



Industrial Leak Detection
Air Leak Testing
Vacuum Metrology

VIC Leak Detection

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HYDROCARBON LEAKAGE LEAK RATES AND DETECTION IN PRODUCTION APPLICATIONS



As the worldwide leader in advanced leak detection equipment, Vacuum Instrument Corporation has been working to meet the needs of the industrial and high technology markets for more than 30 years. The specialized engineering, manufacturing and service capabilities of our company back up our products and have proven to reduce expenses and ensure the quality of our customer's products. VIC Leak Detection is the largest system integrator for fine leak detection and is the only integrator that manufactures their own mass spectrometer instruments.

Over 100 million parts have been tested by our leak detection systems for the automotive, fire safety, appliance, medical, food packaging, semiconductor, nuclear, and aerospace industries. Throughout our growth we have developed and built systems that improve the manufacturing process and meet or surpass the most stringent testing requirements. The quality of our equipment is continually improving to meet industry's latest needs.

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OVERVIEW

Until recently government requirements for fuel system components leakage have been lenient (10^{-2} cc/sec). Amendments to the EPA Clean Air Act of 1990 and the California Air Resources Board have imposed new evaporative vehicle emission standards resulting in a more stringent leak test requirement.

Detecting hydrocarbon (HC) leaks in automotive fuel systems is done in numerous ways. The methodology that is used depends on the size of the leak to be detected and the test time allowed. Very large leaks are found by an inspector viewing droplet formation on the outside of a fluid filled item. Very small leaks require high vacuum techniques using tracer gases. In-between these two extremes are other test, such as submerged bubble testing and tracer accumulation tests.

Beginning in 1999 the EPA requires that all new vehicles sold in the United States pass a three-day "SHED" test. If, during any 24-hr period the total HC emissions exceed 2 grams, the vehicle will fail (and for 2004 the "SHED" test specification changes to 0.05 grams). A vehicle fuel system contains many components such as the tank, vapor canister, filler neck, fuel rails, etc. which must be tested for leakage. To insure total emissions are below 2 grams subsystem designers must budget a leak threshold to each component. The designer must also consider the effect of permeation and select materials well suited to hold or transport gasoline liquid and vapor. Permeation leaks have long response times that are difficult to test quickly but may show up during a prolonged shed test.

Modern assembly techniques insure consistent product quality but manufacturing variations may still cause a defect to occur. Leak location is unpredictable and can exist at joint seals, assembly connections, mold flash areas and the wall due to a failure in the molding process.

Leaks in fuel systems can occur as a liquid or vapor. Liquid and vapor leaks behave differently and require separate analysis. A gas tank assembly is analyzed due to the unique function of containing both vapor and liquid hydrocarbons.

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LIQUID LEAK RATE ANALYSIS

LEAK ASSUMPTIONS - Leaks can be found in numerous configurations, ranging from straight pinholes to gaseous cavities with single or multiple holes leading to and from the cavity (figure 1).

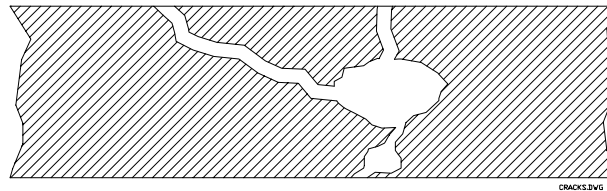


Figure 1

For the purposes of analysis, it is assumed that the leaks are round, continuous, and of uniform diameter (figure 2).

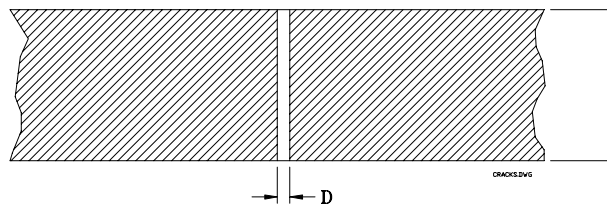


Figure 2

Since the leak diameters (D) that are being analyzed are small (less than 50 micron) when compared to the leak length (L) through the test wall (1-3mm), and the differential driving pressure is small, the Reynolds number will be below 2000. This implies that the flow is laminar.

Laminar flow can be defined as a volumetric flow rate (S) by the following:

$$S = \frac{V}{t} \quad (\text{Eq. 1})$$

Where V is volume and t is time.

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The volumetric flow can also be written as function of the cross sectional area of the crack (A) and fluid velocity (c):

$$S = Ac = \frac{\pi D^2 c}{4} \quad (\text{Eq. 2})$$

The average velocity through the crack is defined by:

$$c = \frac{D^2}{32\mu} \left(-\frac{\Delta P}{\Delta L} \right) \quad \text{or} \quad c = \frac{D^2}{32\mu} \left(\frac{P_1 - P_2}{L} \right) \quad (\text{Eq. 3})^1$$

Here P_1 is the pressure on the inside wall of the leak, P_2 is the pressure on the outside wall of the leak, and μ is the dynamic viscosity

A common method for specifying flow is as a mass flow. For incompressible fluids, such as liquids, the density (ρ) will remain constant, and the mass flow rate for a liquid (Q_{mL}) is defined by equation 4.

$$Q_m = Ac\rho = \frac{\pi D^2 c \rho}{4} \quad (\text{Eq. 4})$$

combining equations 3 and 4:

$$Q_m = \frac{\pi D^4 (P_1 - P_2) \rho}{128 L \mu} \quad (\text{Eq. 5}) \quad (\text{Mass flow rate for a liquid})$$

The mass flow, Q_m is commonly given in mg/sec. where D and L are in meters, P_1 and P_2 are in Pascals, ρ are in mg/meter³ and μ are in Newton-sec./meter².

For vapor flow, the density of the gas will change with pressure, therefore equation 5 is written as follows:

$$Q_m = \frac{\pi D^4 (P_1 \rho_1 - P_2 \rho_2)}{128 L \mu} \quad (\text{Eq. 6})$$

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The density of a gas can be written as:

$$\rho = \frac{nN_A \bar{M}}{V} \quad (\text{Eq. 7})$$

Here n is the number of moles, N_A is Avogadro's number and M is the molecular mass.

For an ideal gas, volume is expressed as:

$$V = \frac{nRT}{P} \quad (\text{Eq. 8})$$

Where R is the universal gas constant and T is the temperature in degrees Kelvin.

combining equations 7 and 8 the density at P_1 and P_2 are

$$\rho_1 = \frac{N_A \bar{M} P_1}{RT} \quad (\text{Eq. 9})$$

$$\rho_2 = \frac{N_A \bar{M} P_2}{RT} \quad (\text{Eq. 10})$$

Substituting eq. 9 and 10 into eq. 6 and replacing the Boltzmann's constant (k) for R/N_A , the resulting vapor mass flow rate is shown below:

$$Q_v = \frac{\pi D^4 \bar{M} (P_1^2 - P_2^2)}{128 L \mu k T} \quad (\text{Mass flow rate for a vapor}) \quad (\text{Eq.11})$$

The mass flow for a vapor, Q_v , is commonly given in mg/sec. where D and L are in meters, P_1 and P_2 are in Pascal's, M is in mg, μ is in Newton-sec./meter², k is in joules/Kelvin, and T is in degrees Kelvin.

Another method for expressing vapor flow is to multiply the volumetric flow (S) by the average pressure (P_a). The result will give a value that is directly proportional to the mass flow of a gas. This is known as the vapor throughput (Q_p), which holds true when the temperature is held constant, since $PV=nRT$. The result is shown in equation 12.

$$Q_p = S P_a = \frac{V P_a}{t} \quad (\text{Eq. 12})$$

$$\text{where } P_a = \frac{P_1 + P_2}{2} \quad (\text{Eq. 13})$$

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Substituting equations 2, 3 and 13 into equation 12 becomes:

$$Q_p = \frac{\pi D^4 (P_1^2 - P_2^2)}{256 \mu L} \quad (\text{Vapor throughput}) \quad (\text{Eq.14})$$

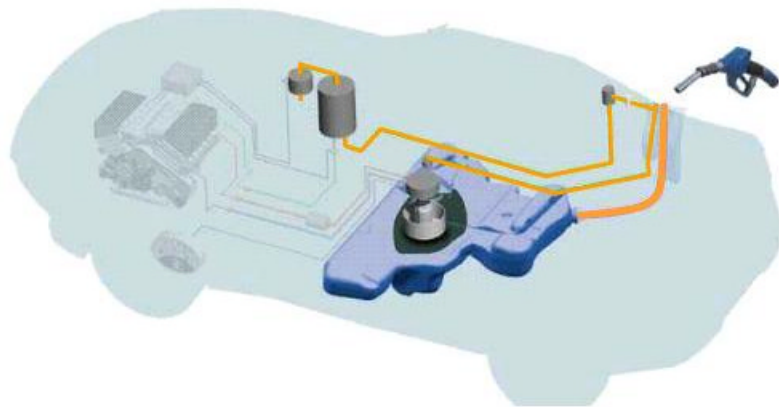
The mass flow, Q_p is commonly given in Pa-m³/sec. where D and L are in meters, P_1 and P_2 are in Pascals, and μ are in Newton-sec./meter². (To convert to atm-cc/sec multiply by 10)

It is important to note that two different gases could have the same Q_p value under the same conditions, but have a different mass flow due to different molecular weights.

ANALYSIS OF GASOLINE LEAK RATES IN GAS TANKS

Obviously, gas tanks come in many shapes, sizes and materials. The intent of this paper is to give the reader further insight into the analysis process. However, the reader should not interpret this as a complete analysis for gas tank leakage, but rather as a guide in the analysis of their particular application.

To begin we must understand where leaks can occur. In gasoline tanks, the most obvious and common location is at the mechanical connections to the gas tank. This would include filler necks, vents, sensors, etc. These components are typically located on the top of the tank and are not continuously exposed to liquid gasoline. Mechanical weld joints and mold flashing areas are another possible leakage site which depending on the fill level may be submerged under liquid gasoline.



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Do not assume that liquid gasoline will plug a fine capillary closing off the leak path. Given the right circumstance a liquid plug with vapor on both sides may form trapping a gas pocket. Eventually the plug will dissipate leaving the channel open to leak.

Since the leak location can be anywhere on the tank, this analysis will assume the worst case. At the bottom of the tank, the total driving pressure on the leak would include the tank vapor pressure, and the hydrostatic pressure from the liquid gasoline. The sum of the vapor and hydrostatic pressure forces liquid from the tank. Above the liquid, the remaining volume of the tank is filled with vapor. Since the vapor pressure is constant through out, location is not a factor. It should be noted that the reader should determine the vertical change in height from the lowest point of the gas tank to the surface of the liquid gasoline as it is filled during the “SHED” test, accounting for the orientation of the tank in the vehicle (figure 3).

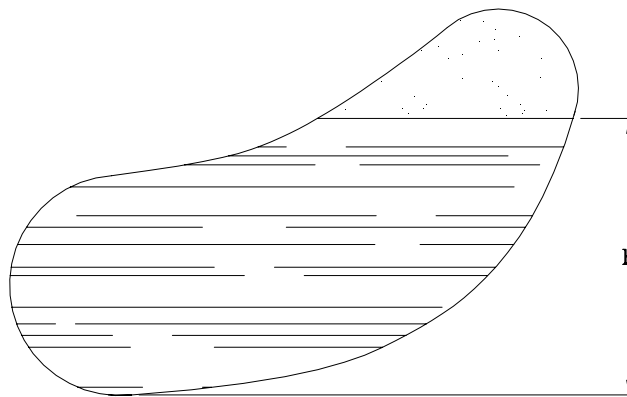


Figure 3

The pressure at the bottom of the tank will be the total of the vapor pressure and the hydrostatic pressure created by the weight of the gasoline as shown below:

$$P_1 = P_v + P_h = P_v + \rho gh \quad (\text{Eq. 15})$$

P_v = vapor pressure on the inside of the tank

P_h = hydrostatic pressure at a depth h

g = acceleration of gravity

h = depth of liquid gas

combining equations 5 and 15

$$Q_m = \frac{\pi D^4 (P_v + \rho gh - P_2) \rho}{128 L \mu} \quad (\text{Worst case liquid leak equation}) \quad (\text{eq.16})$$

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The curves of figure 4 and 5 were calculated from equations 16 and 14 respectively and show the leakage at various pressures and a wall thickness of 3mm. For the liquid analysis, the tank is filled to a depth of 254 millimeters. Note viscosity values for both gasoline liquid and vapor are estimates. Gasoline is a mixture of many hydrocarbons and additives and actual experimental results may differ from theoretical due to changes in viscosity.

**GAS TANK LIQUID LEAK RATES
(3mm WALL) (FILLED TO 254 mm)**

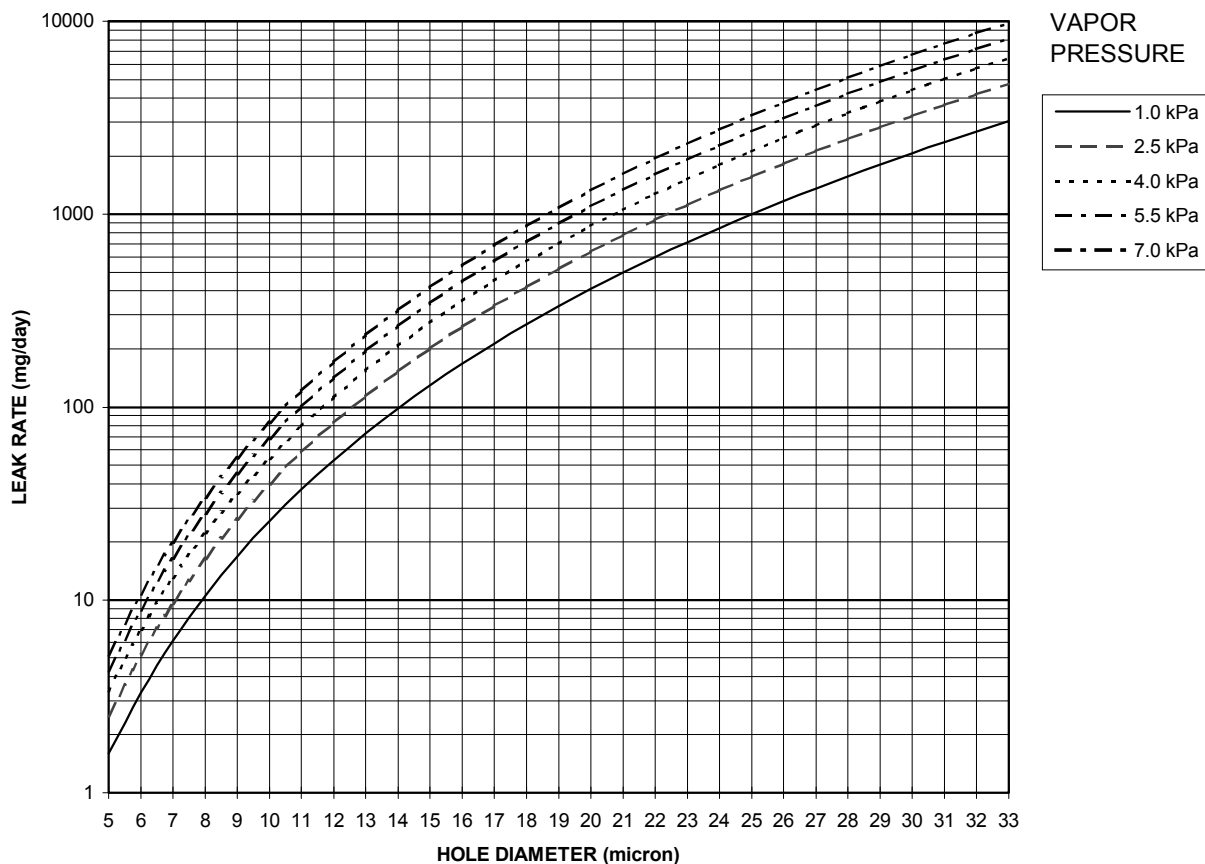


Figure 4

The maximum vapor pressure defined by the EPA for gasoline tank testing is 2.5 kPa. Figure 4 shows that a vapor pressure of 2.5 kPa liquid gasoline will leak at a rate of 100 mg/day through a 12.6 micron hole in a 3 mm wall. In comparison, figure 5 shows that under the same condition gasoline vapor will leak 100 mg/day through a hole 13.8 microns in diameter.

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**GAS TANK VAPOR LEAK RATES
(3mm WALL)**

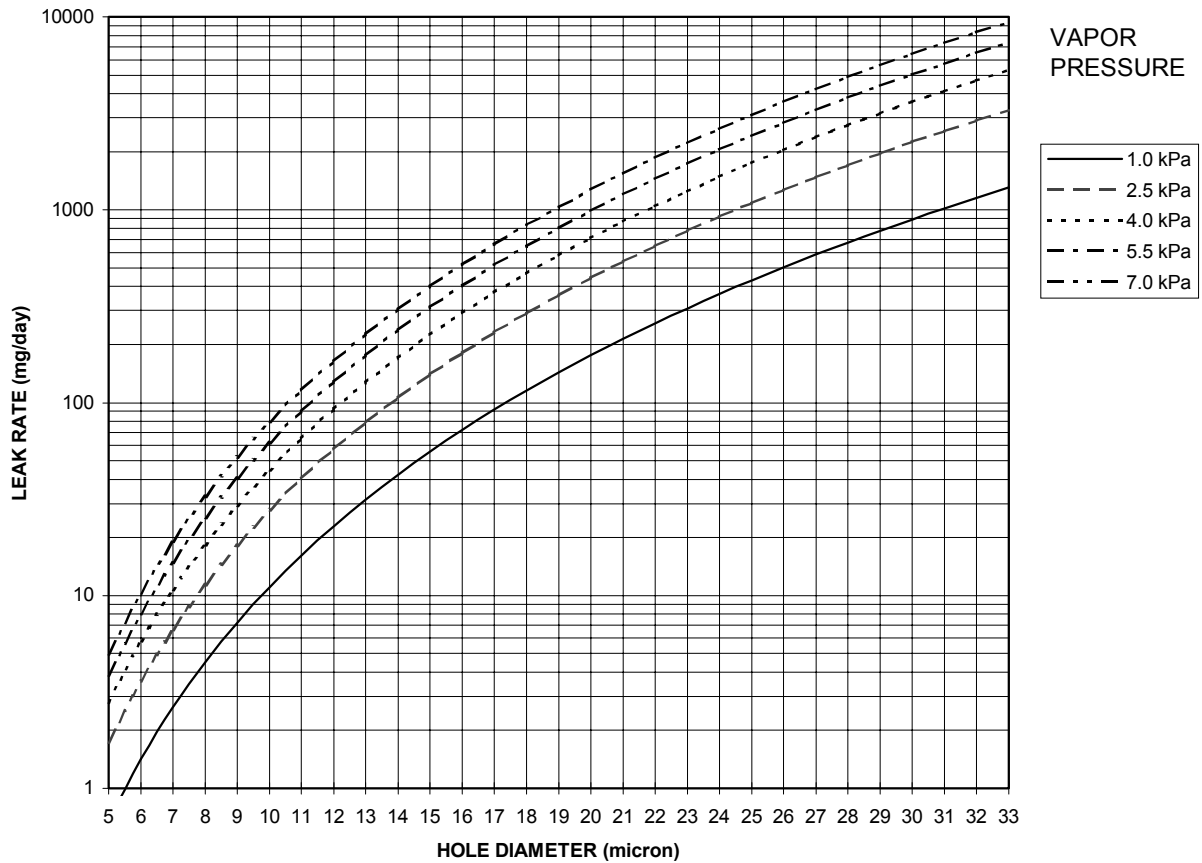


Figure 5

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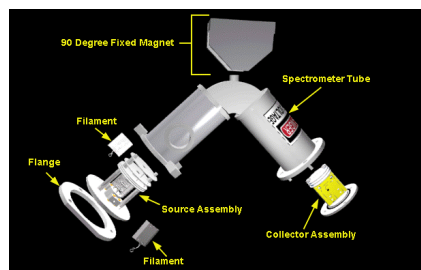


SAFETY FACTOR CONSIDERATIONS FOR LEAK RATES IN GAS TANKS

The part manufacture must consider the effects of the shed test when calculating leak rates. During the shed test the gas tank is heated and cooled over a 24-hour period that may alter the geometry of the leak path. Production testing requires that a reliable test be performed quickly without heating or cooling, subjecting the test part to two different test situations. This is an important consideration as the leak rate is a function of the hole diameter to the fourth power. Thus, a slight increase or decrease in hole size will cause a dramatic change in leak rate. To compensate for these factors the manufacture may want add a safety factor to their leak specifications; to insure passing an EPA shed test.

EQUIVALENT HELIUM LEAKAGE

A common leak detection method uses a tracer gas and a mass spectrometer tuned to detect only the tracer gas specified.



Mass Spectrometer Tube

Helium is a common tracer gas, due to it's inert properties, cost, and availability. The first step in designing a leak test system is to specify a reject threshold for hydrocarbons.

After an upper threshold of HC leakage has been determined you must consider the effects of helium leak testing. Leakage through a fixed hole or defect will change due to changes in test pressure and gas viscosity. The design of every leak test system must start with a conversion to a Helium leakage at the specified test pressure.

When designing a production test system the test part manufacturer must specify a safe helium charge pressure. To maximize sensitivity and decrease response time the highest charge pressure possible should be used without effecting the parts integrity.

Gas tanks have extremely thin walls that may rupture if over pressurized. In the case of both plastic and metal gas tanks, an absolute charge pressure differential of 1 to 2 psi is commonly used.

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**HELIUM LEAK RATES
(3mm WALL)**

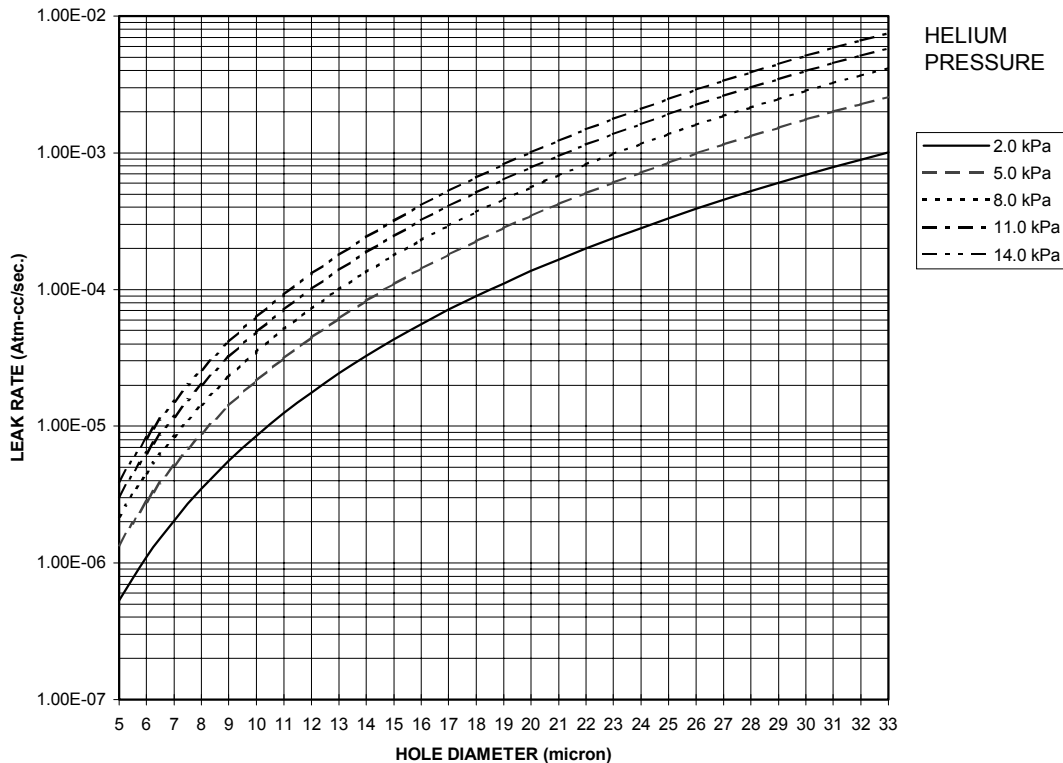


Figure 6

Figure 6 was calculated from equation 6 and shows the helium leakage through holes sizes ranging from 5-33 microns in a 3 mm wall at a pressure differential of 2-14 kPa (0.29-2.03 psia). Using figure 6 an equivalent helium leakage is determined for the critical hole sizes that yielded a 100 mg/day HC leak at a vapor pressure of 2.5 kPa. For gasoline liquid and vapor, the critical hole sizes are 12.6 and 13.8 microns respectively, as calculated from equation 6. At a test pressure of 14 kPa (2 psi) the helium leakage for a 12.6 and 13.8 micron hole is 1.59×10^{-4} and 2.29×10^{-4} respectively.

Production leak detection is commonly divided into two general approaches; accumulation and hard vacuum testing. Each of these approaches has a specific application characterized by system cost, sensitivity, cycle time and required maintenance. A suitable test system must contain the test part and capture helium from all potential leak sights. The test part may be precharged or charged within the chamber.

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ATMOSPHERIC TESTING

The atmospheric pressure method relies on an enclosure that contains the test part and traps helium leaking from any leak site. As helium leaks into the chamber the concentration steadily increases. The test consists of sealing the part within the chamber, charging with helium and waiting for the concentration to increase. A reject limit is established by comparing the end to start concentration or by measuring the rate or rise. Ambient helium present when the chamber is closed introduces a background level measured by the detector. Enough helium must enter the chamber during the test to be detected above this background level. The increase in helium concentration is dependent on the chamber tare volume, part leakage and accumulation time. The equation of concentration increase is:

$$\text{INCREASE IN CONCENTRATION} = \frac{\text{LEAKRATE} \times \text{DWELL TIME}}{\text{CHAMBER TARE VOLUME}} \quad (\text{Eq. 17})$$

(chamber tare volume = chamber volume - part volume)

From the above equation, it is apparent that it will benefit to reduce the chamber tare volume as much as possible. However, adequate space must remain around the part for gas mixing. Generally as part size increases so does the chamber tare volume. A careful examination of the equation describing accumulation testing indicates that large parts with high volume can not be tested for small leaks without a long dwell time. If the calculated dwell time is clearly too long and the production rate can not be met, an alternative leak test approach is required.

HARD VACUUM TESTING

The two weaknesses of accumulation testing are due to ambient air surrounding the test part. First, the ambient air contains an ever-present helium background of 5 PPM that must be overcome before detection can take place. Second, the surrounding air is dense and impedes the flow of helium leaking from the part from reaching the detector.

A second leak test method that improves upon accumulation testing eliminates the effects of helium background by removing the surrounding Air by creating a high vacuum. A typical system includes a chamber designed to withstand a pressure differential of 1 atmosphere, evacuation pumps, control valves and a mass spectrometer helium leak detector. The pumps serve two functions. First, they evacuate the chamber to remove air and reduce the partial pressure of ambient helium. Second, the pumps maintain a stable pumping speed to provide a fast helium response time and a steady helium signal.

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The test consists of containing the part within the chamber, evacuated the ambient air and measuring the partial pressure of helium present. The partial pressure of helium present in the chamber has two origins. First, ambient air remaining in the chamber contains 5 PPM and causes a pressure dependent background signal given by:

$$P_{\text{He, ambient}} = P_{\text{Total}} \times 5 \times 10^{-6} \quad (\text{Eq. 18})$$

Second, helium leaking from a test part will cause a pressure increase dependent on the pumping speed of the vacuum pump and the size of the leak. The general vacuum formula $Q=PS$ is written as:

$$P_{\text{He, leak}} = \frac{Q_{\text{Leak}}}{S_{\text{Pump}}} \quad (\text{Eq. 19})$$

The total partial pressure of helium is the sum of equations 18 and 19 given by the following equation:

$$P_{\text{He}} = \frac{Q_{\text{Leak}}}{S_{\text{Pump}}} + P_{\text{Total}} \times 5 \times 10^{-6} \quad (\text{Eq. 20})$$

Process electronics zero out the effects of background. As with accumulation testing a scale factor is used to convert the helium detectors output signal to a calibrated helium leak rate.

SELECTING THE SYSTEM

The decision on which leak test method to employ is the responsibility of the part manufacture and the leak test system supplier. Factors including leak rate limits, cycle time and investment cost must be considered. The first step in selecting a system type starts with a determination of the leak rate threshold.

To begin, one can eliminate accumulation testing as a possibility if the required dwell time is clearly too long. The equations required to calculate dwell time are simple and only take a few minutes to complete. The design evaluation starts with known values for the leak rate, cycle time and part volume. Values to be determined are the size of the accumulation chamber and the reject helium concentration.

As mentioned earlier ambient Air contains a helium concentration of 5 PPM that fixes the start concentration for a test. In the vicinity of the leak test station where test parts are charged and discharged the helium concentration can rise. With good housekeeping, the rise in ambient helium can be minimized by using exhaust fans and purging the chamber with fresh air. In the presence of changing background levels, a practical measurable helium concentration change is 1 PPM.

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A typical 26-gallon vehicle gas tank occupies $100,000 \text{ cm}^3$. Adding sufficient space for air flow and charge fittings results in a chamber volume of about $200,000 \text{ cm}^3$. The tare or free volume is then $100,000 \text{ cm}^3$. Equation 17 is used to calculate the dwell time required. Figure 7 shows the required dwell time for leaks up to 7.00×10^{-3} .

HELIUM LEAK RATES VS. DWELL TIME

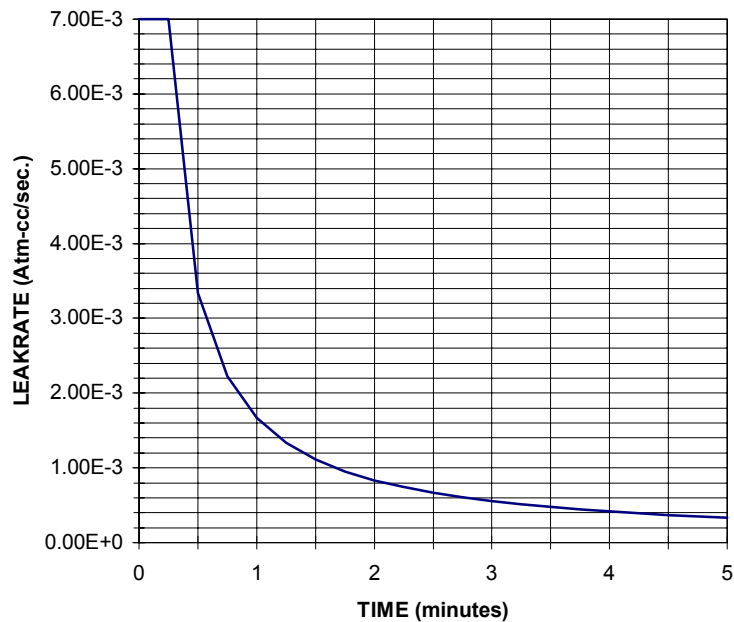


Figure 7

The accumulation time of a system is inversely proportional to the leak size. For example, with the system described, to detect a 1×10^{-3} leak would require a dwell time of 100 seconds. If the leak is reduced by a factor of 10, to 1×10^{-4} , the required dwell time will increase to 1000 seconds. Much of the usefulness of an accumulation system is for detecting large leaks.

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CONCLUSIONS

The analysis of the flow conditions for fine gasoline leak rates with low drive pressure showed that laminar flow conditions existed and established flow formulas can be applied. This analysis covered HC vapor pressures ranging from 1 to 7 kPa and a helium test pressure of 2 to 14 kPa.

At the low end, a gasoline tank with a vapor pressure of 1 kPa will leak 100 mg/day through a 17.4 micron hole in a 3mm wall. At a higher pressure of 7.0 kPa (1 psi), 100 mg/day of HC will pass through a 10.5 micron hole in a 3mm wall. Assuming a helium test pressure of 14 kPa (2 psi), the equivalent helium leak rate for a 10.5 and 17.4 micron hole is 7.67×10^{-5} and 5.78×10^{-4} atm-cc/sec respectively.

For the detection of very fine holes, modern testing techniques are limited at this time to accumulation and high vacuum tests systems. The application threshold between the two techniques depends on the reader's application and time restraints allowed for each part test.

It is clear that finding such small leaks using accumulation testing is no easy task. The expected accumulation times to reach 1 PPM for a 5.78×10^{-4} and 7.67×10^{-5} atm-cc/sec are 180 and 1320 seconds respectively, for the system described. A helium concentration of 1 PPM is close to the detection limit for accumulation testing and is only good for go / no go type testing. Many component manufacturers are implementing statistical process control that requires an output signal with moderate to high resolution. To increase output signal strength a more practical threshold of 10 PPM is suggested. Accumulation times to reach 10 PPM for 5.78×10^{-4} and 7.67×10^{-5} atm-cc/sec leaks are 30 and 220 minutes respectively. In comparison a high vacuum system typically has a part test cycle time of 20 to 60 seconds and gives a high-resolution output.

One can use established formulas to convert leakage for changes in viscosity and pressure but these methods give no insight to the size and geometry of the leak path. The methods describe in the paper use the leak path hole diameter as the medium for calculating equivalent leak rates. Once the hole size is known, leakage for any gas, liquid and pressure is easily calculated. One must be careful in defining the correct operating pressure to insure a realistic hole diameter is first calculated. If a hole size is calculated assuming an unrealistically low vapor pressure, the resulting hole size will be larger than actual. The larger hole diameter will yield a higher equivalent helium leak and may jeopardize passing the shed test.

From the hole size calculated, one can select the correct test method that meets production needs and insures compliance with EPA standards.

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