TEST SCENARIOS AND HAZARDS FOR AUTOMOTIVE EVAPORATIVE EMISSION SYSTEM LEAK DETECTION

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1.0 PREAMBLE

Automotive evaporative emission control systems typically contain a rich hydrocarbon-air mixture and any possible leaks must be controlled to prevent hydrocarbon emissions to the atmosphere. Like all automotive systems, there is some possibility of failure and this leads to the need to test the systems for leaks. Such tests are carried out on board the vehicle by the on-board diagnostics (OBD) system and in automotive shops for inspection and maintenance purposes. It is notable that the requirement to test for evaporative emission system leaks is relatively new and equipment and standards are evolving, both for OBD and inspection / service tests.

Because the evaporative emission control systems contain flammable vapours, it is possible for leaks to lead to flash fire / explosion hazards. Some hazards exist for vehicles operating with leaking evaporative systems. Further hazards are associated with the testing procedures that determine whether an evaporative system is leaking and with tests designed to find leaks. In other industries where systems may contain flammable vapours, (such as marine, aerospace and chemical processing), there are strong standards to control the associated fire/explosion hazards, both for reasons of worker safety and safety of the high-value equipment involved [1]. The automotive service industry does not have the same system of standards in place as these other industries. Given that, the question is: **"What are the best practices to leak testing and leak detection issues which balances productivity and cost while providing a safe environment for workers and the public?"**

This report addresses that question by examining the hazards and methods involved in leak detecting and leak finding as well as methods of mitigating or minimizing the hazards.

2.0 TEST SCENARIOS

There are two tasks in leak testing. The first is leak testing; that is, deciding whether there is any leak that is greater than the allowable threshold. The second, for systems that fail the first test, is leak finding; that is locating the leak (or leaks) so as to make a repair. This is typically followed by a repeat of the threshold test to prove that the repair was successful.

2.1 Leak Threshold Testing This is a pass/fail test which looks for leaks greater than an allowable threshold. For automotive evap systems, the allowable leak threshold has been defined since 1996 by regulations which require the vehicle's On Board Diagnostics (OBD) system to detect emission control system failures [2]. For 1996 to 1999 vehicles, the evap system was deemed acceptable if the total leakage rate was less than the flow that would pass through a single 0.040" (1 mm) diameter hole. From 2000 on, the allowable leak rate was reduced to the flow through a 0.020" (½ mm) diameter hole. The vehicle's OBD system is required to perform a threshold leak test periodically during operation. Leak threshold testing is also a part of many inspection / maintenance (I/M) programs.

To test for leaks that exceed the allowable threshold, OBD and inspection systems typically change the pressure in the evap system. Then they either measure the flow required to maintain the changed test pressure or they stop maintaining the test pressure and measure how fast the system pressure comes back towards normal. Threshold leak detection can use either vacuum pressure or positive pressure as the test pressure. Operating vehicles typically have engine vacuum available to draw down the evap system or a small air pump can be used to either suck down the system or pump it up to a known test pressure. If vehicles fail an OBD test, they typically set the Malfunction Indicator Light (MIL) commonly known as the "Check Engine" light and set a computer code that can be read by service technicians.

2.2 Leak Finding For evap systems that fail the leak threshold test, the second task is finding the leaks. Automotive leak detection systems typically pressurize the evap system using a mist or "smoke" mixture so that the leaks can be found by visual inspection. The smoke method has a productivity advantage in that it rapidly draws attention to significant leaks. Other methods for finding very fine leaks include the soap bubble method and helium leak detection methods. However, these techniques tend to be time consuming for automotive systems due to the complexity and difficulty of access for the typical evap system.

The ease of finding leaks depends somewhat on leak location. A major study of vehicle diurnal emissions [3] found 151 vehicles with leaks. There were eleven liquid fuel leaks below the ½ tank level and the remaining leaks were almost equally distributed between the fuel tank system and the evaporative emission control system, (Figure 1). The other issue is leak size since leaks can vary from a major leak, (such as missing filler cap or a dis-lodged hose) to an accumulation of several very small leaks through cracks, porosity and loose seals which just exceed the allowable threshold.

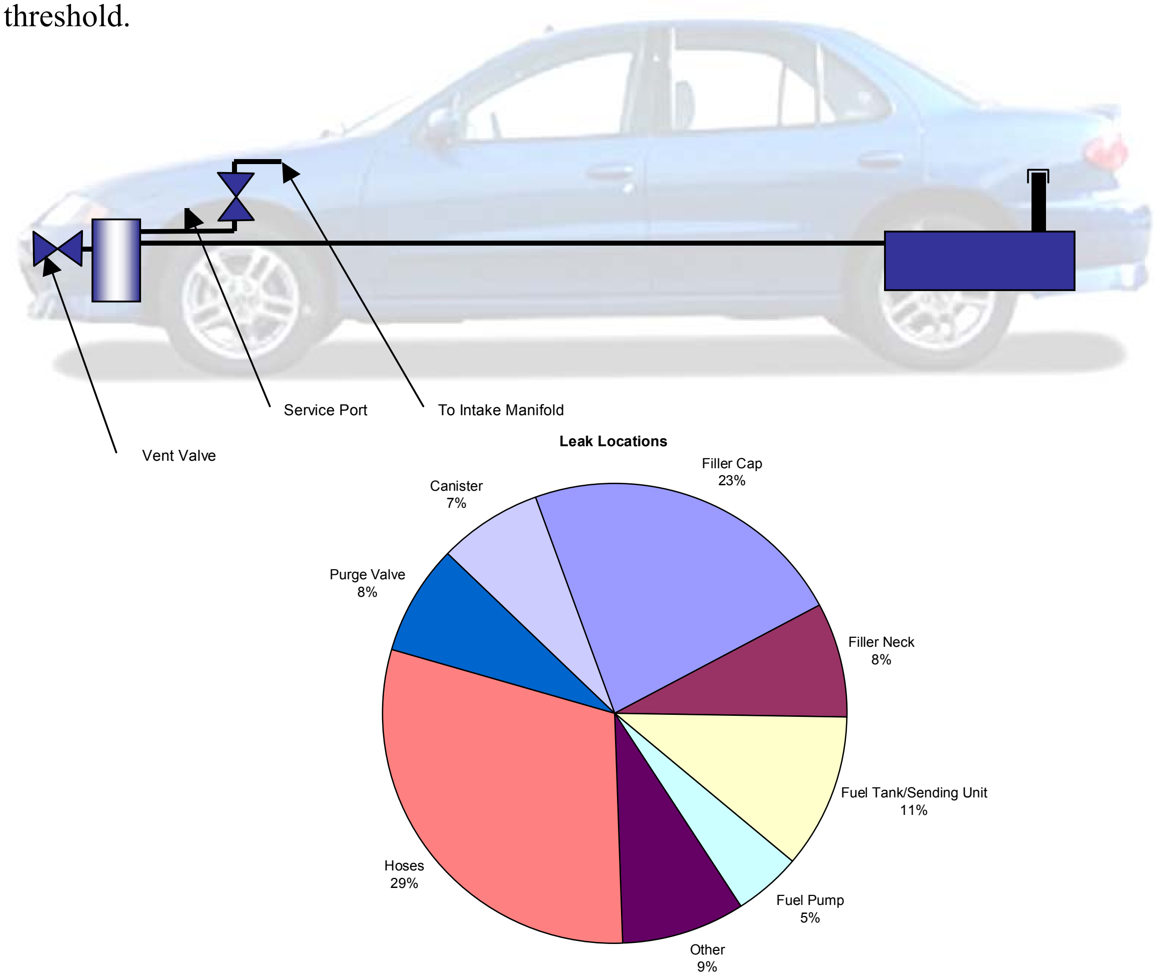

Figure 1. Typical Distribution of Leak Locations. (Note that 47% are associated with fuel tank and pump, 44% with evap control system and hoses, 9% other).

2.3 Typical Leak Testing Pressure / Time Profiles Some of the hazards of automotive leak testing are affected by the pressure / time profile of the test method. This section describes test pressure profiles to provide a basis for discussion.

2.3.1 Vacuum Test Pressure / Time Profiles. Figure 2.3.1 shows some typical pressure / time profiles for leak tests using a vacuum test pressure. The evaporative system starts at some initial pressure level, (which may typically be above atmospheric because of the fuel vapour pressure which in turn depends on fuel volatility and temperature). The tests start with a Ramp section where vacuum is applied to the system until it reaches the Test Vacuum level. For application of a given vacuum source, if the system doesn't reach Test Vacuum, it must have a gross leak. Once the system reaches Test Vacuum, the Figure shows two types of test profile. In the first, (Figure 2.3.1(a)), the vacuum source is sealed off and the system pressure is monitored as the pressure returns to normal. The system fails its threshold test if the vacuum declines by more than a specified amount within a certain time, (with the limit or end time depending on system volume and thus on fuel tank size and level). Figure 2.3.1(b) shows a variation of the test where the vacuum source is used to draw the system down to a Test Vacuum level. The vacuum is then controlled at this level while the flow required is monitored. If the measured flow is above a critical level, the system is determined to have a leak and it fails.

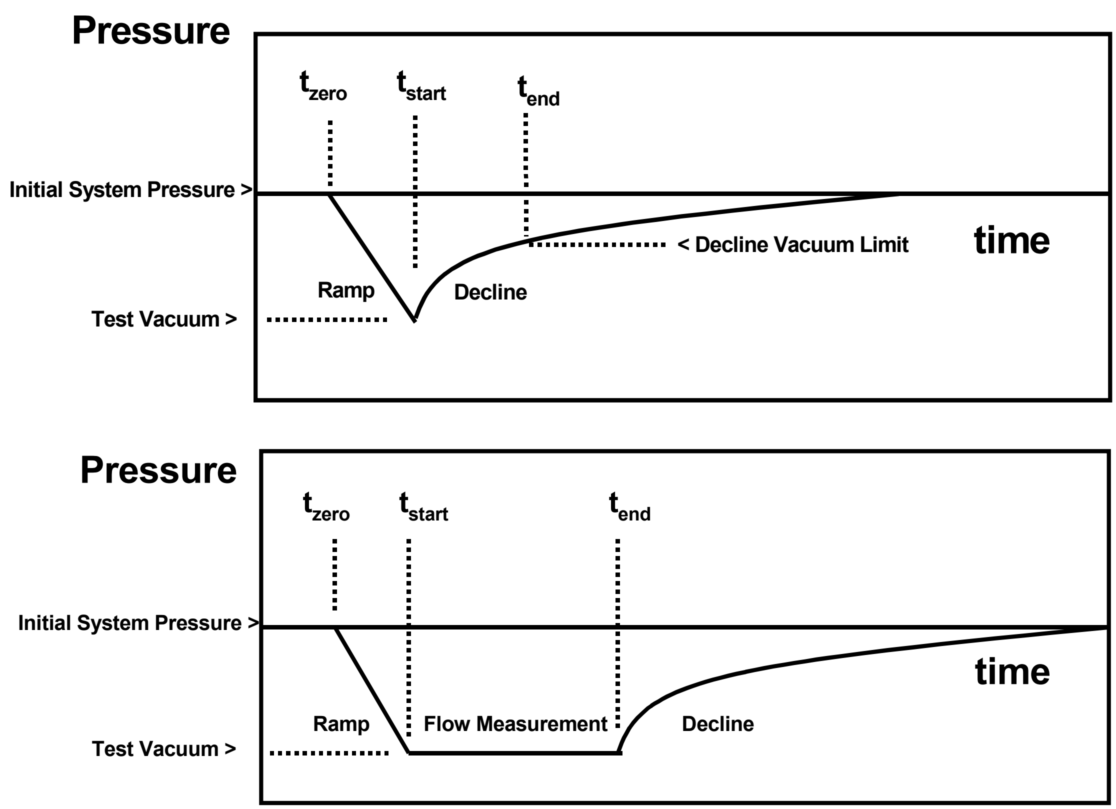

Figure 2.3.1 Typical pressure / time traces for vacuum-based tests
(a) Ramp and vacuum decline test showing allowable decline
(b) Ramp and maintain vacuum test

2.3.2 Pressure Test Pressure / Time Profiles. Figure 2.3.2 shows pressure / time profiles for evap system leak tests using a positive test pressure. Similar to the vacuum-based tests, each test starts with a Ramp where pressure is applied to get from the initial system pressure to the specified Test Pressure. Then, Figure 2.3.2(a) shows a test where the pressure source is turned off and the pressure is monitored as it declines back towards initial system pressure. A rapid decline is a sign of a leak. If the pressure passes a specified Decline Pressure Limit within a certain time (which depends of system volume), the system is determined to fail the leak threshold test. Figure 2.3.2(b) shows a test where the pressure source runs to maintain the system at the Test Pressure while the flow required to maintain pressure is measured. If the flow is above a certain limit, the system is determined to fail the leak threshold test.

The test pressures and vacuums used in these tests are quite low ... typically in the range of 5 to 15 inches of water, (1.25 to 3.75 kPa). The times vary, being as short as a few seconds for computer-automated systems like the OBD. For manual-reading inspection / maintenance tests, the times can be many seconds to more than a minute. Note that the leak-finding process using pressurized smoke to detect leak flows follows a test pressure profile like Figure 2.3.2(b). The test pressure is maintained for the time required to find the leak or leaks which is typically a period measured in minutes.

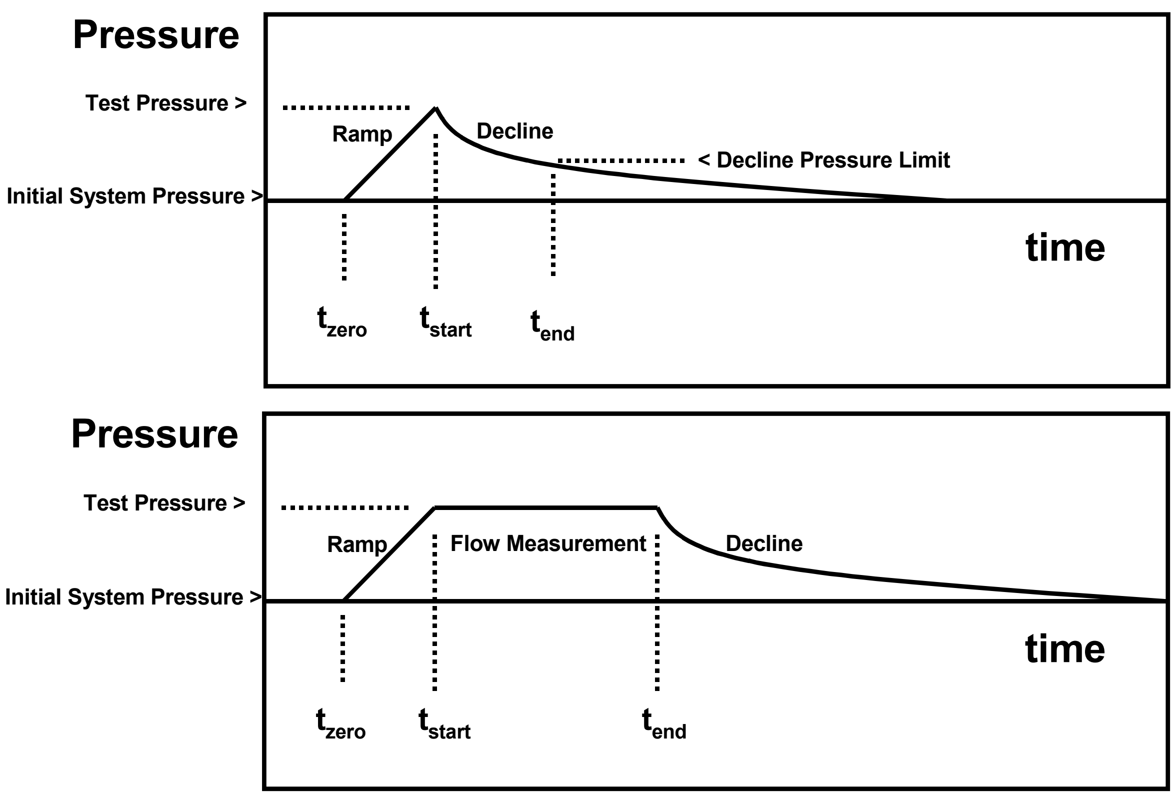

Figure 2.3.2 Typical pressure / time traces for pressure-based tests
(a) Ramp and pressure decline test showing allowable decline
(b) Ramp and maintain pressure test

The most acute hazards associated with evap emission control system leak testing are from the possibility of forming and igniting flammable mixtures. The degree of hazard depends on how much flammable mixture is formed. Greater quantities of flammable mixture are more likely to find an ignition source, will produce a more damaging flash fire or explosion when ignited, and are more likely to lead to secondary ignition of other materials. For this reason, it is desirable to limit the test pressures and flow rates as well as the test time periods.

In a vacuum-pressure test, the vehicle system is drawn down to the vacuum test pressure by pulling some mixture out of the evap lines and tank vapour space. The quantity of vapour removed depends on system volume and test pressure. For example, with a 50 Litre (13 US gallon) vapour space initially at 100 kPa (14.5 psia) atmospheric pressure, the system can be drawn down to a 10"H2O (2.5 kPa) vacuum by rapidly extracting a little over[1] 1.25 Litres of evap system contents, (2.5% of system volume). For an OBD test on an idling vehicle, this withdrawal can be accomplished by closing the canister vent valve and pulsing the manifold purge valve for a short time, on the order of a second. Any vapour withdrawn is consumed by the engine so no flammable mixture is released. For a shop diagnostic test, assuming a typical 11 Litre/minute flow rate, it would take a little over 7 seconds to extract 1.25 Litres and that small quantity of evap system contents would be released in the shop. With either an OBD test or a shop diagnostic test, the next step is for the system pressure to come back to normal ... either slowly due to evaporation of more gasoline vapor or rapidly due to air inflow at a leak. The air that leaks into the system could reduce the fuel concentration in the evap system lines and/or tank vapour space slightly. However the overall dilution caused by drawing in air equivalent to about 2.5% of the system volume is small and unlikely to leave a significant quantity of flammable mixture in the tank vapour space. In contrast, a manual or shop test which continuously draws flow out of the evap emission control system could create a substantial amount of flammable mixture inside the system if there is a leak in the tank vapour space [4]. To avoid this, it is desirable to limit the operating time of vacuum test equipment.

With positive pressure test systems, the test equipment forces either air or an inert gas into the evap emission control system and tank vapour space to raise the pressure. Again, to simply raise the pressure by 10 "H2O, the minimum volume input would be about 2.5% of the system volume: 1.25 Litres for a 50 Litre (13 gallon) vapour space to test whether the system is tight. However, if the technician needs to find a leak, the flow must typically be continued, (with added visible mist), for a period of time typically measured in minutes. This leak-finding test has the potential to produce significantly more flammable mixture because the test flow rate is continued for a long period of time, as discussed below in Section 4.

[1] (The "little over" qualifier is because there will be some fuel evaporation during the extraction time. If the extraction is fast, the amount of evaporation is negligible and if the extraction is slow, the amount of evaporation can become significant).

3.0 GASOLINE VAPOUR AND VAPOUR / AIR MIXTURE PROPERTIES

The stoichiometric (chemically correct) mixture of gasoline vapour and air is about 2½% gasoline vapour and vapour / air mixtures are flammable between about 1.2% vapour (Lower Explosive Limit, LEL) and 7% to 9% vapour (Upper Explosive Limit, UEL). These numbers are all somewhat variable because gasoline is a complex mixture of hydrocarbons, generally with some oxygenates (such as alcohols and ethers) mixed in and the composition changes from supplier to supplier, region to region and season to season.

In typical fuel tank and evaporative emission control systems, the concentration of gasoline vapour is well above UEL. The actual concentration depends on the fuel volatility, fuel temperature and vapour space pressure as well as on the history of when the system was last exposed to air. As a typical situation, a low-volatility, (7 psi Reid Vapour Pressure), gasoline has a vapour pressure around 26 kPa and a volumetric vapour concentration around 25% when it comes to equilibrium at 20°C [4]. At higher temperatures or with higher volatility gasoline, (eg. Canadian winter gasoline), the vapour pressure and vapour concentration would be higher. At lower temperatures or with weathered gasoline, the vapour concentration would be lower. However, the normal situation is that the fuel tank vapour space contains an air/vapour mixture with about 3 times more vapour than the UEL. (For further discussion see references [4] and [5]).

Although liquid gasoline composition is variable, the vapour properties are fairly consistent and it is common to treat gasoline vapour as being equivalent to pure pentane [6]. (For weathered gasoline, the vapour would be heavier, equivalent to some pentane / hexane mix and for fresh winter gasoline, the vapour would be lighter, equivalent to some pentane / butane mix). Pure gasoline vapour is much heavier than air, being typically about 2½ to 3 times as heavy. Mixtures of gasoline vapour with air become lighter as air is added but are still typically 12% heavier than air at UEL and 2% heavier than air at LEL. This means that gasoline vapour and the hazardous vapour/air mixtures tend to sink to the floor and pool on the floor in typical environments.

4.0 LEAK TESTING FIRE AND EXPLOSION HAZARDS

There are various hazards dealing with automotive systems and test equipment that produces pressures or vacuums. This section concentrates only on flash fire and explosion hazards associated with the fuel vapour in the evaporative emission control system and fuel tank vapour space. The flash fire hazards are classified in two groups: those inside the vehicle system and those outside the vehicle system.

4.1 Fire and Explosion Hazards Inside the Vehicle Systems As discussed in Section 3, the fuel tank vapour space normally contains a mixture too rich to ignite. The various lines of the evaporative emission control system may contain a similar rich vapour mixture or may contain almost pure air shortly after a purge cycle. However, addition of significant quantities of air to the tank vapour space can push all or part of it into the flammable range. The danger of a flammable mixture inside the vehicle system is that it might be ignited, either by some internal ignition source or by an external fire flashing into the tank through a significant opening such as an open line or fuel fill opening. If the tank vapour space does ignite, the rapid pressure rise in the enclosed tank space can rupture the fuel tank with devastating results, (rapid spillage of liquid fuel and a much larger flash fire involving the entire contents of the fuel tank).

It is possible for air to be added to the tank vapour space by a vehicle malfunction or by a leak test procedure. A bad example of a vehicle malfunction would be a combination of mis-connections and failed components in the evaporative emission control system such as a tank vapour line incorrectly connected to the vacuum of the intake manifold and simultaneously an unsealed fuel tank cap. While the vehicle operated, the engine would continually draw air through the fuel tank. Hence, the vehicle might come into the shop with a flammable tank vapour space.

Leak detection efforts can also add air to the tank vapour space. For example, attaching a vacuum leak test device to the vehicle evap emission control system will draw air in through the leak while the vacuum is applied. If the leak is significant, the the air drawn into the tank will mix with tank vapours and reduce the local fuel concentration, possibly to the flammable range. For example, simply drawing a vapour space down to 10 inches of water (2.5 kPa vacuum) requires withdrawing at least 2½% of the vapour space volume if there is no leak. If there is a leak, attempting to hold the tank at 10 inches vacuum would draw in a couple litres per minute for a marginal leak, (just over 0.040 ") and 10 or more liters per minute for an open hose [7]. Obviously, the quantity of air drawn in and degree of hazard produced depends on the leak size and the duration of applied vacuum. Vacuum test units are normally used for threshold leak detection, it would obviously be desirable to limit the time required for a pass/fail determination so as to limit the quantity of flammable mixture potentially created in the tank vapour space. On-board diagnostics use automation and multiple sensors to accomplish their check within 10 or 15 seconds. While it is not feasible to automate shop leak diagnosis to the same degree, it is still desirable to minimize the vacuum-on time.

Attaching a pressure leak test device to the vehicle evap emission control system forces external gas into the vehicle's tank vapour space. If the working fluid is air, this will mix with tank vapours and reduce the local fuel concentration, again possibly to the flammable range. If the pressure leak test devices is being used for leak finding rather than threshold leak detection, the pressure and gas flow is likely to be applied for a longer time. Typically, the smoke-filled gas is applied for a sufficient time to fill the vapour space to the leak point, force smoke out the leak and wait for the smoke to be detected, often a period of several minutes. Depending on where the leak is, this likely means that the entire tank is exposed to the gas / smoke combination [5]. If the working fluid is air, this could result in a vehicle tank being filled with a flammable mixture during the leak finding procedure and potentially being left flammable at the end of the repair procedure. A computational modelling study of flow into a fuel tank showed that the vapour space would become flammable for a range of typical leak detection flow rates [4] if the test fluid was air. In contrast, using Nitrogen as a test fluid would eliminate the flammability hazard inside the tank vapour space. The expelled vapours could still be ignited once they mixed with air outside the fuel tank but there would be no possibility of flashback and explosion inside the fuel tank.

<u>4.2 Fire and Explosion Hazards Outside the Vehicle Systems</u> Fuel vapour from evap system and tank vapour spaces can also lead to hazards outside the vehicle, specifically the possibility of a flash fire or explosion in fumes exiting the vehicle or pooling on the shop floor. The fuel vapour, which is normally too rich to burn while inside the vehicle systems, will mix with air as it enters the shop environment and will further diffuse into the air with time. In general, any fuel vapour falls to the floor because it is heavier than air. However, there is a flammable zone between the pure air on one side and the concentrated vapour on the other so the vapour pool is easily ignited.

Fuel vapour fire and explosion hazards outside the vehicle can be produced by leaking fuel or evap systems and also by leak test procedures. The hazards associated with vapour leaking from gasoline-fuelled vehicles are a familiar and well-understood risk for vehicle service shops. This history of experience is reflected in the construction codes, safe practices and insurance rates for such enterprises. To put the added hazard due to leak detection in perspective, it is worth reviewing the "normal" hazards. For example, vehicles sometimes come in with liquid fuel leaks or liquid is leaked during replacement of components like fuel pumps or filters. When liquid gasoline leaks onto a warm component, it will all evaporate, forming about 200 volumes of vapour for every volume leaked. For example, 0.1 L of gasoline, (a little over 3 oz.), produces 20 litres of gasoline vapour which mixes with 14 to 83 times its volume of air to form around 1000 L of flammable mixture.

Repair procedures also routinely lead to vapour releases. As discussed in [5], the common practise of venting fuel tank pressure by opening a fuel tank cap or evaporative emissions line can dump up to 20 litres of fuel tank vapour space contents onto the shop floor. Assuming this is in the range of 25-50% gasoline vapour, it mixes with 6 to 42 times its volume of air so it could produce around 500 L of flammable mixture.

Vacuum test units draw vapour space mixture out of the vehicle to achieve a test vacuum around 7 to 15 inches of water. For a "tight" vehicle system with low gasoline volatility, the quantity required to reach the test vacuum is ideally only about 1½ to 3% of the system vapour space volume. Once a tight system is at test vacuum, a small flow rate is required to maintain vacuum while fuel evaporates. Since the total vapour space volume is typically less than 100 L, the vacuum system would ideally only discharge a few litres of vapour/air mixture in the shop. Typically this is significantly less than the quantity already discharged when the vapour space was bled down to atmospheric. If vehicle evap system has a significant leak, the maximum flow rate of the vacuum system comes into play. Typically, this can be limited to a few litres per minute [7] so the quantities of mixture are still modest compared with fuel tank venting.

Pressure test units, particularly those used for smoke leak detection are likely to run for a longer time period than vacuum test units. This is because the test must not only pressurize the system but also fill the evap system and potentially the tank vapour space until the technician can spot the flow out the leak. During the time that the smoke-filled test gas is filling the evap system and tank vapour space, it is also purging the vapour space contents out through the leak. This has the potential to put more fuel vapour/air mixture onto the shop floor than a leak threshold test or a fuel tank vent procedure [5]. Since the hazard of displaced fuel vapour is an unavoidable part of leak finding, technician awareness and education is important to minimize test time and ensure a low hazard environment. The basic elements of a low hazard environment are those of a normal automotive shop ... a clear area under the vehicle with good ventilation and no ignition sources near floor level. An operating exhaust suction hose on the floor under the car would be an enhancement but could not be relied on to clear away heavy vapours from a major leak, particularly since the leak location is unknown at the start of the procedure.

An additional hazard in the event of a flash fire in the service shop is that the fire might flash back into the vehicle fuel tank, resulting in a more significant explosion and fire. Flash fires can propagate through hoses and holes filled with a flammable mixture provided the minimum diameter is greater than the quench distance, which is about 1.75 mm (0.070 inches) for fuel vapours. Examples of greater leaks would include broken or missing hoses or a missing filler cap.

5.0 HAZARD REDUCTION

There are three main approaches to reducing the fire and explosion hazards associated with leak testing. They are:

-minimizing the test time and flow rates to limit the amount of flammable mixture produced,
-control of any vented vapour to avoid ignition sources and dilute it to non-flammability,
-use of inert gas to prevent flammable mixture production inside vehicle systems.

5.1 Minimizing Test Time and Flow Rates. Minimizing the time and vapour flow rates involved is a good strategy for any procedure that involves opening the evaporative emission control or fuel systems. Experience has shown that when you fill a shop with flammable mixture there is a good chance it will find an ignition source and the explosion will be devastating. In contrast, if you produce a few litres of flammable mixture it is unlikely to be ignited before diluting below the LEL. Even if a small quantity of vapour is ignited, a small flash fire is less likely than a big one to injure people, damage buildings and ignite secondary fires. For leak test procedures, the implications are slightly different for threshold pass/fail tests and for leak finding tests.

The pass / fail tests to determine whether there is a leak above the critical threshold should:

-be designed to provide an answer within a short test period,
-should have a limited flow rate so that, in the event of a major leak, the quantity of flammable mixture produced is minimal.
-if there is an unacceptable leak, should indicate the size of the leak, (major / minor) to aid the next step of finding it.
-if possible, should isolate the leak location as being in the evaporative emission control system and lines as opposed to being in the tank vapour space.

The smoke tests used to actually find leaks should be designed to control pressure and flow rates to minimize vapour hazards outside the vehicle. If possible, such tests should be carried out on the evaporative emission control system independent of the tank vapour space.

5.2 Controlling and Diluting Vented Vapour. Controlling and diluting vented vapours is particularly appropriate for vacuum test units. The units are drawing a mixture of flammable vapours out of the vehicle system and expelling it into the shop where it might be ignited. The best practises would involve:

-including a flame arrester at some point to prevent any flash fire ignited in the shop from propagating back through the test equipment to the vehicle. (Vapour mixtures drawn from the vehicle should be too rich to burn but are potentially flammable under some circumstances).
-enhancing the dilution of the vapours drawn from the system, hopefully to the point where even a pure gasoline vapour mixture would become non-flammable.
-disposing of the vapour in a method that ensures adequate dilution and prevents worker

contact with the toxic compounds, (benzene, toluene, etc.). This could be handled by running a discharge hose to the vehicle exhaust extraction system for example.

For pressure test units, the vapour being discharged into the shop is coming from the (unknown) leak site somewhere on the vehicle. This is not amenable to direct control so best practise simply involves technician education to recognize the hazards plus normal repair shop practises of good ventilation, keeping a clear area around vehicles and avoiding ignition sources near floor level.

5.3 Using Inert Gas for Testing. Inert gas such as Nitrogen does not contain oxygen and cannot form flammable mixtures with hydrocarbon vapours.

Using inert gas is particularly appropriate for test systems that apply pressure to the vehicle vapour system since it avoids creating a flammable mixture inside the vehicle systems. This is important since it avoids the escalation that can occur with an exploding fuel tank and rapid release of the fuel tank's liquid contents. Computational studies [4] and common sense indicate that forcing air into a hydrocarbon-rich environment will produce a flammable mixture. In contrast, forcing Nitrogen into the same space inerts the mixture inside the system. Concentrated fuel vapours being forced out of the system may still become flammable as they mix with air outside the vehicle. However, the volume of flammable mixture that can be formed is less than if air was used as the original driver and the possibility of flashback from that flammable mixture into the vehicle system is eliminated.

There is also some safety benefit to using inert gas as a driver for venturi-type vacuum test systems since it ensures the mixture is locally inert as it passes through the test instrument and thus prevents flash-back through the test instrument. Again, it must be recognized that the use of inert gas only reduces the risk of flash fire once the vapours are discharged from the instrument. Use of Nitrogen would inert most mixtures but not the worst case of a highly concentrated fuel vapour.

6.0 SUMMARY & CONCLUSIONS

Like any automotive service procedure, the requirement for leak detection testing involves some degree of hazard for an inspection station or service shop. Specifically, there are added flash fire hazards involved with either releasing fuel vapour from the fuel and evap systems or adding air to the fuel vapour inside the vehicle systems. The hazard due to heavy vapours released from the test equipment or vehicle during testing, (either with vacuum or pressure test systems) is similar to fuel vapour hazards already familiar to the automotive service industry. The requirement for leak testing and diagnosis means some increase in the occurrence frequency of these hazards. However, the added hazard is not large compared with the familiar example of bleeding down fuel tank pressure for a warm fuel tank. Safe practises such as technician awareness, minimizing test time, minimizing test flow rates and control of vented vapour can minimize the added hazard of leak testing procedures.

The hazard of creating a flammable mixture in the tank vapour space due to air-based pressure testing adds a new risk which is not so familiar to automotive shops. This added hazard can be controlled by using an inert gas, (such as Nitrogen), for the smoke generation. Since this is a practise which minimizes a hazard without significantly affecting productivity, it would be considered the best available practise.

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