system, some helium will be lost. A small quantity will be, in fact, dispersed in the test area and some more will remain inside the circuit. Furthermore, during the recovery phase, helium can be contaminated by air infiltration, moisture and oil. The storage tank must be checked to ensure that helium inside has enough concentration and is pollution free so that leak testing is affordable. Helium concentration restoration and tank cleaning procedures must be periodically executed.

### 7.6.7 Outside-in helium spraying

In the outside-in helium spraying technique, the sample to be tested is connected to a vacuum group and to a mass spectrometer. The unit is evacuated and its surface is "probed" with a pointed jet of helium by a suitable diffuser. Coming over a leak, the detector senses the helium entering from the leak allowing the location and data about the leak size. This method is classified under vacuum test methods, even if it is a special case. This technique can be used where it is needed to locate small leaks since its sensitivity is not limited by the background helium level.

However, it is not free of limitations. This method, like sniffing, is operator dependant. Moreover, helium is lighter than air; it tends upwards, so helium sprayed in the bottom of the unit may pass through a leak in the upper part. Helium has a tendency to accumulate and then saturate the working area if it is not used with good ventilation. In this condition, leak location becomes difficult. In case of a big leak, a lot of helium reaches the mass spectrometer and a long time may be needed to reduce the helium level to a value compatible with testing, but, during this time, operator can perform other tasks.

Since the unit to be tested is evacuated, its internal pressure is lower than atmospheric pressure. Therefore, if the working condition requires a pressure inside, this leak testing method will stress the part in the opposite way. This testing technique is, however, is widely used in research and in all applications involving big plants which cannot be leak tested using other methods. It is not the most suitable solution

for testing in high productivity lines or series production manufacturing industries. It is important to note that parts to be checked must be kept in an area free from helium contamination before leak testing. If high pressure air is used for a preliminary pressure decay test, the high pressure air compressor inlet must also be in a "fresh air" atmosphere.

### 7.6.8 Outside-in helium leak testing

In the outside-in helium leak testing technique, the part to be tested is covered with a suitable hood to contain helium and connected to a vacuum group and mass spectrometer. The test consists of evacuating the unit and flooding the hood with helium. Helium, in fact, due to its atomic characteristics, has a high penetration capability. So a mass spectrometer can detect the helium leaked into the component through cracks and porosities not detectable using other systems. The part is evacuated to less than 15 Pa (100  $\mu$ m Hg). The unit may be also subjected to a vacuum rise test to ensure that it is "clean" from water vapor contamination, other non-condensable gases, and free of very large system leaks. After evacuation, the internal circuit is connected to the mass spectrometer. If any helium has leaked into the circuit, the mass spectrometer detects it. In this way, it is possible to quickly establish whether a sample leaks and to establish the total leak rate. This method is able to detect leak rates up to  $1.8 \cdot 10^{-5}$  mbar  $\cdot$  l/s, that is 2.5 g (0.1 oz) of R134a refrigerant per year. The sensitivity of this method is related to the helium concentration. The following picture shows the relationship between helium leak rate and refrigerant leak considering 10% helium 90% air.

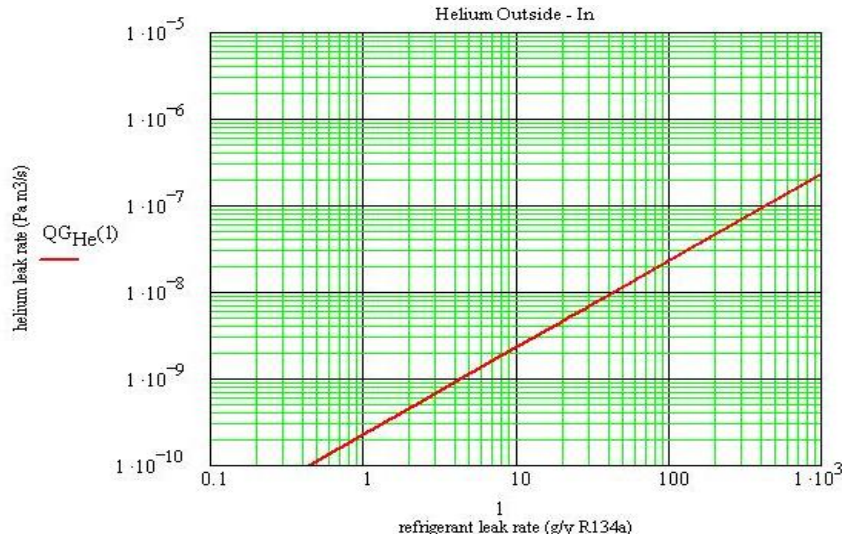


Fig. 16 – Outside – in helium leak rate

There are several practical realizations of this testing method. The test system can be designed with one or multiple stations, usually two, for production rate requirements since multi-station machines allow testing several parts, one for each station, simultaneously. The containment hood, appropriated to the product sizes so as to completely cover the test unit, may be created in such a way to reduce helium dispersion during loading and unloading operations. Advances in vacuum and helium technologies provide improved sensitivity and faster test cycles even with low helium concentration, even values typically used of 10% helium 90% air. In this case, the containment hood uses a helium ratio transducer to monitor the mixture inside it. Recirculation fans and mixing ducts maintain the preset concentration of helium to air uniformly distributed in the internal volume. The system will only replenish the helium when needed. Adoption of this state of the art solution saves helium thereby reducing operation costs.

This leak testing method has some advantages. It is a final global leak test and this technique is very useful on production lines where a test piece must be accepted or rejected. The test is fully automatic and hands free. The total process time to leak test a part, regardless of its volume, is low, even less than 80 seconds for a medium size unit.

However, there are also some shortcomings; some precautions must be taken for the proper use of this system. This method is a “go – no go” test and is for leak detection only. For the leak location an additional system is required. If the test unit has a large leak, i.e. an overlooked brazed joint, the escaping helium, at this much volume and concentration, would render the system inoperable for long time. It is convenient to use a preliminary leak test for identification of gross leakages. A pressure decay test can be easily combined in the outside-in leak testing machine. This initial nitrogen filling, besides the mechanical stress and leakage test, allows purging the circuit to be tested, lowering its humidity. On a successful completion of the pressure decay test the component is ready for final test. At the end of cycle, the part may be filled again with nitrogen, at a low pressure, to avoid helium to enter into its internals when disconnected.

Since the unit to be tested is evacuated, its internal pressure is lower than atmospheric pressure. Therefore, if the working condition requires a pressure inside, this leak testing method will stress the part in the opposite way. This problem can be mitigated using a proper preliminary pressure decay test. It is important to note that parts to be checked must be kept in an area free from helium contamination before outside-in leak testing. If high-pressure air is used for a preliminary pressure decay test, the high-pressure air compressor inlet must also be in a “fresh air” atmosphere. At the end of cycle, the unit may



be filled with low-pressure nitrogen to avoid helium infiltration into the part when disconnected.

### 7.6.9 Inside-out helium vacuum chamber leak testing

In inside-out techniques, also known as “global hard-vacuum test”, the test configuration is reversed. The component is placed inside an air tight chamber equipped with service hoses and a vacuum pumping group with a mass spectrometer. The unit is connected to the service hoses, the chamber is closed, and the part is evacuated and then pressurized with helium. The chamber is subsequently evacuated and, once a suitable vacuum level is reached, the inlet valve of the leak detector is opened. The leak detector begins to analyze the residual gas molecules present in the chamber. Helium molecules escaping from the component are conveyed and measured in the leak detector. At the end of cycle, the vacuum chamber is vented. The leak detector finds the leak and it gives the total measure. Referring to the complexity of the test and the desired degree of automation, different test systems may be realized from the simplest to more elaborate. As an example, a two chamber machine can be designed so that while in one chamber the test cycle is in progress while in the other the part is being unloaded and loaded. In many industrial applications, to reach the vacuum level inside the test chamber in acceptable times, an auxiliary pumping group is needed. The dimensioning of the pumping group depends on different parameters, such as the size of the expected leaks, the dimensions of the parts to test and the cycle time.

The vacuum chamber helium inside-out leak test method has some advantages. A sniffer is not used; testing is automatic and not very operator dependant. The sensitivity achievable with this test is very high. In laboratory applications it is not impossible to get  $10^{-10}$  mbar · l/s. However, in practical applications in the refrigeration industry, due to unit uncleanness, dirt accumulation inside the chamber and oil and moisture contamination, the limit is considered  $10^{-6}$  mbar · l/s. The following picture shows the theoretical relationship among refrigerant leak rate, internal helium pressure and helium leak rate.

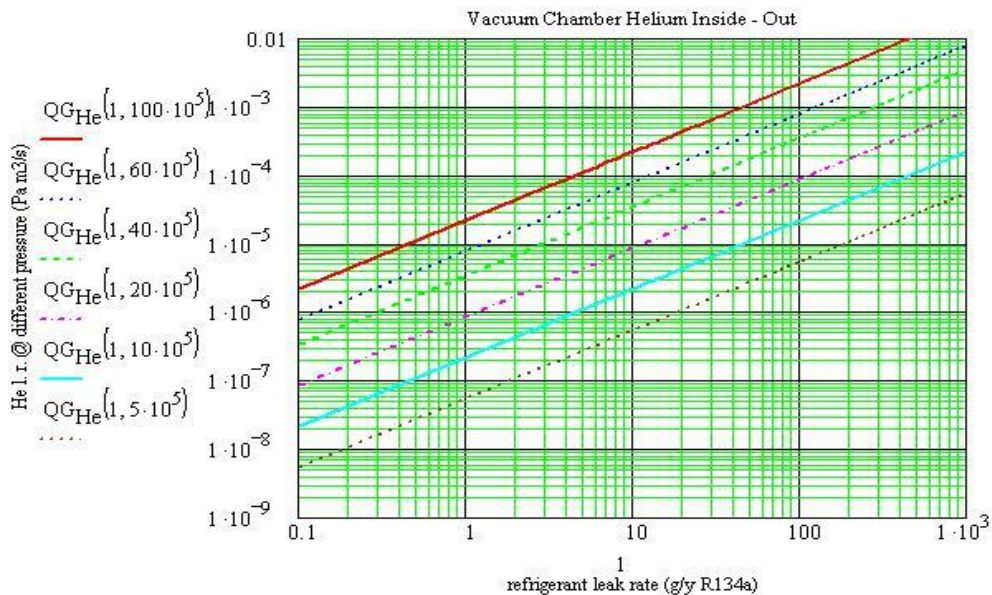


Fig. 17 – Vacuum chamber inside – out helium leak detection

Despite these advantages, vacuum chamber inside-out leak test method has several drawbacks. It is an expensive test system. While the sniffing test requires only the leak detector and the ability of the operator, the hard-vacuum test requires more complex and expensive equipment, but it enormously limits the reliance on the human factor. This fact makes this test attractive in many industrial contexts, while the sniffing test has its application in the maintenance and the analysis of defective parts.

In design and realization of the vacuum chamber, particular care must be taken to avoid helium contamination. In fact, if some helium remains on the chamber inner surface or in some internal components, the background helium level will be high and the sensitivity will consequently be reduced. Consequently, test equipment performance, especially its sensitivity, is strongly affected by vacuum chamber clearness and contamination. To achieve the best performance from this machine, periodic maintenance, cleaning and purging procedures are required. If the test unit has a big leak, large amounts of helium would leak out of the test unit and into the vacuum chamber, the mass spectrometer and the vacuum pumping station. The helium, at this much volume and concentration, would render the system inoperable for long time.

To avoid this phenomenon, is good practice to use a preliminary leak test to detect big leaks. A pressure decay test can be combined with the vacuum chamber inside-out leak test. This initial nitrogen filling, besides the mechanical stress and leakage test, allows purging of the circuit to be tested, lowering its humidity. On a successful completion of the pressure decay test the component is ready for final helium test. At the end of cycle, the part may be filled again with nitrogen, even at a low pressure, in order to purge its internal circuit from the helium residuals before vacuum chamber venting.

Unlike the sniffing test, the hard-vacuum test is a global method, that quantitatively defines the total leak of the piece, but that does not determine its position. Other techniques are required for determining leak location. Because helium is a quite expensive gas and to reduce the helium concentration it is not acceptable to spread it in the working area, so is good practice to use helium recovery/reclaim stations to empty the unit at the end of leak testing. The recovered helium can be reutilized for successive tests. Helium recovery systems are costly equipments and, as already discussed above, they are not trouble free.

#### 7.6.10 Inside-out hydrogen sniffer detectors

As in the other inside-out techniques, the unit to be tested is evacuated and then pressurized with the hydrogen/nitrogen mixture. An operator moves the sniffer over the part and tests with the probe around suspected leak sites.

Comparing with helium sniffer leak testing, this method has the same difficulty of operator dependency, but has many advantages. Hydrogen is ideal for leak testing. It is the lightest element, with higher molecular speed and lower viscosity than any other gas. Therefore, it easily fills the unit to be tested, mixes quickly with any gas, and is easily evacuated and dissipated. Since hydrogen mixes very quickly with other gases, this method requires a low vacuum level compared with helium filling. As a result, the vacuum group is very simple – a Venturi vacuum generator is enough. Hydrogen easily disperses into air, so its concentration in the working area falls quickly to the background level even in case of big leaks.

In addition, hydrogen has the highest leakage rate of any other gas. Hydrogen detectors are based on semiconductor sensors and, do not contain any moving parts, are robust for industrial use and completely maintenance free. They are unaffected by the presence of other gases. Moreover, these sensors do not require suction for functioning, so the probes can be used without worrying about dust. In addition, the probe can be equipped with a protective cover that allows it to be used on wet objects. Hydrogen has a very low background concentration (0.5 ppm) and the detectors are sensitive enough to detect up to  $5 \cdot 10^{-7}$  mbar · l/s (or 0.5 g/y (0.018 oz/y) R134a refrigerant) using a mixture of 5% hydrogen 95% nitrogen, ten times more sensitive respect to helium sniffing. This blend is standard industrial grade mix, inexpensive, non-flammable (as for ISO10156 specification) easily available from industrial gases suppliers. The following figure gives an idea about the relationship among tracer gas leak rates, internal test pressure and refrigerant leak rates. Obviously the maximum internal pressure is limited by operator safety concerns.

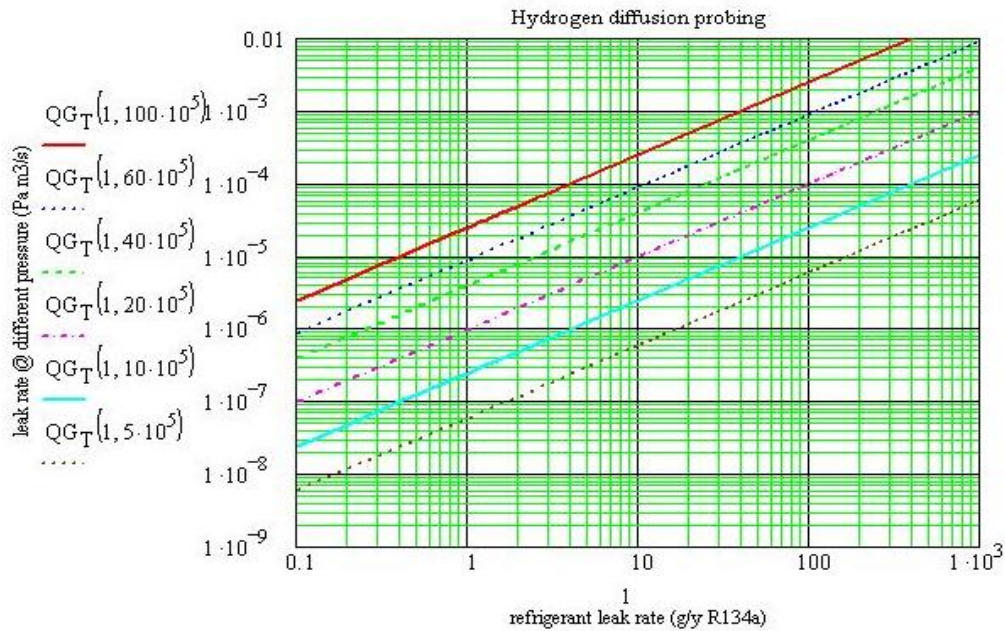


Fig. 18 – Hydrogen diffusion probe leak detection sensitivity at several internal pressure

There are some shortcomings or rather some suspicions in using hydrogen as a tracer gas. Hydrogen escapes rapidly from a leak almost in vertical direction, so a leak can be precisely detected and located only if the detector is directly above it. This characteristic causes someone to think that leak detection

with hydrogen is more difficult than with helium. However, even if a skilled operator has no difficulty in managing this problem, detectors can be easily integrated in special designs, e.g. a funnel-shaped device, to facilitate leak detection. Another common doubt of the hydrogen/nitrogen mixture is component separation and hazards related to hydrogen. Even though the hydrogen/nitrogen mix is widely available, big industries with high production lines think that in big cylinders hydrogen tends to accumulate in the higher section of the bottle. This would cause working with different hydrogen concentrations during the bottle life. On other hand, in-house mixing of hydrogen and nitrogen would assure the proper mixture, but it is very hard to achieve due to the risks related to hydrogen handling.

Hydrogen leak testing is a manual operation but, with a proper sampling probe, it can also be automated. Approaches similar to the accumulation method can be favorably applied. Although hydrogen quickly disperses in air and, even in case of big leak, the working area is not saturated by hydrogen, it is convenient to save tracer gas using a preliminary leak test for gross leakage identification. A pressure decay test can be easily integrated in the hydrogen testing machine.

## 8. HOW TO CHOOSE THE TEST METHOD

The specification of the acceptable leak rate and the test method are the first parameters to take into consideration in the plan of a product.

The questions to be answered are:

- Which type of total leak can damage the product?
- How many points (welding points, joints etc...) must be tested?
- How long must the product last?

The answer to these questions is usually established in terms of a volume or gas mass that flows in a definite time (e.g. 10 g (0.35 oz) of R134a refrigerant in seven years). Sometimes answering this question



is not exactly straightforward. For example, to define the total leak specifications of a refrigeration system is simple, but to define the valid specifications for a single component and a single welding point is much more complex.

Every leak testing methodology has advantages and disadvantages. For leaks comprised in the range  $10^{-1}$  and  $10^{-3}$  mbar · l/s all the test methods are able to recognize a leak. Besides sensitivity, in selecting the proper testing method, many other parameters have to be considered. Among them are repeatability, accuracy, report capability, operator dependency, cost of the equipment and the necessary work force required to run it. In addition, the cost of the tracer gas has an important impact especially in case of series controls. In some cases a gas recovery system, cutting down its consumption, should be considered.

For clarification, in the following a sample application is treated.

Let 84 grams (3 oz) of R134a in 5 years, at internal pressure of 1800 kPa (261 psia) and room temperature, be an acceptable leakage. This leak corresponds to 16.8 g/y (0.59 oz/y) of refrigerant

$$F = 84/5 = 16.8 \text{ g/y} = 16.8 / (365 \cdot 24 \cdot 3600) = 5.33 \cdot 10^{-7} \text{ g/s}$$

The equivalent leak rate can be computed by the kinetic theory of perfect gas. Since the molar weight of R134a is 102.03, the equivalent molar flow is:

$$F_m = F / M = 5.33 \cdot 10^{-7} / 102 = 5.22 \cdot 10^{-9} \text{ mol/s}$$

It is known that a mole of a gas occupies a volume of  $22.4 \cdot 10^{-3} \text{ m}^3$  (0.79 ft<sup>3</sup>) at atmospheric pressure and 0 °C (32 °F). Then the molar volume at room temperature and atmospheric pressure is:

$$V_m = 22.4 \cdot 10^{-3} \cdot 300 / 273.16 = 24.6 \cdot 10^{-3} \text{ m}^3/\text{mol}$$

Let  $p$  the atmospheric pressure, the volumetric leak flow will be:

$$Q = F_m \cdot V_m \cdot p = 5.22 \cdot 10^{-9} \cdot 24.6 \cdot 10^{-3} \cdot 10^5 = 1.28 \cdot 10^{-5} \text{ Pa} \cdot \text{m}^3/\text{s} = 1.28 \cdot 10^{-4} \text{ mbar} \cdot \text{l/s}$$

The internal pressure has effects on the leak rate. The flow through an orifice depends not only on the pressure difference at the two sides of the orifice, but also on their absolute values. Let  $P_1$  and  $P_2$  the absolute pressures, to both edges of an orifice, that cause the rate of  $Q_1$  leak, and  $P_3$  and  $P_4$  the absolute pressures that cause, in the same orifice, the  $Q_2$  leak rate. Then the following relationship yields:

$$\frac{Q_1}{Q_2} = \frac{P_1^2 - P_2^2}{P_3^2 - P_4^2}$$

This equation allows computing the equivalent leakage when different pressure values are used. For example, resuming the previous case, the leak of  $Q_1 = 1.28 \cdot 10^{-4} \text{ mbar} \cdot \text{l/s}$  from  $P_1 = 1800 \text{ kPa}$  (261 psia) to  $P_2 = 100 \text{ kPa}$  (14.5 psia), corresponds to a flow rate  $Q_2$  from the atmospheric pressure to vacuum:

$$Q_2 = 1.28 \cdot 10^{-4} \cdot \frac{1^2 - 0}{18^2 - 1^2} = 3.9 \cdot 10^{-7} \text{ mbar} \cdot \text{l/s}$$

If the leak testing is executed in a vacuum chamber, pressurizing the unit to 100 kPa (14.5 psia), the limit leak rate should be  $3.93 \cdot 10^{-7} \text{ mbar} \cdot \text{l/s}$ .





The flow through a leak also depends on the fluid viscosity; the less the viscosity, the larger the flow rate. Therefore, the flow  $Q_1$  of a medium of viscosity  $\nu_1$  is related to the flow  $Q_2$  of a medium of viscosity  $\nu_2$  by the relationship:

$$\frac{Q_1}{Q_2} = \frac{\nu_2}{\nu_1}$$

Returning to the previous example, considering that the tracer gas is helium, the R134a leak can be converted in the equivalent of leak for helium, based on various the viscosity ( $\nu$ ) of two gases

$$\frac{Q_{R134a}}{Q_{He}} = \frac{\nu_{He}}{\nu_{R134a}}$$

Since the viscosity of the R134a is 0.012 cP and that one of helium 0.0178 cP, it follows that the permissible leak for helium is:

$$Q_{He} = 3.9 \cdot 10^{-7} \cdot 0.012 / 0.0178 = 2.6 \cdot 10^{-7} \text{ mbar} \cdot \text{l/s}$$

Even though these considerations are useful to identify the best suited testing techniques, they are not precise. Several approximation and simplification errors are introduced in the various steps. The perfect gas assumption is a useful approximation but, especially for refrigerants that should be more properly considered vapors, is not exactly respected. In addition, there is no confidence that if a leak occurs at

1800 kPa (261 psia), this leak happens also to 100 kPa (14.5 psia), especially if the pressure acts in opposite sense. Moreover, the flow computations are applicable accurately in known flow regimen, but, obviously, this is not the case. In order to obviate these error sources, it is better to carry out the tests with sensitivity ten times higher than that obtained with theory, to provide a wide safety margin.

## 9. CONCLUSION

The growing demand for components and systems with less and less acceptable losses seems the industry trend due to several compelling market demands, such as economic requirements, environmental protection specifications, safety constraints and quality production requirements. The result is stricter quality controls for leak testing. Researchers, technicians, scientists, producers etc... working with hermetically closed elements and vessels, vacuum or only tight seals have to become familiar with measurements and location of leaks. However, this technical field is nearly unknown even in engineering and in important project organizations. A brief analysis of some of the most commonly used leak detection techniques, with particular attention to the refrigeration industry were presented. Every methodology has advantages and disadvantages; the right choice is a trade-off between them and the production requirements. For determining the best choice of test method to be used, it is necessary to accurately consider all admitted leak limits and all the other factors, not only the technological requirements, but also the corporate image, the regulation developments and the new requirements of the market.



## ANNEX A

### Vacuum unit conversion chart

1 atm = 760 Torr = 1013 mbar = 101325 Pa = 14.7 psia = 760 mm Hg

### Leak rate unit conversion table

At constant  $\Delta P$  of 100 kPa

	std cc/s	mbar l/s	Torr l/s	Pa m <sup>3</sup> /s
1 std cc/s		1	0.75	0.1
1 mbar l/s	1		0.75	0.1
1 Torr l/s	1,3	1,3		0.13
1 Pa m <sup>3</sup> /s	10	10	7.5	

### Approximate Leak Rate Equivalents for Refrigerant Leakage

Gas leak rate (mbar l/s)	Conversion factor	Helium leak rate
1 g/y R22 = $9.00 \times 10^{-6}$	x 0.66	<b><math>5.9 \times 10^{-6}</math></b> mbar l/s
1 g/y R12 = $6.43 \times 10^{-6}$	x 0.64	<b><math>4.1 \times 10^{-6}</math></b> mbar l/s
1 g/y R134a = $7.63 \times 10^{-6}$	x 0.71	<b><math>5.4 \times 10^{-6}</math></b> mbar l/s
1 g/y R600a = $1.34 \times 10^{-5}$	x 0.40	<b><math>5.3 \times 10^{-6}</math></b> mbar l/s
1 g/y SF6 = $5.33 \times 10^{-6}$	x 0.77	<b><math>4.1 \times 10^{-6}</math></b> mbar l/s

### Approximate Leak Rate Equivalents for R134a Refrigerant Leakage

Gas leak rate (R134a)	Helium leak rate (mbar · l/s)	Bubble immersion (time to form one bubble)
300 g/y (9.6 oz/y)	$1.8 \cdot 10^{-3}$	13 seconds
100 g/y (3.2 oz/y)	$1.2 \cdot 10^{-3}$	45 seconds
30 g/y (1 oz/y)	$1.5 \cdot 10^{-4}$	130 seconds
10 g/y (0.3 oz/y)	$8 \cdot 10^{-5}$	270 seconds
3 g/y (0.1 oz/y)	$1.2 \cdot 10^{-5}$	23 minutes
1 g/y (0.03 oz/y)	$5.4 \cdot 10^{-6}$	180 minutes
0.5 g/y (0.02 oz/y)	$1.5 \cdot 10^{-6}$	210 minutes

## ANNEX B

### Gas Properties

#### Viscosity and Molar Weight of Some Gases

Gas	Formula	Viscosity (Pa · s) at 15 °C	Molecular weight (g/mol)
Air		$18.3 \cdot 10^{-6}$	28.8
Nitrogen	N <sub>2</sub>	$17.6 \cdot 10^{-6}$	28.0
Oxygen	O <sub>2</sub>	$20.0 \cdot 10^{-6}$	32
Argon	Ar	$21.9 \cdot 10^{-6}$	40
Hydrogen	H <sub>2</sub>	$8.7 \cdot 10^{-6}$	2.0
	5% H <sub>2</sub> 95% N <sub>2</sub>	$17.2 \cdot 10^{-6}$	26.7
	10% H <sub>2</sub> 90% N <sub>2</sub>	$16.7 \cdot 10^{-6}$	25.4
Helium	He	$19.4 \cdot 10^{-6}$	4.0
	10% He 90% N <sub>2</sub>	$18.4 \cdot 10^{-6}$	
Carbon dioxide	CO <sub>2</sub>	$14.5 \cdot 10^{-6}$	44
R134a	CH <sub>2</sub> FCF <sub>3</sub>	$11.61 \cdot 10^{-6}$	102.03
R290	C <sub>3</sub> H <sub>8</sub>	$8.114 \cdot 10^{-6}$	44.1
R404A		$11.87 \cdot 10^{-6}$	97.6
R407C		$12.31 \cdot 10^{-6}$	86.2
R410A		$13.19 \cdot 10^{-6}$	72.59
R600a	CH(CH <sub>3</sub> ) <sub>2</sub> CH <sub>3</sub>	$7.397 \cdot 10^{-6}$	58.12

#### Conversion of Leak Rate in Laminar Flow

Gas	Relative leak rate (helium) multiply by
Air	1.077
Nitrogen	1.12
Argon	0.883
Hydrogen	2.23
Neon	0.626
Helium	1
Water vapor	2.09



### Conversion of Leak Rate in Molecular Flow

Gas	Relative leak rate (helium) multiply by
Air	0.374
Nitrogen	0.374
Argon	0.316
Hydrogen	1.41
Neon	0.447
Helium	1
Water vapor	0.469
Carbon dioxide	0.301
R134a	0.198
SF <sub>6</sub>	0.167

### Diffusion Coefficient

Gas	Diffusion coefficient (mm <sup>2</sup> /s)
Nitrogen	17.5
Oxygen	17.5
Argon	14.7
Hydrogen	67.1
Helium	69.7
Water vapor	21.9
Carbon dioxide	13.4

## ANNEX C

### Equation of State

An equation of state is a constitutive equation describing the state of a system subject to a given set of conditions. An equation of state is useful to depict the properties and the evolution of such a system. Referring to physical systems, and specifically a thermodynamic system, it provides a mathematical relationship among two or more state functions associated with the matter, such as temperature (T), pressure (P), volume (V), etc.... The most common use of an equation of state is to predict the state of gases and liquids or solids, and their mixtures.

#### **Ideal Gas Law**

One of the simplest and best known state equations is the ideal gas law:

$$p \cdot V = n \cdot R \cdot T$$

where p is the gas pressure (Pa or N/m<sup>2</sup>), V is the volume occupied by the gas (m<sup>3</sup>), T is the gas absolute temperature (K), n is the gas quantity in number of moles, and R is the universal gas constant:

$$R = 8.314472 \text{ J / (mol} \cdot \text{K)}$$

This equation is roughly accurate for gases at low pressures and high temperatures, and becomes increasingly inaccurate at higher pressures and lower temperatures. Furthermore, it fails to predict phase transition, like condensation from gas to liquid and evaporation from liquid to gas. Therefore, many other equations of state, more accurate, have been developed. At present there is no single state equation that accurately predicts the properties of all gases and vapors under all conditions.

#### **Van der Waals Equation of State**

The Van der Waals state equation (1873) was one of the first gas law working better than the ideal gas law:

$$\left(p + \frac{a}{(V/n)^2}\right) \cdot \left(\frac{V}{n} - b\right) = R \cdot T$$

where p is the gas pressure (Pa or N/m<sup>2</sup>), V is the volume occupied by the gas (m<sup>3</sup>), T is the gas absolute temperature (K), n is the gas quantity in number of moles, R is the universal gas constant, a and b are constants depending on the specific material. They can be computed from the critical properties as:

$$a = 3 \cdot P_c \cdot V_c^2 \quad b = \frac{V_c}{3}$$

where P<sub>c</sub>, V<sub>c</sub>, T<sub>c</sub> are the pressure, volume and temperature at the critical point.

Now this equation is considered obsolete, its agreement with experimental data is limited. Modern equations are only slightly complex but much more accurate.

#### **Redlich - Kwong Equation of State**

The Redlich-Kwong state equation (1949) it is still used due to its simple form:

$$p = \frac{R \cdot T}{(V/n) - b} - \frac{a}{\sqrt{T} \cdot (V/n) \cdot (V/n + b)}$$

where  $p$  is the gas pressure (Pa or  $N/m^2$ ),  $V$  is the volume occupied by the gas ( $m^3$ ),  $T$  is the gas absolute temperature (K),  $n$  is the gas quantity in number of moles,  $R$  is the universal gas constant,  $a$  and  $b$  are constants depending on the specific material. They can be computed from the critical properties as:

$$a = \frac{0.42748 \cdot R^2 \cdot T_c^{2.5}}{P_c} \quad b = \frac{0.08664 \cdot R \cdot T_c}{P_c}$$

where  $P_c$ ,  $V_c$ ,  $T_c$  are the pressure, volume and temperature at the critical point.

### Peng-Robinson Equation of State

The Peng-Robinson state equation (1976) provides reasonable accuracy near critical points, particularly for the compressibility factor computation. Moreover, it allow one to predict liquid density.

$$p = \frac{R \cdot T}{(V/n) - b} - \frac{a \cdot \alpha}{(V/n)^2 + 2 \cdot b \cdot (V/n) - b^2}$$

where  $p$  is the gas pressure (Pa or  $N/m^2$ ),  $V$  is the volume occupied by the gas ( $m^3$ ),  $T$  is the gas absolute temperature (K),  $n$  is the gas quantity in number of moles,  $R$  is the universal gas constant,  $\alpha$ ,  $a$  and  $b$  are constants depending on the specific material. They can be computed from the critical properties as:

$$a = \frac{0.42748 \cdot R^2 \cdot T_c^{2.5}}{P_c} \quad b = \frac{0.08664 \cdot R \cdot T_c}{P_c}$$

$$\alpha = (1 + (0.37464 + 1.54226 \cdot \omega - 0.26992 \cdot \omega) \cdot (1 - (\frac{T}{T_c})^{0.5}))^2$$

where  $P_c$ ,  $V_c$ ,  $T_c$  are the pressure, volume and temperature at the critical point and  $\omega$  is the acentric factor for the specific fluid. The term  $\alpha$  is a temperature dependent function which takes into account the attractive forces between molecules.



## ANNEX D

### Mass Spectrometer

This instrument allows revealing a wide range of leaks with a high facility of uses. It is possible to carry out measurements either quantitatively either qualitatively. Qualitative measures are easier and suitable for quality control applications.

The detection technique is based on the separation of a gas, from the other gases, in vacuum due to an ionization process. In very low pressure (or vacuum) the molecules of rest gasses are transformed in ions by electron impact. The ionized particles of different mass to charge ratios ( $q/m$ ) are separated by a magnetic field and their ions are collected in different position. These ionic current are related to each gas concentration, therefore it is possible to state the partial pressures of present gases. The low pressure (less than  $2 \cdot 10^{-2}$  Pa or  $1.5 \cdot 10^{-1}$   $\mu\text{m Hg}$ ) required for operation of the mass spectrometers is produced by an integrated high vacuum pump system. The auxiliary vacuum pump required for rough pumping the tested equipment can either be incorporated or be attached via suitable connection.

Two types of mass spectrometers exist, the simplest has a narrow passing band with single gas (normally helium), the second has a wide passing band and programming function to select among a gases ranges (helium, R12, R22, R134a, R600a, etc.) in order to recognize and to measure the leak for every type of gas.

Mass spectrometers used as leak detectors are the most sensitive instruments for leak testing.



## ANNEX E

### References

Leak detection and location are widespread treated in literature. Here is reported a short list of internet sites or papers where to go deep into this issue:

- [1] Introduction to Helium Mass Spectrometer Leak Detection – Lexington, USA.
- [2] Leak Detection Methods and Defining the Sizes of Leaks - 4th International Conference of Slovenian Society for Nondestructive Testing - Ljubljana, Slovenia
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- [6] Boiler & Pressure Vessel Code Section V, Leak Testing, American Society of Mechanic Engineers, New York, N.Y.
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- [10] Leakage Testing Handbook; NASA Contractor Report; NASA CR952, Marr, J. William, - NASA, Washington, D. C. 1968
- [11] Leak Testing Volume of ASNT Handbook, McMaster, American Society for Nondestructive Testing, Columbus, OH, 1980.





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