Evaporative Emission Control Technologies for Gasoline Powered Vehicles

December 2010

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Executive Summary

Evaporative emission control technology was the first to be used on passenger vehicles as a way to control smog forming hydrocarbons in the early 1960's. Evaporative emissions from motor vehicles constitute about half of the reactive organic gas (ROG) inventory in California [1] and nearly 40% in the Northeastern United States. Ozone is considered to be a respiratory irritant harmful to humans and plants and is regulated by the U.S. EPA which sets a National Ambient Air Quality Standard (NAAQS) for ozone concentration. Areas that are out of attainment or experience concentrations above this ozone concentration, like California, regulate evaporative emissions to reduce ground-level ozone. In addition to the negative health effects of ground level ozone, it is also a greenhouse gas.

Evaporative emissions are broken down into five primary sources; diurnal, running loss, hot soak, permeation and refueling. The magnitude of the relative components depends greatly on the engine design, fuel delivery and application. A brief description of the major types of evaporative emissions is given below.

> Diurnal emissions result from the evaporation of gasoline due to temperature fluctuation during the day and night.
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> Running loss emissions represent gasoline that is vaporized from the engine and fuel system while in operation.
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> Hot Soak emissions occur during the first hour that the vehicle is parked after normal operation.
>
> Permeation occurs continuously once the polymer components of the fuel system become saturated with fuel.
>
> Refueling emissions occur as gasoline is pumped into the tank displacing the gasoline rich vapor.

The function of the automobile evaporative emission control system is to block or capture the above sources of vaporized hydrocarbons and prevent their release into the atmosphere. There are varying levels of complexity and efficacy of these controls with the most advanced systems equipped on partial zero emission vehicles being certified to California's PZEV standard under the state's LEV II emission standards.

Companies that manufacture evaporative emission controls have responded to the challenge of reducing VOC emissions from gasoline powered vehicles. Through their efforts, a wide range of cost-effective technologies have been developed to block HC emissions via the above mechanisms. Manufacturers of Emission Controls Association (MECA) member companies, together with engine manufacturers, have worked together to meet California's PZEV requirements on over 50 light-duty vehicles and employed evaporative canisters on motorcycles and marine engines.

Interest in evaporative emissions control has grown considerably in recent years around the world. MECA is engaged with California on their LEV III regulation that proposes to extend the most advanced evaporative controls across the entire on-road, light and medium-duty vehicle fleet. This document has been prepared to supplement information already made available by MECA on emission control technologies and provides an overview of the types of technologies being developed for new gasoline fueled cars and trucks.

Today's cleanest gasoline vehicles, certified to California's PZEV emission limits require near zero evaporative emissions and include additional technologies such as canister scrubbers to virtually eliminate bleed emissions from the carbon canisters during periods of low purge. Some vehicles also incorporate carbon based air-intake HC traps to prevent engine breathing losses from escaping through the intake manifold and air induction system (AIS) after the engine is shut off.

Today, viable emission control technologies exist to reduce fuel system based HC evaporative emissions from all types of spark-ignited engines including small handheld equipment up to large spark-ignited (LSI) vehicles. Applications include marine and recreational off-road vehicles. The major technologies that control permeation emissions include:

- Fuel tanks made of low permeation polymers
- Multilayer co-extruded hoses
- Low permeation seals and gaskets

Technologies designed to control diurnal, hot soak and refueling HC emissions include:

- Advanced carbon canisters
- High working capacity activated carbon
- Honeycomb carbons scrubbers
- Air induction system (AIS) HC traps

The most stringent evaporative emission control regulations are enforced in the United States. Vehicles certified to California's PZEV low emission vehicle standards must demonstrate near zero evaporative emissions from the fuel system at 0.054 g/test using a rig test of a vehicle's fuel system. The California Air Resources Board (CARB) is proposing to extend these requirements across the entire light-duty and medium-duty passenger vehicle fleet (<14,000 lbs GVWR) by 2022 as part of their LEV III regulations.

Demands on vehicle manufacturers to achieve higher fuel efficiency through the use of smaller displacement, boosted engines and hybrid electric powertrains will create challenging operating conditions for evaporative emission control technologies. The lower purge volumes that result from smaller displacement engines or hybrid systems under partial or full electric drive will require the development of specialty carbon adsorbents and advanced canister designs to achieve the lowest evaporative emissions demanded by future regulations. Gasoline vehicles in other parts of the world and SI off-road equipment everywhere can benefit from much of the same technologies applied to passenger vehicles in the U.S. This paper will describe the types of technologies that are being used to meet the current and future evaporative emission regulations.

1.0 Introduction

Evaporative emissions from gasoline powered vehicles consist of volatile organic compounds (VOCs), or hydrocarbons, released from the fuel system, rubber and other plastic components of the vehicle, such as tires, plastic interior and exterior trim, carpeting etc. This paper will focus on the hydrocarbon vapors emitted from the fuel system as these represent the major sources of evaporative emissions from mobile vehicles and equipment. This paper will further focus on fuel-related evaporative emissions from light-duty vehicles. Some of the same types of technologies that are discussed here for passenger cars have been successfully applied to other spark-ignited off-road vehicles and equipment and will not be covered here. A more detailed discussion of regulations and evaporative control technologies in these applications can be found in MECA's white papers specific to those applications available at www.meca.org.

Evaporative emissions from motor vehicles constitute about half of the reactive organic gas (ROG) inventory in California [1] and nearly 40% in the Northeastern United States. Evaporative emissions depend on ambient temperatures and the vapor pressure of the fuel supply. VOCs and other hydrocarbons (HC), such as those emitted from the tailpipe of motor vehicles, react with NOx in the presence of sunlight to form photochemical smog which is the primary component of ground level ozone. Ozone is considered to be a respiratory irritant harmful to humans and plants and is regulated by the U.S. EPA which sets a National Ambient Air Quality Standard (NAAQS) for ozone concentration. Areas that are out of attainment or experience concentrations above this ozone concentration, like California, regulate evaporative emissions to reduce ground-level ozone. In addition to the negative health effects of ground level ozone, it is also a greenhouse gas.

Evaporative emissions are broken down into five primary sources; diurnal, running loss, hot soak, permeation and refueling. The magnitude of the relative components depends greatly on the engine design, fuel delivery and application.

Diurnal emissions result from evaporation of gasoline due to temperature fluctuation during the day and night. As the fuel tank warms during the day or while parked in the sun, expansion of the gasoline vapor above the liquid is vented from the tank. During the night, as the tank cools, fresh air is pulled into the tank to mix with the gasoline vapors to start the process again the next day.

Gasoline vapors coming from the engine and fuel system while in operation are known as running losses. The primary source of running loss emissions in earlier passenger cars was from the carburetor. Modern vehicles may emit small amounts of emissions from the fuel cap and vapor canister. Most of these HCs end up being captured by the evaporative emission control system and routed back through the intake of the engine to be consumed during combustion.

Emissions attributed to the hot soak occur during the first hour that the vehicle is parked after normal operation. During this time, the engine remains hot and, without convective cooling, continues to heat the fuel system. This source is primarily attributed to carbureted vehicles and equipment. In modern vehicles equipped with fuel injectors and carbon canisters, the hot soak vapors would be captured and stored until the next time the engine is running. At this time they would be purged into the intake air of the engine and combusted.

Permeation of gasoline molecules can occur during normal operation or extended periods of parking a vehicle. This is caused by the saturation of the plastic and rubber components of the fuel system such as plastic fuel tanks and rubber hoses and results in relatively constant permeation through these components. Significant advances in polymer chemistry and laminated forming techniques have significantly reduced permeation as a source of emissions in modern vehicles.

Refueling emissions can occur as gasoline is pumped into the tank displacing the gasoline rich vapor causing it to be emitted into the atmosphere. In modern passenger vehicles, these vapors are stored in the EVAP canister and purged into the intake air of the engine to be combusted.

The function of the automobile evaporative emission control system is to block or capture the above sources of vaporized hydrocarbons and prevent their release into the atmosphere. There are varying levels of complexity and efficacy of these controls with the most advanced systems equipped on partial zero emission vehicles (PZEV) being certified to California's tightest evaporative standard under the state's LEV II and future LEV III emission standards.

Evaporative emission controls were the first type of emission control system on automobiles and is often the least expensive approach to controlling VOC and HC emissions from gasoline powered engines. In the 1960s positive crankcase ventilation systems were introduced to capture crankcase vapors and prevent them from being vented to the atmosphere. The technology has advanced to include carbon canisters, low permeation hoses, active purge systems and on-board vehicle refueling (ORVR) controls. Eventually on-board diagnostic sensors were integrated to insure proper functioning of the entire fuel evaporative control system. Hot soak emissions were a problem in carbureted engines releasing gasoline vapors from the fuel bowl as the temperature in the engine compartment increased after shut down. Initially air filter assemblies were used to capture these emissions and later carbon canisters were connected with a hose to the fuel bowl. The introduction of fuel injection greatly reduced evaporative emissions due to hot soak and running loss as they isolated the fuel from the atmosphere at all time except for refueling. On-board refueling vapor recovery (ORVR) systems have been required on all passenger vehicles in the U.S. since 2000 and capture vapors emitted from the tank during refueling in the carbon canister and later emit them into the combustion chamber during canister purging.

Today's cleanest gasoline vehicles, certified to California's PZEV emission limits require near zero evaporative emissions and include additional technologies such as canister scrubbers to virtually eliminate bleed emissions from the carbon canisters during periods of low purge. Some vehicles also incorporate carbon based air-intake HC traps to prevent engine breathing losses from escaping through the intake manifold and air induction system (AIS) after the engine is shut off. Figure 1 shows the benefit that advanced evaporative controls can have on the relative amounts of evaporative emissions contributed from different parts of a vehicle. The bar chart quantifies the mass of evaporative emissions that contribute to the SHED test measurement for a typical LEV II and PZEV certified vehicle. The background emissions represent the non-fuel related evaporative emissions from carpets, rubber and plastic parts. The emissions that are readily impacted by advanced evaporative control technology are those emitted by the air induction system (AIS) and fuel system. Carbon AIS traps can reduce emissions by 0.10 to 0.15 g/test and incorporating canisters with auxiliary scrubbers onto a LEV II vehicle reduces tank venting emissions by as much as 0.1 g/test. The advanced emission control technologies used on PZEV vehicles are very effective and leave background emissions as the major contributor (65%) to the total evaporative emissions.

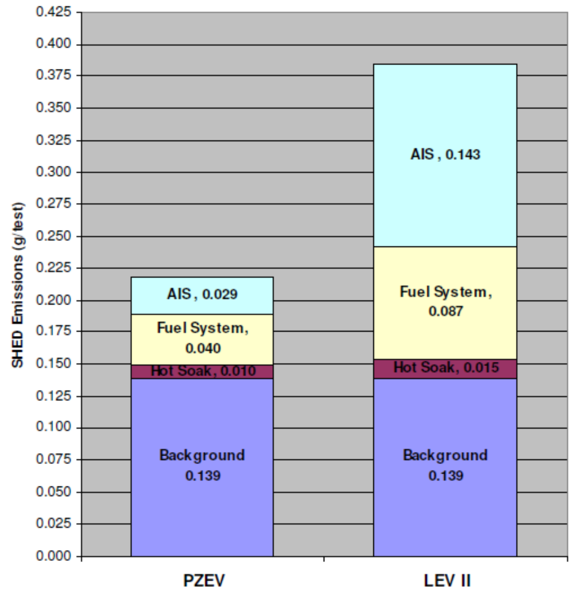

Figure 1: Relative contribution to full vehicle emissions from different sources for PZEV and LEVII certified vehicles.

After a brief review of the evaporative emission regulations in the United States, this paper will describe the specific evaporative control system technologies in greater detail.

2.0 Current Evaporative Emission Regulations in the U.S.

California has enforced evaporative emissions on light-duty vehicles since 1970. The current requirements under CARB's low emission vehicle program were fully implemented in 2006 for the entire fleet. The evaporative emission standards are shown below for the three-day diurnal-plus-hot soak test and the two-day diurnal-plus-hot-soak test. The standards are expressed in total vehicle HC evaporative emissions and include both fuel and non-fuel vehicle emissions. The three-day diurnal test insures that running loss emissions, high temperature hot soak and diurnal emissions are controlled whereas the two-day diurnal test verifies that the canister is well purged during vehicle operation. For 2001 and newer vehicles, additional testing of the ORVR system is required to insure that refueling emissions do not exceed 0.2 g/gal. of fuel dispensed. The standards apply to gasoline-fueled, liquefied-petroleum-gas-fueled, and alcohol-fueled passenger cars, light-duty trucks, medium-duty vehicles, and heavy-duty vehicles.

Included in these requirements are flexible-fuel vehicles, dual-fuel vehicles, hybrid-electric vehicles, and zero-emission vehicles with fuel fired heaters. Table I shows the evaporative emission limits for the current California LEV II standards.

Table I: CARB LEV II Evaporative Emission Standards

Class of Vehicle	Hydrocarbon Standards		
	Three-Day Diurnal + Hot Soak (grams per test)	**Two-Day Diurnal + Hot Soak (grams per test)**	**Running Loss* (grams per mile)**
Passenger Cars	0.50	0.65	0.05
Light-Duty Trucks (under 8,501 lbs. GVWR)			
under 6,000 lbs. GVWR	0.65	0.85	0.05
6,001 - 8,500 lb. GVWR	0.90	1.15	0.05
Medium-Duty Vehicles (8,501 - 14,000 lbs. GVWR)	1.00	1.25	0.05
Heavy-Duty Vehicles (over 14,000 lbs. GVWR)	1.00	1.25	0.05

The standards were also adopted by U.S. EPA as part of their Tier II light-duty vehicle standards with a different phase-in period. Both agencies introduced the standards in 2004 with requirements for 40% of the fleet in California and 25% federally. California completed the phase in by 2006 with full harmonization by both agencies in 2009 for evaporative emissions. The fleet average evaporative limits for EPA's Tier II standards are shown in Table II. The evaporative emission control system standards include a useful-life requirement of 15 years or 150,000 miles, whichever comes first.

Table II: Evaporative Emission Limits under EPA's Tier II Standards

	Vehicle Type	Model Year	3 day Diurnal + Hot Soak (g/test)	Supplemental 2 day Diurnal + Hot Soak (g/test)	Running Loss (g/mi)
Federal	LDV/LLDTs	2004	0.95	1.20	0.05
	HLDTs	2004	1.20	1.50	0.05
	MDPVs	2004	1.40	1.75	0.05
	LDV	2009	0.50	0.65	0.05
	LLDT	2009	0.65	0.85	0.05
	HLDT	2010	0.90	1.15	0.05
	MDPV	2010	1.00	1.25	0.05

California allows manufacturers to certify to their zero-fuel evaporative standards as a way to generate credits toward meeting the states zero-emission vehicle (ZEV) requirements. The PZEV requirements are compared to the LEV II limits for passenger cars and light-duty trucks in Figure 2. In addition to tighter limits for the diurnal tests, manufacturers must also meet a near zero (0.054 g/test) limit for the fuel system using a rig test. The EVAP test procedures will be described in greater detail in Section 2.1.

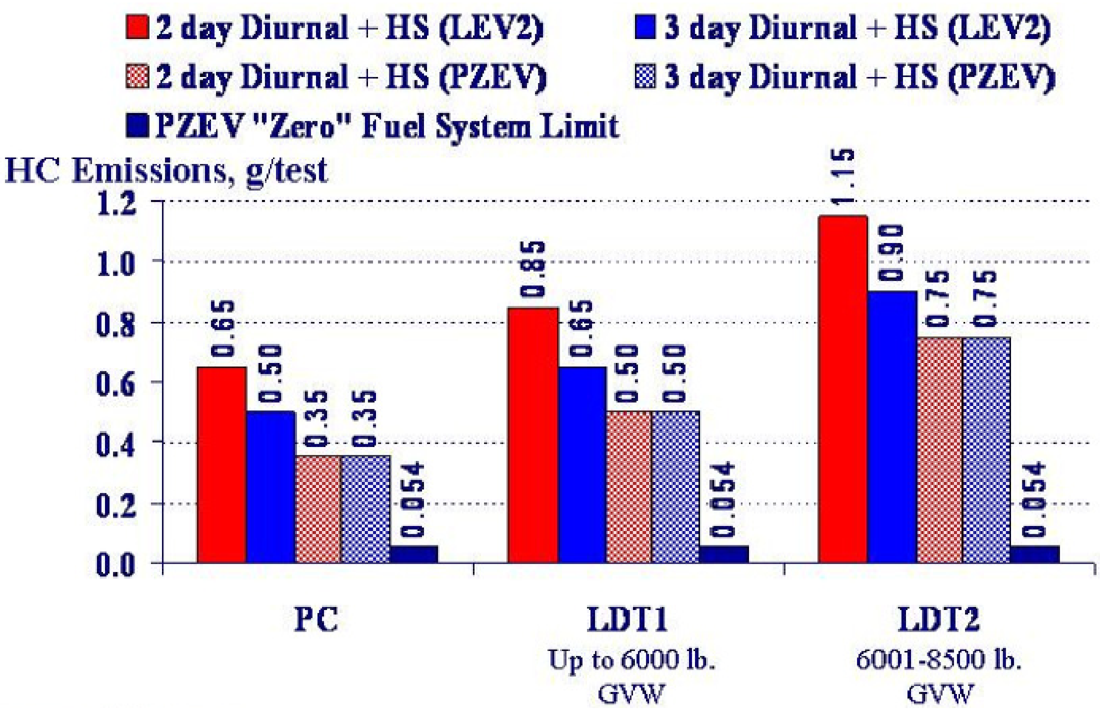

Figure 2: CARB LEVII and PZEV Evaporative Requirements

Meeting the PZEV limits requires the use of advanced fuel and evaporative control systems that are capable of essentially eliminating fuel-related evaporative emissions. These advanced technologies include a pressurized and sealed fuel system such as an insulated, bladder fuel tank, larger chambered carbon canister equipped with a bleed emissions scrubber and an AIS carbon filter. A more detailed description of LEVII and PZEV technologies will be provided in Section 3.0.

2.1 ARB's Proposed Evaporative Emission Requirements for LEV III

ARB is in the final stages of finalizing their evaporative emission requirements as part of their LEV III proposal that will be presented to the Board in April of 2011. ARB is proposing to extend "zero" evaporative emission technology to all light-duty and medium-duty vehicles. Phase-in of these proposed vehicle evaporative emission requirements would begin with model year 2018 and be complete by model year 2022. The phase-in would require that 60% of the fleet is in compliance in the 2018-19 time frame ramping up to 80% compliance by 2020 to 2021 and full coverage of the fleet by 2022. To certify to the new standards ARB is also proposing to require the use of an E10 certification fuel starting with the 2014 model year for new vehicles. Because all gasoline fuel in California contains 10% ethanol, this will bring certification data more in-line with real world emissions. All certifications would need to use the E10 fuel starting in model year 2018.

Vehicle manufacturers would have two options for evaporative emissions compliance. The first option is to comply with the current "zero" evaporative, whole vehicle standard that varies with vehicle weight and use the current complete fuel system rig test to confirm that the fuel system has no more than 0.054 g/test of evaporative emissions.

Table III: Option 1 of ARB's Proposed LEV III Evaporative Standards

Class of Vehicle	3-Day Diurnal + Hot Soak and 2-Day Diurnal + Hot Soak		Running Loss (grams per mile)
	Whole Vehicle (grams per test)	Fuel System Only (grams per test)	
PC	0.350	0.0	0.05
LDT: < 6000 lbs GVWR	0.500	0.0	0.05
LDT: 6000 – 8500 lbs GVWR	0.750	0.0	0.05
MDV: 8500 – 14000 lbs GVWR	0.750	0.0	0.05
HDV: > 14000 lbs GVWR	0.750	0.0	0.05

The second option allows manufacturers to comply with a lower whole vehicle emissions standard and use a new bleed emissions test protocol to confirm that the carbon canister bleed emissions are less than or equal to 0.02 g/test for all light-duty vehicle classes and less than or equal to 0.03 g/test for medium-duty and heavy-duty vehicle classes (Table 4). Within this second option, manufacturers would be allowed to comply with a fleet average whole vehicle standard within each weight class. Manufacturers will be required to report the highest value of the 3-Day Diurnal and 2-Day Diurnal plus hot soak for a given certification test vehicle. The test procedures for the fuel system rig test and bleed emissions test will be described in Section 2.2. Evaporative emission system certification for hybrid electric vehicles will have specific test procedures as these vehicles can have low canister purge rates relative to non-hybrid vehicles.

Table IV: Option 2 of ARB's Proposed LEV III Evaporative Standards

Class of Vehicle	Highest* Diurnal + Hot Soak (grams per test)	Running Loss (grams per mile)	Bleed Emissions Test (grams per test)
PC, LDT1	0.300	0.05	.020
LDT2	0.400	0.05	.020
LDT3, LDT4	0.500	0.05	.020
MDV, HDV	0.600	0.05	.030

Europe and other countries around the world have implemented evaporative emission standards on automobiles and other gasoline powered vehicles since 1983. Most of these have followed the European standards for fuels and emission limits and will not be discussed here.

These EURO based regulations for evaporative emissions are generally less stringent than U.S. or California regulations. Evaporative limits have also been established for non-automotive applications including motorcycles, small and large off-road spark-ignited engines as well as marine engines. Although these will not be covered here, some information on evaporative emission standards and technologies for non-automotive applications can be found in MECA's small engine[2] and motorcycle[3] white papers.

2.2 Test Methods for Measuring Evaporative Emissions

The apparatus used to evaluate the diurnal and hot soak emissions from automobiles is known as a SHED or Sealed Housing for Evaporative Determination. To conduct the measurements, the vehicle is driven into the chamber and the doors are sealed. The SHED is equipped with analyzers to measure HC emissions inside the chamber at various intervals. A flame ionization detector (FID) measures the total hydrocarbons at the beginning and end of each test to determine emissions from the hot soak and each diurnal day. An infrared detector is used to distinguish between fuel based HC's and non-fuel based HCs such as those from polymers, rubber and plastics. The two-day plus hot soak test consists of running the vehicle on a Federal Test Procedure (FTP) drive cycle with a loaded carbon canister followed by a one-hour hot soak at elevated temperature and monitoring over two-diurnal days. The result that is reported is the total of the hot soak and the highest value from one of the diurnal days. The canister is pre-loaded with a mixture of butane and nitrogen to simulate the state of the canister if the vehicle is not driven for several days or recently refueled. The hot soak simulates parking the vehicle at 72 ^{o}F after driving. The temperature range for the diurnal day to represent a California ambient environment consists of a soak at 65 ^{o}F followed by a 12 hour ramp up to 105 ^{o}F and a subsequent 12 hour cool down to 65 ^{o}F. The U.S. EPA diurnal cycle consists of a temperature cycle from 72 ^{o}F to 95 ^{o}F.

The three-day diurnal test for CARB includes an additional running loss test which involves an FTP drive cycle performed at an ambient temperature of 105 ^{o}F. Additional emissions measurements are taken at the filler cap and canister to make sure that the purge system is functioning properly and emissions are contained during operation. Following the running loss test, the vehicle emissions are measured after a one-hour hot soak at 105 ^{o}F followed by three days of diurnal cycles as in the two-day test. The results that are reported for the three-day diurnal test combine the emissions measured during the hot soak and the highest of the three diurnal days.

In order to meet the PZEV emission requirements, manufacturers must demonstrate elimination of fuel system related evaporative emissions. The zero-evaporative standard has two components that must be tested separately. First, the whole vehicle must be tested in a SHED for the two and three-day diurnal to show that emissions from all HC sources do not exceed 0.35 g/test for passenger cars under LEV II and Tier 2. Larger vehicles are allowed higher whole vehicle limits as shown in Figure 1. Second, to test only the emissions from the fuel system components, a rig test is used. For this test, the fuel system of the vehicle is reassembled inside the SHED and subjected to diurnal testing. The emissions from this test must not exceed 0.054 g/test.

The rig test requires that a support frame and the entire fuel system be assembled inside a SHED apparatus. The assembly includes the fuel tank, fuel metering system, including injectors and fuel vapor control system such as the canister. The testing takes over 160 days to complete including time to age the components and a 140 day stabilization period. The actual SHED diurnal testing takes about 1-2 weeks. The bleed emissions test or mini-rig test that ARB has included under compliance option 2 of the LEV III proposal was suggested by MECA as a way to insure against backsliding by de-contenting advanced canister technologies from PZEV vehicles that might occur if only a whole vehicle test was required. Because a whole vehicle test combines evaporative emissions from the fuel system with non-fuel related VOCs, without a separate fuel system test, manufacturers could trade-off higher fuel related emissions for lower non-fuel emissions to pass a higher vehicle limit. This may result in the removal of the best available canister technologies and lead to higher overall evaporative emissions during real world operation.

The bleed emissions test is much simpler because it only tests the critical fuel vapor control components in a SHED apparatus.[5] The components involved in the test include the fuel tank, tank vent lines and carbon canister (Figure 3). Under this test, the canister can be aged and prepared in under 2 weeks resulting in a total test time of only two and a half weeks. Only the canister venting emissions are measured and included to meet the 0.02 g/test limit as proposed for LEV III.

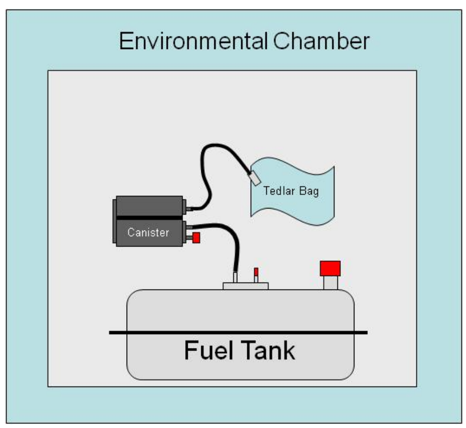

Figure 3: Test set-up for a bleed emissions or mini-rig test

3.0 Technologies to Control Evaporative Emissions

Evaporative emissions from vehicles can be significantly reduced by addressing the primary sources of HC leakage from the fuel system such as permeation, diurnal, and refueling. The technologies employed in modern fuel systems to address these mechanisms will be the topic of this section. The sources of these emissions are better illustrated in Figure 4 which depicts a typical fuel system.

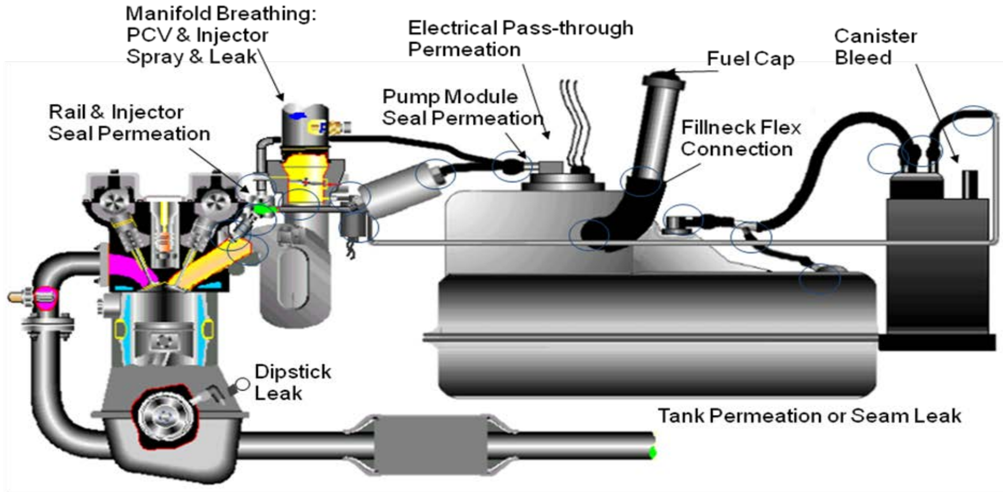

Figure 4: Fuel system with emission control technology. Circles identify common joints and connectors as sources of liquid and vapor leakage.

3.1 Permeation Controls

Permeation emissions can be addressed by reducing the permeability of plastics and polymers to gasoline in either the liquid or vapor phase. This can be accomplished through both design and selection of materials. Reducing the number of joints and connectors in a fuel system and the design of the fuel tank are some of the ways to reduce fuel leakage and permeation. Fuel system design is not within the scope of this paper but we will touch briefly on materials of construction as a way to control permeation. This is important in tanks, hoses, seals and connectors. Although metal tanks offer the highest barrier to permeation, they add weight and limit the shape necessary to meet stringent packaging requirements. Advanced tanks consist of coextruded, multilayer construction with a barrier layer of ethylene vinyl alcohol and fluoropolymers to reduce permeation. Furthermore, polymers can be treated via sulfonation or fluorination to further reduce permeability.

Similar approaches of material selection can be applied to fuel hoses, seals, fuel caps and gaskets used within the fuel system. The use of coextruded, low permeation polymers such as nylon, fluoropolymers, and fluoroelastomers can be employed in fuel lines to significantly reduce permeation emissions. Special challenges in permeation emissions and materials compatibility have resulted since the introduction of ethanol blends in gasoline. The newest vehicles and, in particular, Flexible Fuel Vehicles (FFV) are equipped with the lowest permeation materials in the fuel tanks, hoses, seals and gaskets. Older vehicles and, in particular, spark-ignited off road engines like those used in lawn equipment, marine engines, recreational motorcycles and ATVs still use conventional fuel system materials which are not compatible with ethanol levels above 10%. There is a concern that if this equipment and vehicles are fueled with ethanol-gasoline blends greater than E10 they will result in significant emissions of hydrocarbons into the atmosphere contributing to ozone formation. Furthermore these engines are not calibrated to operate on higher ethanol blends. The low permeation technology discussed here is equally effective in reducing evaporative emissions from all types of gasoline powered vehicles and equipment but require technology forcing regulations for implementation.

3.2 Carbon Canisters

One of the essential components of the evaporative emission control system is the carbon canister. The canisters employed on automobiles, and other gasoline powered vehicles and equipment, are similar and consist of a plastic housing containing high surface area carbon adsorbent material. Hydrocarbon molecules are attracted to the non-polar surface of the activated carbon and stored within the pores by physical adsorption or physisorption. Canister filling occurs during diurnal events and refueling. Canisters come in many shapes and sizes and are proportional to the volume of vapor generated in the fuel tank (Figure 5).

Figure 5: Examples of the shapes and sizes of EVAP canisters for on-road and off-road applications.

Advanced canisters employ multiple chambers and specially designed carbon adsorbents to achieve very low or zero evaporative emissions depending on the level of evaporative emission that must be achieved. The carbon technology will be discussed in Section 3.2.1. As HC vapors are forced out of the tank during heating or refueling, they enter the first chamber of the canister and pass through to the second chamber (see Figure 6).

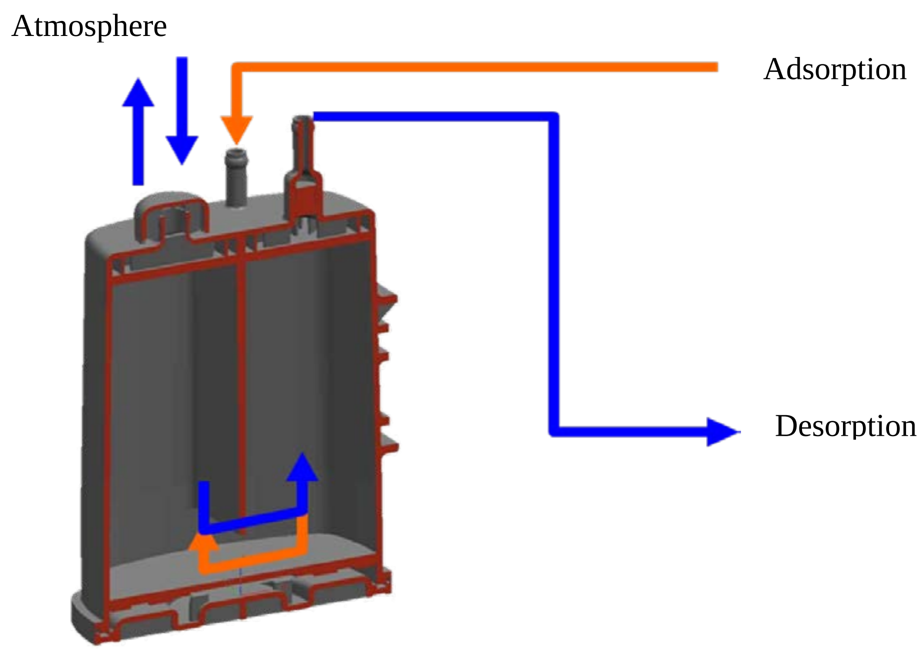

Figure 6: Inside of EVAP canister without carbon adsorbent to show chambers and adsorption/desorption process.

Canister purging occurs during engine operation. In early automotive canister designs and more recent off-road applications such as spark-ignited marine engines which employ carbon canisters, the purging occurs passively by the vacuum created during cooling of the tank and fuel. The tank vacuum will pull clean ambient air through the canister causing desorption of the hydrocarbon molecules from the carbon surfaces. The vacuum created during engine operation pulls air through the carbon bed resulting in desorption of HCs and drawing them into the intake of the engine. A sudden surge in HCs into the combustion chamber can result in excessive hydrocarbons in the tailpipe. Control of the vapor concentration of the purge air stream by the engine control system is necessary to meet both exhaust and evaporative emission standards. Proper metering of purge flow using the purge valve and restricting vapor flow from the fuel tank with a flow management orifice are methods that are used to prevent large HC vapor transients from entering the intake of the engine but yet allow high gas flow during refueling events.

Important elements of canister design used to control bleed emissions include cross-sectional area and pressure drop. The length-to-diameter (L/D) ratio of the canister can be optimized to increase diffusion path length while minimizing pressure drop.[5] The working capacity is another important design parameter for carbon canisters that is also affected by the L/D ratio. Working capacity represents the amount of hydrocarbons by weight that can be maintained within the activated carbon charge of the canister under a well defined test procedure. In general the L/D ratio is optimized for working capacity without compromising backpressure within the constraints of packaging. Increasing the L/D ratio of the canister increases the localized airflow over the carbon bed during purging resulting in more effective removal of the adsorbed HCs.[5] Carbon canisters are very effective and extremely durable control technologies with little or no deterioration of performance over the full useful life of the vehicle.

The zero evaporative emissions required of PZEV vehicles has put engineering focus on the small levels of bleed emissions from the canister which occur during diurnal loading. Bleed emissions are those that that pass through the canister prior to breakthrough. Breakthrough represents the first appearance of HCs in the air from a canister. In automotive applications, this is the point when the total concentration of HC emitted from the canister reaches 5000 ppm. Bleed emissions represent adsorbed hydrocarbons that desorb and diffuse from the canister. Bleed emissions are a function of soak time, concentration gradient, temperature and hydrocarbon species.

Additionally, smaller displacement engines, or partial electric operation like that of gasoline-electric hybrids will result in less available purge air to clean the carbon canister. The canister designs for these applications use a third, smaller chamber filled with specially designed, easy to purge carbons, known as a scrubber, to effectively capture these canister bleed emissions. This chamber is referred to as the auxiliary chamber and is filled with a high capacity carbon that is often extruded into a honeycomb shape to maximize geometric surface area while minimizing flow restriction. The emission reduction benefits of incorporating a scrubber or auxiliary chamber on a carbon canister are shown in Figure 7. Bleed emissions are reduced by 95 to 295 mg/test depending on the level of purge. A low purge design would represent a hybrid vehicle whereas a normal purge would be a conventional PZEV design. The most advanced canisters being developed for the lowest purge vehicles such as plug-in hybrids may incorporate a heat transfer medium to warm the carbon and improve the purge efficiency.

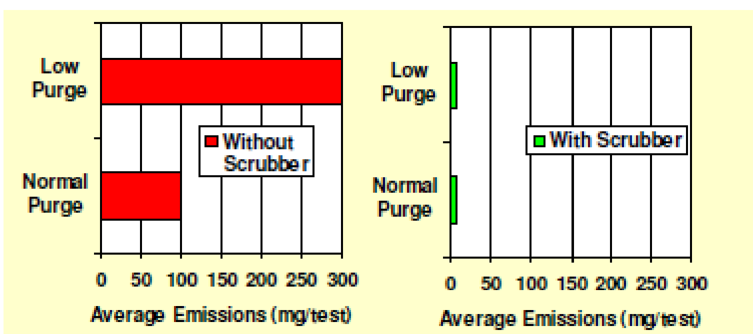

Figure 7: Canister bleed emissions with and without a scrubber

3.3 Activated Carbon

At the core of the canister function is the activated carbon that is charged inside the chambers. Carbon is available in different particle sizes and working capacities. The particle size or granule size controls the back pressure whereas the working capacity is a function of surface area and porosity. The working capacity describes the activation level of the carbon and is expressed as Butane Working Capacity in units of grams of butane adsorbed per 100 cc of carbon. Marine applications require a special water proof pelletized carbon. The porosity of carbon is described as a function of pore sizes including micropores (< 20 angstroms), mesopores (20-50 angstroms) and macropores (>500 angstroms). Vapor migration into the carbon particle occurs via gas phase and surface diffusion of the hydrocarbon molecules (Figure 8). Hydrocarbon molecules are driven to migrate and redistribute within the pores of the carbon by a combination of concentration gradient and surface energy.

Another important property of the activated carbon is the heel or the residual hydrocarbons remaining on the carbon after purging. The pore size distribution of the carbon directly affects both the working capacity and heel of the carbon. High working capacity is achieved by increasing the pore volume within a critical size range depending on the size of the hydrocarbon molecules being adsorbed. A smaller pore size range is associated with the heel as pores of this size range trap the hydrocarbons and prevent them from being purged. High activity carbons that have a high working capacity also have a tendency for stronger adsorption or heel during purging. This can lead to higher diurnal emissions. Advanced carbon designs that release HCs easily with a small volume of purge air are best suited for smaller engines and hybrid powertrains. These carbons tend to have a lower working capacity and are not ideal for use in the entire canister. Bleed emissions are best reduced by using an activated carbon where the working capacity and low heel are optimized. The shape must be controlled to minimize back pressure or flow restriction. The carbon used in the auxiliary chamber of PZEV canisters is typically extruded into small honeycomb monoliths as shown in Figure 9.

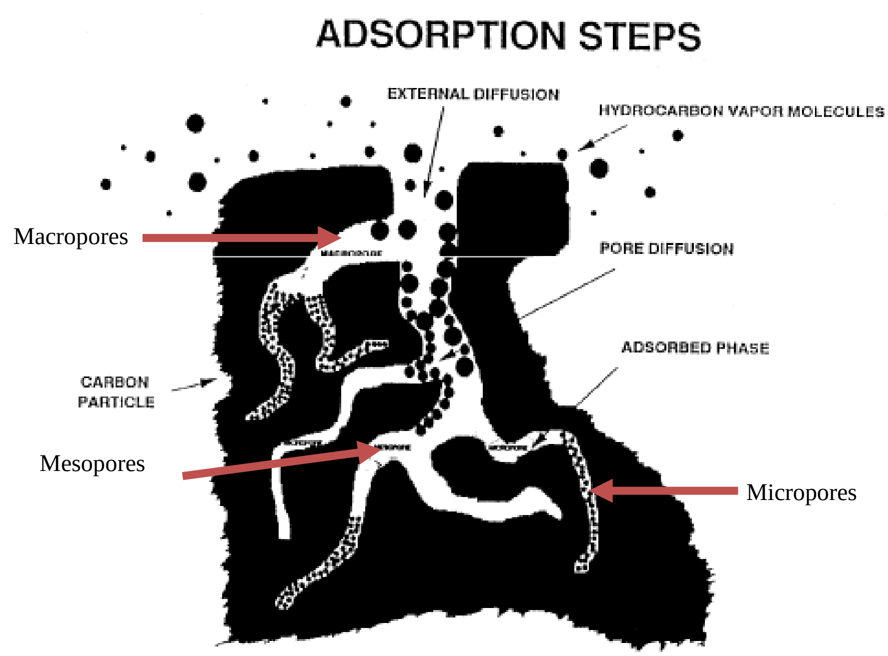

Figure 8: Pore types and diffusion mechanisms within an activated carbon particle.

Figure 9: Examples of extruded activated carbon honeycombs like those used in auxiliary chambers of PZEV canisters.

3.4 Air Intake Systems (AIS)

When the engine is shut off, the concentration of hydrocarbons in the cylinders and intake manifold is higher than the concentration upstream of the throttle body and air intake. In the absence of intake airflow, fuel vapors will migrate past the air induction system and into the atmosphere. These emissions are on the order of 0.1 g per diurnal with some additional losses during hot-soak cycles. Because of the zero evaporative requirement on PZEV vehicles, these emissions will be detected in the SHED test and must be controlled. These slow moving bleed emissions can be captured by incorporating a small hydrocarbon trap into the air induction system of the vehicle. The earliest designs utilized activated carbon within the air cleaner element. The size and shape of engine air induction traps can vary from honey combs to carbon coated paper or thin panels of activated carbon (Figure 10). In some applications, zeolite based coatings have been applied to metal honeycomb substrates to control air intake evaporative emissions. This design offers low pressure drop, high HC capture efficiency and clean desorption. An example of this technology is shown in Figure 11.

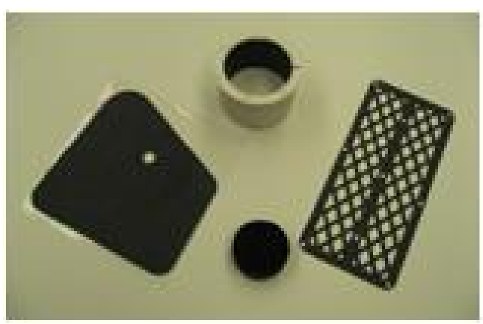

Figure 10: Example of carbon shapes used in vehicle air intake systems

Figure 11: Zeolite based AIS hydrocarbon trap

Because these traps are not intended to capture a large amount of hydrocarbons, their working capacity is extremely low and they have a very low pressure drop. They are extremely effective in reducing the HC emissions by 100-200 mg/test which is significant when trying to meet near zero PZEV limits. Figure 12 compares the AIS emissions from a small four cylinder as well as a large eight cylinder vehicle both with and without air induction traps. This test isolated the air induction emissions from the other types of emissions in a SHED test to show that these traps can be up to 90% efficient in capturing emissions from the air intake system.

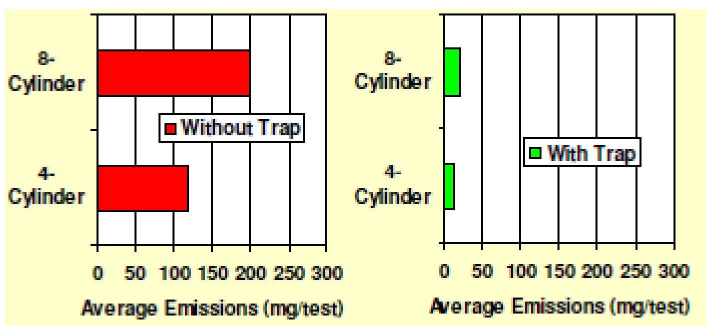

Figure 12: Air induction system emissions with and without an AIS carbon trap

3.5 On-Board Refueling Vapor Recovery

On-board refueling vapor recovery (ORVR) systems are designed to capture hydrocarbons dispersed in the vapor of the fuel tank that are displaced during refueling. Although the heart of the system is the carbon canister, there are a number of other valves and seals to prevent escape of vapor through the fuel filler pipe and preventing liquid gasoline from exiting the fuel tank when tipped beyond horizontal. The displaced vapor is directed into the carbon EVAP canister and trapped. During engine operation, fresh air is purged through the canister to regenerate the carbon so that it is ready for subsequent fueling or diurnal events. The purged vapors are consumed in the combustion process. Today, all new passenger vehicles manufactured in North America are equipped with ORVR systems.

4.0 On-Board Diagnostic Requirements

Modern EVAP control systems incorporate on-board diagnostic controls that test the fuel system integrity and insure that they are functioning properly. Fuel tank pressure sensors are being used to alert the driver when a fuel cap is missing or not sealed properly. This functions by applying a slight vacuum to the fuel tank and monitors if it is maintained. On OBDII equipped vehicles, the system will perform an integrity check during normal operation. If the leak rate exceeds a limit value, the Malfunction Indicator Lamp (MIL) will be illuminated.

During canister purge, the Powertrain Control Module (PCM) monitors the HC air mixture going into the combustion chamber so that the overall air/fuel ratio does not impact the vehicle tailpipe emissions. The PCM must control the fuel delivery to each individual cylinder. The exact control of purge emissions in Flex Fuel Vehicles (FFV) poses challenges as they are able to use multiple fuels with various vapor pressures.

5.0 Conclusion

- Evaporative emissions from mobile sources have raised health and environmental concerns, but a number of technologies exist that can greatly reduce VOC emissions from gasoline-powered vehicles and equipment.
- Regulations are necessary to prevent back-sliding and decontenting of technology from vehicles and insure that the best available evaporative controls continue to be installed on vehicles.
- Low permeability rubber and polymers are being deployed in fuel tanks, hoses, seals and gaskets of modern fuel systems to minimize permeation losses.
- Carbon canisters remain at the heart of vehicle EVAP controls to capture fueling, diurnal and hot soak emissions of hydrocarbons.
- EVAP controls offer an extremely effective and durable means to control ozone forming HC emissions over the life of the vehicle.
- PZEV and hybrid vehicles use the most advanced carbon technology as part of the auxiliary chamber in PZEV canisters and air induction systems to achieve near-zero evaporative emissions despite low purge volumes.
- The types of technologies deployed on PZEV vehicles can be implemented within the entire gasoline vehicle fleet and beyond to off-road spark-ignited vehicles and engines that have yet to benefit from EVAP emission controls.

6.0 References

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