

**Leak Detection Methods:
A Comparative Study of Technologies and Techniques
Short version**

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1 Introduction

In the refrigeration industry, components and systems must be leak tested to ensure that refrigerant leakages are below specified limits. The three basic functions of leak testing are 1) determining if there is leakage or not (detection), 2) measurement of leak rate and 3) leakage location. There are many methods and types of test equipment for solving these problems, but unfortunately there is no single technique that fits every situation. Each test method is suitable only for a specific leak rate or for fixed forms and technologies. In most instances where leak detection is used, 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. This reference limit depends on the maximum acceptable leak rate, consistent with the reasonable working life expectation for final products, and, especially in certain countries, on rules and regulations constraints. The acceptable leak rate, depending on refrigerant type and application, usually spans from 15 g/y (0.5 oz) of refrigerant for large air conditioning systems and/or automotive applications to 0.5 g/y (0.01 oz) for domestic refrigerators.

This acceptance level is the main parameter to consider when selecting the appropriate method or combination of testing methods. Several other factors must be taken into account as well. In particular, system costs, complexities, environmental impact, reliability, influence of external conditions, operator dependence and user-friendliness should all be considered.

There is a lot of literature available about leak-testing, leak detection and leak location methods; provided here in Annex C are some references. This article presents some leak detection techniques and compares their performance with special attention paid to refrigerant leakages.

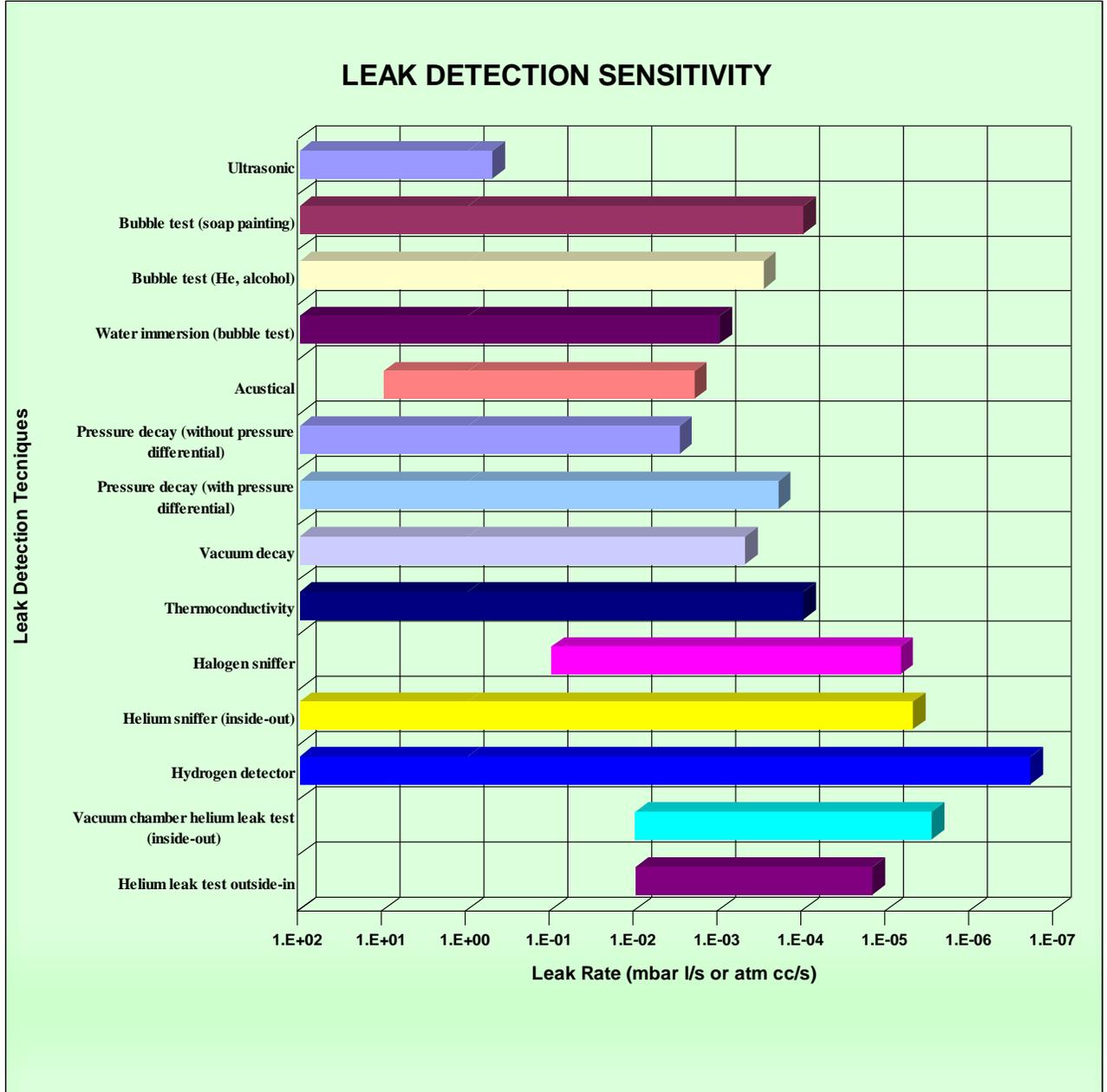
2 Leak testing methods

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 leak test methods are underwater bubble test, bubble soap paint, pressure and vacuum decay, and tracer gas detectors (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 (10.5 oz) or more refrigerant leakages). Tracer gas leak testing methods are much more precise than the previous group but, in many cases, their theoretical sensitivity is more than is required. In a practical sense, however, this is limited by environmental and working conditions.

Each method mentioned above and each its advantages and drawbacks are discussed briefly in the following.

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.



2.1 Water immersion bubble test method

The water-immersion bubble test, also called "bubble testing" or "dunking", is a traditional and relatively primitive technique of leak detection. It consists of immersing a charged or pressurized part, usually with high-pressure dry air or nitrogen, in a water tank and watching for escaping bubbles. The larger and more

frequent the bubbles, the bigger the leakage. Relatively small leaks are possible, but very difficult, to detect.

The main limitation of this method is sensitivity, which 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 at atmospheric pressure, it can be stated from the previous equations that the bubble volume is $V = 4.2 \cdot 10^{-3} \text{ cm}^3$ and therefore the minimum detectable leak rate is:

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

This is a theoretical value. The real sensitivity is strongly influenced by many external factors, such as illumination conditions, water turbidity, unit location and placement, and water movement. All these issues, together with operator dependency, limit the useful sensitivity to $5 \cdot 10^{-4} \text{ mbar} \cdot \text{l/s}$, although $1 \cdot 10^{-3} \text{ mbar} \cdot \text{l/s}$ is usually considered.

Some tricks to can be used improve to this method.

- Increasing the internal pressure in increments may increase the probability of finding a leak and can be less time-consuming in pinpointing the leak.
- 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 liquids may give some advantages in system performance, but 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.

In conclusion, this technique does offer leak detection accuracy in the $10^{-3} \text{ mbar} \cdot \text{l/s}$ range in high volume production applications and, in most cases, leak location and is very economical. However, the disadvantages range from a relatively low sensitivity, high operator dependency and possible part contamination, to fluid waste and the likelihood of having to dry the parts after testing. Moreover, especially when

dealing with big coils, excessive unit handling, putting parts in and out of tanks, adds to the complexity of production and results in higher part damages. There are also some more hidden costs. In fact, this process requires use of a large amount of space and produces a certain amount of wastewater. This is especially true for big units, such as large heat exchangers; the tank could be very large and require a lot of water. Dryers cost money to operate and maintain as well.

2.2 Soap solution bubble test

Instead of submersing the part in water, the pressurized unit to be tested is sprayed with a soap solution and the operator is able to see the bubbles formed by gas escaping from 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 water immersion. It allows detection of leaks up to 10^{-5} mbar · l/s and is suitable for very large systems.

This soap solution method is best used when the approximate area where a leak may exist is known. In this case, the soap solution is only used in that specific area to test for and pinpoint a leak. It is the simplest and least expensive method, material wise, known today. However, if the operator does not know where the leak might be, it can be more expensive because of labor costs.

Increasing the gas pressure raises the probability of pinpointing the leak and is less time-consuming. However, for operator safety, the pressure must be limited to 1700 kPa (250 psi).

The soap-solution bubble test is limited by some drawbacks. The area to be sprayed must be a simple and easily accessible surface. On finned pipes or the bottom part of a large heat exchanger, it could be extremely difficult, if not impossible, for the operator to spray the part and watch for a bubble. Moreover, the application is not well suited for high productivity lines.

2.3 Pressure decay test

This method consists of pressurizing the system with a high pressure gas, usually dry air or nitrogen. Then the part is isolated from the gas supply and, after a stabilizing period, its internal pressure is monitored over time. The pressure drop Δp is measured in the time Δt . 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 is leak-free. 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 systems allow for measuring pressure variation up to 70 Pa (0.010 psig) at test pressure and, 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. Longer test times allow for 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, some even hours. The higher the pressure, the faster you can determine if a leak is present. However, operator safety concerns limit the maximum admissible pressure value without safety precautions. Components can be leak tested at low pressures, less than 2 MPa (290 psig) without protection, and higher pressures, 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) as well as burst test and the European EN378 rules. Burst test is designed to test the mechanical strength of the refrigeration tubing circuit, to find ruptured tubing, and badly 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.

Pressure decay proof is a go/no-go test. While it detects the presence of a leak, locating the leak requires the use of other techniques such as soap bubbles, or better, tracer gas detection.

Usually, the limit of sensitivity for pressure decay test is in the range of $10^{-3} \text{ mbar} \cdot \text{l/s}$ without pressure differential and $10^{-4} \text{ mbar} \cdot \text{l/s}$ for pressure decay test with pressure differential.

This leak testing technique has some advantages. This method will positively identify whether or not a leak exists by monitoring the pressure drop. If any pressure drop occurs, it means a leak is definitely present. Furthermore, this method can be realized completely automatically, so as to avoid operator errors. This procedure is a preliminary leak test that detects large leaks before the final automatic leak test operation using a tracer gas, e.g. helium. This test will detect over 90%, 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 tracer gas will leak out of the test unit. The resulting helium contamination, in this much volume and concentration, would render the system inoperable for hours. Another advantage of nitrogen filling, besides the mechanical stress and leakage test, is the purging of the circuit to be tested, lowering its humidity. Upon a successful completion of the pressure decay test, the component is ready for final test.

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

2.4 Vacuum decay test or Pressure rise test

A 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 pressures 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 the vacuum decay test it 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 the solvent entering into the leak. This approach, however, has some shortcomings, such as the possibility of solvent freezing, causing temporary leak-stuffing, or elastomer gaskets becoming damaged by solvents.

With respect to the pressure decay test, this technique has some advantages. This method is less sensitive to temperature changes since the pressure inside the part is lower than atmospheric pressure. Vacuum-meters are usually very sensitive to small pressure changes, so the theoretical sensitivity might be very high, up to $1 \cdot 10^{-5}$ mbar \cdot l/s.

However, surface out-gassing and liquid evaporation affect and limit the real sensitivity. For instance, a small quantity of water, even a few grams, starts evaporating at 2 kPa (0.3 psia) and at 1 Pa (7.5 μ m Hg) the water vapor content is so high that the consequent pressure increase is comparable to a leak, creating a false positive.

In refrigerating 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 \cdot l/s

The vacuum decay method can be realized in a fully automatic procedure and, in this way, it is independent of the operator.

This technique is a "go no-go" test. It detects the total system leak and more than one leak can exist; leak location requires other techniques.

In a 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.

2.5 Tracer gas leak testing

The term “tracer gas leak testing” describes a group of 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 (CFC, HCFC and HFC refrigerant), helium, and a mixture of nitrogen 95% hydrogen 5%. Despite the simplicity of their electronic detection devices, halogens are losing their appeal as a 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 more interest.

Helium has been used successfully as a tracer gas for long time due to its physical properties. It is neither toxic nor flammable and 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 flows 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 disperses slowly into the atmosphere, so, in the case of big leaks, its high concentration will contaminate the area for a long time, even hours. Also, Helium is costly, even if it is less expensive than halogen gases. The most suitable helium detector is based on a mass spectrometer, which is an expensive and delicate apparatus requiring much care and maintenance, and is more suitable for a laboratory than for the manufacturing industry.

A relatively new tracer gas is a mixture of nitrogen 95% and hydrogen 5%. Hydrogen has a number of properties that make it an excellent tracer 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, it 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 leakage rate of any gas. Moreover, the normal background concentration of hydrogen (0.5 ppm) is ten times less than helium. Hydrogen tracer gas detectors use a semiconductor sensor and have no moving parts, making them completely maintenance free. These devices are not affected by the presence of other gases. Pure hydrogen should never be used as tracer gas, but a standard industrial grade mix of 5% hydrogen in nitrogen is inexpensive, non-flammable (as for ISO10156 specification), and readily available from industrial gas 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 by putting the unit to be tested in a room containing the tracer gas or, very rarely, spraying the tracer gas on the unit surface.

Each of these methods is described in detail in the following sections.

2.5.1 Sniffing

“Sniffing” is the simplest realization of an “inside-out” test. The sniffing technique of leak detection utilizes a detector probe or sniffer to sense leaks from a unit previously filled and pressurized with a tracer gas. Before filling the unit with a 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. However, the cost of the tracer gas may be significant and, in case of a particularly expensive gas, the use 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, and rejecting good parts (because of the inability to quantify the leak). Some sniffers and the relevant detectors require periodic maintenance to assure proper functioning, since they are complex systems composed of vacuum pumps, mass spectrometer and vacuum fittings. Electronic detectors, without moving parts, are very profitable. Some detectors are sensitive to other gases than the tracer used. Therefore, when using these sensors, attention to the chemical environmental conditions is required.

The minimum leak rate measurable by a sniffer is the concentration of the tracer gas in the working area, a value known as “background level.” This level may change during the production cycle and increases due to leaking units. Relating to the tracer gas used, in case of a big leak in the part under test, a lot of tracer gas escapes from it and may remain for a long time in the working area, strongly affecting the subsequent 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, in order to simplify the equipment.

It is important to note that sniffing techniques are local methods, allowing 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 a result, the test is successful, but the part is defective. Global tests, such as vacuum chamber inside-out and outside-in methods, avoid this problem.

2.5.2 Accumulation leak testing

This method is a variation of sniffer leak testing. The part to be tested is placed in an enclosed containment hood, then pressurized with the tracer gas. The sniffer is connected to the hood where the leaked tracer gas has accumulated during the test time. When accumulated, the tracer gas is more readily sensed by the detector. The gas sensor will measure the 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 sensitivity depend on the residual volume and the test time. The tracer gas partial pressure increment Δp , the tracer gas flow Q , residual volume V and the test time Δt can be expressed with a sample equation:

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

This method is used in very special applications (e.g. small components are to be tested for small leaks).

2.5.3 Vacuum chamber inside-out leak testing

Vacuum chamber inside-out leak testing is the most complex system of leak detection, but it is theoretically suitable to find very small leakages, using the 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 as to detect the tracer gas flow through a leak and drawn in by the pumping group. In this way, the leakage is detected. It is a go/no-go" test, so finding the leak location requires other techniques.

This method has some advantages. This technique is fully automatic, so it depends very little on an operator. Its sensitivity, depending on tracer gas and test time, can reach 10^{-10} mbar · l/s, even if for 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 could call for a high pumping speed. Some gas detectors require periodic maintenance to ensure proper performance, since they are complex systems composed of vacuum pumps, a mass spectrometer and vacuum fittings. The cost of the tracer gas may be significant besides and, in case of a particularly expensive gas, the use of a suitable gas recovery and reclaim system should be considered, further increasing the overall costs as well as the system complexity. In the case of big leak in the part under test, a lot of tracer gas escapes, relative to the tracer gas used. 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. To avoid this, 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 to simplify the equipment.

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.

2.5.4 Outside-in leak testing

In this testing technique, the unit to be tested is put into an enclosure containing the tracer gas. The part is connected to a vacuum group and evacuated. A tracer gas

detector (i.e. helium mass spectrometer) is placed in the vacuum line in order to detect the tracer gas flow in a leak and pulled in by the pumping group.

This method has some advantages. This technique is fully automatic, so it is not operator dependent. The sensitivity, depending to tracer gas and test time, can reach 10^{-6} mbar · l/s. The gas containment hood can be realized to prevent dispersion, in order to reduce working area pollution and tracer gas consumption, saving money by 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. Relating to the tracer gas used, in case of a big leak in the part under test, a lot of tracer gas escapes from it. 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 as to simplify the equipment.

Another disadvantage is that this method does not identify where the leak is, only determines 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.

2.6 Applications

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

2.6.1 Halogen leak detectors

The working principle of the halogen detector is based on the measurement of positive ion 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 an inside-out system; their use for outside-in methods is very limited.

In an inside-out method, they 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 refrigerant. 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 an outside-in approach, an evacuated vessel is connected to a halogen detecting instrument and is sprayed with 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 a high environmental impact, so it rarely used.

Halogen leak detectors are used extensively in refrigerating and air conditioning maintenance to locate leaks in refrigerant-charged systems due to their high sensitivity.

In the 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 performances are 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 tricky 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.

2.6.2 Inside-out helium sniffer detectors

A Helium sniffer detector probe is 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 $7.5 \cdot 10^{-2}$ μ 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. The 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 μ m Hg). Then, considering a standard pumping speed of 1 cm^3/s , the sensitivity is:

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

The slower the pumping speed, the higher the sensitivity. However, the slower the pumping, the longer it will take the helium to arrive at the mass spectrometer to be measured. The most commonly used pumping speed, a trade-off between sensitivity and response time, is 1 cm^3/s that, with a pipe 5 m (16.4 ft) in length, which provides a delay time of about one second. Because of this delay time, the sniffer speed and its distance from the part to be tested are critical factors. The nearer the probe, the higher the helium concentration entering the mass spectrometer and therefore the better the test quality. Conversely, the faster the detector movement, the less helium is taken in.

Furthermore, the sensitivity of this method, strongly limited by the background helium level, is not as good as those achievable with other techniques based on mass spectrometers.

The helium sniffer leak testing method has the big advantage of determining leak location but, as stated above, has some drawbacks.

Helium sniffer leak detection implies manual operation, is strongly operator dependant, and operator experience is the determining factor in the outcome of the testing procedure.

Helium disperses slowly into the atmosphere, so in case of leakages, the background level increases limiting the successive tests. In case of a big leak, the working area may become contaminated for a long time. It is good practice to use a preliminary leak test (i.e. a pressure decay test) to detect gross leakages. This test may be integrated in the same helium inside-out machine.

Helium is an expensive gas and as stated before it is not advisable to spread it into the ambient area, so it 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.

2.6.3 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. Passing over a leak, the detector senses the helium entering from the leak, identifying the location and leak size data. This method is still classified under vacuum test methods, even if it is an exception.

This technique can be used where it is necessary 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 so it rises, therefore 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 well ventilated. In this condition, determining the leak location becomes difficult.

In case of a big leak, a lot of helium reaches the mass spectrometer and a long time is needed to reduce the helium level to a value compatible with testing, but, during this time, the 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, widely used in research and in all those applications involving big plants, which cannot use other methods. It is not the most suitable solution for testing in high productivity lines or serious production manufacturing industries.

It is noteworthy 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.

2.6.4 Outside-in helium leak testing

In the "outside-in" helium leak testing technique, the part to be tested is placed in a containment hood suitable to contain helium and connected to a vacuum group equipped with 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 μ 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.

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 may be designed so as 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 at only 10% helium. 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 reducing operation costs.

The hood must be the appropriate size to completely cover the test unit and can be designed to be adjustable, "collapsing" and thereby lowering the volume and therefore helium consumption.

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

However, there are also some shortcomings and some precautions that must be taken for the proper use of this system. This method is a go/no-go test for leak detection only. To pinpoint the leak location another system is required. If the test unit has a large leak such as an overlooked brazed joint, the escaping helium, at this much volume and concentration, would render the system inoperable for long time. It is best to use a preliminary leak test for gross leakage identification. 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. Upon a successful completion of the pressure decay test the component is ready for final test. At the end of the cycle, the part may be filled again with nitrogen, at a low pressure, so as to avoid helium being “sucked into” it 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 positive pressure inside, this leak testing method will stress the part in the opposite way. This problem can be mitigated using a proper preliminary pressure test.

It is worth noting 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 getting into the part when disconnected.

2.6.5 Inside-out helium vacuum chamber leak testing

In “inside-out” techniques, known also as “global hard-vacuum test”, the test configuration is reversed. The component is placed inside an airtight chamber provided with service hoses and a vacuum pumping group with a mass spectrometer. The unit is connected to the service hoses, the chamber is closed, 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 by the leak detector. At the end of the cycle, the vacuum chamber is vented. The leak detector finds the leak and gives the total measurement. 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 realized so that in one chamber the test cycle is in progress while in the other chamber a part is unloaded and reloaded. In many industrial applications, in order for the test chamber to reach the vacuum level in acceptable times, an auxiliary pumping group is needed. The dimensioning of the pumping group depends on different parameters, such as the body of the expected leaks, the dimensions of the parts to test and the cycle time.

Vacuum chamber helium inside-out leak test method has some advantages. A sniffer is not used; testing is automatic and not operator dependant. The sensitivity achievable with this test is very high. In a laboratory application, it is not impossible to get 10^{-10} mbar · l/s. However, in practical application in the refrigeration industry, the limit is considered 10^{-6} mbar · l/s.

Despite these advantages, vacuum chamber inside-out leak test method has several drawbacks. It is an expensive 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 incidence of the human factor. This fact makes this test attractive in many industrial contexts, while the sniffing test has its applications in the maintenance and the analysis of the 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’s inner

surface or in some internal components, the background helium level will be high and the sensitivity will consequently be reduced.

If the test unit has a large leak, a lot 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 a long time.

To avoid this occurrence, it 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 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, 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 does not determine its position. Other techniques are required for leak location.

Since helium is an expensive gas, and to reduce the helium concentration in the working area, it is not convenient to spread it in the ambient air, so it 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. However, helium recovery systems are costly. It is beneficial to perform a feasibility study on the subject of helium recovery to determine if the equipment investment plus upkeep is financially viable when compared to the cost savings of recovering helium.

2.6.6 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.

Compared 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, it is easily evacuated and dissipated. Since hydrogen mixes very quickly in 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 often sufficient. Hydrogen easily disperses into air, so its concentration in the working area falls quickly to the background level even in the case of big leaks.

In addition, hydrogen has the highest leakage rate of any other gas. Hydrogen detectors are based on semiconductor sensors and since they contain no moving parts, are tough enough for industrial use and completely maintenance free. They are also 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, and are ten times more sensitive compared to helium sniffers. This blend is standard industrial grade mix, inexpensive, non-flammable (as for ISO10156 specification) and readily available from industrial gases suppliers.

There are some doubts that exist about using hydrogen as tracer gas. Hydrogen escapes rapidly from a leak in an almost vertical direction, so a leak can be precisely detected and located only if the detector is directly above it. This might cause 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. funnel-shaped devices, to facilitate leak detection. Another common doubt about using a hydrogen/nitrogen mixture is component separation and hazards related to hydrogen. Even though the hydrogen/nitrogen mix is widely available, large industries with high production lines think that in big cylinders hydrogen tends to accumulate in higher section of the bottle. This would cause a problem of 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. An approach 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.

3 How to Choose the Test Method

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

The questions are:

- Which type of total leak can damage the product?
- How many points (weldings, joints etc...) must be tested?
- How much time 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 to this question is not much straightforward. For example, to define the total leak specifications of refrigeration system is simple, but to define the

valid specifications for the single components and the 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 parameters have to be considered. Among them are repeatability, accuracy, report capability, operator dependency and, least but not the last, cost of the equipment and the necessary work force. In addition, the cost of tracer gas has an important incidence especially in case of series controls. In some cases, a gas recovery system, cutting down consumption, is to be taken into account.

For sake of clarity, 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 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 ft³) 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 $Q_1 = 1.28 \cdot 10^{-4}$ mbar · l/s from $P_1 = 1800$ kPa (261 psia) to $P_2 = 100$ kPa (14.5 psia), corresponds to a flow rate Q_2 from the atmospheric pressure to vacuum:

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

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

The flow through a leak depends also on the fluid viscosity; the less the viscosity, the larger the flow rate. Therefore, the flow Q_1 of a medium of viscosity ν_1 is related to the flow Q_2 of a medium of viscosity ν_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 (ν) 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, 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, it 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 to these error sources, it is better to carry out the tests with sensitivity ten times higher than that obtained with theory, in order to create a wide safety margin.

4 Conclusion

The growing demand for components and systems with fewer acceptable losses is the industry trend, due to several compelling market demands, such as economic requirements, environmental protection specifications, safety constraints and quality products requirement. The end 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. Remarkably, this technical field is nearly unknown even in engineering and important project organizations. A brief analysis of some of the most commonly used leak detection techniques, with particular reference 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 the choice of the test methodology that will 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, 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 ΔP of 100 kPa

	std cc/s	mbar l/s	Torr l/s	Pa m ³ /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 ³ /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 = 9.00×10^{-6}	x 0.66	5.9×10^{-6} mbar l/s
1 g/y R12 = 6.43×10^{-6}	x 0.64	4.1×10^{-6} mbar l/s
1 g/y R134a = 7.63×10^{-6}	x 0.71	5.4×10^{-6} mbar l/s
1 g/y R600a = 1.34×10^{-5}	x 0.40	5.3×10^{-6} mbar l/s
1 g/y SF6 = 5.33×10^{-6}	x 0.77	4.1×10^{-6} 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

Mass Spectrometer

This instrument reveals a wide range of leaks with a high facility of uses. It is possible to carry out measurements either quantitatively or 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 test 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 currents 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 $1.5 \cdot 10^{-1}$ μ 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 a suitable connection.

Two types of mass spectrometers exist, the simplest having a narrow passing band with a 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 as leak detectors are used as the most sensitive instruments for leak testing.

ANNEX C

References

Leak detection is a widespread subject. To follow is a short list of internet sites or papers that go deeper into this issue:

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