Control of Emissions from Marine SI and Small SI Engines, Vessels, and Equipment

Draft Regulatory Impact Analysis

Chapter 5

Feasibility of Evaporative Emission Control

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Section 213(a)(3) of the Clean Air Act presents statutory criteria that EPA must evaluate in determining standards for nonroad engines and vehicles including marine vessels. The standards must "achieve the greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the engines or vehicles to which such standards apply, giving appropriate consideration to the cost of applying such technology within the period of time available to manufacturers and to noise, energy, and safety factors associated with the application of such technology." This chapter presents the technical analyses and information that form the basis of EPA's belief that the proposed evaporative emission standards are technically achievable accounting for all the above factors.

The proposed evaporative emission standards for Small SI equipment and Marine SI vessels are summarized in the Executive Summary. This chapter presents available emissions data on baseline emissions and on emission reductions achieved through the application of emission control technology. In addition, this chapter provides a description of the proposed test procedures for evaporative emission determination.

Evaporative emissions from equipment and vessels using spark-ignition (SI) engines can be very high. This is largely because Small SI and Marine SI applications generally have fuel tanks that are vented to the atmosphere and because materials used in the construction of the plastic fuel tanks and hoses generally have high permeation rates. Evaporative emissions can be grouped into five categories:

DIURNAL: Gasoline evaporation increases as the temperature rises during the day, heating the fuel tank and venting gasoline vapors. We also include, under this heading, diffusion losses which are vapors that will escape from an open vent even without a change in temperature.

PERMEATION: Gasoline molecules can saturate plastic fuel tanks and rubber hoses, resulting in a relatively constant rate of emissions as the fuel continues to permeate through these components.

RUNNING LOSSES: The hot engine and exhaust system can vaporize gasoline when the engine is running.

HOT SOAK: The engine remains hot for a period of time after the engine is turned off and gasoline evaporation continues.

REFUELING: Gasoline vapors are always present in typical fuel tanks. These vapors are forced out when the tank is filled with liquid fuel.

5.1 Diurnal Breathing Loss Evaporative Emissions

In an open fuel tank, the vapor space is at atmospheric pressure (typically about 14.7 psi), and contains a mixture of fuel vapor and air. At all temperatures below the fuel's boiling point, the vapor pressure of the fuel is less than atmospheric pressure. This is also called the partial pressure of the fuel vapor. The partial pressure of the air is equal to the difference between atmospheric pressure and the fuel vapor pressure. For example, in an open-vented fuel tank at 60˚F, the vapor pressure of typical gasoline would be about 4.5 psi. In this example, the partial pressure of the air would be about 10.2 psi. Assuming that the vapor mixture behaves as an ideal gas, then the mole fractions (or volumetric fractions) of fuel vapor and air would be equal to their respective partial pressures divided by the total pressure; thus, the fuel would be 31 percent of the mixture (4.5/14.7) and the air would be 69 percent of the mixture (10.2/14.7).

Diurnal emissions occur when the fuel temperature increases, which increases the equilibrium vapor pressure of the fuel. For example, assume that the fuel in the previous example was heated to 90˚F, where the vapor pressure that same typical fuel would be about 8.0 psi. To maintain the vapor space at atmospheric pressure, the partial pressure of the air would need to decrease to 6.7 psi, which means that the vapor mixture must expand in volume. This forces some of the fuel-air mixture to be vented out of the tank. When the fuel later cools, the vapor pressure of the fuel decreases, contracting the mixture, and drawing fresh air in through the vent. When the fuel is heated again, another cycle of diurnal emissions occurs. It is important to note that this is generally not a rate-limited process. Although the evaporation of the fuel can be slow, it is generally fast enough to maintain the fuel tank in an essentially equilibrium state.

As fuel is used by the engine, and the liquid fuel volume decreases, air is drawn into the tank to replace the volume of the fuel. (Note: the decrease in liquid fuel could be offset to some degree by increasing fuel vapor pressure caused by increasing fuel temperature.) This would continue while the engine was running. If the engine was shut off and the tank was left overnight, the vapor pressure of the fuel would drop as the temperature of the fuel dropped. This would cause a small negative pressure within the tank that would cause it to fill with more air until the pressure equilibrated. The next day, the vapor pressure of the fuel would increase as the temperature of the fuel increased. This would cause a small positive pressure within the tank that would force a mixture of fuel vapor and air out. In poorly designed gasoline systems, where the engine or exhaust is very close to the fuel tank the engine/exhaust heating may cause large amounts of gasoline vapor to be vented directly to the atmosphere.

Several emission-control technologies can be used to reduce diurnal evaporative emissions. Many of these technologies would also control running loss and hot soak emissions and some could be used to control refueling emissions. We believe manufacturers will have the opportunity use a wide variety of technology approaches to meet the proposed evaporative emission standards. The advantages and disadvantages of the various possible emission-control strategies are discussed below. This section summarizes the data and rationale supporting the diurnal emission standard for Marine SI vessels and Small SI equipment presented in the Executive Summary.

5.1.1 Baseline Emissions

5.1.1.1 Marine Vessels

We tested two aluminum marine fuel tanks in their baseline configurations for diurnal emissions. Aluminum fuel tanks were used so that permeation emissions would not occur during the testing. The 17 gallon aluminum tank was constructed for this testing, but is representative of a typical marine fuel tank; the 30 gallon aluminum tank was removed from an 18 foot runabout. The fuel tanks were tested with the venting through a length of $^5/_8$ inch hose to ensure that the emissions measured were a direct result of the fuel temperature heating and not diffusion through the vent (see Section 5.1.3). The advantage of using the aluminum fuel tanks for this testing was to exclude permeation emissions from the measured results. All of the testing was performed with fuel tanks filled to 40 percent of capacity with 9RVP[1] test fuel.

The diurnal test results are presented in units of grams per gallon capacity of the fuel tank per day. These units are used because gallons capacity is a defining characteristic of the fuel tank. Diurnal vapor formation itself is actually a function of the vapor space above the fuel in the fuel tank rather than the total capacity.

Table 5.1-1 presents the test results compared to anticipated results. The anticipated results are based on the Wade model which is a set of theoretical calculations for determining diurnal emissions based of fill level, fuel RVP, and temperature profile. These calculations are presented in Chapter 3. Although the Wade model over-predicts the vapor generation, it does show a similar trend with respect to temperature. To account for this over prediction, we use a correction factor of 0.78. This correction factor is based on empirical data[1], has historically been used in our automotive emission models, and appears to be consistent with the data presented below.

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[1] Reid Vapor Pressure (psi). This is a measure of the volatility of the fuel. 9 RVP represents a typical summertime fuel in northern states.

Table 5.1-1: Baseline Diurnal Evaporative Emission Results (varied temperature)

Temperatures	*Capacity [gallons]*	*Measured [g/gallon/day]*	*Wade Model [g/gallon/day]*	*Corrected Wade [g/gallon/day]*
22 - 36°C (72 - 96°F)	17	1.40	2.30	1.79
22 - 36°C (72 - 96°F)	30	1.50	2.30	1.79
24 - 33°C (74 - 91°F)	30	1.13	1.33	1.04
22 - 30°C (71 - 86°F)	30	0.88	1.02	0.80
25 - 31°C (77 - 88°F)	30	0.66	0.88	0.69
26 - 32°C (78 - 90°F)	30	0.85	1.04	0.81
28 - 31°C (82 - 87°F)	30	0.47	0.43	0.34

5.1.1.2 Small SI Equipment

We contracted with an outside lab for the testing of thirteen Small SI fuel tanks over various test temperature profiles.[2,3] This testing was performed with the tanks filled to 50 percent capacity with certification gasoline and is discussed in more detail below in the Section 5.2.1. This data is presented in Table 5.1-2. In addition, in cases where the fuel temperature profiles were within the input range of the Wade model for diurnal emissions, theoretical emissions were also calculated using the same correction factor discussed above for marine fuel tanks. As shown below, the measured values are fairly consistent with the theoretical values.

Table 5.1-2: Fuel Temperature Measurements During Operation of Small SI Equipment

Equipment Type	Fuel Capacity [gallons]	Temperature Profile °C	Measured HC grams/gallon	Theoretical HC grams/gallon
Riding mower	1.1	15.7 - 28.4	0.92	0.91
	1.4 x 2	21.9 - 29.7	0.88	0.71
	1.7	19.5 - 30.3	0.82	0.94
	2.5	27.0 - 35.0	1.29	1.16
	3.0	26.6 - 28.4	0.25	0.17
	6.5	24.3 - 33.2	1.20	1.08
	6.5 x 2	20.5 - 23.9	0.26	0.23
Walk-behind mower	0.34	23.3 - 33.0	0.76	1.18
	0.25	28.7 - 46.7	4.92	NA*
	0.22	28.7 - 59.7	36.9	NA*
Generator set	8.5	20.6 - 25.8	0.45	0.38
	7.0	25.8 - 50.0	9.90	NA*
Pressure washer	1.8	19.0 - 50.6	11.6	NA*

* outside the temperature range of the model

The California Air Resources Board performed diurnal testing on seven pieces of handheld equipment and 20 pieces of non-handheld equipment by placing the whole equipment in a SHED.[4] They filled the fuel tanks to 50 percent with 7 RVP fuel and tested over their 65-105° F summer day test cycle. Because the entire piece of equipment was included in these tests, not only were diurnal venting emissions measured, but tank and hose permeation as well (plus any potential leaks). Average test results by equipment type are presented in Table 5.1-3.

Table 5.1-3: ARB Measurement of Evaporative Emissions from Small SI Equipment (7 RVP California Certification Fuel, 50% Fill, 65-105°F)

Equipment Type	Number of Data Points	Average Measured HC [grams/day]
Handheld equipment	7	1.04
Walk-behind lawnmowers	12	3.51
Generators	2	11.2
Riding Mowers	3	8.70
Edgers	2	1.53
Tiller	1	4.12

ARB also performed tests on a subset of the equipment using fuel containing MTBE and fuel containing ethanol to investigate fuel effects. They observed nearly a 50 percent increase in emissions when an ethanol blend was used compared to an MTBE blend. The reason for this increase was not discussed, but may have largely been a permeation effect. On five pieces of equipment, a California wintertime cycle (51.6-69.5° F) was used as well. As would be expected, the emissions were reduced significantly. The theoretical models predict about an 85 percent reduction in diurnal venting emissions and about a 60 percent reduction in permeation. The observed results were about a 70 percent reduction which is in this range.

5.1.2 Insulation of the Fuel Tank

The diurnal vapor generated in a fuel tank is directly related to the diurnal temperature trace of the fuel. A reduction in temperature variation causes less vapor to be formed. To investigate this effect we used insulation around the fuel tank to reduce the effect of the ambient air temperature variation on the fuel temperature variation. In our preliminary testing, we insulated a 23 gallon rotationally molded marine fuel tank using 3 inch thick construction foam with an R-value of 15 as defined by 16 CFR 460.5. This testing was performed with the fuel tank vent open to atmosphere. Table 5.1-4 presents the fuel temperatures and evaporative emissions over the three day test.

We tested this fuel tank over a three day diurnal test with an ambient temperature of 72-96°F. This experiment resulted in a 50 percent reduction in emissions from baseline on the highest of these three test days. The baseline emissions were measured to be 2.5 g/gallon/day; however it should be noted that for both the baseline test and the insulated tank tests we did not control for permeation or diffusion. Over this test, the emissions decreased for subsequent days. We believe this was due to the fuel temperature cycle stabilizing. Although we did not control for permeation or diffusion, the results from this preliminary experiment directionally show the effect of insulation on diurnal emissions.

Table 5.1-4: Evaporative Emission Results for Insulated Flat, Plastic Tank

Test Day	*SHED Temperature*	*Fuel Temperature*	*Evaporative HC*
Day #1	22-36°C (72-96°F)	22-28°C (72-82°F)	1.2 g/gal/day
Day #2	22-36°C (72-96°F)	26-30°C (78-86°F)	1.0 g/gal/day
Day #3	22-36°C (72-96°F)	26-30°C (80-86°F)	0.8 g/gal/day

In boats with installed fuel tanks, the fuel tank is generally hidden beneath the deck. As a result, there is a certain amount of "inherent" insulation caused by the boat itself. This effect is increased for a boat that is stored in the water. The water acts as a cooling medium for the fuel tank, especially if it is installed in the bottom of the boat. In addition, the thermal inertia of the fuel in the tank can act to dampen temperature variation imposed from the diurnal heating of the ambient air. To investigate this effect, we tested several boats by recording the ambient air temperature and fuel temperatures over a series of days. Two boats were tested on trailers outside in the summer, two boats were tested on trailers in a SHED, and two boats were tested in the water on summer days. Table 5.1-5 presents the average results of this testing. The temperature traces are presented in Appendix 5A.

Table 5.1-5: Ratio of Fuel to Ambient Temperature Swing for Boats

Boat Type	*Test Conditions*	*Capacity [gallons]*	*Fuel Tank Fill Level*	*Temperature Ratio**
9 ft. personal watercraft	outside, on trailer	13	50%	66%
16 ft. jet boat	outside, on trailer	40	50%	52%
18 ft. runabout	in SHED, on trailer	30	40%	68%
16 ft. jet boat	in SHED, on trailer	40	90%	33%
18 ft. runabout	outside, in water	30	100%	19%
21 ft. deck boat	outside, in water	20	90%	27%

* Average ratio of change in fuel temperature to change in ambient air temperature over test days.

In their comments on the proposed rule, the National Marine Manufacturers Association presented temperature data on 18 foot runabout, with a 32 gallon tank, tested in a SHED with an ambient temperature of 72-96°F.[5] The average fuel to ambient temperature ratio was 54 percent for this testing. This ratio is in the range of EPA test results for boats tested on a trailer. Brunswick also included temperature data in their comments.[6] The average days test on a boat on the water was 19 percent, which is consistent with our water tests. Brunswick's average for boats tested while stored out of the water was 27 percent which is considerably lower than the EPA and NMMA testing. Combining all of the EPA and industry data, the average fuel to ambient temperature ratio (based on test days) is about 20 percent for boats in the water and 50 percent for boats stored out of the water.

During diurnal testing of lawnmowers, ARB found that the fuel and tank skin temperature follow the ambient temperature closely.[7] This same phenomenon would be expected for other Small SI equipment as well (and portable fuel tanks) because of the small fuel volumes and because these tanks are generally exposed to ambient air. One issue that we considered was that Small SI equipment is often stored in garages or sheds. In that case, we were interested in if the garage or shed acts to insulate the fuel tanks from ambient temperature swings. ARB collected data on four garages and one shed. This data included summer and winter California temperature measurements. For each test, the inside and outside temperature were measured for five days. This data is presented in Table 5.1-7. For the garages, the inside temperature was generally warmer than outside, but the variable temperature swings were smaller. For the shed, the inside temperature was warmer and showed higher heat builds than the outside temperature. Table 5.1-6 also presents an estimate of the effect on diurnal emissions using the theoretical equations presented in Chapter 3. No conclusive evidence of was observed to suggest that these fuel tanks are generally subject to inherent insulation.

Table 5.1-6: Comparison of Ambient to Inside Diurnal Temperature Swings

Season	*Enclosure*	*Inside Temperature °C*		*Outside Temperature °C*		*Emission*
		Avg T	*Avg Delta T*	*Avg T*	*Avg Delta T*	*Effect*
Winter	garage D	13.8	6.4	10.1	9.3	-8%
	garage G	12.1	9.2	5.8	14.3	-9%
	garage J	13.5	2.4	8.0	7.3	-55%
Summer	garage A	27.4	3.6	22.4	12.2	-63%
	garage D	35.9	11.7	30.3	15.6	20%
	garage G	27.4	15.7	21.3	19.5	23%
	garage J	27.6	8.9	23.7	20.3	-61%
	shed	27.1	20.1	23.6	14.1	119%

Some of the variance between the fuel temperature and ambient temperature, especially for larger fuel tanks, is likely due to the thermal inertia of the fuel in the tank. The fuel has mass and therefore takes time to heat up. ARB performed a study in which the fuel temperature and ambient temperature were recorded for aboveground storage fuel tanks.[8,9] Three fuel tanks sizes were included in the study: 350, 550, and 1000 gallons. Because of the large size of these tanks, the thermal inertia effects would be expected to be larger than for typical fuel tanks used in Marine SI and Small SI applications. For the 350 gallon fuel tank, ARB also measured the effect of insulating the fuel tank on temperature. Table 5.1-7 presents the results of this testing. Note that the test results are the average of five days. Ambient temperature on these test days typically had a minimum in the 60-70˚F range and a maximum temperature in the 95-105˚F range.

EPA performed testing on 17 gallon marine fuel tank in a SHED over a single 72-96˚F diurnal test and measured both ambient and fuel temperature.[10] This data is also included in Table 5.1-7. Note that for the smaller tank, there is little difference between the ambient and fuel temperature profiles. However, for larger tanks, the fuel temperature has about a 25-30 percent smaller temperature swing than the ambient temperature. Note that the insulated fuel tank had a temperature ratio similar to the fuel tank stored in a boat in the water.

Table 5.1.7: Ratio of Fuel to Ambient Temperature for Uninsulated Fuel Tanks

Fuel Tank Type	*Tank Capacity [gallons]*	*Temperature Ratio**
marine fuel tank	17	95%
aboveground storage tank (with insulation)	350	75% (18%)
aboveground storage tank	550	70%
aboveground storage tank	1000	76%

* Average ratio of change in fuel temperature to change in ambient air temperature over test days.

5.1.3 Diffusion Effect

For the purposes of this discussion, diffusion refers to the process in which gasoline vapor penetrates air in an attempt to equalize the concentration throughout the gas mixture. This transport phenomenon is driven by the concentration gradient and by effective area. In the case of a mobile source fuel system that has a vent to atmosphere, the fuel vapor concentration is near saturation in the fuel tank and near zero outside of the fuel system. Therefore, the diffusion rate is primarily a function of the path between the fuel tank and atmosphere. The following equation describes the relationship between the flux of gasoline vapor out of the tank, the concentration gradient, and the vent path:

$$Flux = \frac{mass}{area \times time} = D \times \frac{\Delta C}{\Delta x}$$

where: D = diffusion coefficient (constant)
ΔC = concentration gradient
Δx = path length
area = cross sectional area of vent

Based on the above equation, diffusion from a tank through a vent hose would be a function of the cross-sectional area divided by the length of the hose. Therefore a longer hose would theoretically limit fuel vapor venting due to diffusion. Whenever a hydrocarbon (HC) molecule escapes from the fuel tank, a new molecule of air enters the fuel tank to replace the escaped HC. This brings the concentration of HC vapor in the fuel tank out of equilibrium. To balance the partial pressures in the fuel tank, more HC must evaporate as HC in the vapor space is depleted. In this way, the vapor concentration in the fuel tank remains saturated.

5.1.3.1 Marine Fuel Tank Data

In testing diurnal emissions from fuel tanks with open vents, the configuration of the vent can have a significant effect on the measured emissions due to the diffusion of vapor out of any opening in the fuel tank. Depending on the size and configuration of the vent, diffusion can actually occur when the fuel temperature is cooling. Most marine vessels with an installed fuel tank vent through a hose. As shown below this configuration can minimize diffusion.

To quantify the diffusion component for a typical fuel tank, we ran four 72-96°F diurnal tests on a 17 gallon aluminum marine fuel tank using various configurations for venting The first configuration was with the fuel cap cracked open and the vent sealed, the second configuration was with a 68 cm length of vent hose, and the third configuration was with a 1000 micron (1 mm) limiting flow orifice in the vent opening. This 1000 micron orifice was large enough to allow venting without any measurable pressure increase in the fuel tank during the diurnal test. The fourth configuration was a combination of the limited flow orifice and the vent hose. Table 5.1-8 presents the results of this testing.

Table 5.1-8: Diurnal Test Results with Varied Venting Configurations

Vent Configuration	*Evaporative HC [g/gallon/day]*
cracked fuel cap	2.05
68 cm of $^5/_8$" fuel hose	1.40
1000 micron orifice	1.47
1000 micron orifice + 68 cm of $^5/_8$" fuel hose	1.34

The above testing showed a 50 percent higher emission rate for the tank vented through a cracked fuel cap compared to one vented through a hose. In the test with the cracked fuel cap, an increase in HC concentration in the SHED was observed throughout the test, even when the fuel temperature was cooling. For the other three tests, the HC concentration leveled off when the temperature began to cool. This suggests that the difference in measured emissions of 0.6 - 0.7 g/gal/day was due to diffusion losses.

To further investigate this diffusion effect, we tested the 17 gallon aluminum tank with several venting configuration, at two constant temperature settings. Under these conditions, all of the measured evaporative emissions would be expected to be due to diffusion. As seen in Table 5.1-9, diffusion can be very high with too large of a vent opening unless a vent hose is used. The two lengths of vent hose tested did not show a significant difference in diffusion emissions. We believe that the vent hose limits diffusion by creating a gradual gradient in fuel vapor concentration.

Table 5.1-9: Constant Temperature Test Results with Varied Venting Configurations

Vent Configuration	*22°C (72°F)* *Evaporative HC [g/gal/day]*	*36°C (96°F)* *Evaporative HC [g/gal/day]*
½" I.D. fitting	5.65	10.0
68 cm of $^5/_8$" fuel hose	0.11	0.18
137 cm of $^5/_8$" fuel hose	0.07	0.24
1000 micron orifice	0.28	0.41

The above data suggest that, at least for open vent fuel systems, the size and configuration of the venting system can have a significant effect on evaporative emissions. In marine applications, there is typically a vent hose attached to the fuel tank. Diffusion emissions appear to be minimal if the fuel tank is vented through a length of hose. This is probably because the long residence times in the hose cause more opportunities for molecular collisions which direct the HC molecules back towards the fuel tank.

One study looked at the evaporation of liquids from a tube filled to various fill heights.[11] As the fill height decreased (effectively increasing the length of the tube above the liquid surface) the evaporation quickly decreased. These results are consistent with the observed effects of venting through a hose in our testing. Installed marine fuel tanks typically vent through a hose to the outside of the boat; therefore, diffusion losses are likely relatively small for these applications. Another study was performed on automotive fuel caps which suggests that a crack in the gasket on the fuel cap of 1 percent of the gasket area can result in more than 2 grams of HC emissions per day.[12]

5.1.3.2 Small SI Fuel Tank Data

For Small SI applications (and portable marine fuel tanks), the tanks are typically vented through an opening in the fuel cap. Therefore, unless the cap is sealed, we would expect diffusion emissions to occur. The above data suggest that diffusion can account for a significant portion of the evaporative HC emissions measured from a metal tank with a small vent in the cap over a 72-96°F diurnal test. Because diffusion would still occur at constant temperature, the contribution of diffusion to measured diurnal emissions would increase, on a percentage basis, as the diurnal temperature swing approached zero.

To investigate the effect of fuel cap design on diffusion for Small SI applications, we implemented a test program which included four fuel tank configurations (one metal and three plastic) and the corresponding fuel caps. These four fuel tanks were taken from lawnmowers using engines from the three lawnmower engine manufacturers with the highest U.S. sales and represent the majority of lawnmower fuel tanks on the market. Table 5.1-10 presents a description of these fuel tanks.

Table 5.1-10: Lawnmower Fuel Tanks Used in Diurnal/Diffusion Testing

Tank	Tank description	Fuel Cap Vent Description
BM	metal, 800 ml	Three 1/16" dia. holes drilled in top of cap. Four similar holes drilled in fibrous gasket
BP	plastic, 1175 ml	Three torturous pathways through plastic gasket, with venting between tank/cap threads. (Also performed test using a modified cap similar to the cap used on the metal tank.)
HP	plastic, 950 ml	Pinhole in gasket center leading to two indentations in rubber gasket at mating surface, with venting between tank/cap threads
TP	plastic, 920 ml	Four indentations in rubber gasket at mating surface, with venting between tank/cap threads

We contracted with two outside laboratories to perform the diurnal/diffusion tests for the Small SI equipment fuel tanks shown above.[13,14,15,16] In this effort, the fuel tanks were sealed, except for the vents in the fuel cap, and filled to 40 percent of capacity with 9 RVP fuel. These tanks were then tested in a mini-SHED over the EPA 72-96°F 24-hour diurnal test procedure. To minimize the effect of permeation on the test results, new fuel caps and plastic fuel tanks were used for each test that had not been exposed to fuel or fuel vapor prior to the test.

Under this testing, emissions continued to climb even when temperature was cooling back from 96˚F to 72˚F. These emissions were clearly not driven by temperature, so they were determined to represent diffusion emissions. Total diffusion for the test was determined by recording the HC emissions that occurred during the last 12 hours of the test (during the cooling event) and then multiplying these emissions by two to represent 24 hours. Although the peak temperature occurs after nine hours, only the last 12 hours were used to ensure that the fuel in the tank was not still heating due to a thermal time lag. Diffusion was then subtracted off the total HC measurement to determine non-diffusion diurnal emissions. For the fuel cap with the three holes drilled straight through it, the emissions were so high that it went out of measurement range near the end of the tests performed by one of the contractors. However, all of the observed diffusion rates were linear, making it simple to extrapolate the data where necessary. Table 5.1-11 presents the diurnal and diffusion data from these tests and compares it to the theoretical diurnal emissions using the Wade equations discussed above. Charts in Appendix 5B present the time series of the measured HC compared to the mini-SHED temperature.

Table 5.1-11: Diurnal and Diffusion Emissions from Lawnmower Fuel Tanks (g/gal/day) over a 72-96-72 °F (22.2-35.6-22.2 °C) Temperature Profile

Tank	Total HC	Diffusion	Diurnal	Wade Diurnal
BM	47.8	43.6	4.2	1.8
BP	2.1	0.1	2.0	1.8
BP cap 2*	24.1	19.3	4.8	1.8
HP	1.6	0.1	1.5	1.8
TP	2.1	0.2	2.0	1.8

* modified to be similar to cap on metal tank (BM)

The fuel caps in the above table for the lawnmower tanks labeled as BM and BP cap 2 resulted in very high diffusion emissions. Although this fuel cap type is a common design used in Small SI applications, it may represent one of the worst case configurations for diffusion. There are three small holes in the cap itself, and four small holes in the fibrous material imbedded in the inside of the cap. Presumably, this design was intended to minimize fuel from splashing out of the tank while still allowing the tank to breathe to prevent pressure or vacuum from occurring in the tank. Because the carburetor on this lawnmower is gravity fed, too much vacuum in the fuel tank could cause the engine to stall from lack of enough fuel. The reason that this may be a worst case configuration is that there is a direct (and relatively large) path for fuel vapor to escape from the fuel tank.

The other three fuel cap designs were also from stock lawnmower fuel systems. In all three of these designs, the venting occurred through small grooves in the gasket that seals the mating between the fuel cap and the fuel tank. The venting then occurs through the thread paths between the cap and tank. As a result, vapor and air must pass through a tortuous pathway to enter or leave the tank. This tortuous pathway appears to limit diffusion in much the same way as venting through a long hose does.

The above emission testing was repeated except that the vents in the fuel cap were sealed and the tank was vented through a 8 inch length of 1/4" I.D. hose. A lawnmower air intake filter was attached to the end of this hose in order to simulate the venting configuration on a lawnmower with running loss control. To minimize the effect of permeation, a low permeation barrier hose was used that had never before been exposed to fuel or fuel vapor. The test results in which the tanks were vented through hoses are presented in Table 5.1-12.

Table 5.1-12: Diurnal and Diffusion Emissions from Lawnmower Fuel Tanks (g/gal/day) with Modified Venting Through Hose/Air Filter to Simulate Running Loss Control over a 72-96-72 °F (22.2-35.6-22.2 °C) Temperature Profile

Tank	Total HC vent through stock cap	Total HC vent through hose/filter	Reduction in Total HC
BM	47.8	12.9	34.8
BP BP cap 2*	2.1 24.1	1.9 1.9	0.2 22.2
HP	1.6	2.0	(0.4)
TP	2.1	2.9	(0.7)

* modified to be similar to cap on metal tank (BM)

As shown in the table above, venting through the hose greatly reduced the measured emissions compared to the BM cap vent. When vented through the hose configuration, diffusion emissions were on roughly the same order as when the tortuous cap vents were used. This is consistent with the data presented earlier on marine fuel tanks vented through a hose. In an in-use running loss system, a valve or limited flow orifice would likely also be in the vent line. These components would likely further reduce, or even eliminate, diffusion emissions.

There was some concern that diffusion may have been underestimated in the above tests because air flowing back into the fuel tank during the cooling period may have limited diffusion by pulling HC molecules back into the fuel tank. In addition, we believed that testing at constant temperature would allow us to more directly measure diffusion. Therefore, the above testing was repeated at a constant temperature of 29°C.[17,18,19] However, it should be noted that this testing may have overestimated diffusion somewhat because of small temperature fluctuations (less than 0.5 °C) around the average during the test. Therefore, any HC measurements from the "constant" temperature testing may have overstated diffusion due to vapor generated by the repeated mini-diurnal cycles during in the test. These test results are presented in Table 5.1-13.

Table 5.1-13: Isothermal [29 °C] Diurnal and Diffusion Emissions from Lawnmower Fuel Tanks (g/gal/day) with Modified Venting Through Hose/Air Filter to Simulate Running Loss Control

Tank	Total HC vent through stock cap	Total HC vent through hose/filter	Reduction in Total HC
BM	43.2	8.9	34.3
BP	1.3	1.0	0.3
BP cap 2*	29.3	1.0	28.3
HP	1.0	0.8	0.2
TP	0.9	0.9	0.0

* modified to be similar to cap on metal tank (BM)

At constant temperature, the relationship between measured diffusion emissions between the venting configurations was consistent with the variable temperature testing. However, the indicated diffusion results were somewhat higher. These higher results were influenced by two effects. In the variable temperature testing, the diffusion was measured during the cooling period when air was being drawn into the fuel tank. This would reduce diffusion into the SHED because escaping HC molecules would need to overcome the air flow into the tank. At the same time, the constant temperature test may have overstated diffusion due to the measured small fluctuations in temperature that may have caused mini-diurnal cycles. Likely, the actual diffusion rates are somewhere in-between the results presented in Tables 5.1-11 and 5.1-12. Appendix 5B contains data charts that present the results of the Small SI diffusion testing in more detail.

Although the results are presented above on a gram per gallon basis for comparison with diurnal emissions, diffusion appears to be more a function of orifice size that fuel tank size. Presumably, the diffusion rate on a grams per day basis would be the same through a given orifice regardless of size of the vapor space. This is reflected in the data above in that the permeation rates on a gram per gallon basis from the lawnmower fuel tanks with holes in the fuel cap were much larger than for the marine fuel tank in the testing discussed earlier. At the same time, larger fuel tanks may be designed with larger orifice sizes to account for higher amounts of vapor expansion in the tank.

5.1.4 Carbon Canister

The primary diurnal evaporative emission control device used in automotive applications is a carbon canister. With this technology, vapor generated in the tank is vented through a canister containing activated carbon (similar to charcoal). The fuel tank must be otherwise sealed; however, this only results in a minimal amount of pressure in the tank. The activated carbon collects and stores the hydrocarbons. Once the engine is running, purge air is drawn through the canister and the hydrocarbons are burned in the engine. These carbon canisters generally are about a liter in size for an automotive tank and have the capacity to store three days of vapor over the test procedure conditions. For automotive applications, this technology reduces diurnal emissions by more than 95 percent.

In a marine application, the vessel may sit for weeks without an engine purge; therefore, canisters were not originally considered to be a practical technology for controlling diurnal vapor from boats. Since that time, however, we have collected information showing that, during cooling periods, the canister is purged sufficiently enough so that it can be used effectively to reduce diurnal emissions. When the fuel in the tank cools, fresh air is drawn back through the canister into the fuel tank. This fresh air will partially purge the canister and return hydrocarbons back to the fuel tank.[20,21] Therefore, the canister will have some open sites to collect vapor during the next heating event. Test data presented below show that a canister that starts empty is more than 90 percent effective at capturing hydrocarbons until it reaches saturation. Once the canister reaches saturation, it is still capable of achieving more than a 60 percent reduction in diurnal emissions due to passive purging. Passive purging occurs as a result of fresh air that is pulled through the canister during fuel tank cooling periods. With the addition of an engine (active) purge, greater reductions would be expected.

We tested a 30 gallon aluminum fuel tank over three, multiple-day diurnal cycles with and without a charcoal canister. The carbon canister was 2.1 liters in size with a butane working capacity (BWC) of 11 g/dL (based on EPA test) and was aged using multiple 24 hour diurnal cycles prior to testing. In our first test, the fuel temperature was cycled from 72-96°F using a heating blanket in a SHED for at total of 28 days. Because we were not able to test over weekends, we brought the fuel temperature down to 72°F and held it to prevent the generation or purging of vapors. On Mondays, we saw higher vapor rates than the rest of the week which was likely due to the vapor redistributing itself equally through the canister over the weekend when the temperature was held constant. Under normal conditions, the continued diurnal cycles would maintain a gradient through the canister and this effect would not occur. Appendix 5C contains graph showing the results of the 28 day test. This test is interesting because we began with a purged canister and were able to observe the loading of the canister over the first few days. It took about five test days to achieve canister breakthrough and another ten test days before the canister loading/purging cycle stabilized.

Once the canister was saturated, the emissions results stabilized. Therefore, for the subsequent canister tests, we began with a loaded canister and tested for four days. The results were collected beginning after the first night so that the canister would have a cooling cycle for back-purge. Table 5.1-14 presents our test results for the baseline and stabilized with canister diurnal emission rates.

Table 5.1-14: EPA Diurnal Emission Test Results With and Without a Canister on a 30 Gallon Aluminum Marine Fuel Tank [g/gal/day]

Temperature Range	*Baseline*	*With a Canister*	*Reduction*
22.2-35.6°C (72-96°F)	1.50	0.52	65%
25.6-32.2°C (78-90°F)	0.85	0.28	67%
27.8-30.6°C (82-87°F)	0.47	0.14	71%

Marine manufacturers raised the concern that the high humidity in the areas where boats are used would be detrimental to this technology. They stated that the carbon could become saturated with water vapor, thereby reducing the available sites for hydrocarbon capture. These manufacturers also commented that carbon canisters may not be able to survive shocks and vibration that would be seen on a boat. Carbon canisters have been used in automotive applications for decades, which are subject to high humidity (rainy days) and shocks and vibration. In addition, one manufacturer, who is a primary supplier to the automotive industry, has developed a new grade of carbon that has low moisture adsorption characteristics and about 40 percent harder than typical automotive carbon.[22,23] This carbon has been designed specifically for marine applications. Based on this manufacturer's testing, more than a 60 percent reduction in diurnal vapor emissions can be achieved with a passive purge system. This reduction is based on a canister capacity of 0.03 to 0.04 liters of carbon per gallon of fuel tank capacity.

The National Marine Manufacturers Association has initiated a test program has to demonstrate the durability of carbon canisters in marine applications. This test program includes installing carbon canisters on a total of fourteen boats made by four boat builders.[24] These boat types include cruisers, runabouts, pontoon boats, and fishing boats. The carbon canister design used for these boats is a simple cylinder that can be cut to length with end caps and mounting brackets. The canisters were installed in the vent lines and a valve was added to prevent fuel from reaching the canister during refueling. These canisters use marine grade carbon. At the end of this test program, each of the canisters were tested for working capacity and each canister showed good performance.[25] These canisters will be evaluated further, including destructive testing.

Another issue that has been raised has been the ability of carbon canisters to pass the Coast Guard flame test. The carbon canisters could be made out of a variety of materials, including metal. Even a thin-walled nylon fuel tank could be manufactured to pass the flame test if a flame-resistant coating or cover were used. One study attempted to ignite a carbon canister that was loaded with fuel vapor.[26] When an ignition source was applied to the canister vent, the gases exiting the canister were ignited and burned as a small, steady flame until the canister tube opening began to melt. No explosion occurred.

Recently, the California Air Resources Board (ARB) performed similar testing on a commercial mower and a generator with 6 gallon fuel tanks and 0.65 liter canisters.[27] Their testing showed better than 50 percent reductions, on average, in diurnal emissions through the use of canisters without an engine purge. The testing was performed over two diurnal temperature ranges, 53-71°F and 65-105°F which are intended to represent an average day and a high temperature episode.

Over a decade ago, testing performed on a car showed similar results.[28] A 1988 Regency 98 with an 18 gallon fuel tank was subjected to an 8 day diurnal without driving. This diurnal was performed using a 72-96°F temperature profile, a tank filled to 40 percent with 9RVP gasoline, and a purged canister at the beginning of testing. The test results showed, that the canister loading/purging cycle began to stabilize after 6 days. Due to the canister back-purge, the stabilized diurnal emission rate about 11.5 grams per day which was more than a 50 percent reduction compared to baseline.

A manufacturer of activated carbon performed studies of ethanol fuel blend and carbon bed temperature on carbon efficiency.[29] Testing was performed with carbon canisters using gasoline, E10, and E85 fuel for onboard vapor refueling emissions efficiency. The emissions control was similar for each of the test fuels. Testing was also performed to measure gasoline working capacity for carbon soaked at temperatures ranging from 25 to 80˚C. Over this range only a 10 percent decrease in working capacity was observed with increasing temperature. Over the 25-40˚C range, which is more representative of boat or Small SI equipment use, the effect was only 1-2 percent. Based on the results from these studies, carbon canister efficiency would be expected to be effective at reducing diurnal emissions over the range of fuels and temperatures that may be seen in use.

5.1.5 Sealed System with Pressure Relief

Evaporative emissions are formed when the fuel heats up, evaporates, and passes through a vent into the atmosphere. By closing that vent, evaporative emissions are prevented from escaping. However, as vapor is generated, pressure builds up in fuel tank. Once the fuel cools back down, the pressure subsides. One way to control these emissions is to seal the fuel system. However, depending on the fuel tank design, a pressure relief valve may be necessary which would limit the control.

5.1.5.1 Pressure Relief Valve

For most marine applications, U.S. Coast Guard safety regulations require that fuel tanks be able to withstand at least 3 psi and must be able to pass a pressure impulse test which cycles the tank from 0 to 3 psi 25,000 times (33 CFR part 183).[2] The Coast Guard also requires that these fuel tanks must be vented such that the pressure in the tank in-use never exceeds 80 percent of the pressure that the tank is designed to withstand without leaking. The American Boat and

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[2] These regulations only apply to boats with installed fuel tanks and exclude outboard boats. However, ABYC recommended practice effectively extends many of these requirements to outboard boats as well.

Yacht Council makes the additional recommendation that the vent line should have a minimum inner diameter of 7/16 inch.[30] However, these recommended practices also note that “there may be EPA or state regulations that limit the discharge of hydrocarbon emissions into the atmosphere from gasoline fuel systems. The latest version of these regulations should be consulted.”

To prevent pressure from building too high in marine tanks, we first considered a 2 psi pressure relief valve. This is a typical automotive rating and is below the Coast Guard requirements. With this valve, vapors would be retained in the tank until 2 psi of pressure is built up in the tank due to heating of the fuel. Once the tank pressure reached 2 psi, just enough of the vapor would be vented to the atmosphere to maintain 2 psi of pressure. As the fuel cooled, the pressure would decrease. In our August 14, 2002 proposal (67 FR 53050) we considered standards based on a 1 psi valve which would only achieve a modest reduction over the proposed test procedure. However this reduction would be significantly greater in use because the test procedure is designed to represent a hotter than average day. On a more mild day, there would be less pressure buildup in the tank and the valve may not even need to open. With the use of a sealed system, a low pressure vacuum relief valve would also be necessary so that air could be drawn into the tank to replace fuel drawn from the tank when the engine is running.

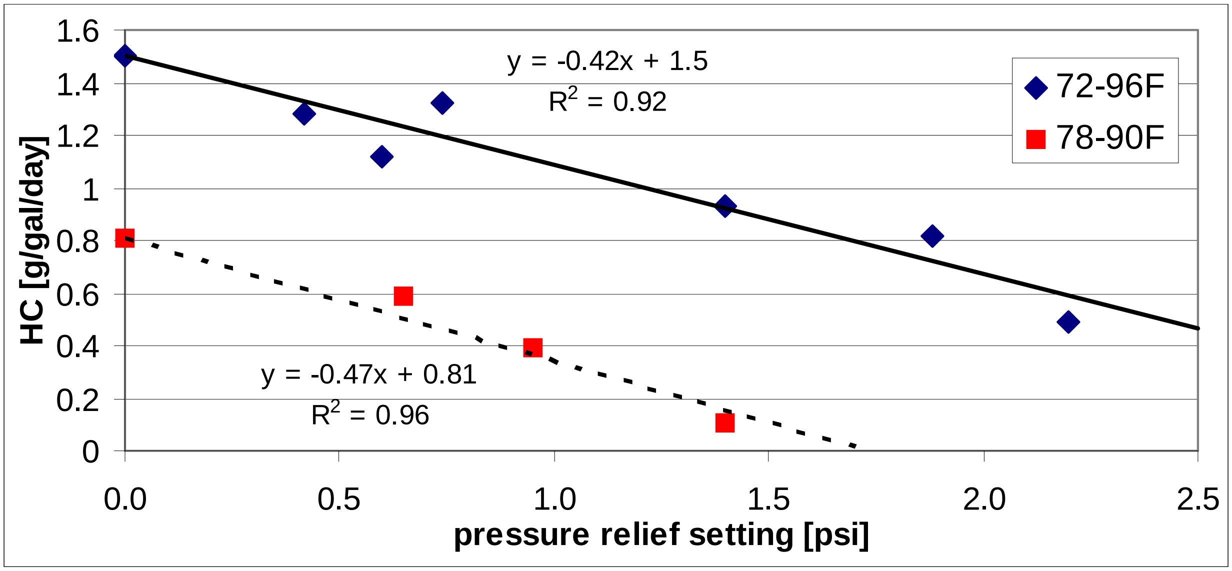
Manufacturers of larger plastic fuel tanks have expressed concern that their tanks are not designed to operate under pressure. For instance, although they will not leak at 3 psi, rotationally molded fuel tanks with large flat surfaces could begin deforming at pressures as low as 0.5 psi. At 2.0 psi, the deformation would be greater. This deformation would affect how the tank is mounted in the boat. Also, fuel tank manufacturers commented that some of the fittings or valves used today may not work properly under 2 psi of pressure. Finally, they commented that backup pressure-relief valves would be necessary for safety. For smaller fuel tanks, such as used in personal watercraft, portable fuel tanks, and Small SI equipment, pressure is less of an issue because of the smaller internal surface area of these fuel tanks. In addition, the construction of these fuel systems are generally vertically integrated which allows for more precise control of design parameters. For instance, personal watercraft manufacturers are already sealing their fuel systems to prevent fuel from spilling into the water. These systems generally have pressure relief valves ranging from 0.5 to 4.0 psi. In addition, portable fuel tanks are designed to be sealed without any pressure relief.

We looked at two types of pressure relief strategies: pressure relief valves and limited flow orifices. Because the Coast Guard requires that fuel systems not exceed 80 percent of their design capacity of 3 psi, we only looked at pressure relief strategies that would keep the pressure below 2.4 psi under worst case conditions.

For the pressure relief valve testing, we looked at several pressures ranging from 0.5 to 2.25 psi. The 2.25 psi valve was an off-the-shelf automotive fuel cap with a nominal 2 psi pressure relief valve and 0.5 psi vacuum relief valve. For the other pressure settings, we used another automotive cap modified to allow adjustments to the spring tension in the pressure relief valve. We performed these tests on the 17 gallon aluminum fuel tank to remove the variable of permeation. Emissions were vented through a hose to prevent diffusion losses from affecting the measurements. We operated over two temperature profiles. The first set of tests were performed in a variable temperature SHED with a 72-96°F air temperature profile. This temperature profile was based on the existing automotive cycle which is intended to represent a typical summer day on which a high ozone event may occur. The second set of tests were performed using a heating blanket to create a 78-90°F fuel temperature profile. This testing was intended to represent a fuel tank in a boat, where the tank may be inherently insulated, during the same ambient temperature profile. This inherent insulation creates a time lag on the heating and cooling of the fuel and reduces the amplitude of the temperature profile by half.

As shown in Figure 5.1-1, there was a fairly linear relationship between the pressure setting of the valve and the emissions measured over the proposed test procedure. In addition, the slopes of the lines are similar for both test temperature scenarios. This suggests that over a smaller temperature profile, a greater percent reduction in HC can be achieved at a given pressure setting. This is reasonable because, in each case, a constant amount of vapor is captured. In other words, regardless of the temperature profile, the same amount of vapor must be generated to create a given pressure. For instance, with a 1 psi valve, about 0.4 grams/gallon of HC are captured over each temperature profile. However, this represents a 50 percent reduction over a 78-90°F temperature profile while only about a 25 percent reduction over the 72-96°F temperature profile.

Figure 5.1-1: Effect of Pressure Cap on Diurnal Emissions



The California Air Resources Board tested a lawnmower in a SHED for diurnal emissions in a baseline configuration, a sealed system, and with various pressure relief settings.[31] Because the whole lawnmower was tested, permeation (and potentially leakages) were measured as well as diurnal venting emissions. The testing was performed over a 65-105°F temperature cycle with the fuel tank filled to 50 percent with 7 RVP fuel. For the system as a whole, they measured a 76 percent reduction in emissions when the tank was fully sealed compared to the open vent configuration. This suggests that diurnal venting made up about 76 percent of the evaporative emissions measured. Testing using 2, 3, and 4 psi pressure relief valves showed reductions of 43 percent, 43 percent, and 63 percent respectively. They also collected pressure data over various diurnal temperature cycles on a lawnmower fuel tank. Over the 65-105°F cycle, the measured a pressure increase of about 2.5 psi. Even under an extreme cycle of 68-121°F, the measured increase in tank pressure was about 3.6 psi.

5.1.5.2 Limited Flow Orifice

Another strategy for maintaining a design pressure is to use a limited flow orifice on the vent. In our testing, we are looked at three orifice sizes: 25, 75, and 1,000 microns in diameter. Again, we performed tests over a 72-96°F diurnal using a 17 gallon aluminum tank. To get these exact orifice sizes, we ordered from a company that specializes in boring holes with a laser device. These orifices were relatively inexpensive. It should be noted that a smaller tank would need a smaller orifice and a larger tank could use a larger orifice to build up the same pressure in the tank. The test results are presented in Table 5.1-15. For all of the tests with the limited flow orifices, no vent hose was attached.

Table 5.1-15: Diurnal Evaporative Emissions with Limited Flow Orifices

Orifice Diameter (microns)	*Peak Pressure [psi]*	*Evaporative HC [g/gallon/day]*
baseline (open vent with hose)	0.0	1.40
1000	0.0	1.47
75	1.6	1.16
25	3.1	0.24

By limiting the flow of the vapor from the tank, emissions were reduced with some pressure build up in the tank. However, because the vapor is flowing from the tank even at low pressure, this strategy is less effective for reducing diurnal emissions than a pressure relief valve. Generally, a higher peak pressure is necessary with the LFO for a given emission reduction. In addition, the limited flow orifice would have to be sized for worst case conditions to prevent the tank from reaching too high of a pressure. A LFO sized for worst case conditions would be less effective under typical conditions because the vapor flow out of the tank could be too low for the LFO to create a restriction. In comparison, a pressure relief valve would achieve higher percent reductions under typical conditions than for worst case conditions because the valve would open less often.

5.1.5.3 Vacuum Relief Valve

For some fuel tanks, pressure relief is not necessary. An example of this is portable marine fuel tanks which are currently equipped with a manual sealing valve. This valve can be sealed by the operator during storage to prevent vapor from escaping. Although pressure will build up during diurnal heating, the fuel tanks are designed to withstand this pressure. However, the valve must be opened by the operator during engine operation so that a vacuum does not form in the fuel tank as fuel is drawn to the engine. If this vacuum were to become too high, it could cause the engine to stall by restricting fuel to the engine.

The existing design requires that the operator close the valve whenever the engine is not running for diurnal emissions to be controlled. If an automatic vacuum relief valve were used, then the operator would not need to operate the sealing mechanism. It would always control diurnal (and other breathing loss) emissions. At the same time, the vacuum relief valve would allow air to be drawn into the fuel tank when the engine is operating to prevent a significant vacuum from being formed.

One manufacturer's approach to this automatic valve design is to use a diaphragm valve such as those used in automotive fuel systems.[32] This inexpensive design would be able to seal the tank under pressure, yet open at very low vacuums. This design (or other vacuum relief valve designs) could be used in any nonroad application where the fuel system is able to withstand pressure.

5.1.6 Selective Permeability Membrane

Another approach we investigated was fitting a molecular membrane in the vent line. The theory was that the membrane would allow oxygen and nitrogen to pass through, but block most longer-chain hydrocarbon molecules. We used a membrane fabricated using Teflon AF® which is an amorphous fluoropolymer. Because oxygen and nitrogen (and some smaller hydrocarbons) can pass through the membrane, hydrocarbons can be trapped in the fuel tank. However, the process for molecules passing through the membrane is slow, so it is important to size the membrane properly to prevent pressure build-up. This membrane could be placed in the vent line or directly in an opening in the top of the fuel tank.

Similar membranes are already used for several applications. One manufacturer provides membranes for a variety of uses such as oxygen or nitrogen enrichment of air or for separation of hydrocarbons from air.[33] One of these uses is to act as a vapor processor to prevent hydrocarbon vapor from escaping from retail gasoline stations in California.[34] Another membrane used for similar applications allows hydrocarbons to permeate but blocks smaller gases. This membrane is used in hydrocarbon recovery applications.[35] In the above noted applications, the membranes are typically used with a pump to provide a pressure drop across the membrane which causes permeation through the membrane. Typically, adequate mixing is needed to maintain an efficient diffusion rate.

We tested an amorphous fluoropolymer membrane with a surface area of about 40 cm^2 in the vent line of both a 30 and a 17 gallon aluminum fuel tank over three temperature cycles. The membrane was applied to a wire mesh in a cylindrical shape with the an outside diameter not much larger than the vent hose. Hydrocarbon emissions and fuel tank pressure were measured. Over these tests we consistently saw a pressure build up, even over a 24 hour test. To investigate the impacts of surface area, we increased the surface area by using 3 filters in parallel (single vent line to assembly). Our test results suggest that the pressures associated with this technology are comparable with the pressure relief valves needed to achieve the same reductions. However, this technology may have the potential for meeting our proposed standards if used in conjunction with a pump to provide a pressure differential across the filter without allowing pressure (and mixing) to build up in the fuel tank. Our test results are presented in Table 5.1-16.

Table 5.1-16: Diurnal Venting Emissions with Selective Permeable Membranes

Tank Size [gallons]	Venting	72-96°F		78-90°F		81.6-86.4°F	
		g/gal/day	psi	g/gal/day	psi	g/gal/day	psi
30	open	1.50	0	0.85	0	0.47	0
	1 filter	0.24	2.9	0.14	1.5	0.19	0.6
	3 filters	0.39	2.2	–	–	–	–
17	open	1.40	0	–	–	–	–
	3 filters	0.45	2.1	0.30	1.2	–	–

5.1.7 Volume Compensating Air Bag

Another concept for minimizing pressure in a sealed fuel tank is through the use of a volume compensating air bag.[36] The purpose of the bag is to fill up the vapor space in the fuel tank above the fuel itself. By minimizing the vapor space, less air is available to mix with the heated fuel and less fuel evaporates. As vapor is generated in the small vapor space, air is forced out of the air bag, which is vented to atmosphere. Because the bag collapses as vapor is generated, the volume of the vapor space grows and no pressure is generated.[3] Once the fuel tank cools as ambient temperature goes down, the resulting vacuum in the fuel tank will open the bag back up.

We tested a 6 gallon portable plastic fuel tank with a 1.5 gallon volume compensating bag made out of Tedlar. Tedlar is a light, flexible, clear plastic which we use in our labs for collecting exhaust emissions samples. In our testing, the pressure relief valve never opened because the volume compensating bag was able to hold the vapor pressure below 0.8 psi for each of the three days. This testing supports the theory that a volume compensating bag can be used to minimize pressure in a fuel tank, which in turn, reduces emissions when used in conjunction with a pressure relief valve.

We did see an emission rate of about 0.4 g/gal/day over the 3 day test. The emission rate was fairly constant, even when the ambient temperature was cooling during the test. This suggests that the emissions measured were likely permeation through the tank. Other materials

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[3] The Ideal Gas Law states that pressure and volume are inversely related. By increasing the volume of the vapor space, the pressure can be held constant.

may be more appropriate than Tedlar for the construction of these bags. The bags would have to hold up in a fuel tank for years and resist permeation while at the same time be light and flexible. One such material that may be appropriate would be a fluorosilicon fiber.

5.1.8 Bladder Fuel Tank

Probably the most effective technology for reducing evaporative emissions from fuel tanks is through the use of a collapsible fuel bladder. In this concept, a non-permeable bladder would be installed in the fuel tank to hold the fuel. As fuel is drawn from the bladder, the vacuum created collapses the bladder. Therefore, there is no vapor space and no pressure build up. Because the bladder would be sealed, there would be no vapors vented to the atmosphere. In addition, because there is no vapor space, vapor is not displaced during refueling events. We have received comments that bladder tanks would be cost prohibitive because its use would increase tank costs by 30 to 100 percent depending on tank size. However, bladder fuel tanks have positive safety implications as well and are already sold by at least one manufacturer to meet market demand in niche applications. Information on this system is available in the docket.[37]

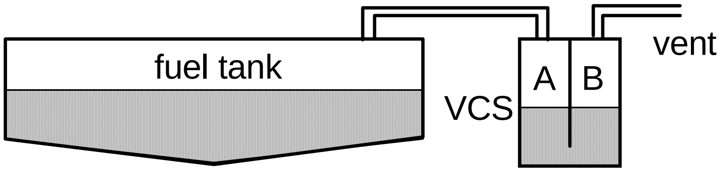
We tested a marine bladder fuel tank in our lab for both diurnal and permeation emissions. Over the diurnal test procedure we saw an emission rate of 0.2 g/gal/day. Because the system was sealed, this measured emission rate was likely due to permeation through the bladder and not due to diurnal losses. We later tested the bladder fuel tank for permeation emissions at 29°C and measured a permeation rate of 0.46 g/gal/day. The bladder used in our testing was constructed out of polyurethane. The manufacturer of this bladder tank is now working with a lower permeability material known as THV. THV is a fluoropolymer that can be used to achieve more than a 95 percent reduction in permeation from current bladder fuel tanks made out of polyurethane.[38] In addition, THV is resistant to ethanol. Permeation rates for these materials are presented in Appendix 5D.

5.1.9 Floating Fuel and Vapor Separator

Another concept used in some stationary engine applications is a floating fuel and vapor separator. Generally small, impermeable plastic balls are floated in the fuel tank. The purpose of these balls is to provide a barrier between the surface of the fuel and the vapor space. However, this strategy does not appear to be viable for fuel tanks used in mobile sources. Because of the motion of Small SI equipment and Marine SI vessels, the fuel sloshes and the barrier would be continuously broken. Even small movements in the fuel could cause the balls to rotate and transfer fuel to the vapor space. In addition, the unique geometry of many fuel tanks could case the balls to collect in one area of the tank. However, we do not preclude the possibility that some form of this approach could be made to work effectively in some mobile source applications.

5.1.10 Liquid Vapor Trap

Figure 5.1-2: Liquid Vapor Trap



One company has developed a liquid vapor trap that it refers to as a fuel vapor containment system (VCS).[39] The VCS behaves similar to a liquid trap used in sink drains in that trapped liquid creates a barrier to gases. This trap would be placed in the vent line to limit fuel vapor emitted from the fuel tank. Figure 5.1-2 presents an illustration of the basic concept.

When the temperature in the fuel tank increases, the vapor would expand in the fuel tank. The fuel vapor would enter chamber A and force more of the liquid into chamber B. This would provide room for the vapor to expand without allowing vapor to escape through the vent. As the fuel tank cools, the vapor would condense. This would cause the level of the liquid in chamber A to rise while the level of the liquid in chamber B would drop. Some pressurization may occur in the fuel tank with this system, but it would be much less than for a sealed fuel tank due to the expansion chamber. Any pressure or vacuum in the fuel system would be a function of the VCS design and would be expected to be less than 0.5 psi. In addition, a pressure relief valve could be added to the system to protect against any high pressure excursions.

In the initial testing of the VCS, the manufacturer has used water as the liquid barrier. However, they stated that ethylene-glycol or even oil could be used which would be more stable liquids and would resist freezing. Diurnal testing was performed on a 25 gallon fuel tank equipped with a roughly 3 gallon VCS unit.[40] Testing was performed in a mini-SHED over the EPA 72-96˚C diurnal cycle for two days. The tank was filled to 50 percent capacity with 9 RVP certification gasoline. The total weight loss was 1.1 grams on the first day and 2.6 grams on the second day. Using the higher of the two days, we get a diurnal emission rate of about 0.1 g/gal/day. The peak pressure during this testing was approximately 0.5 psi.

5.2 Running Loss Emissions

Running loss emissions are similar to diurnal emissions except that the fuel temperature rise is due to heat from the engine or other heat producing components, such as hydraulic systems, when the engine is running. This section summarizes the data and rationale supporting the running loss emission standard for Small SI equipment presented in the Executive Summary.

5.2.1 Baseline Emissions

To investigate running loss emissions, we instrumented seven riding lawnmowers, three walk-behind lawnmowers, two generators, and one pressure washer to measure the fuel temperature during typical operation. Many of the temperature measurements were made by a contractor.[41] Of the riding mowers, two had fuel tanks in front near the engine, three had fuel tanks in rear away from engine (but near the hydraulic system), and two were “zero-turn” mowers that had pairs of side saddle tanks that were relatively close to the rear mounted engine.

All of the riding mowers had plastic fuel tanks. One of the walk-behind mowers had a metal tank directly mounted to the block while the others had plastic tanks near the top/side of the engine. Both generators had plastic tanks mounted above the engine while the pressure washer had a metal tank mounted above the engine. All of the equipment vented through the fuel caps. The pressure washer had a metal fuel tank mounted above the engine. The equipment was operated in the field until the fuel temperature stabilized. For lawnmowers, the fuel temperature stabilized within 20 to 30 minutes while the larger equipment took up to an hour.

By measuring the increase in fuel temperature during operation, we were able to make a simple determination of the running loss emissions vented from the fuel tank. Other potential running loss emissions would be from the carburetor, due to permeation increases due to heating the fuel, or vibration-induced leaks in the fuel system. However, we believed that the majority of the running loss emissions would be due to breathing losses associated with heating the fuel. Table 5.2-1 presents the results of the temperature testing.

We contracted with an independent testing laboratory to test fuel tanks from most of the above pieces of equipment over the measured fuel temperature profiles.[42] For three of the tests on larger fuel tanks, we found that the measured emissions were inconsistent with theoretical predictions. An investigation of the test data suggested that the test had been ended too soon to see the full effect of the heat build. Repeat tests were performed with a longer sample time.[43] From this data we get the running loss emissions due to the breathing losses associated with the heating of the fuel tank. New tanks were purchased for this testing that had not been previously exposed to fuel so permeation emissions would not be included in the emission measurements. Table 5.2-1 also presents the test results for the above equipment.

Table 5.2-1: Fuel Temperature Measurements During Operation of Small SI Equipment and Hydrocarbons Measured Over This Temperature Profile

Equipment Type	Fuel Capacity [gallons]	Min. Temp °C	Max. Temp °C	HC [g/hr]
Riding mower front tank near engine	1.7 1.1	19.5 15.7	30.3 28.4	1.4 1.0
Riding mower rear tank away from engine	6.5 3.0 2.5	24.3 26.6 27.0	33.2 28.4 35.0	7.8 0.7 3.2
Zero-turn riding mower 2 saddle tanks near engine	6.5 x 2 1.4 x 2	20.5 21.9	23.9 29.7	3.4 2.5
Walk-behind mower (plastic)	0.34 0.25	23.3 28.7	33.0 46.7	0.3 1.2
Walk-behind mower (metal)	0.22	28.7	59.7	8.1
Generator set	8.5 7.0	20.6 25.8	25.8 50.0	1.8 69.3
Pressure washer	1.8	19.0	50.6	20.3

The California Air Resources Board performed running loss tests on several pieces of Small SI equipment.[44] This equipment included four lawnmowers (2 new and 2 old), one string trimmer, two generators, two ATVs, and two forklifts. To measure running loss emissions, the equipment were operated on California certification fuel in a SHED and the exhaust was routed outside the SHED. Running loss emissions were determined by measuring the HC concentration in the SHED. Therefore the measurements included all evaporative emissions during operation including those from fuel heating, permeation, carburetor losses, and, for the two older lawnmowers, liquid fuel leaks. Although the ATVs and forklifts are not considered to be small offroad engines, these data can be used as surrogates for equipment that were not tested. Table 5.2-2 presents this data.

Table 5.2-2: Results from ARB Running Loss Tests

Equipment Type	Model Year*	Running Loss [g/hr]
lawnmower	2000 2001 1994 1989	0.8 2.6 27.0 12.1
string trimmer	1999	0.6
generator	1995 2001	19.5 1.8
ATV	2001 2001	21.4 1.3
forklift	1995 1987	1.8 7.4

* the 2000 and 2001 equipment were new at the time of testing

5.2.2 Control Technology

Running loss emissions can be controlled by sealing the fuel cap and routing vapors from the fuel tank to the engine intake. In doing so, vapor generated heat from the engine will be burned by the engine. It may be necessary to use a valve or limited flow orifice in the purge line to prevent fuel from entering the line in the case of the equipment turning over and to limit the vapor to the engine during operation. Depending on the configuration of the fuel system and purge line, a one way valve in the fuel cap may be desired to prevent a vacuum in the fuel tank during engine operation. We anticipate that a system like this would eliminate running loss venting emissions. However, higher temperatures during operation would increase permeation somewhat. In addition, the additional length of vapor line would increase permeation. Considering these effects, we still believe that the system described here would result in more than a 90 percent reduction in running loss emissions from Small SI equipment.

A secondary benefit of running loss control for Small SI equipment has to do with diffusion emissions. As discussed above, venting a fuel tank through a hose (rather than through an open orifice) greatly reduces diffusion. In the system discussed above, all venting losses would occur through the vapor hose to the engine intake rather than through open vents in the fuel cap. Therefore, the diffusion effect should be largely eliminated.

Another approach to reducing running loss emissions would be to insulate the fuel tank or move it further from heat sources such as the engine or hydraulic system. With this approach, the fuel cap vent would likely still be used, but diffusion could be controlled using a tortuous vent path in the cap as described above.

For marine fuel tanks we are not considering running loss emissions. For portable fuel tanks and installed fuel tanks on larger vessels, we would not expect there to be significant heating of the fuel tanks during engine operation due to the distance from the engine and the cooling effect of operating the vessel in water. For personal watercraft, the fuel tanks have a sealed system with pressure relief that should help contain running loss emissions. For other installed fuel tanks, we would expect the diurnal emission control system to capture about half of any running losses as well.

5.3 Fuel Tank Permeation

The polymeric material (plastic) of which many gasoline fuel tanks manufactured generally has a chemical composition much like that of gasoline. As a result, constant exposure of gasoline to these surfaces allows the material to continually absorb fuel. Permeation is driven by the difference in the chemical potentials of gasoline or gasoline vapor on either side of the material. The outer surfaces of these materials are exposed to ambient air, so the gasoline molecules permeate through these fuel-system components and are emitted directly into the air. Permeation emissions continue at a nearly constant rate, regardless of how much the vehicle or equipment is used. Because of these effects, permeation-related emissions can therefore add up to a large fraction of the total emissions from nonroad equipment.

This section summarizes the data and rationale supporting the permeation emission standard for Small SI and Marine SI fuel tanks presented in the Executive Summary.

5.3.1 Baseline Fuel Tank Technology and Emissions

Fuel tanks may be constructed in several ways. Portable marine fuel tanks and some small, higher production-volume, installed marine fuel tanks are generally blow-molded using high-density polyethylene (HDPE). Larger, installed marine fuel tanks are generally either rotationally-molded using cross-link polyethylene (XLPE) or are constructed out of welded aluminum. Some boat builders even construct the fuel tanks out of fiberglass as part of the vessel construction. Fuel tanks on Small SI equipment may be injection molded, blow molded or rotationally molded. Blow-molded and injection-molded tanks are primarily made of HDPE, but nylon is used as well in some applications. Rotationally molded fuel tanks are generally made out of XLPE.

Blow molding is widely used for the manufacture of Small SI, portable marine, and PWC fuel tanks. Typically, blow molding is performed by creating a hollow tube, known as a parison, by pushing high-density polyethylene (HDPE) through an extruder with a screw. The parison is then pinched in a mold and inflated with an inert gas. In automotive applications, non-permeable plastic fuel tanks are produced by blow molding a layer of ethylene vinyl alcohol (EVOH) or nylon between two layers of polyethylene. This process is called coextrusion and requires at least five layers: the barrier layer, adhesive layers on either side of the barrier layer, and HDPE as the outside layers which make up most of the thickness of the fuel tank walls. However, multi-layer construction requires additional extruder screws which significantly increases the cost of the blow molding machine.

Injection molding can be used with lower production volumes than blow molding due to lower tooling costs. In this method, a low viscosity polymer is forced into a thin mold to create each side of the fuel tank. The two sides are then welded together. In typical fuel tank construction, the sides are welded together by using a hot plate for localized melting and then pressing the sides together. The sides may also be connected using vibration or sonic welding.

Rotational molding has two advantages over blow molding, which is widely used for forming automotive parts. First, the tooling cost is an order of magnitude lower than for blow-molding. Therefore, for small production volumes such as seen for marine applications, rotational molding is more cost-effective. Manufacturers of rotationally molded plastic fuel tanks have commented that they could not produce their tanks with competitive pricing in any other way. The second advantage of rotational molding is that larger parts can generally be molded on rotational molding machines than on blow-molding machines. Plastic marine fuel tanks can exceed 120 gallons.

Installed plastic marine fuel tanks are often produced in many shapes and sizes to fit the needs of specific boat designs. These fuel tanks tanks are generally rotationally-molded out of cross-link polyethylene. Cross-link polyethylene, which has a permeation rate comparable to HDPE, is used in larger marine applications because of its ability to pass the U.S. Coast Guard flame resistance requirements (33 CFR 183.590). Rotational-molding is also used in some Small SI applications where there are low production volumes of unique fuel tanks. XLPE is used in these fuel tanks as well because the fuel tank is often exposed and must be able to withstand impacts such as flying debris.

5.3.1.1 Baseline permeation test data

5.3.1.1.1 Marine fuel tanks

To determine the baseline permeation emissions from marine fuel tanks, we have collected permeation data on several plastic fuel tanks. Because gasoline does not permeate through aluminum, we did not perform permeation testing on aluminum fuel tanks.

We tested ten plastic fuel tanks that were either intended for marine use or are of similar construction. This permeation testing was performed at 29°C with gasoline. Prior to testing, the fuel tanks were stored with gasoline in them for about 20 weeks to ensure stable permeation rates. Table 5.3-1 presents the measured permeation rates for these fuel tanks in grams per gallon of fuel tank capacity. Where the internal surface area was either easily determined or supplied by the manufacturer, we also calculated the permeation rate in terms of grams per square meter of inside surface area. The 31 gallon tank showed much lower permeation than the other fuel tanks. This was likely due to the thickness of the walls in this tank. Even after stabilization, permeation is a function of material thickness. According to Fick's Law, if the wall thickness of a fuel tank were double, the permeation rate would be halved.[45]

Table 5.3-1: Permeation Rates for Plastic Marine Fuel Tanks Tested by EPA at 29°C

Tank Capacity [gallons]	Permeation		Construction	Application
	[g/gal/day]	[g/m²/day]		
3.3	0.96	12.7	HDPE	portable marine
6.0	0.61	6.8	HDPE	portable marine
6.0	1.18	13.1	HDPE	portable marine
6.0	0.75	8.4	HDPE	portable marine
6.6	0.83	9.1	HDPE	portable marine
6.6	0.77	8.4	HDPE	portable marine
6.0	0.60	8.3	cross-link	marine test tank
23	0.64	8.1	cross-link	installed marine
31	0.44	5.5	cross-link	installed marine

The Coast Guard tested three rotationally-molded, cross-link polyethylene marine fuel tanks at 40°C (104°F) for 30 days.[46] The results are presented in Table 5.3-2. Because permeation emissions are a function of surface area and wall thickness, there was some variation in the permeation rates from the three tanks on a g/gal/day basis. These results are not directly comparable to the EPA testing because of the difference in test temperature. However, we can adjust the permeation rates for temperature using Arrhenius' relationship[47] combined with empirical data collected on permeation rates for materials used in fuel tank constructions (described below). These adjusted permeation rates are shown in Table 5.3-2 and are consistent with the EPA test data.

Table 5.3-2: Permeation Rates for Cross-Link Marine Fuel Tanks at 40°C

Tank Capacity [gallons]	Measured Permeation Loss [g/gal/day]	Average Wall Thickness [mm]	Adjusted to 29°C [g/gal/day]
12	1.48	5.3	0.71
18	1.39	5.6	0.67
18	1.12	6.9	0.54

5.3.1.1.2 Small SI equipment fuel tanks

The California Air Resources Board (ARB) investigated permeation rates lawn & garden equipment fuel tanks. The ARB data is compiled in several data reports on their web site and are included in our docket.[48,49,50,51,52] Table 5.3-3 presents a summary of this data which was collected using the ARB Test Method 513.[53] Where multiple tests were run on a given tank or tank type, the average results are presented. Although the temperature in the ARB testing is cycled from 18 - 41°C rather than held at a constant temperature, the average temperature is 29˚C which is similar to the EPA testing. Therefore, the permeation results would likely be similar if the data were collected at the average temperature of 29°C used in the EPA testing.

Variation in permeation rates on a gram per square meter basis is likely due to differences in the wall thicknesses. Note that surface area measurements were not available for all of the fuel tanks. Smaller fuel tanks would be expected to have higher emissions on a gram per gallon basis due to the increased surface area to volume ratio. However, lower permeation rates were observed for the fuel tanks less than 1 quart, potentially due to relatively thicker walls or due to a difference in material used for these applications.

Table 5.3-3: Permeation Rates for Plastic Lawn and Garden Fuel Tanks Tested by ARB Over a 18-41°C Diurnal

Tank Capacity [gallons]	Permeation Loss [g/gal/day]	Permeation Loss [g/m^2/day]
0.06	0.20	5.39
0.08	0.26	6.67
0.09	0.12	--
0.09	0.19	5.88
0.10	0.28	--
0.12	0.53	9.01
0.15	0.42	7.32
0.16	0.29	4.79
0.25	1.32	11.56
0.25	0.73	10.65
0.25	0.67	9.75
0.25	0.74	10.75
0.25	0.86	12.54
0.25	0.68	9.91
0.25	1.06	9.24
0.25	1.24	10.84
0.25	0.99	8.68
0.25	0.67	9.80
0.25	0.66	9.65
0.25	0.62	9.07
0.25	1.39	12.17
0.25	1.26	11.03
0.29	1.27	15.00
0.38	0.27	--
0.38	1.30	10.66
0.38	0.92	9.18
0.38	0.08	--
0.50	1.39	12.69
0.50	1.04	8.53
0.55	1.24	--
0.74	1.82	--
1.4	1.72	7.81
1.7	1.14	--
1.8	1.47	6.19
3.9	3.28	4.84
5.0	3.20	--
5.0	2.75	--
5.0	3.82	8.80
7.5	2.07	2.86

Some handheld equipment, primarily chainsaws, use structurally-integrated fuel tanks where the tank is molded as part of the body of the equipment. In these applications the frames (and tanks) are typically molded out of nylon for strength. We tested structurally-integrated fuel tanks from four handheld equipment manufacturers at 29˚C on both gasoline and s 10 percent ethanol blend. The test results suggest that these fuel tanks are capable of meeting the proposed standards using their current materials. In the cases where the permeation rates were higher than the proposed standards, it was observed that the fuel cap seals had large exposed surface areas on the O-rings, which were not made of low permeation materials. Emissions could likely be reduced significantly from these tanks with improved seal designs. Table 5.3-4 presents the results of this testing. Note that permeation emissions are 20 to 70 percent higher on E10 than on gasoline for these fuel tanks.

Table 5.3-4: Permeation Rates for Nylon Handheld Fuel Tanks Tested by EPA at 29°C

Tank ID	Application	Material	Test Fuel	Permeation Loss [g/m^2/day]
R1	clearing saw (0.24 gallons)	nylon 6	gasoline	0.34
R2			E10	0.42
R3			E10	0.48
B1	hedge clipper (0.05 gallons)	nylon 6, 33% glass	gasoline	0.62
B2			E10	1.01
B3			E10	1.12
B4			E10	0.93
W1	chainsaw (0.06 gallons)	nylon 6, 30% glass	gasoline	1.45
W2			E10	2.18
W3			E10	2.46
G1	chainsaw (0.06 gallons)	nylon 6, 30% glass	gasoline	1.30
G2			E10	1.41
G3			E10	2.14

5.3.1.1.3 Portable fuel tanks

The California Air Resources Board (ARB) investigated permeation rates from portable fuel containers. Although this testing was not on Small SI or marine fuel tanks, the fuel tanks tested are of similar construction.[54,55] The ARB data is compiled in several data reports on their web site and is included in our docket. Table 5.3-5 presents a summary of this data which was collected using the ARB Test Method 513.[56] Due to the increasing surface to volume ratio with decreasing fuel tank sizes, data presented in terms of grams per gallon for smaller tanks would be expected to be higher for the same grams per surface area permeation rate. Although the temperature in the ARB testing is cycled from 18 - 41°C rather than held at a constant temperature, the results would likely be similar if the data were collected at the average temperature of 29°C which is used in the EPA testing.

Table 5.3-5: Permeation Rates for HDPE Portable Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Tank Capacity [gallons]	Permeation Loss [g/gal/day]
1.0	1.63
1.0	1.63
1.0	1.51
1.0	0.80
1.0	0.75
1.0	0.75
1.3	0.50
1.3	0.49
1.3	0.51
1.3	0.52
1.3	0.51
1.3	0.51
1.3	1.51
1.3	1.52
2.1	1.88
2.1	1.95
2.1	1.91
2.1	1.78
2.5	1.46
2.5	1.09
5.0	0.89
5.0	0.62
5.0	0.99
5.0	1.39
5.0	1.46
5.0	1.41
5.0	1.47
6.6	1.09

5.3.1.2 Effect of temperature on permeation rate

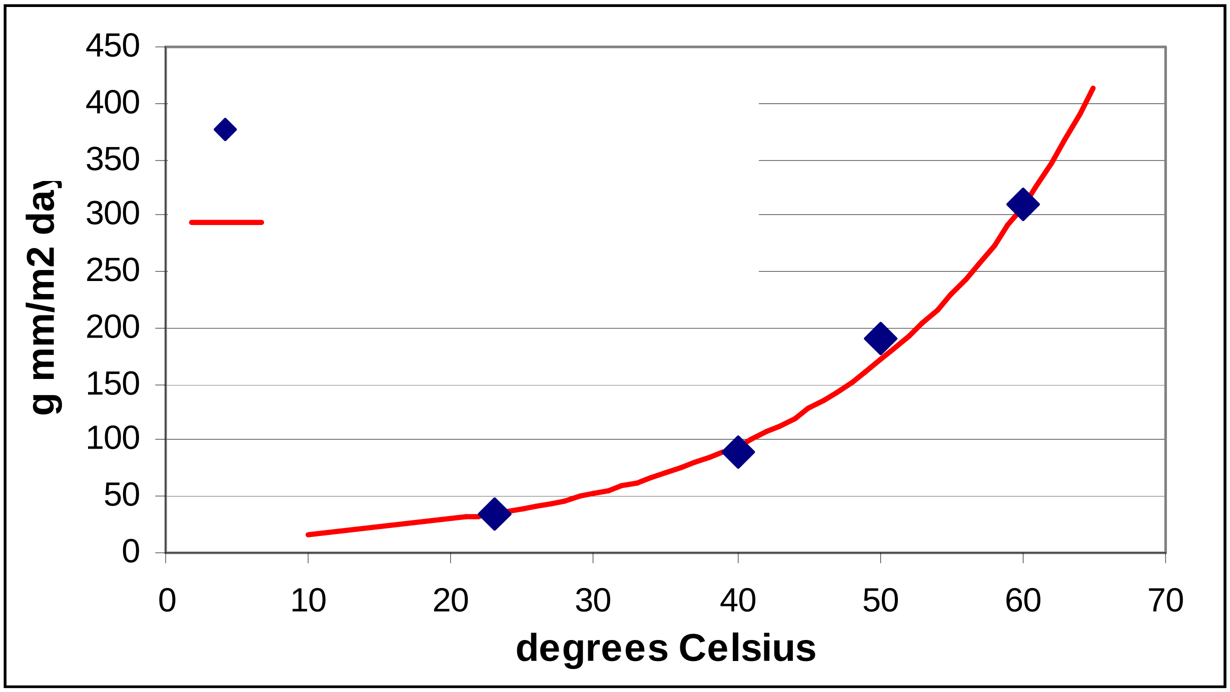
It is well known that the rate of permeation is a function of temperature. For most materials, permeability increases by about a factor of 2 for every 10°C increase in temperature.[57] To determine this relationship for nonroad fuel tanks, we performed permeation testing on nine HDPE Small SI fuel tanks at both 29°C and 36°C (85°F and 96°F).. This sample set included both baseline and surface treated fuel tanks. On average (excluding the outlier), the temperature effect was equivalent to nearly a factor of 2 increase in permeation per 10°C increase in temperature. The one outlier likely resulted from measurement error due to the very low permeation levels (0.5 grams lost over 2 weeks). Table 5.3-6 presents the test results.

Table 5.3-6: Effect of Temperature on Permeation from HDPE Small SI Fuel Tanks

Tank	Treatment	29°C [g/m^2/day]	36°C [g/m^2/day]	Increase per 10°C
A	untreated	11.5	17.1	92%
B		11.4	16.6	86%
C		11.2	17.0	97%
D	sulfonated	2.48	4.10	127%
E		2.73	3.98	85%
F		2.24	3.42	100%
H	fluorinated	0.56	0.75	60%
I		0.62	0.68	17%
J		0.22	0.31	80%

Published data collected on HDPE samples at four temperatures[58,59] suggest that the permeation of gasoline through HDPE increases by about 80 percent for every 10°C increase in temperature. This relationship is presented in Figure 5.3-1, and the numeric data can be found in Appendix 5D.

Figure 5.3-1: Effect of Temperature on HDPE Permeation



Another study was performed on the permeation from complete automotive fuel systems.[60] These fuel systems, which included fuel tanks, hoses, and other components, were tested at both 29°C and 40°C on three fuel types (gasoline, ethanol blend, and MTBE blend).

The effect of temperature on permeation did not appear to be significantly affected by fuel type. Table 5.3-7 presents this data for ten automotive fuel systems tested on gasoline. This data showed more than a factor of 2 increase in permeation per 10°C increase in temperature.

Table 5.3-7: Effect of Temperature on Permeation from Automotive Fuel Systems

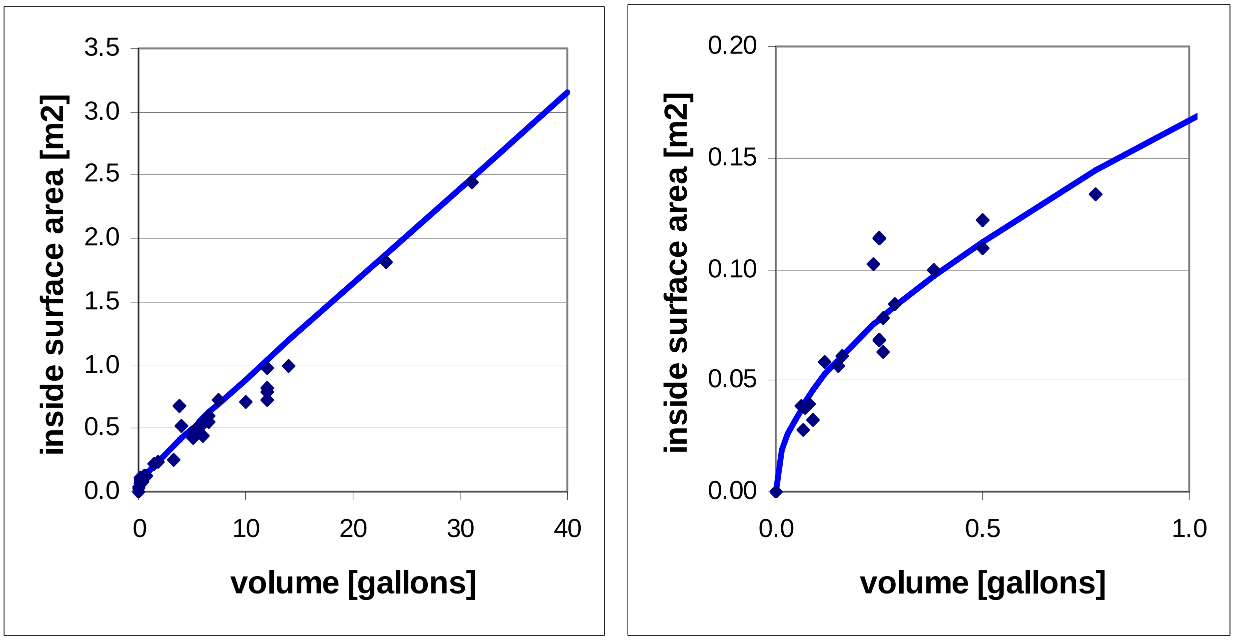
Fuel System	Fuel Tank	29°C [mg/hr]	40°C [mg/hr]	Increase per 10°C
2001 Toyota Tacoma	Metal	9	20	101%
2000 Honda Odyssey	Plastic (enhanced evap)	21	55	136%
1999 Toyota Corolla	Metal	10	24	124%
1997 Chrysler Town & Country	Plastic (enhanced evap)	23	52	110%
1995 Ford Ranger	HDPE	309	677	102%
1993 Chevrolet Caprice Classic	Fluorinated HDPE	95	255	143%
1991 Honda Accord LX	Metal	40	110	148%
1989 Ford Taurus GL	Metal	24	52	100%
1985 Nissan Sentra	Metal	53	148	152%
1978 Olds Cutlass Supreme	Metal	57	122	99%

5.3.1.3 Units for reporting the permeation rate (g/gal/day vs. g/m^2/day)

Much of the permeation data presented in this chapter is in units of grams of hydrocarbons lost in a day divided by the capacity of the fuel tank (g/gal/day). For diurnal emissions, these units are used because the vapor generation is a function of fuel tank volume. For permeation emissions, we considered using these units because the capacity of the fuel tank is generally readily available; either identified on the fuel tank or readily measured. However, although volume is generally used to characterize fuel tank emission rates, permeation is actually a function of surface area. Because the surface to volume ratio of a fuel tank changes with capacity and geometry of the tank, two similar shaped tanks of different volumes or two different shaped tanks of the same volume could have different g/gal/day permeation rates even if they were made of the same material and used the same emission control technology. For this reason, the final standards are based on units of grams per square meter of inside surface area (g/m^2/day).

This chapter presents permeation data for a large number of Small SI, marine, and other fuel tanks. For many of these fuel tanks, we had information on both the volume and inside surface area. Figure 5.3-2 presents the relationship between fuel tank volume in gallons and inside surface area in square meters. As a fuel tank becomes smaller, its surface to volume ratio increases. This relationship can be seen better in the chart to the right which presents only data for fuel tanks less than 1 gallon. A hyperbolic curve is fit through the data in Figure 5.3-2 to represent this relationship. This is seen better in the right-side chart which presents only smaller tank sizes. In addition to fuel tank volume, the surface to volume ratio is affected by geometry of the fuel tank. A long flat-fuel tank would have a higher surface to volume than a cube or spherical design. Larger plastic fuel tanks, used primarily in marine vessels, tend to have somewhat high surface to volume ratios for this reason.

Figure 5.3-2: Relationship Between Tank Volume and Inside Surface Area



5.3.1.4 Effect of fuel tank fill level on permeation

Permeation is driven by the chemical potential of the fuel or vapor in contact with the plastic. In a fuel tank, the vapor is essentially at equilibrium with the fuel in a fuel tank. Therefore, the permeation rate is the same through the surfaces in contact with saturated vapor as it is through the surfaces in contact with the liquid fuel. Because the permeation rate of saturated vapor and liquid fuel are the same, the fill level of the fuel tank during a permeation test does not affect the measured results.

The fact that liquid fuel and saturated fuel vapor result in the same permeation rates is supported by published literature.[61,62,63,64] In two of these studies, permeation was measured for material samples using the cup method illustrated in Figure 5.3-3. In these tests, no significant difference was seen between the permeation rates for material samples exposed to liquid fuel or to fuel vapor. To test for permeation with fuel vapor, the cup was inverted so that the fuel was on the bottom and the sample was taken off the top. Table 5.3-8 presents the data from these two reports. In both cases, the material being tested was a fluoroelastomer.

Figure 5.3-3: Cup Method

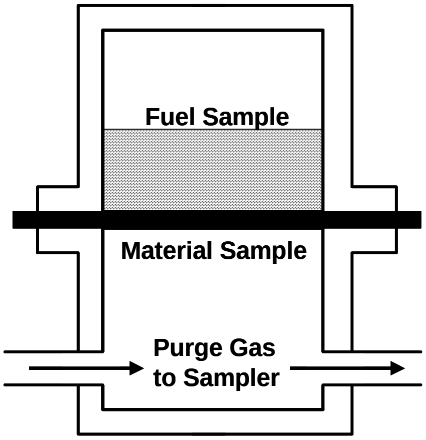


Table 5.3-8: Permeation Measured in Cup Method with Fuel Versus Vapor Fuel Exposure

Paper	Fuel	Temperature	Liquid Fuel Exposure	Fuel Vapor Exposure
SAE 2001-01-1999	CE10	40˚C	30.5 g/m^2/day	29.5 g/m^2/day
SAE 2000-01-1096	CE10	23˚C	0.3 g/test	0.3 g/test
		40˚C	2.6 g/test	2.5 g/test
	CM15	23˚C	3.1 g/test	2.9 g/test
		40˚C	9.5 g/test	8.5 g/test

One commenter presented test data suggesting that fill level may affect permeation emissions.[65] They tested four HDPE jugs, two filled to 40 percent and two filled to 100 percent with gasoline and saw a 15 percent difference in the average permeation results for the two fill levels (1.3 g/gal/day for 40 percent fill and 1.5 g/gal/day for 100 percent fill). Although this small measured difference was likely due to test variability, we performed our own testing to study the effect of fill level. For this testing, we used two 6-gallon HDPE portable marine fuel tanks. The fuel tanks were soaked with gasoline for 12 weeks to ensure a stabilized permeation rate. Each tank was tested at both 50 percent and 90 percent fill. No significant difference in permeation rate was observed for either tank. Table 5.3-9 presents the results in terms of g/gal/day at 29°C.

Table 5.3-9: Effect of Fuel Tank Fill Level on Permeation for Two Portable Marine Fuel Tanks [g/gal/day]

	50% fill	90% fill
Tank 1	1.16	1.21
Tank 2	0.77	0.78

Another study showed mixed results. Four automotive fuel systems (including fuel tank, hose, and other components) were tested for permeation with the fuel tanks filled with Fuel C to both 20 percent and 100 percent of capacity.[66] Prior to the testing, the fuel tanks were soaked with fuel at the specified fill levels until a stable permeation rate was achieved. It was not clear what fraction of the permeation came from the fuel tanks compared to other fuel system components or how the fuel level affected the exposure of the other components. In this study, two of the fuel systems saw no significant change in permeation as a result of a change in fill level. These two fuel system were on older vehicles, one with an untreated and one with a fluorinated HDPE fuel tank. Two other fuel systems, using fuel tanks that meet automotive enhanced evaporative emission requirements, showed significant reductions in fuel system permeation (32 percent and 49 percent) when tested with the fuel tank filled to only 20 percent capacity. The study presented no rationale for this effect; however, it should be noted that these were very low permeation systems and measurement error would presumably be larger. These data are presented in Table 5.3-10. In addition, it is possible that the change in fill level affected whether or not there was fuel in the hoses. As discussed later in this chapter, the vapor concentration in fuel hoses may be significantly lower than saturated when exposed only to vapor due to diffusion constraints.

Table 5.3-10: Effect of Fuel Tank Fill Level on Permeation for Four Automotive Fuel Systems at 29˚C [g/hour]

	Description of Fuel Tank	20% fill	80% fill
Rig 2	enhanced evap system	0.013	0.019
Rig 4	enhanced evap system	0.021	0.041
Rig 5	HDPE fuel tank	0.350	0.349
Rig 6	fluorinated HDPE fuel tank	0.095	0.094

The California Air Resources Board also performed testing on three pairs of portable fuel tanks.[67] All of the fuel tanks were identical 1 gallon tanks made out of HDPE. Each pair was filled to a different level with California certification fuel (30 percent, 50 percent and 70 percent fill). The fuel tanks were then sealed and subjected to five days of the California diurnal test (65-105˚F) and weight loss was measured daily. Over the five days of testing, the tanks with lower fill levels actually saw significantly higher permeation than the other tanks. Looking at the last day of testing, which represents some conditioning of the fuel tanks by the fuel resulting in more stabilized permeation rates, the permeation rates are similar regardless of the fill level. This data, which is presented in Table 5.3-11, suggests that the fuel vapor in the tanks permeated at the same rate as (or higher than) the liquid fuel.

Table 5.3-11: Effect of Fuel Tank Fill Level on Permeation for Three Pairs of Portable Fuel Tanks [g/day]

Tank	Fill Level	5-Day Permeation	Last Day Permeation
30a	30%	1.79	1.87
30b		1.57	1.91
50a	50%	1.53	1.91
50b		1.03	1.43
70a	70%	1.26	1.85
70b		1.08	1.43

5.3.1.5 Effect of background concentration on permeation

As discussed above, permeation is driven by the difference in chemical potential between the inside and outside of the tank. If the concentration of vapor outside the fuel tank were large enough, it could reduce the permeation rate of fuel through the tank. One commenter presented test data suggesting that, at very low concentrations of vapor in the boat around the fuel tank, that the permeation rate would be significantly reduced.[68] This test data was based on two three hour tests on 5 gallon HDPE bottles at 35°C. They measured 0.57 g/hr with a background concentration of 26 ppm and 0.36 g/hr with a background of 212 ppm. No repeat tests were run. It is not clear why the above results were measured. Compared to the concentration of the fuel vapor in the tank, this difference between 212 and 26 ppm is minuscule (about three orders of magnitude difference from saturated vapor). It is more likely that this effect was due to test variation.

To investigate this potential effect on permeation emissions further, we performed our own testing. First, we measured the concentration of fuel vapor around the fuel tank on a summer day in a runabout with the tank installed in the hull. This concentration was 1400 ppm. We then tested two different fuel tanks for permeation with different background concentrations. The background concentration was maintained by controlling the bleed of fresh air through the test container or SHED. Each test ran for about two weeks and the permeation rates were determined using the weight loss method. Prior to the testing, the tanks were soaked until a stable permeation rate was achieved, then new fuel was added to the tank just prior to beginning the test. The fuel tank was soaked until the fuel temperature stabilized at 29°C before the beginning weight was measured. The results, which are presented in Table 5.3-12, showed no significant difference in permeation as a function of background concentrations of hydrocarbon vapor.

Table 5.3-12: Effect of Background Concentration on Permeation

Fuel Tank	Background [ppmC]	Permeation [g/gal/day]
6 gallon HDPE	30 1500	0.77 0.78
23 gallon cross-link PE	30 150 1350	0.64 0.67 0.66

5.3.2 Fuel Tank Permeation Reduction Technologies

There are several strategies that can be used to reduce permeation from plastic fuel tanks. This section presents data collected on five permeation control strategies: sulfonation, fluorination, non-continuous barrier platelets, coextruded continuous barrier, and alternative materials.

5.3.2.1 Sulfonation

Sulfonation is a process where the surface of the fuel tank is treated to minimize permeation. The sulfonation process uses sulfur trioxide is used to create the barrier by reacting with the exposed polyethylene to form sulfonic acid groups on the surface. Current practices for sulfonation are to place fuel tanks on a small assembly line and expose the inner surfaces to sulfur trioxide, then rinse with a neutralizing agent. However, sulfonation can also be performed off-line. Either of these processes can be used to reduce gasoline permeation by more than 90 percent from new tanks.[69]

We tested several sulfonated marine fuel tanks at 29°C for permeation. This testing included both HDPE blow-molded fuel tanks and cross-link polyethylene rotationally-molded tanks. Both gasoline and alcohol fuel blends were investigated. In some cases, the fuel tanks were exposed to durability testing as described in Section 5.6.2. The fuel tanks were stored with fuel in them (soaked) for preconditioning, then they were drained and then filled with fresh fuel prior to each permeation test. The purpose of the soak periods was to ensure that the fuel permeation rate had stabilized and the purpose of the pressure cycles and slosh testing was to evaluate the durability of the barrier treatment.

We also collected data from ARB and other sources on the effectiveness of sulfonation for reducing permeation emissions from plastic fuel tanks. Most of this research has been performed on blow-molded HDPE fuel tanks. As shown in these data, it is important that the resin formulation be matched to the sulfonation process. The following discussions look at sufonation results on HDPE and on cross-link polyethylene separately.

HDPE fuel tanks

We tested several HDPE fuel tanks that were sulfonated on the internal surfaces. These included three 6-gallon and one 3.3 gallon portable marine fuel tanks and three all-terrain vehicle (ATV) fuel tanks. These fuel tanks were sent to a sulfonater for barrier treatment. Multiple fuel tanks were used so that they could be tested on certification gasoline , E10 (10 percent ethanol), and M15 (15 percent methanol). The test results, presented in Table 5.3-13, showed more than a 90 percent reduction in permeation emissions from baseline. However, the two fuel tanks that were subjected to slosh testing saw emission levels above the proposed standard. This may have been a material compatibility issue as discussed below. The test results are consistent with similar data collected by the California Air Resources Board.

Table 5.3-13: EPA Permeation Data on Sulfonated HDPE Fuel Tanks at 29°C

Treatment	Fuel	Soak Period	g/gal/day	$g/m^2/day$
6 gallon portable marine fuel tanks				
baseline	gasoline	15 weeks	0.77	8.53
sulfonated	gasoline	16 weeks	0.04	0.45
sulfonated	gasoline, sloshed	12 weeks	0.39	4.30
sulfonated	E10	24 weeks	0.14	1.58
sulfonated	M15	24 weeks	0.08	0.84
4 gallon ATV fuel tanks				
sulfonated	gasoline	20 weeks	0.13	1.05
sulfonated	E10	24 weeks	0.06	0.45
sulfonated	M15	24 weeks	0.08	0.64
3.3 gallon portable fuel tank				
baseline	E10	14 weeks	0.96	12.7
sulfonated	E10	14 weeks	0.06	0.83
sulfonated	E10, sloshed	38 weeks	0.16	2.09

We performed slosh testing on the 6 and 3.3 gallon portable marine fuel tanks with E10 fuel. This slosh testing included 1 million cycles consistent with the proposed durability test procedure. After the slosh testing, the permeation rates were measured to be 2.0 and 4.3 $g/m^2/day$ for the 3.3 and 6 gallon fuel tanks, respectively. As discussed below, we believe that the impact of the durability testing on the effectiveness of sulfonation can be minimized if the sulfonation process and material properties are matched properly. However, this data supports the need for the proposed durability testing requirements.

The California Air Resources Board (ARB) collected test data on permeation rates from sulfonated portable fuel containers using California certification fuel.[70] The results show that sulfonation can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 29°C. The average emission rate for the 32 sulfonated fuel tanks is 0.35 g/gal/day; however, there was a wide range in variation in the effectiveness of the sulfonation process for these fuel tanks. Some of the data outliers were actually higher than baseline emissions. This was likely due to leaks in the fuel tank which would result in large emission increases due to pressure built up with temperature variation over the diurnal cycle. Removing these five outliers, the average permeation rate is 0.17 g/gal/day with a minimum of 0.01 g/gal/day and a maximum of 0.64 g/gal/day. This data suggests that more than a 90 percent reduction in permeation from HDPE fuel tanks is possible through sulfonation. This data is presented in Table 5.3-14.

Table 5.3-14: Permeation Rates for Sulfonated Plastic Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Tank Capacity [gallons]	Permeation Loss [g/gal/day]
1	0.05
1	0.05
1	0.05
1	0.06
1	0.06
1	0.06
1	0.08
1	0.12
1	0.14
1	1.23
1	1.47
1	1.87
2	0.02
2	0.02
2	0.48
2	0.54
2	1.21
2.5	0.03
2.5	0.08
2.5	0.32
2.5	0.38
2.5	0.42
2.5	0.52
2.5	0.64
2.5	0.80
5	0.01
5	0.04
5	0.05
5	0.06
5	0.11
5	0.13
5	0.15

Variation can occur in the effectiveness of this surface treatment if the sulfonation process is not properly matched to the plastic and additives used in the fuel tank material. For instance, if the sulfonater does not know what UV inhibitors or plasticizers are used, they cannot maximize the effectiveness of their process. Earlier data collected by ARB showed consistently high emissions from sulfonated fuel tanks; however, ARB and the treatment manufacturers agree that this was due to inexperience with treating fuel tanks and that these issues have since been largely resolved.[71]

ARB also investigated the effect of fuel slosh on the durability of sulfonated surfaces. Three half-gallon fuel tanks used on Small SI equipment were sulfonated and tested for permeation before and after being sloshed with fuel in them 1.2 million times.[72,73] These fuel tanks were blow-molded HDPE tanks used in a number of Small SI applications including pressure washers, generators, snowblowers, and tillers. The results of this testing show that an 85 percent reduction in permeation was achieved on average even after the slosh testing was performed. Table 5.3-15 presents these results which were recorded in units of g/m^2/day. The baseline level for Set #1 is an approximation based on testing of similar fuel tanks, while the baseline level for Set #2 is based on testing of those tanks.

The sulfonater was not aware of the materials used in the fuel tanks sulfonated for the slosh testing. After the tests were performed, the sulfonater was able to get some information on the chemical make up of the fuel tanks and how it might affect the sulfonation process. For example, the UV inhibitor used in some of the fuel tanks is known as HALS. HALS also has the effect of reducing the effectiveness of the sulfonation process. Two other UV inhibitors, known as carbon black and adsorber UV, are also used in similar fuel tank applications. These UV inhibitors cost about the same as HALS, but have the benefit of not interfering with the sulfonation process. The sulfonater claimed that if HALS were not used in the fuel tanks, a 97 percent reduction in permeation would have been seen.[74] To confirm this, one manufacturer tested a sulfonated tank similar to those in Set #2 except that carbon black, rather than HALS, was used as the UV inhibitor. This fuel tank showed a permeation rate of 0.88 g/m^2/day at 40°C[75] which was less than half of what the CARB testing showed on their constant temperature test at 40°C.[76] A list of resins and additives that are compatible with the sulfonation process is included in the docket.[77,78]

Table 5.3-15: Permeation Rates for Sulfonated Fuel Tanks with Slosh Testing by ARB Over a 18-41°C Diurnal

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Set #1 Approximate Baseline	g/m^2/day	10.4	10.4	10.4	10.4
Set #1 Sulfonated	g/m^2/day % reduction	0.73 93%	0.82 92%	1.78 83%	1.11 89%
Set #1 Sulfonated & Sloshed	g/m^2/day % reduction	1.04 90%	1.17 89%	2.49 76%	1.57 85%
Set #2 Average Baseline	g/m^2/day	12.1	12.1	12.1	12.1
Set #2 Sulfonated	g/m^2/day % reduction	1.57 87%	1.67 86%	1.29 89%	1.51 88%
Set #2 Sulfonated & Sloshed	g/m^2/day % reduction	2.09 83%	2.16 82%	1.70 86%	1.98 84%

About a year and a half after the California ARB tests on the Set #2 fuel tanks, we performed permeation tests on these fuel tanks. During the intervening period, the fuel tanks remained sealed with California certification fuel in them. We drained the fuel tanks and filled them with fresh California certification fuel. We then measured the permeation rate at 29°C. Because this is roughly the average temperature of the California variable temperature test, similar permeation rates would be expected. The untreated fuel tanks showed slightly lower permeation over the constant temperature test. This difference was likely due to the difference in the temperature used for the testing. However, the sulfonated fuel tanks showed an increase in permeation. This increase in permeation appears to be the result of the 1.5 year additional fuel soak. After this long soak, the average permeation reduction changed from 84 to 78 percent. Table 5.3-13 presents this comparison.

Table 5.3-16: Permeation Rates [g/m²/day] for Sulfonated Fuel Tanks Tested by ARB and EPA on CA Certification Gasoline with a 1½ Year Fuel Soak Differential

Technology Configuration	Temperature	Tank 1	Tank 2	Tank 3	Average
Baseline, CARB testing	18-41°C	12.1	12.1	12.1	12.1
Baseline, EPA testing after 1.5 year additional fuel soak	29°C % change	11.5 -5%	11.4 -6%	11.2 -7%	11.4 -6%
Sulfonated, CARB testing	18-41°C	2.09	2.16	1.70	1.98
Sulfonated, EPA testing after 1.5 year additional fuel soak	29°C % reduction	2.48 78%	2.73 76%	2.24 80%	2.5 78%

After the above testing, we drained the fuel tanks and filled them with certification gasoline splash-blended with 10 percent ethanol (E10). We then soaked the fuel tanks for 20 weeks to precondition them on this fuel. Following the preconditioning, we tested these fuel tanks for permeation at 29˚C (85˚F). Table 5.3-17 presents these emission results compared to the emission results for three baseline tanks (untreated) that were subject to the same preconditioning. Percent reductions are presented based on the difference between the sulfonated fuel tanks and the average results of the three untreated fuel tanks.

Table 5.3-17: Permeation Rates for Sulfonated Fuel Tanks on E10 Fuel at 29˚C

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Baseline (untreated)	$g/m^2/day$	13.9	13.7	14.4	14.0
Sulfonated	$g/m^2/day$ % reduction	3.91 72%	4.22 70%	2.92 79%	3.69 74%

An in-use durability testing program was also completed for sulfonated HDPE fuel tanks and bottles.[79] The fuel tank had a 25 gallon capacity and was removed from a station wagon that had been in use in southern California for five years (35,000 miles). The fuel tank was made of HDPE with carbon black used as an additive. After five years, the sulfonation level measured on the surface of the plastic fuel tank did not change. Tests before and after the aging both showed a 92 percent reduction in gasoline permeation due to the sulfonation barrier compared to the permeation rate of a new untreated tank. Testing was also done on 1 gallon bottles made of HDPE with 3 percent carbon black. These bottles were shown to retain over a 99 percent barrier after five years. This study also looked at other properties such as yield strength and mechanical fatigue and saw no significant deterioration.

One study looked at the effect of alcohol in the fuel on permeation rates from sulfonated fuel tanks.[80] In this study, the fuel tanks were tested with both gasoline and various methanol blends. No significant increase in permeation due to methanol in the fuel was observed.

XLPE fuel tanks

We tested eight sulfonated cross-link polyethylene (XLPE) fuel tanks for permeation emissions. These tanks were produced by marine fuel tank manufacturers specifically for this testing. The fuel tanks were then treated by a sulfonater. For the first four tanks tested, the fuel tanks were molded using the resin formulation and processes currently used by the fuel tank manufacturers. When the sulfonation was applied, we observed that the barrier was soft and could be scraped off easily. When tested, the barrier on these fuel tanks was not as effective as had been seen on HDPE fuel tanks.

Because the barrier could be scratched off, the sulfonater ascertained that the sulfonation had poor surface penetration and the darkness of the barrier suggested heavy oxidation. For the next batch of four test tanks, the sulfonater worked with the material supplier and roto-molder and attempted to develop a formulation that may be more compatible with sulfonation. They decided to use the same material, but bake it in the oven longer to remove more oxygen from the surface of the fuel tank. Four bake times were used to produce the four 6-gallon test tanks: 11, 12, 14, and 16 minutes. It was observed that the sulfonation barrier could not easily be scratched off these fuel tanks. We tested the four sulfonated on E10 (10 percent ethanol) using the same procedures as for the HDPE tanks discussed above. The test results did not show a significant improvement.

Another approach may be to mold an inner liner of HDPE inside a XLPE shell. These materials readily bond with each other and sulfonation has been demonstrated for HDPE. This construction, which is currently used in chemical storage applications, is performed in the oven through the use of a “drop box” in the mold containing the HDPE. This drop-box is opened part way through the oven cycle allowing for a HDPE layer to be molded on the inside of the fuel tank.

5.3.2.2 Fluorination

Another barrier treatment process is known as fluorination. The fluorination process causes a chemical reaction where exposed hydrogen atoms are replaced by larger fluorine atoms which form a barrier on the surface of the fuel tank. In this process, fuel tanks are generally processed post production by stacking them in a steel container. The container is then voided of air and flooded with fluorine gas. By pulling a vacuum in the container, the fluorine gas is forced into every crevice in the fuel tanks. As a result of this process, both the inside and outside surfaces of the fuel tank would be treated. As an alternative, fuel tanks can be fluorinated on-line by exposing the inside surface of the fuel tank to fluorine during the blow molding process.

However, this method may not prove as effective as off-line fluorination which treats the inside and outside surfaces.

We tested several fluorinated marine fuel tanks at 29°C for permeation. This testing included both HDPE blow-molded fuel tanks and cross-link polyethylene rotationally-molded tanks. Both gasoline and alcohol fuel blends were investigated. In some cases, the fuel tanks were exposed to durability testing as described in Section 5.6.2. The fuel tanks were stored with fuel in them (soaked) for preconditioning, then they were drained and then filled with fresh fuel prior to each permeation test. The purpose of the soak periods was to ensure that the fuel permeation rate had stabilized and the purpose of the pressure cycles and slosh testing was to evaluate the durability of the barrier treatment.

We also collected data from ARB and other sources on the effectiveness of fluorination for reducing permeation emissions from plastic fuel tanks. Most of this research has been performed on blow-molded HDPE fuel tanks. However, we believe that fluorination can also be applied effectively for injection-molded HDPE tanks as well. The following discussion looks at each material separately as well as rotationally-molded cross-link polyethylene.

Blow-molded HDPE fuel tanks

We tested one fluorinated HDPE fuel tank which we bought off the shelf and sent to a fluorinater for barrier treatment. The fuel tank type used was a 6-gallon portable marine fuel tank. The fuel tank was soaked for 20 weeks with certification gasoline prior to testing. We measured a permeation rate of 0.05 g/gal/day (0.56 g/m^2/day) which represents more than a 95 percent reduction from baseline. We then began soaking this fuel tank on E10, subjected it to the proposed pressure and slosh testing, and retested the fuel tank. The post durability testing result showed a permeation rate of 0.6 g/gal/day (6.8 g/m^2/day). As discussed below, we believe that the impact of the durability testing on the effectiveness of fluorination on can be minimized if the fluorination process and material properties are matched properly. In addition, this fuel tank was treated to a significantly lower level of fluorination than is now available. However, this data supports the need for the proposed durability testing requirements.

The California Air Resources Board (ARB) collected test data on permeation rates from fluorinated fuel containers using California certification fuel.[81,82] The results show that fluorination can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 30°C. For the highest level of fluorination, the average permeation rate was 0.04 g/gal/day which represents a 95 percent reduction from baseline. Earlier data collected by ARB showed consistently high emissions from fluorinated fuel tanks; however, ARB and the treatment manufacturers agree that this was due to inexperience with treating fuel tanks and that these issues have since been largely resolved.[83] The ARB data is presented in Table 5.3-18.

Table 5.3-18: Permeation Rates for Fluorinated Plastic Fuel Containers Tested by ARB Over a 18-41°C Diurnal

Barrier Treatment*	Tank Capacity [gallons]	Permeation Loss [g/gal/day]
Level 4 (average =0.09 g/gal/day)	1	0.05
	1	0.05
	1	0.06
	5	0.11
	5	0.11
	5	0.15
Level 5 (average =0.07 g/gal/day)	1	0.03
	1	0.04
	1	0.05
	1	0.05
	1	0.07
	1	0.08
	1	0.11
	1	0.11
	1	0.12
	2.5	0.04
	2.5	0.04
	2.5	0.05
	2.5	0.07
	2.5	0.07
	5	0.05
	5	0.10
	5	0.11
SPAL (average =0.04 g/gal/day)	5	0.04
	5	0.04
	5	0.04

*designations used in ARB report; shown in order of increasing treatment

All of the data on fluorinated fuel tanks presented above were based on fuel tanks fluorinated by the same company. Available data from another company that fluorinates fuel tanks shows a 98 percent reduction in gasoline permeation through a HDPE fuel tank due to fluorination.[84]

ARB investigated the effect of fuel slosh on the durability of fluorinated surfaces. Two sets of three fluorinated fuel tanks were tested for permeation before and after being sloshed with fuel in them 1.2 million times.[85,86] These fuel tanks were 0.5 gallon, blow-molded HDPE tanks used in a number of Small SI applications including pressure washers, generators, snowblowers, and tillers. The results of this testing show that an 80 percent reduction in permeation was achieved on average even after the slosh testing was performed for Set #1. However, this data also showed a 99 percent reduction for Set #2. This shows the value of matching the barrier treatment process to the fuel tank material. Table 5.3-19 presents these results which were recorded in units of g/m^2/day. The baseline level for Set #1 is an approximation based on testing of similar fuel tanks, while the baseline for Set #2 is based on testing of those tanks.

Table 5.3-19: Permeation Rates for Fluorinated Fuel Tanks with Slosh Testing by ARB Over a 18-41°C Diurnal

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Set #1 Approximate Baseline	g/m^2/day	10.4	10.4	10.4	10.4
Set #1 Fluorinated	g/m^2/day % reduction	1.17 89%	1.58 85%	0.47 96%	1.07 90%
Set #1 Fluorinated & Sloshed	g/m^2/day % reduction	2.38 77%	2.86 73%	1.13 89%	2.12 80%
Set #2 Approximate Baseline	g/m^2/day	12.1	12.1	12.1	12.1
Set #2 Fluorinated	g/m^2/day % reduction	0.03 >99%	0.00 >99%	0.00 >99%	0.01 >99%
Set #2 Fluorinated & Sloshed	g/m^2/day % reduction	0.07 99%	0.11 99%	0.05 >99%	0.08 99%

About a year and a half after the California ARB tests on the Set #2 fuel tanks, we performed permeation tests on these fuel tanks. During the intervening period, the fuel tanks remained sealed with California certification fuel in them. We drained the fuel tanks and filled them with fresh California certification fuel. We then measured the permeation rate at 29°C. Because this is roughly the average temperature of the California variable temperature test, similar permeation rates would be expected. The untreated fuel tanks showed slightly lower permeation over the constant temperature test. This difference was likely due to the difference in the temperature used for the testing. However, the fluorinated fuel tanks showed an increase in permeation. This increase in permeation appears to be the result of the 1.5 year additional fuel soak. Even after this long fuel soak, the fluorination achieves more than a 95 percent reduction in permeation. Table 5.3-20 presents this comparison.

Table 5.3-20: Permeation Rates [g/m^2/day] for Fluorinated Fuel Tanks Tested by ARB and EPA on CA Certification Gasoline with a 1½ Year Fuel Soak Differential

Technology Configuration	Temperature	Tank 1	Tank 2	Tank 3	Average
Baseline, CARB testing	18-41°C	12.1	12.1	12.1	12.1
Baseline, EPA testing after 1.5 year additional fuel soak	29°C % change	11.5 -5%	11.4 -6%	11.2 -7%	11.4 -6%
Fluorinated, CARB testing	18-41°C	0.07	0.11	0.05	0.08
Fluorinated, EPA testing after 1.5 year additional fuel soak	29°C % reduction	0.56 95%	0.62 95%	0.22 98%	0.47 96%

After the above testing, we drained the fuel tanks and filled them with certification gasoline splash-blended with 10 percent ethanol (E10). We then soaked the fuel tanks for 20 weeks to precondition them on this fuel. Following the preconditioning, we tested these fuel tanks for permeation at 29˚C (85˚F). Table 5.3-21 presents these emission results compared to the emission results for three baseline tanks (untreated) that were subject to the same preconditioning. Percent reductions are presented based on the difference between the fluorinated fuel tanks and the average results of the three untreated fuel tanks. The slight increase in permeation on the E10 fuel was similar for the baseline and fluorinated fuel tanks and still resulted in permeation rates well below the proposed standard.

Table 5.3-21: Permeation Rates for Fluorinated Fuel Tanks on E10 Fuel at 29˚C

Technology Configuration	Units	Tank 1	Tank 2	Tank 3	Average
Baseline (untreated)	g/m^2/day	13.9	13.7	14.4	14.0
Fluorinated	g/m^2/day % reduction	0.43 97%	0.62 96%	0.62 96%	0.56 96%

Another study also looked at the effect of alcohol in the fuel on permeation rates from fluorinated fuel tanks.[87] In this study, the fuel tanks were tested with both gasoline and various methanol blends. No significant increase in permeation due to methanol in the fuel was observed.

Under their rule for small offroad equipment, California may issue executive orders to manufacturers with low emission products. As of August, 2006, ARB has issued 5 executive orders for low permeation fuel tanks.[88] Under these executive orders, three fluorination approaches have been approved. The California fuel tank permeation standard is 1.5 g/m^2/day tested at 40˚C on California certification fuel. Table 5.3-22 presents the test results for the fuel tanks with ARB executive orders. Note that the reported emissions are the average of five test samples.

Table 5.3-22: ARB Fuel Tank Executive Orders for Small Offroad Equipment

EO#	Test Fuel	g/m^2/day
C-U-05-015	Phase II	1.10
C-U-06-019	Phase II	0.30
C-U-06-006	Phase II	0.38

One automobile manufacturer used fluorination to reduce permeation on HDPE fuel tanks to meet the LEV I vehicle standards. This manufacturer used similar or more stringent requirements for fuel soak, durability, and testing than finalized today. At 40°C, this manufacturer stated that they measured 0.15-0.2 g/day for fluorinated tanks compared to over 10 g/day for untreated HDPE fuel tanks.[89]

Injection-molded HDPE fuel tanks

The issue has been raised by manufacturers that HDPE intended for injection-molding has a somewhat different composition than HDPE used for blow-molding. To address this concern, testing has been performed on fluorinated, injection-molded fuel tanks as well.[90] These fuel tanks were tested using California's TP-901 test procedures which preconditioning steps including fuel soak, slosh testing, and pressure-vacuum cycling. California Phase II gasoline was used for this testing.

Three similar fuel tanks were tested also over the proposed Federal test procedure.[91] Under this testing, E10 fuel was used. Weight loss tests were performed before and after the durability tests in 40 CFR 1501.515.[92] These durability tests included slosh testing, pressure vacuum cycling, and UV exposure. Results from this testing are presented in Table 5.3-23. The permeation was significantly higher when tested on E10 fuel, especially when accounting for differences in test temperature. In addition, permeation increased somewhat after the durability testing. However, the measured permeation rates were well below the proposed fuel tank permeation standard on E10 after the durability testing.

Table 5.3-23: Permeation Rates for Fluorinated, Injection-Molded Fuel Tanks [$g/m^2/day$]

Test Procedure	Test Temperature	Tank 1	Tank 2	Tank 3	Average
California TP-901	40˚C	0.28	0.26	0.27	0.27
Federal Baseline	28˚C	0.32	0.47	0.42	0.41
After Durability Testing	28˚C	0.30	0.92	0.57	0.60

XLPE fuel tanks

We tested several fluorinated cross-link polyethylene (XLPE) fuel tanks for permeation emissions. The first tank was a 6 gallon test tank produced by a marine fuel tank manufacturer specifically for this testing. The remaining fuel tanks were purchased on the open market. The fuel tanks were then treated by a fluorinater. We tested the first tank on certification gasoline. After a 20 week soak, we observed a permeation rate of 0.11 g/gal/day (1.52 $g/m^2/day$), which represented more than an 80 percent reduction in permeation.

The remainder of the fluorinated tanks were tested on E10 (10 percent ethanol) using the same procedures as for the HDPE tanks discussed above. These fuel tanks were treated at a level equivalent to what the fluorinater uses for automotive applications. All of the fuel tanks were treated both on the inside and outside. The test results, presented in Table 5.3-24, showed emission reductions of about 40 percent on average. Emission results from the sloshed fuel tanks were not significantly different than from the tanks that were not sloshed.

Table 5.3-24: EPA Permeation Data on Fluorinated Cross-Link Fuel Tanks at 29°C on E10

Fuel Tank	Capacity	Soak Period	g/gal/day	$g/m^2/day$	slosh test?
1	12 gallons	29 weeks	0.27 0.39 0.32 0.36 0.38	4.1 5.9 4.9 5.4 5.8	no no no no no
2	12 gallons	29 weeks	0.39 0.34 0.42 0.32	5.7 5.0 6.2 4.6	yes no no no
3	12 gallons	29 weeks	0.28 0.22 0.22	3.4 2.6 2.8	yes no no

5.3.2.3 Barrier Platelets

Another approach to creating a permeation barrier in a fuel tank is to blend a low permeable resin in with the HDPE and extrude it with a single screw. The trade name typically used for this permeation control strategy is Selar®. The low permeability resin, typically nylon or EVOH, creates non-continuous platelets in the HDPE fuel tank which reduce permeation by creating long, tortuous pathways that the hydrocarbon molecules must navigate to pass through the fuel tank walls. Although the barrier is not continuous, this strategy can still achieve greater than a 90 percent reduction in permeation of gasoline. EVOH has much higher permeation resistance to alcohol than nylon; therefore, it would be the preferred material to use for meeting our proposed standard which is based on testing with a 10 percent ethanol fuel.

We tested several portable gas cans and marine tanks molded with low permeation non-continuous barrier platelets 29°C. Six of fuel tanks tested were constructed using nylon as the barrier material. The remainder of the fuel tanks were constructed using ethylene vinyl alcohol (EVOH) as the barrier material. The advantage of EVOH is that it has much better resistance to alcohol than nylon. Five of the nylon based fuel tanks were tested on certification gasoline. The sixth tank was tested on E10 (10 percent ethanol) to evaluate the effectiveness of this material with alcohol blended fuel. The fuel tanks with the EVOH barrier were all tested on E10.

Testing was performed after the fuel tanks had been filled with fuel and stored at room temperature. The purpose of the soak period was to ensure that the fuel permeation rate had stabilized. Although 20 weeks was generally accepted as an acceptable period, we soaked the tanks with gasoline for 22 weeks and the tanks with E10 for 37 weeks. The fuel tanks were drained and then filled with fresh fuel prior to the permeation tests. Because the barrier platelets are integrated in the tank wall material, it did not seem likely that pressure or slosh testing would significantly affect the performance of this technology.

Table 5.3-25 presents the results of the permeation testing on the fuel tanks with barrier platelets. These test results show more than an 80 percent reduction for the nylon barrier tested on gasoline. However, the nylon barrier does not perform as well when a fuel with a 10 percent ethanol blend is used. Testing on a pair of 2 gallon tanks with nylon barrier showed 80 percent percent higher emissions when tested on E10 than on gasoline. We also tested fuel tanks that used EVOH barrier platelets. EVOH has significantly better resistance to permeation on E10 fuel than nylon (see Appendix 5D for material properties). For the fuel tanks blended with 6 percent EVOH, we observed an average permeation rate of about 1.4 $g/m^2/day$ on E10 fuel which meets our proposed permeation standard.

Table 5.3-25: Permeation Rates for Plastic Fuel Containers with Barrier Platelets Tested by EPA at 29°C

Percent Selar®*	Tank Capacity [gallons]	Test Fuel	Fuel Soak [weeks]	g/gal/day	g/m²/day
Nylon barrier platelets					
unknown**	2	gasoline	40	0.54	3.7
unknown**	2	E10	40	0.99	6.8
4%	5	gasoline	22	0.35	4.1
4%	5.3	gasoline	22	0.11	1.2
4%	6.6	gasoline	22	0.15	1.6
4%	6.6	gasoline	22	0.14	1.5
EVOH barrier platelets					
2%	6.6	E10	37	0.23	3.0
4%	6.6	E10	37	0.14	1.9
4%	6.6	E10	37	0.15	2.0
6%	6.6	E10	37	0.08	1.4
6%	6.6	E10	37	0.09	1.4

*trade name for barrier platelet technology used in test program
** designed to meet California permeation requirement

Manufacturers raised the concern about whether or not a tank using barrier platelets would have a stabilized permeation rate after 20 weeks. In other words, manufacturers were concerned that this technology may pass the test, but have a much higher permeation rate in-use. We tested one of the 4 percent and 6 percent EVOH tanks on E10 again after soaking for a total of 104 weeks (2 years). The measured permeation rates were 2.0 and 1.4 g/m^2/day for the 4 percent and 6 percent EVOH tanks, respectively, which represents no significant changes in permeation from the 37 week tests. In contrast we measured the 4 percent nylon tanks again after 61 weeks and measured a permeation rates of 2.8 and 2.7 g/m^2/day which represented about an 80-90 percent increase in permeation compared to the 22 week tests.

The California Air Resources Board (ARB) collected test data on permeation rates from portable fuel containers molded with low permeation non-continuous barrier platelets using California certification fuel. These fuel tanks all used nylon as the barrier resin. The results show that this technology can be used to achieve significant reductions in permeation from plastic fuel containers. This data was collected using a diurnal cycle from 18-41°C which is roughly equivalent to steady-state permeation testing at 30°C. Because the data is reported in g/gal/day, we only include the data on fuel tanks here that are compatible in size with marine fuel tanks. This test data showed that more than a 90 percent reduction in permeation is achievable through the use of nylon barrier platelets. However, all of this testing was performed on California certification fuel which does not include ethanol.

Table 5.3-26: Permeation Rates for Plastic Fuel Containers with Barrier Platelets Tested by ARB Over a 18-41°C Diurnal

Percent Selar®*	Tank Capacity [gallons]	Permeation Loss [g/gal/day]
4%	5	0.08
	5	0.09
(average =0.12 g/gal/day)	5	0.13
	5	0.16
	5	0.17
	6	0.08
	6	0.10
6%	5	0.07
	5	0.07
(average =0.09 g/gal/day)	5	0.07
	5	0.08
	5	0.12
	5	0.17
	6	0.06
	6	0.07
8%	5	0.08
	5	0.10
(average =0.07 g/gal/day)	6	0.05
	6	0.06

*trade name for barrier platelet technology used in test program

Dupont, who manufacturers Selar®, has performed testing on HDPE with higher blends of EVOH (known as Selar RB®). Table 5.3-27 presents permeation rates for HDPE and three Selar RB® blends when tested at 60°C on xylene.[93] Xylene is a component of gasoline and gives a rough indication of the permeation rates on gasoline. This report also shows a reduction of 99 percent on naptha and 98 percent on toluene for 8 percent Selar RB®.

Table 5.3-27: Xylene Permeation Results for Selar RB® at 60°C

Composition	Permeation, g mm/m^2/day	% Reduction
100% HDPE	285	–
10% RB 215/HDPE	0.4	99.9%
10% RB 300/HDPE	3.5	98.8%
15% RB 421/HDPE	0.8	99.7%

5.3.2.4 Alternative Materials

Permeation can also be reduced from fuel tanks by constructing them out of a lower permeation material than HDPE. Examples of alternative materials are metal, various grades of plastic, and new fiberglass construction.

5.3.2.4.1 Metal

Gasoline does not permeation through metal. Therefore, the only permeation from a metal fuel tank would be through rubber gaskets or O-rings that may be used to seal connections on the fuel tank. Examples would be the gasket or O-ring in a fuel cap or a bolted-on component such as a sender unit for a marine tank. Presumably, the exposed surface area of the gaskets would be small enough that a metal fuel tank would be well below our proposed permeation standard. One issue with metal fuel tanks, however, is fuel leakage due to corrosion. A study sponsored by the Coast Guard in 1994 showed that aluminum (and even stainless steel) fuel tanks are prone to failure, both in salt water and fresh water applications., due to corrosion.[94] Fuel leakages would not only be an environmental issue, but could be a safety issue as well. Aluminum fuel tank manufacturers have stated that corroding fuel tanks are typically due to improper installation.

5.3.2.4.2 Alternative Plastics

There are grades of plastics other than HDPE that could be molded into fuel tanks. One material that has been considered by manufacturers is nylon; however, although nylon has excellent permeation resistance on gasoline, it has poor chemical resistance to alcohol-blended fuels. As shown in Appendix 5D, nylon could be used to achieve more than a 95 percent percent reduction in permeation compared to HDPE for gasoline. However, for a 10 percent ethanol blend, this reduction would significantly less depending on the grade of nylon. For a 15 percent methanol blend, the permeation would actually be several times higher through nylon than HDPE.

Some handheld equipment, primarily chainsaws, use structurally-integrated fuel tanks where the tank is molded as part of the body of the equipment. In these applications, the frames (and tanks) are typically molded out of nylon for strength. We tested structurally-integrated fuel tanks from four handheld equipment manufacturers at 29˚C on both gasoline and a 10 percent ethanol blend. The test results suggest that permeation emissions are 20 to 70 percent higher on E10 than on gasoline for these fuel tanks. Note these fuel tanks are capable of meeting the proposed standards using their current materials. In the cases where the permeation rates were higher than these standards, it was observed that the fuel cap seals had large exposed surface areas on the O-rings, which were not made of low permeation materials. Emissions could likely be reduced significantly from these tanks with improved seal designs. Table 5.3-28 presents the results of this testing.

Table 5.3-28: Permeation Rates for Nylon Handheld Fuel Tanks Tested by EPA at 29°C

Tank ID	Application	Material	Test Fuel	Permeation Loss [g/m^2/day]
R1	clearing saw	nylon 6	gasoline	0.34
R2			E10	0.42
R3			E10	0.48
B1	hedge clipper	nylon 6, 33% glass	gasoline	0.62
B2			E10	1.01
B3			E10	1.12
B4			E10	0.93
W1	chainsaw	nylon 6, 30% glass	gasoline	1.45
W2			E10	2.18
W3			E10	2.46
G1	chainsaw	nylon 6, 30% glass	gasoline	1.30
G2			E10	1.41
G3			E10	2.14

Other materials which have excellent permeation resistance even with alcohol-blended fuels are acetal copolymers and thermoplastic polyesters. These polymers can be used to form fuel tanks in the blow-molding, rotational-molding, and injection-molding processes. An example of an acetal copolymer is known as Celcon® which has excellent chemical resistance to fuel and has been shown to be durable based on exposure to automotive fuels for 5000 hours at high temperatures.[95] As shown in Appendix 5D, Celcon would result in more than a 99 percent reduction in permeation compared to HDPE for gasoline. On a 10 percent ethanol blend, the use of Celcon would result in more than a 95 percent reduction in permeation. Two thermoplastic polyesters, known as Celanex® and Vandar®, are also being considered for fuel tank construction and are being evaluated for permeation resistance by the manufacturer. Celcon has a more crystalline structure than Vandar resulting in lower permeation but less impact resistance.

We tested a 1-liter blow-molded Vandar fuel tank and three rotationally-molded 3-liter fuel tanks made of impact toughened Celcon for permeation at 29°C on E10 fuel. Prior to the permeation testing, the fuel containers were soaked in E10 for more than 20 weeks. These test results are included in Table 5.3-29 below. For the Celcon tank tests, higher emissions were observed in the second week than the first week. This behavior was seen in repeat tests and was likely due to deterioration of the epoxy seal used in this testing. Therefore, the actual emission rates of the material are likely lower than presented below. More detailed data on this testing is available in the docket.[96]

Table 5.3-29: Permeation Results Acetal Copolymer Fuel Tanks at 29°C on E10

Material Name	Material Type	g/gal/day	g/m^2/day
Vandar V1	thermoplastic polyester	1.7	5.6
Impact C10 Resistant C11 Celcon C13	modified acetal copolymer	0.13 0.09 0.10	0.75 0.53 0.59

Fuel tank manufacturers have expressed some concern that the acetal copolymer is not as tough as cross-link polyethylene. Thermoplastic polyesters have better impact resistance, but higher permeation. The impact toughened fuel tanks mentioned above were in response to these concerns. Also, the rotational molding process must be better controlled to use these materials in comparison to XLPE. The temperature profile must be tightly controlled to uses Celcon, or formaldehyde gases may form. The moisture level of Vandar must be kept low prior to molding.

Acetal copolymers are also used today to produce many fuel resistant automotive components such as low permeation fuel caps. This construction has been used for many years in automotive applications and now acetal copolymers are being used to manufacture low permeation fuel caps for nonroad equipment as well.

Another low permeation thermoplastic that can be used in the manufacture of fuel tanks is a polyester/polycarbonate alloy. One example is marketed under the trade name of Xenoy 6620. This engineered plastic is impact modified and is intended for the injection molding process. The polyester provides good chemical resistance and the polycarbonate provides the impact resistance. Permeation testing was performed on a fuel tank made of Xenoy 6620 following the California test procedures. At 40˚C on California Phase II CERT fuel, the measured permeation rate was 0.26 g/m^2/day.[97] The manufacturer of this material also has a version that is modified slightly so that it can be used in the blow-molding process.

5.3.2.4.3 Low Permeation Fiberglass

One manufacturer has developed a low permeation fiberglass fuel tank construction.[98] The composite tanks are fabricated using a glass fiber reinforced closed cell urethane composite sheet as substrate and assembled with structural urethane adhesive as a fastening medium. These fuel tanks may be hand constructed, or for larger volume production, they may be molded at lower cost. Once fully assembled with necessary fuel fittings the tank is coated with fiberglass reinforced resin, sufficient for H-24 ABYC (American Boat and Yacht Council) and 33 CFR 183.510 standards for fuel systems mechanical strength requirements. A final gel coat finish may was applied for aesthetics.

Permeation control is achieved by incorporating fillers into a resin system and coating the assembled tank interior and exterior. This filler is made up of nanocomposites (very small particles of treated volcanic ash)[4] which are dispersed into a carrier matrix. This construction creates a tortuous pathway for hydrocarbon migration through the walls of the fuel tank. We tested a 14 gallon fuel tank provided by this manufacturer and measured a permeation rate of 0.97 g/m^2/day on E10 fuel at 29°C. Other advantages of this technology are improved strength and flame resistance compared to plastic fuel tanks.

5.3.2.5 Multi-Layer Construction

Fuel tanks may also be constructed out of multiple layers of materials. In this way the low cost and structural advantages of traditional materials can be utilized in conjunction with higher grade materials which can provide effective permeation resistance. Today, fuel tanks are made in many ways including higher volume blow-molding, lower volume injection molding, and very low volume rotational-molding. The discussion below presents data on several multi-layer fuel constructions.

5.3.2.5.1 Blow-Molded Coextruded Barrier

Coextruded barrier technology has been long established for blow-molded automotive fuel tanks. Data from one automobile manufacturer showed permeation rates of 0.01-0.03 g/day for coextruded fuel tanks at 40°C on EPA certification fuel. They are using this technology to meet LEV II vehicle standards. For comparison, this manufacturer reported permeation rates of more than 10 g/day for standard HDPE fuel tanks.[99]

Another study looks at the permeation rates, using ARB test procedures, through multi-layer fuel tanks.[100] The fuel tanks in this study were 6 layer coextruded plastic tanks with EVOH as the barrier layer (3 percent of wall thickness). The outer layers were HDPE and two adhesive layers were needed to bond the EVOH to the polyethylene. The sixth layer was made of recycled polyethylene. The two test fuels were a 10 percent ethanol blend (CE10) and a 15 percent methanol blend (CM15). See Table 5.3-30.

Table 5.3-30: Permeation Results for a Coextruded Fuel Tank Over a 18-41°C Diurnal

Composition	Permeation, g/day	% Reduction
100% HDPE (approximate)	6 - 8	–
3% EVOH, 10% ethanol (CE10)	0.2	97%
3% EVOH, 15% methanol (CM15)	0.3	96%

The California Air Resources Board tested two sets of three 5-gallon portable fuel containers.[101] Each set was manufactured by a different company, but all of the fuel tanks were blow-molded with a coextruded barrier layer. Testing was performed over the California 18-41˚C temperature cycle with California Phase II gasoline. Testing was performed with and

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[4] Chemically modified montmorillonite for nanocomposite formulation

without the spouts removed. The test data presented in Table 5.3-31 was after 174 days of fuel soak with the spouts removed and the openings welded shut. California reported the test results in grams per gallon. Table 5.3-31 also presents approximate g/m^2/day values based on the relationship between tank capacity and inside surface area used in the NONROAD2005 emissions model.

Table 5.3-31: ARB Permeation Results for a Coextruded Portable Fuel Tanks

Fuel Tank	Permeation, g/gal/day	Approximate Rate in g/m^2/day
B1	0.01	0.09
B2	0.01	0.11
B3	0.01	0.11
Average	0.01	0.10
M1	0.01	0.14
M2	0.02	0.21
M3	0.02	0.18
Average	0.02	0.17

Another approach has recently been developed in which a multi-layer fuel tank can be blow-molded with only two layers.[102] In this construction, a barrier layer of a polyarylamide known as Ixef MXD6 is used on the inside of a HDPE fuel tank. Ixef has permeation properties similar to EVOH. Test results showed a permeation rate of 0.8 g-mm/m^2/day at 60˚C on CE10 for a test film of Ixef. Unlike EVOH, Ixef can be exposed directly to the fuel which removes the need for an inner layer of HDPE. In addition, a tie material can be blended into the HDPE which will allow the polyarylamide to bond directly to the HDPE rather than using an adhesive layer.

5.3.2.5.2 Rotational Molded Dual-layer Construction

As discussed above, an inner layer can be molded into the inside of a rotationally molded fuel tank through the use of a drop-box that opens after the XLPE tank begins to form. Through this method, a XLPE fuel tank could be molded with a low permeation inner barrier. With this construction, it may be possible to reduce the amount of XLPE used depending on the structural characteristics of the inner liner material. For instance, acetal copolymer can be rotationally molded and could be used as the inner liner. This way, the permeation characteristics of an acetal copolymer could be achieved through an inner liner while still retaining the toughness of XLPE . One issue would be that acetal copolymers do not readily adhere to XLPE. Therefore fitting designs would need to account for this.

Another material that could be used in a multi-layer approach is nylon which comes in many grades. Typical nylon grades used in Small SI fuel tank constructions may not perform well in marine applications because of the hygroscopic nature of these nylons. In other words, typical nylon adsorbs water which can make it brittle. In addition, E10 fuel permeates through nylon much more readily than gasoline.

One manufacturer is working with a nylon known as Rilsan® polyamide 11 (PA 11) in constructing low permeation multi-layer rotational-molded fuel tanks.[103] Rilsan® polyamide 11 has two advantages to traditional nylons in that it is not hygroscopic and it is more resistive to alcohol fuels. One manufacturer has manufactured fuel tanks using the PA11 as an inner liner in a polyethylene shell. The manufacturer using this approach reports a permeation rate of about 3 g-mm/m^2/day on fuel CE10 at 28°C compared to about 30 g-mm/m^2/day for XLPE. In addition, the nylon used in multi-layer constructions is formulated with a polyethylene graft that causes it to adhere well to XLPE. This prevents the layers from separating in use.

We tested two 10 gallon multi-layer rotational molded fuel tanks at 29°C with E10 fuel after a 35 week soak with two fuel changes during that period.[104] One of the tanks was molded with an outer shell of medium-density polyethylene while the other was molded with an outer shell of cross-link polyethylene. The long soak period was due to test equipment problems and the fuel was changed with each test attempt. However, it presents valuable data on the longer term effectiveness of this technology. This test data is presented in Table 5.3-31. The manufacturer reported that this tank design passed testing on the Coast Guard burn, pressure, shock, and impulse test requirements.[105,106,107,108] In addition, a tank of this construction was tested and passed the tank durability tests for snowmobiles specified in SAE J288.[109] These tests include cold (-40˚C) and hot temperature (60˚C) immersion and drop tests.

Typically, multi-layer rotational-molded fuel tanks are constructed with the use of a drop box which adds the inner-layer material into the mold after the first material sets. Other approaches are to use a meltable bag containing the inner-layer material or even to pull the mold from the oven to add the inner-layer material. However, one manufacturer, that participated in the SBREFA process, has stated that they have developed a method to mold the inner liner without the use of a drop box or other approach that lengthens molding cycle time. This fuel tank manufacturer is selling fuel tanks using this construction for use in Small SI equipment and is selling mono-layer XLPE rotational-molded tanks for use in boats.

Table 5.3-31: Permeation Results PA 11/PE Fuel Tanks at 29°C on E10

Tank	Outer Shell	g/gal/day	g/m^2/day
1	MDPE	0.05	0.71
2	XLPE	0.06	0.79

Under their rule for small offroad equipment, California may issue executive orders to manufacturers with low emission products. As of August, 2006, ARB has issued 5 executive orders for low permeation fuel tanks.[110] Under these executive orders, two basic multi-layer rotomolded (XLPE and nylon) approaches have been approved. The California fuel tank permeation standard is 1.5 g/m^2/day tested at 40˚C on California certification fuel. However, most of the testing was performed on fuel CE10 which is a significantly more aggressive fuel for permeation. Table 5.3-32 presents the test results for rotational-molded fuel tanks with ARB executive orders. Note that the reported emissions are the average of 3-5 test samples.

Table 5.3-32: ARB Fuel Tank Executive Orders for Small Offroad Equipment

EO#	Test Fuel	$g/m^2/day$
C-U-05-005	CE10	0.81
	Phase II	0.18
C-U-06-014	CE10	0.10
	CE10	0.00
	CE10	0.09

There is another approach to dual-layer rotomolded fuel tanks under development that uses a “single shot” approach to molding.[111] In this method a material known as polybutylene terephthalate cyclic oligimor (CBT) is combined with the XLPE in the mold. Because of the different melt rates and viscosities of the two materials, during the mold process, the CBT® polymerizes into a thermoplastic known as polybutylene terephthalate (PBT) to form a barrier layer on the inside of the fuel tank. Adhesion between the PBT and XLPE comes from mechanical bonding between the two layers. This material can be used without lengthening the cycle time for rotational molding, and it does not require forced cooling.[112] Initial testing shows a permeation rate of <1 $g/m^2/day$ when tested with fuel CE10 at 40˚C for a sample with a 3.9 mm total wall thickness.[113] This wall thickness for this testing was composed of 0.9mm CBT and 3.0mm XLPE. PBT itself has a permeation rate on CE10 at 40˚C of less than 0.05 $g\text{-}mm/m^2/day$.

5.3.2.5.3 Injection-Molded Dual-Layer Construction

To add a barrier layer in the injection molding process, a thin sheet of the barrier material may be placed inside the mold prior to injection of the poleythylene. The polyethylene, which generally has a much lower melting point than the barrier material, bonds with the barrier material to create a shell with an inner liner.

5.3.2.5.4 Thermoformed Multi-Layer Construction

As an alternative, multiple layers can be created through thermoforming.[114] In this process, sheet material is heated then drawn into two vacuum dies. The two halves are then fused while the plastic is still molten to form the fuel tank. Before the halves are fused together, it is possible to add components inside of the fuel tank. Low permeation fuel tanks can be constructed using this process by using multi-layer sheet material. This multi-layer sheet can be extruded using similar materials to multi-layer blow-molded fuel tank designs. A typical barrier construction would include a thin EVOH barrier, adhesion layers on both sides, a layer of HDPE regrind, and HDPE layers on the outside surfaces.

This process has low capital costs compared to blow-molding and should be cost competitive with injection molding and rotational-molding. Manufacturers have indicated that this construction could be coated with an intumescent material which would help it pass the Coast Guard fire test. This coating could be applied directly to the multi-layer plastic sheets while they are still hot after extrusion. Once the plastic cools, it could be applied using flame ionization or electric arcing to increase the surface are of the plastic for adhesion.

EPA tested two, 5.6 gallon, thermoformed fuel tanks for permeation. These fuel tanks were constructed as described above with a thin EVOH barrier and were soaked with E10 for 27 weeks prior to testing. Due to test variability, testing was repeated at 35 and 44 weeks (fresh fuel was added prior to each weight loss test). From day to day, a constant weight loss was not always observed, and weight gains were occasionally seen. This variability in measured weight loss was likely due to the very low permeation rates combined with the effect of atmospheric conditions on measured weight. The highest variations in weight loss were observed when storms passed through suggesting that the changes in barometric pressure and relative humidity were affecting the buoyancy of the fuel tanks (discussed in more detail in Section 5.6.2.3). In the third round of testing (after 44 weeks), barometric pressure and humidity were measured and deemed to be relatively stable. In addition, a smaller tank with sand in it (rather than fuel) was measured simultaneously as a control to give some indication of the buoyancy effect. A small weight loss was measured for the control tank, suggesting that the measured test results may slightly overstate the permeation for the thermoformed fuel tanks. Table 5.3-33 presents the test results for each of the three tests.

Table 5.3-33: Permeation Results Multilayer Thermoformed Fuel Tanks at 29°C on E10

Soak (weeks)	Tank	g/gal/day	g/m^2/day
27	#16 #21	0.01 0.01	0.15 0.05
35	#16 #21	0.01 0.01	0.07 0.09
44	#16 #21	0.01 0.00	0.11 0.04
Average	#16 #21	0.01 0.01	0.11 0.06

5.3.2.5.5 Epoxy Barrier Coating

Another approach that has shown promising results is to coat a plastic fuel tank with a low permeation epoxy barrier coating. Early attempts at coating a plastic fuel tank resulted in coatings that eventually wear off due to the difficulty of bonding some materials to HDPE and XLPE. However, because fluorination increases the surface energy of the plastic, a low level of fluorination can be used to make it possible to apply an epoxy coating, even to XLPE. Because this approach is applied to the fuel tank post-molding, it can be used for any plastic fuel tank, regardless of the production molding method.

We performed permeation testing on six 12 gallon rotationally-molded XLPE fuel tanks with a thin, low-permeation epoxy coating. This coating was a two-part epoxy that was sprayed onto the tank and thermally cured in 45 minutes. Prior to the permeation measurements, the fuel tanks were soaked with E10 fuel at about 25°C for 15 weeks. The tanks were then drained and fresh E10 was added prior to the 29°C constant temperature permeation test. Inspection of the externally coated fuel tanks showed that the epoxy was unevenly applied and that some bare spots existed. This was reflected in the unsatisfactory permeation results. A more careful coating would be expected to result in similar results as the internal coatings. One of the externally coated fuel tanks was over-coated with a 1-part epoxy that was cured with a 45 second UV exposure. This tank was soaked for an additional 6 weeks prior to retesting. These test results, which are presented in Table 5.3-34, show that this technology can be used to reduce permeation emissions by more than 90 percent.

Table 5.3-34: EPA Permeation Data on Epoxy Coated XLPE Fuel Tanks at 29°C on E10

Fuel Tank Set	Coating	Soak Period	g/gal/day	g/m^2/day	slosh test?
1	Inside Thermocured	15 weeks	0.04 0.001 0.07	0.6 0.02 1.0	no no yes
2	Outside Thermocured*	15 weeks	0.13 0.23 0.23	1.9 3.3 3.3	no no yes
3	Outside UV cured	additional 6 weeks	0.03	0.4	no

* inspection showed uneven application of the coating which affected permeation results

Since the above testing was performed, the fluorinater and the epoxy manufacturer who developed this approach have performed more testing on their UV cured, 1-part epoxy. The testing was performed on epoxy coated HDPE bottles and 2 gallon fuel tanks using the California ARB test procedure of 40°C with California certification fuel.[115] At 29°C, we would expect the permeation rate to be about half of these levels due to the relationship between permeation and temperature discussed above in Section 5.3.1.2. The results for this testing were reported to be 0.3 g/m^2/day on average for both the bottles and tanks on gasoline. The bottles had a permeation rate of 0.5 g/m^2/day on gasohol (ethanol blend). This technology resulted in better than 95 percent reductions in permeation. Table 5.3-35 presents the test results after a 9 week fuel soak at 40°C.

Table 5.3-35: Permeation Data: Epoxy Coated HDPE Fuel Tanks at 40°C on CA Cert Fuel

Fuel Tank	g/gal/day	g/m^2/day
1	0.04	0.25
2	0.02	0.09
3	0.02	0.11
4	0.08	0.49

Roto-molders of marine fuel tanks generally use cross-link polyethylene. The advantage of XLPE is that its cross-link structure causes it to behave like thermoset which helps the fuel tanks pass the Coast Guard fire test (33 CFR 183.590) by holding their shape longer under exposure to fire. If a flame retardant were included in the epoxy coating, a less expensive material, such as HDPE could be used to make fuel tanks that are subject to the flame test requirement. The manufacturers who have developed the above approach for permeation have developed an additive that provides an intumescent coating to allow the fuel tanks to be produced at a lower cost. Testing on the Coast Guard burn test showed that an HDPE fuel tank would fail around after being exposed to a flame for about 1.5 minutes (the standard is 2.5 minutes). With the intumescent coating, the fuel tank passed the flame test and survived more than 5 minutes.[116]

5.4 Fuel/Vapor Hose Permeation

The polymeric materials (plastic or rubber) used in the construction of gasoline fuel and vapor hoses generally have chemical compositions much like that of gasoline. As a result, constant exposure of gasoline to these surfaces allows the material to continually absorb fuel. Permeation is driven by the difference in the chemical potentials of gasoline or gasoline vapor on either side of the material. The outer surfaces of these materials are exposed to ambient air, so the gasoline molecules permeate through these fuel-system components and are emitted directly into the air. Permeation emissions continue at a nearly constant rate, regardless of how much the vehicle or equipment is used. Because of these effects, permeation-related emissions can therefore add up to a large fraction of the total evaporative emissions.

This section summarizes the data and rationale supporting the permeation emission standard for fuel lines presented in the Executive Summary.

5.4.1 Baseline Hose Technology and Emissions

5.4.1.1 Marine Fuel Hose Subject to 33 CFR part 183

The majority of marine fuel hoses are constructed primarily of nitrile rubber with a chloroprene cover for abrasion and flame resistance. Hoses are designed to meet the Coast Guard requirements in 33 CFR part 183 which reference SAE J1527.[117] Fuel hose for boats with gasoline engines (excluding outboards) must meet the Class 1, Type A requirements which specify a maximum permeation rate of 100 g/m^2/day at 23°C on ASTM Reference Fuel C[118] (50 percent toluene, 50 percent iso-octane). Class 1 refers to hose that is used where liquid fuel is normally continuously in the hose. Type A refers to hose that will pass a 2½ minute flame resistance test.

On a fuel containing an alcohol blend, permeation would likely be higher from these fuel hoses. In fact, the SAE J1527 standard also requires Class 1 hose to meet a permeation rate of 300 g/m^2/day on fuel CM15 (15 percent methanol). Although ethanol is generally less aggressive than methanol, ethanol in the fuel would still be expected to increase the permeation rate significantly through most fuel hoses. Based on the data presented in Appendix 5D, permeation through nitrile rubber is about 50 percent higher when tested on Fuel CE10 (10 percent ethanol) compared to testing on Fuel C.

Fuel fill neck hoses are subject to a less stringent permeation standard under the Coast Guard specifications because they are not normally continuously in contact with fuel (Class 2). This relaxed standard is 300 g/m^2/day on Fuel C and 600 g/m^2/day on Fuel CM15 at 23°C. Where marine fuel hose is typically extruded, fill neck hose is generally constructed by wrapped layers on a mandrill. Fill neck hose is constructed with a larger inner diameter (1.5-2") to accommodate higher fuel rates and with thicker, more heavily reinforced walls, to prevent buckling and pinching.

Marine fuel hose is typically designed to be somewhat lower than the SAE J1527 requirements. Confidential data by one manufacturer supplying baseline marine fuel hose suggested that their fuel feed hose is about 25 percent lower than the Class 1, Type A requirement on Fuel C and about 35 percent lower on Fuel CM15. In their comments on the 2002 proposal for marine evaporative emission control, Lawrence industries stated that the majority of their fill neck hose permeates in the range of 150 to 180 g/m^2/day which is about half of the 300 g/m^2/day requirement required by the Coast Guard.[119]

We collected test data on marine hose permeation through contracts with outside laboratories.[120,121,122,123,124] Data was also available on a fuel feed hose testing funded by the marine industry.[125] All of the hose were prepared by soaking with liquid fuel for long enough periods to stabilize the permeation rate. This data is presented in Table 5.4-1. Note that this data shows somewhat lower permeation than was reported by manufacturers based on their own testing. Especially in the case of the fuel feed hose, this may be a function of the hose construction. This hose was purchased by the contractor without any knowledge of the hose construction. Therefore, it is not known if this is a representative sample of a baseline hose construction or if it contains some sort of barrier material.

Table 5.4-1: Permeation Rates for Baseline SAE J1527 Marine Fuel Hose

Hose Type	I.D.	Fuel Type*	g/m^2/day	Test Temperature
fuel feed hose	3/8"	E10 Fuel CE10	43 88	23 ˚C
vent hose	5/8"	E10	37	28 ˚C
fill neck hose	1.5"	Fuel C	95 98 109	22-36 ˚C temperature cycle
fill neck hose	1.5"	Fuel C Fuel CE10	87 164	23 ˚C
fill neck hose	1.5"	Fuel C E10 Fuel CE10	123 123 274	23 ˚C

* E10 refers to gasoline with 10 percent ethanol

Although fuel hose used in personal watercraft is subject to 33 CFR part 183, personal watercraft manufacturers do not use hose specified in SAE J1527. Fuel hose specifications are contained in a separate recommended practice under SAE J2046.[126] Under this practice, the permeation requirement is 300 g/m^2/day with testing performed in accordance with SAE J1527.

5.4.1.2 Other Marine Fuel Hose

Fuel hose used with outboard engines is not subject to 33 CFR part 183. This hose includes the fuel line from the portable fuel tank to the engine and fuel hose on the engine itself and is generally either constructed out of nitrile rubber with an abrasion resistant cover similar to hose used in recreational vehicle applications or is constructed out of polyvinyl chloride (PVC). One manufacturer of marine hose for use in outboard marine engines supplied permeation data on five hose constructions tested at 23°C.[127] This data is presented in Table 5.4-2 for Fuel C, Fuel CE10, and Fuel CM15 (15 percent methanol). As shown by this data, hose permeation rates can increase dramatically when tested on fuel blended with alcohol. Fuel lines connected to a portable fuel tank are also generally fitted with a primer bulb which is also typically constructed from nitrile rubber.

Table 5.4-2: Permeation Rates for Baseline Fuel Hose [g/m^2/day at 23°C]

Fuel Hose	Fuel C	Fuel CE10	Fuel CM15	gasoline*	E10
C-464-D11	195	420	590	66	192
C-530-D2-CE	5	183	546	4	74
ECO/CPE	228	402	565	53	131
J30R7	426	279	433	27	126
OMC ES1763	141	290	314	43	103

* cited as Marathon 92

5.4.1.3 Small SI Equipment Hose

Fuel hoses produced for use in Small SI equipment are generally extruded nitrile rubber with a cover for abrasion resistance. This hose is often equivalent to SAE J30 R7 hose which as a permeation requirement of 550 g/m^2/day at 23°C[128] on ASTM Fuel C (50 percent toluene, 50 percent iso-octane). On a fuel containing an alcohol blend, permeation would likely be much higher for these fuel hoses. R7 hose is made primarily of nitrile rubber (NBR). Based on the data presented in Appendix 5D, permeation through NBR is 50 percent higher when tested on Fuel CE10 (10 percent ethanol) compared to testing on Fuel C.

One manufacturer performed a study of several hose samples and various fuel types.[129] Permeation testing was performed using the methodology in SAE J30. These hose samples included SAE J30 R7, R8, and R9 hose. The R7 hose samples were constructed with an acrylonitrile inner tube with a chlorosulfonated polyethylene cover layer. The R8 hose samples were constructed using a epichlorohydrin ethyleneoxide copolymer. The R9 hose used a fluoroelastomer barrier for the inner tube with an outer tube made of chlorosulfonated polyethylene compound reinforced with a polyester braid. Over the two week tests, the study showed a peak permeation rate after 4-6 days for R7 and R8 hose and a peak permeation rate after 10-12 days for the lower permeating R9 hose. Table 5.4-3 below presents the two week averages for each of the hose samples and test fuels. In this study, the hose manufacturers were not identified, but the hose samples were each given a letter designation.

Table 5.4-3: Permeation Rates for SAE J 30 Fuel Hose [g/m^2/day at 23°C]

Fuel Hose	Fuel C	Fuel CE10	Fuel CE15	Fuel CM15
SAE J30 R7 “mfr. D”	450	508	541	587
SAE J30 R7 “mfr. E”	330	501	433	707
SAE J30 R8 “mfr. B”	152	385	337	620
SAE J30 R8 “mfr. F”	130	355	308	545
SAE J30 R9 “mfr. A”	2	11	10	73
SAE J30 R9 “mfr. C”	2	6	4	55

Handheld equipment typically use smaller diameter hose made of a single material with no cover. This fuel hose may either be extruded straight run hose or may be more complex injection-molded designs. To determine baseline permeation emission rates from hose on handheld equipment, testing was performed by industry using a modified SAE J30 weight loss procedure.[130] In this modified procedure, E10 fuel was used and the testing followed a 30 day fuel soak intended to stabilize the permeation rate. Table 5.4-4 presents the test results.

Table 5.4-4: Handheld Product Fuel Line Permeation Test Data [E10 fuel at 23˚C]

Hose Identification	Construction	Material	$g/m^2/day$
90014	extruded	NBR	198
90015		NBR	192
90016		NBR	168
S3		NBR	165
S4		NBR	171
H1		NBR	360
H2		NBR	455
S1	injection-molded	NBR	198
S2		NBR/PVC	386

5.4.1.4 Fuel Effects on Hose Permeation

As shown in the data above, adding ethanol or methanol to the test fuel significantly affects the permeation rate through fuel hoses. Because the SAE guidelines typically specify Fuel C for testing, most of the hose data available in the literature is on Fuel C or some blend of Fuel C and ethanol or methanol.

One study looked at the effect of fuel composition on the permeation of several materials used in baseline hose constructions.[131] This data suggests that Fuel C is a more aggressive fuel with respect to permeation than gasoline. In addition, this data shows that permeation for these materials is very low with diesel fuel. Table 5.4-5 presents the data from this study. Appendix 5D includes a table spelling out the acronyms for the hose materials in this table.

Table 5.4-5: Permeation Rates by Fuel and Fuel and Hose Material [g/m^2/day at 21°C]

Material	Fuel C	CE10	CM10	Indolene*	IE10	IM10	Diesel
CFM	nil	35	nil	0.1	20	nil	3
CO	150	270	255	10	80	125	2
ECO	190	390	310	55	180	150	5
ETER	230	400	360	65	205	165	10
39% ACN NBR	300	420	360	110	200	200	15
CSM	490	575	665	210	240	300	nil
CR	640	690	740	320	340	385	10

* "Indolene" refers to a fuel meeting the EPA specifications for certification gasoline

This difference in permeation between Fuel C and gasoline is likely due to the higher aromatic content of Fuel C than of certification gasoline. A second study compared three common fuel system materials on Fuel C and certification gasoline.[132] Fuel C is made up of 50 percent toluene and 50 percent isooctane. As a result, it is half aromatics and half aliphatics. In this study, the certification gasoline was observed to be 29 percent aromatics, 67 percent aliphatics, and 4 percent olefins. The test results were indicative of the effect of aromatics on permeation. Table 5.4-6 presents the permeation rate reported in g-mm/m^2/day for three sample materials: a low permeation fluoroelastomer (FKM), two medium permeation epichlorohydrins (ECO) and two high permeation nitrile rubbers (NBR). This testing, which was performed at 24˚C, gives a good comparison of the effect of gasoline versus Fuel C on permeation.

Table 5.4-6: Fuel C Versus Gasoline Permeation by Hose Material [g-mm/m^2/day]

Material	Fuel C	Indolene*	% difference
FKM-1	3.3	1.2	-64%
ECO-1	180	33	-82%
ECO-3	282	45	-84%
NBR-1	570	255	-55%
NBR-2	705	510	-28%

* "Indolene" refers to a fuel meeting the EPA specifications for certification gasoline

5.4.1.5 Vent Hose Permeation

Permeation occurs not only through hose walls that are in contact with liquid gasoline, but also through surfaces exposed to fuel vapor. In the event that the fuel vapor represents a saturated mix of air and fuel, we would expect permeation to be the same as that for exposure to liquid fuel. In a fuel tank, the walls of the tank are readily exposed to saturated vapor as discussed earlier in Section 5.3.1.4. In a fuel system hose not continuously exposed to liquid fuel, the vapor concentration may be significantly lower than saturation for several reasons. Clearly, if a hose is open to atmosphere, such as vent hose, there would be a gradient through the hose ranging from saturated vapor in the fuel tank to fresh air outside of the fuel system. In addition, if the tank is venting and drawing in air due to diurnal (or other) temperature changes, then the fuel hose will regularly be exposed to varying vapor concentrations.

To investigate permeation rates for vent hose exposed to gasoline vapor, we contracted with an outside laboratory to measure the permeation of fuel through marine hoses under various venting configurations.[133,134] The marine hose used in this testing met the USCG requirements for SD/I vessels in specified in 33 CFR part 183 and SAE Recommended Practice J1527. Each section of hose was connected to a metal fuel reservoir and exposed to liquid fuel for 8 weeks at 40°C to stabilize the permeation rate. The test fuel was EPA certification gasoline blended with 10 percent ethanol (E10) Each section of hose was then soaked for an additional 2 weeks at 40°C in the planned test configuration. After the soak, fresh fuel was added to the reservoirs and permeation was measured in a mini-SHED. Hose sections were tested at constant temperature in three configurations.

One section of hose was tested exposed to liquid fuel. Two sections of hose (1.5 and 5/8" I.D.) were tested with one end connected to the fuel reservoir and the other opened to atmosphere through a fitting in the SHED. This configuration was intended to simulate vent hose at constant temperature. A third configuration was also tested where three sections of hose were configured as vent hose and tested over a 22.2-35.6°C one day diurnal sequence. This test was intended to simulate vent hose in a fuel system exposed to fuel tank breathing caused by temperature variation. The data in this testing, shown in Table 5.4-7, suggest that permeation rates for vent lines are much lower than for hose that is regularly exposed to liquid fuel. This result is likely due to a fuel concentration gradient in the hose which is largely due to one end being exposed to fresh air.

Table 5.4-7: Effect of Venting on Hose Permeation with E10 [g/m^2/day]

I.D. inches	Length feet	Temperature	Liquid Exposure	Vented to Atmosphere
1.5	1	28°C (84°F) constant	123*	3.3
0.625	3		37	5.8
0.625	3	22-36°C (72-96°F) diurnal	–	4.3
0.625	3			4.5
0.625	3			4.9

* taken from Table 5.4-1 on a similar hose for comparison

The marine industry also funded permeation testing on vent hose exposed only to fuel vapor and air.[135] The vent line hose was preconditioned by attaching the hose to a 55 gallon steel drum containing commercial gasoline containing 10 percent ethanol and setting the drum outside during the summer. A carbon canister was attached to the end of the hose to simulate a vent line with diurnal emission control. Permeation was measured after 90, 120, 150, and 180 days of preconditioning. Because of the large size of the test rig, weight loss testing could not be performed. Instead, a sleeve was fitted over the hose and nitrogen was flowed through the sleeve to a carbon trap. The change in the weight of the carbon trap was then measured to determine the permeation rate. As with the fill neck testing, the hose was configured to run vertically from the top of the fuel reservoir (55 gallon drum). Repeat testing was performed on this hose and both values for each hose are presented in Table 5.4-8. The permeation rates for this testing were lower than for similar hose exposed to liquid fuel. Fuel vapor stratification may have been caused by a number of factors including breathing of fresh air into the tank during ambient cooling periods, gravity, and a limiting diffusion rate.

Table 5.4-8: Industry Test Data on Marine Vent Hose Exposed to Fuel Vapor

Hose manufacturer	Permeation [g/m^2/day]
#1	2.7, 2.2 2.7, 2.8 8.9, 8.5 5.7, 6.6
#2	2.2, 2.0 2.5, 2.2 2.5, 2.6

5.4.1.6 Vapor Hose Permeation

Even in a vapor hose that is sealed at one end, stratification may occur for a fuel system due to gravity. An example of vapor hose would be fuel fill neck hose with a sealed cap. Because fuel vapor is heavier than air, even a large diameter hose may see stratification of fuel vapor concentration if it reaches high enough above the surface of the liquid fuel. The stratification of vapor molecules happens slowly but would likely be observed under static conditions. Another cause of low vapor concentration in fuel system hose may occur due to the properties of diffusion discussed above in Section 5.1.3. If the hose diameter is small compared to its length, diffusion of vapor into the hose may be the rate limiting step rather than the permeation rate through the hose. In other words, the fuel vapor may enter the hose much slower than rate at which it could permeate through the hose. This effect could be combined with the other effects discussed above to cause lower permeation for fuel hose exposed to vapor rather than liquid fuel.

The marine industry funded permeation testing on fill neck exposed only to fuel vapor.[136] For the fill neck hose, a three foot section of hose was attached to the top of a five gallon metal fuel reservoir and configured vertically. The fuel reservoir was filled half-way with gasoline containing 10 percent ethanol. Approximately every 30 days, this hose/reservoir assembly was weighed for five days in a row. After the fifth day, the fuel in the reservoir was replaced with fresh fuel. Testing was performed at 23˚C. The only liquid fuel exposure was a weekly inversion of the assembly for about 1 minute. No attempt was made to simulate fuel slosh that would be likely be seen in a boat in the water. Also the hose was configured straight up and down rather than in a more representative configuration as seen on a boat that would include more horizontal orientation for most of the length of the hose. Repeat testing was performed on the hose.[137] During this repeat testing, permeation was also measured for the same fill neck hose exposed to liquid fuel.

Four of the fill neck hose constructions were specified as meeting the A2 designation in SAE J1527. The other two fill neck hose samples were not identified except that they are made by a hose manufacturer that is known to offer fill neck hose with and without a fluoroelastomer barrier. Table 5.4-9 presents the test results which show much lower permeation rates for fill neck hose exposed vapor rather than liquid fuel. Because the end of the hose was not exposed to atmosphere, and because the hose was situated well above the surface of the liquid fuel in a vertical fashion, stratification may have occurred in the hose largely due to gravity. This stratification would be expected to lower the vapor concentration in the hose and therefore lower permeation.

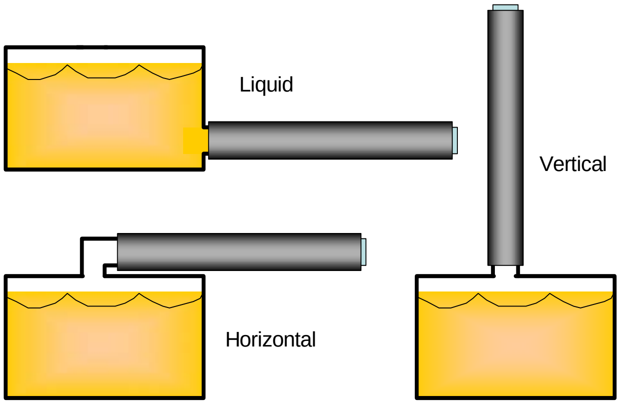
Table 5.4-9: Industry Permeation Data on Marine Fill Neck Hose [g/m^2/day]

Hose manufacturer	Vapor Exposure	Liquid Exposure
#1	4.8, 4.8	129
	4.5, 4.4	114
	4.7, 4.8	113
	4.7, 4.7	121
#2	1.3, 1.1	5.6
	0.6, 6.9	8.5

The marine industry testing was all performed on static test rigs with vertically oriented hose. No consideration was given to how sloshing the test configuration, as would be seen in a boat in the water, would have affected the results. For in-use equipment, especially boats in the water, the fuel is sloshed regularly due to operation or waves. This sloshing may mix up the vapor in the tank and hose. The industry test program also did not consider how a different hose configuration (i.e. more horizontally oriented) would have affected the results. Fill neck hose in boats often runs nearly horizontal from the tank to the edge of the boat, then runs more vertically near the fill port.

We contracted with an outside test lab to investigate the effects of fuel slosh and hose configuration on permeation through marine fill neck hose.[138] All of the testing was performed on 3 foot sections of 1.5" I.D. marine fill neck hose. Testing was performed in each of the three configurations shown in Figure 5.4-1. For each fuel vapor exposure test, the hose was first preconditioned by subjecting it to liquid fuel for 5 weeks followed by fuel vapor for an additional 5 weeks. For the liquid fuel exposure tests, the hose was soaked with liquid fuel for

Figure 5.4-1: Hose Test Configurations



10 weeks. Fuel soaking was performed at 40˚C.

A total of eleven tests were run. For each configuration, testing was performed on three fuels: Fuel C, CE10, and E10. The liquid fuel exposure tests were performed in the static position, while the fuel vapor exposure tests were performed with the fuel tanks on a slosh table. Sloshing was performed at 15 cycles per minute with a deviation of +7˚ to -7˚ from level to simulate movement that might be seen on a boat. An additional two tests were performed to measure permeation through vapor hose in the vertical and horizontal positions without sloshing. Permeation was measured similar to the industry testing using weight loss measurements of the entire test rigs at 23˚C.

The test results from this testing are presented in Table 5.4-10. It was observed that permeation was much lower for vapor fuel exposure than for liquid fuel exposure. Fuel permeation was significantly higher for the horizontal hose configuration than for the vertical hose configuration. This suggests that a large amount vapor stratification was occurring for the vertical hose, while some fuel vapor was collecting in the horizontal hose. The fuel sloshing applied in this testing doubled the permeation through the horizontal hose. Regardless of fuel slosh, no measurable permeation was observed through the vertically oriented hose. Permeation emissions were observed to be about twice as high on fuel CE10 than on Fuel C or E10.

Table 5.4-10: Effect of Hose Configuration, Vapor Exposure, and Test Fuel on Marine Fill Neck Hose Permeation at 23˚C

Hose Configuration	Vapor Exposure	Test Fuel	Permeation [g/m^2/day]
horizontal	stationary	CE10	4.6
	sloshed	CE10	9.1
	sloshed	E10	4.6
	sloshed	Fuel C	9.1
vertical	stationary	CE10	0.0
	sloshed	CE10	0.0
	sloshed	E10	0.0
	sloshed	Fuel C	0.0
liquid soak		CE10	273.7
		E10	123.2
		Fuel C	123.2

In another study, the effects of liquid fuel versus vapor were studied in which the vapor hose was not open to atmosphere.[139] The fuel hose used for this testing was purchased over the counter and was labeled as SAE J30 R7. Further investigation of the hose revealed that this particular grade is made of lower permeation materials than typical Small SI hose constructions. It was constructed of NBR with a relatively high ACN blend (39 percent) and an ECO cover was used. This construction was originally intended to allow the hose to be painted with a lacquer-based paint, then dried in an oven. Although this is a somewhat atypical hose construction, the test results should still reflect the effects of liquid versus vapor on permeation.

In this testing, all of the fuel hose was preconditioned by soaking in liquid fuel for 5 weeks at about 40˚C. This soak was then repeated, except that half of the hose sections were then exposed only to fuel vapor resulting from attaching the hose to the top of a metal fuel reservoir. Three fuels were used; California certification gasoline (CARB II), EPA certification gasoline (gasoline), and EPA gasoline blended with 10 percent ethanol (E10). After the soak period, the fuel was refreshed and weight loss testing was performed at 23˚C. Table 5.4-11 presents the test results. Note that each data point in this table is the average of three hose samples. In this testing, the end of the hose was plugged and the hose was configured horizontally. The lower permeation rates for vapor exposure were likely the result a low vapor concentration in the hose. This low vapor concentration may have been caused because the diffusion into the long narrow hose may have been the rate limiting effect rather than the permeation rate through the hose.

Table 5.4-11: Fuel Hose Permeation with Vapor vs. Liquid Exposure [g/m^2/day]

Test Fuel	Liquid Exposure	Vapor Exposure
CARB II	35.8	0.3
Gasoline	44.5	0.1
E10	80.3	0.7

5.4.2 Hose Permeation Reduction Technologies

Materials used in current automotive fuel lines are two to three orders of magnitude less permeable than nitrile hoses.[140] In automotive applications, multilayer plastic tubing, made of fluoropolymers is generally used. An added benefit of these low permeability lines is that some fluoropolymers can be made to conduct electricity and therefore can prevent the buildup of static charges.[141] Although this technology can achieve more than an order of magnitude lower permeation than barrier hoses, it is relatively inflexible and may need to be molded in specific shapes for each Small SI application. For marine applications, this tubing would not likely meet the Coast Guard or ABYC durability specifications for fuel and vent hose.

Thermoplastic fuel lines for automotive applications are generally built to SAE J2260 specifications.[142] Category 1 fuel lines under this specification have permeation rates of less than 25 g/m^2/day at 60°C on CM15 fuel (15 percent methanol). One thermoplastic used in automotive fuel line construction is polyvinylidene fluoride (PVDF). Based on the data presented in Appendix 5D, a PDVF fuel line with a typical wall thickness (1 mm) would have a permeation rate of 0.2 g/m^2/day at 23°C on CM15 fuel. However, manufacturers involved in the boat building industry have commented that this fuel line would not be flexible enough to use in their applications because they require flexible rubber hose to fit tight radii and to resist vibration. They also commented that the hose they use must pass the Coast Guard flame resistance requirements.[143,144]

Recreational vehicle manufacturers are required to use hose that meets a permeation standard of 15 g/m^2/day at 23°C on gasoline blended with 10 percent ethanol (E10). Low permeation hose constructions that have been identified for these applications could also be used in Small SI equipment. We believe that the same barrier materials that will be used for recreational vehicle hose can also be used for marine hose constructions. Marine hose constructions generally meet the Coast Guard flame resistance requirements either through the use of a flame-resistant cover, or by increasing the wall thickness. Therefore, the addition of an inner permeation barrier would not be expected to affect the flame resistance of the hose. Several low permeation hose constructions are discussed below. Even though most of this data is on hoses not designed for marine applications, the barrier technology can be used in marine hose.

We are proposing that fuel and vapor hose meet our standards on E10 fuel for two reasons. First, ethanol is commonly a component of in-use fuels. Second, for many materials used in hose constructions, permeation would likely be much higher for fuel containing ethanol. For instance, a typical barrier material used in barrier hose constructions is FKM. Based on the data presented in Appendix 5D for FKM, the permeation rate is 3-5 times higher on Fuel CE10 than Fuel C. Therefore, a hose meeting 15 g/m^2/day at 23°C on Fuel C may actually permeate at a level of 40-50 g/m^2/day on fuel with a 10 percent ethanol blend.

There are lower permeation fuel hoses available today that are manufactured for automotive applications. These hoses are generally used either as vapor hoses or as short sections of fuel line to provide flexibility and absorb vibration. One example of such a hose[145] is labeled by General Motors as “construction 6" which is a multilayer hose with an inner layer of a fluoroplastic known as THV sandwiched in inner and outer layers of a rubber known as ECO.[5] A hose of this construction would have less than 8 g/m^2/day at 40°C when tested on CE10.

Permeation data on several low permeation hose designs were provided to EPA by an automotive fuel hose manufacturer.[146] This hose, which is as flexible as non-barrier hose, was designed for automotive applications and is available today. Table 5.4-12 presents permeation data on three hose designs that use THV 800 as the barrier layer. The difference in the three designs is the material used on the inner layer of the hose. This material does not significantly affect permeation emissions through the hose but can affect leakage at the plug during testing (or connector in use) and fuel that passes out of the end of the hose which is known as wicking. The permeation testing was performed using the ARB 18-41°C diurnal cycle using a fuel with a 10 percent ethanol blend (E10).

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[5] THV = tetrafluoroethylene hexafluoropropylene, ECO = epichlorohydrin/ethylene oxide

Table 5.4-12: Hose Permeation Rates with THV 800 Barrier over ARB Cycle (g/m^2/day)

Hose Name	Inner Layer	Permeation	Wicking	Leaking	Total
CADBAR 9610	THV	0.16	0.00	0.02	0.18
CADBAR 9710	NBR	0.17	0.29	0.01	0.47
CADBAR 9510	FKM	0.16	0.01	0.00	0.18

The data presented above shows that there is hose available that can easily meet the proposed hose permeation standard on E10 fuel. Although hose using THV 800 is available, it is produced for automobiles that will need to meet the tighter evaporative emission requirements in the upcoming Tier 2 standards. Hose produced in mass quantities today uses THV 500. This hose is less expensive and could be used to meet the proposed hose permeation requirements. Table 5.4-13 presents information comparing hose using THV 500 with the hose described above using THV 800 as a barrier layer.[147] In addition, this data shows that permeation rates more than double when tested on CE10 versus Fuel C.

Table 5.4-13: Comparison of Hose Permeation Rates with THV 500 and 800 (g/m^2/day)*

Hose Inner Diameter, mm	THV 500		THV 800	
	Fuel C	Fuel CE10	Fuel C	Fuel CE10
6	0.5	1.4	0.2	0.5
8	0.5	1.4	0.3	0.5
10	0.5	1.5	0.2	0.5

* Calculated using data from Thwing Albert materials testing (may overstate permeation)

We contracted with an independent testing laboratory to test several samples of SAE J30 R9 hose and a sample each of automotive vent line and fill neck hose for permeation.[148,149,150,151,152,153] The fuel and vapor hoses had a six mm inner diameter. The test lab used the SAE J30 test procedures for R9 hose with both Fuel C and Fuel CE10. Most of the R9 fuel hose was supplied by recreational vehicle manufacturers who also supplied information on the materials used in the construction of the hose as well. We purchased one sample of the R9 hose (which was labeled as such) from a local auto parts store without knowing its construction. Two additional R9 hoses were tested by a fuel hose manufacturer on fuel CE10 after a four week soak.[154] The SAE permeation specification for R9 hose is 15 g/m^2/day at 23˚C on Fuel C. The R9 hose tested all met this limit, even on ethanol blend fuels which typically result in higher permeation. The automotive vent line showed similar results, but the automotive fill neck showed much lower permeation. Table 5.4-14 presents the test data on the above hose samples.

Table 5.4-14: Test Results on Commercially Available Hose Samples (g/m^2/day)

Hose Sample	Construction	Fuel C	Fuel CE10
SAE J30 R9	FKM/ECO	–	7.6
SAE J30 R9	FKM/ECO	–	2.1
SAE J30 R9	FKM/NBR/CM	–	4.2
SAE J30 R9	FKM/ECO	–	10.9
SAE J30 R9	FKM/ECO	–	5.2
SAE J30 R9	PVC/EEC	–	11.6
SAE J30 R9	FKM barrier	–	6.6
SAE J30 R9	fluorine/hydrin	–	9.0
SAE J30 R9	unknown	10.1	12.1
SAE J30 R9	FKM barrier	–	4.2
SAE J30 R9	FKM barrier	–	6.7
Automotive vent line	unknown	10.9	9.0
Automotive fill neck	unknown	0.33	0.49

Another hose construction that can be used to meet the marine hose permeation standards is known as F200 which uses Teflon® as a barrier layer. Teflon® has a permeation rate of 0.03-0.05 g-mm/m^2/day on 15 percent methanol fuel. F200 hose is used today to meet SAE J30 R11 and R12 requirements for automotive applications. Table 5.4-15 presents data on permeation rates for several F200 constructions.[155]

Table 5.4-15: F200 Typical Fuel Permeation

Film Thickness [mils]	Hose Diameter [in.]	Fuel	g/m^2/day @23°C	g/m^2/day @40°C
2	0.375	TF-2	--	0.7
2	0.275	TF-2	--	1
2	0.275	M25	0.5	4
2	0.470	CE10	--	3
2	0.625	CE10	--	3
1	0.625	CE10	--	4
1	1.5	CE10	1.5	--

Low permeability hoses produced today are generally constructed with a barrier material layer. There are hoses used in some marine applications with a thermoplastic layer (either nylon or EVOH) between two rubber layers to control permeation. Because the thermoplastic layer is very thin, on the order of 0.1 to 0.2 mm, the rubber hose retains its flexibility. Through contract with two independent labs, we tested three samples of marine barrier hose that was available prior to our initial proposal for marine permeation emissions. This hose included two 3/8" samples and one 5/8" sample which all used nylon as the permeation barrier. These hose constructions are used in some sterndrive and inboard applications. Table 5.4-16 presents the permeation test results at 23°C.[156,157,158,159,160,161]

Table 5.4-16: Test Results on Available Barrier Marine Hose Samples (g/m^2/day)

Hose Description	Lab 1		Lab 2*
	Fuel C	Fuel CE10	Fuel C
3/8" marine barrier fuel hose	0.80 --	5.2 11.6	0.36 --
5/8" marine barrier fuel hose	--	3.4	0.76

* average of three tests

Similar testing was performed by the marine industry on commercially available low permeation marine hose.[162] In this testing, the 3/8" I.D. fuel hose samples were connected to metal fuel reservoirs and soaked with gasoline containing 10 percent ethanol at 23˚C for 180 days. The weight of the container/hose assembly was measured for five days in a row approximately every 30 days. The fuel was replaced with fresh fuel after each series of weight measurements. The test report did not specify details on the hose constructions. However, based on the manufacturer part numbers, several of the hoses in this test program were determined to use a nylon barrier layer. One of the hoses included was a baseline rubber construction meeting Coast Guard requirements for SD/I fuel hose. Repeat testing was performed on the hose.[163] During this repeat testing, permeation was also measured for the same hose exposed to fuel CE10. Although the permeation rate was generally higher on fuel CE10, the barrier hose permeation rates were still well below the proposed standard. Table 5.4-17 presents the results of this testing.

Table 5.4-17: Permeation Results for Commercially Available Marine Barrier Hose Tested at 23˚C with Gasoline Containing 10% Ethanol (g/m^2/day)

Hose Construction	Gasoline with 10% Ethanol	CE10
SAE J1527 A1 constructions with nylon barrier	6.2, 5.2 5.6, 5.1 4.4, 3.8 4.4, 3.2	6.1 6.7 10.0 12.1
not reported	0.4, 0.1	0.0

After the initial proposal for marine permeation emissions, two marine hose manufacturers developed hose samples using the F200 hose construction. In addition, other hose manufacturers supplied samples of barrier hose using the F200 hose construction and using THV800 as a barrier layer. These manufacturers stated that they could make marine hose using the same barrier construction. We contracted to have these hose samples permeation tested on fuel CE10 at 23°C following a four week soak.[164] These test results are presented in Table 5.4-18.

Table 5.4-18: Permeation Test Results on New Marine Barrier Hose Constructions

Application	Barrier Material	I.D. [inches]	$g/m^2/day$
marine fill neck	Teflon (F200)	1½	0.2
marine fuel hose	Teflon (F200)	3/8	5.0
fuel hose	Teflon (F200)	1/4	3.8
fuel hose	THV 800	1/4	5.1

Currently, the Coast Guard requires that fuel pumps on engines be located on or near the engine to minimize the length of high pressure fuel lines on the vessel. However, at least one manufacturer sells boats with the high pressure fuel pump in the fuel tank. They received a waiver from the Coast Guard by using fuel lines that use either a glass fiber or stainless steel braid cover and quick connect end fittings that are designed to withstand very high pressures (much higher than would be seen on a boat).[165] This particular fuel line construction also uses Teflon® as a barrier layer. Table 5.4-19 presents permeation test data on this hose.[166]

Table 5.4-19: Permeation Test Data on Reinforced Fuel Hose

Application	I.D. [inches]	Temperature	Fuel	$g/m^2/day$
Marine	0.31 0.25 0.19	23°C	CE10	0.05 0.08 0.05
Outdoor Power Equipment	0.31 0.25 0.19	60°C	CM15	0.52 0.93 1.08

Primer bulbs are typically injection-molded out of nitrile rubber. Fuel lines for some handheld equipment are manufactured in a similar manner. Low permeation primer bulbs and fuel lines could be manufactured using a similar process by molding them from a fluoroelastomer such as FKM. Fluoroelastomers, such as FKM, have similar physical properties as nitrile rubber but are much more fuel-resistant. If the primer bulb or fuel line were molded out of a FKM with a sufficient flurorine concentration, the permeation rate would be less than proposed fuel line permeation standard. Alternatively, primer bulbs could be manufactured to meet the proposed standards by molding a fluoroelastomer inner liner with a nitrile shell to reduce costs. Other materials may be applicable as well (see tables of material properties in Appendix 5D).

Under their rule for small offroad equipment, California may issue executive orders to manufacturers with low emission products. As of August, 2006, ARB has issued 24 executive orders for low permeation fuel lines.[167] The California fuel line permeation standard is 15 $g/m^2/day$ tested at 40˚C on California certification fuel. However, many of the manufacturers tested their products on CE10 fuel which results in significantly higher permeation rates. Some manufacturers even tested at 60˚C. In all cases, the test results were below the 15 $g/m^2/day$ standard, even under the more challenging test conditions. Table 5.4-20 presents the test results for the fuel lines with ARB executive orders. Note that the reported emissions are the average of 5-6 test samples.

Table 5.4-20: ARB Fuel Hose Executive Orders for Small Offroad Equipment

EO#	I.D. [mm]	Test Fuel	Temperature	$g/m^2/day$
C-U-06-016	4.8	CE10	40	3.75
C-U-06-001	6.0	CE10	40	1.42
G-05-016	6.4	CE10	40	4.62
G-05-017	6.4	CE10	40	5.97
G-05-019	6.4	CE10	40	0.02
C-U-05-004	6.4	CE10	40	12.3
C-U-05-010	6.4	CE10	40	10.6
G-05-019*	6.4	CE10	60	0.26
G-05-015a	7.9	CE10	60	11.1
C-U-05-001	8.0	CE10	60	8.22
C-U-06-001*	6.0	CM15	40	3.77
C-U-06-001*	6.0	Fuel C	40	0.78
C-U-06-020	4.5	Indolene	40	3.20
C-U-05-014	6.4	Indolene	40	8.20
C-U-06-021	6.4	Indolene	40	7.40
C-U-06-002	6.4	Indolene	40	5.00
C-U-06-011	6.4	Indolene	40	12.7
C-U-05-011	2.0	Phase II	40	4.63
C-U-06-017	3.5	Phase II	40	10.8
C-U-05-013	4.0	Phase II	40	1.22
C-U-05-006	4.0	Phase II	40	10.3
C-U-05-012	4.0	Phase II	40	7.33
C-U-05-003	4.5	Phase II	40	12.3
G-05-018	4.8	Phase II	40	0.87
C-U-05-009	4.8	Phase II	40	3.94
C-U-06-010	4.8	Phase II	40	4.69
C-U-05-002	6.4	Phase II	40	3.76

* fuel tube

5.4.3 Low Temperature Hose Materials

In some applications, molded fuel hoses are used rather than simple extruded fuel hose. These fuel hoses are typically molded out of nitrile rubber (NBR) or a fluoroelastomer such as FKM. FKM is essentially rubber impregnated with fluorine which results in good fuel permeation resistance. Manufacturers of handheld equipment that may be used in very cold weather have stated that they must use nitrile rubber because the FKM material may become brittle at very low temperatures.[168] Examples of such equipment are ice augers and chainsaws.

Industry has not raised an issue with the capability of using extruded multi-layer hose in cold temperature applications. This type of hose construction has been demonstrated for low temperature use in automobiles and snowmobiles. Extruded fuel hose meeting SAE and ASTM standards is available today which meets a widespread set of safety and durability requirements. Industry has stated that for some applications, such as chainsaws, that extruded fuel hose will not work. In these applications, injection molding is used to manufacture complex fuel hose geometries designed to account for high vibration of the equipment. This vibration generally results in different motion patterns for the carburetor and fuel tank resulting in variable distances between the two.

Industry presented information on FKM fuel lines that became brittle and cracked at very low temperatures.[169,170] However, this information was was based on an FKM compound without a low temperature additive package. There are a wide range of FKM products available on the market. Many of these fluoroelastomers are designed for use at low temperatures.[171,172] For instance, low temperature o-rings are common in automotive applications.[173,174,175] Low temperature grade FKM products are available with a glass transition temperature as low as -40˚C and a brittleness point as low as -60˚C.[176] However, low temperature grade FKM products typically cost several times as much as FKM products intended for less severe temperatures. In addition, these materials have not been demonstrated for use in molded fuel lines for handheld applications.

A lower cost option may be to blend a standard fluorosilicone such as FVMQ with a standard grade FKM. The fluorosilicone brings very low temperature characteristics to the blend. However, the permeation resistance is not nearly as good as for FKM products. The blended product would be intended to create a balance between cost, permeation, and low temperature properties.[177] This product is currently used in automotive o-rings. However, it is not clear if this material could be molded into fuel lines that would meet the appropriate design criteria for handheld applications.

A new material, called F-TPV, has been developed that is a dynamically vulcanized combination of fluorothermoplastic resin and fluoroelastomer compound.[178] The mix of the two materials can be varied to trade-off permeation resistance with material hardness. This material has been shown to have a permeation rate ranging from 3 to 30 g-mm/m^2/day on fuel CE10 at 60˚C. Rubber hose molded out of even the softest version of this material would be expected to be capable of achieving a permeation rate well below the proposed standard. In addition, the impact brittleness temperature is below -50˚C for the full range of material blends discussed above. Finally, the cost of this material is much lower than for low-temperature FKM products. Further development efforts would be necessary to determine the suitability of this material for fuel lines on handheld equipment.

Table 5.4-4, above, presents permeation data on several samples of NBR fuel lines used on handheld equipment today. The permeation rates from these fuel lines range from 165 to 455 g/m^2/day with E10 fuel at 23˚C. Later discussions with industry revealed that the NBR hose with the lower permeation rates had higher acrylonitrile (ACN) contents. Although high ACN rubber cannot achieve the same low permeation rates as FKM or F-TPV, some permeation reductions could still be achieved with this material.

5.5 Other Evaporative Emissions

5.5.1 Other Venting Losses

Hot soak emissions occur after the engine is turned off, especially during the resulting temperature rise. The primary source of hot soak emissions is the evaporation of the fuel left in the carburetor bowl. Other sources can include increased permeation and evaporation of fuel from plastic or rubber fuel lines in the engine compartment.

Refueling emissions occur when the fuel vapors are forced out when the tank is filled with liquid fuel. At a given temperature, refueling emissions are proportional to the volume of the fuel dispensed into the tank. Every gallon of fuel put into the tank forces out one-gallon of the mixture of air and fuel vapors. Thus, refueling emissions are highest when the tank is near empty. Refueling emissions are also affected by the temperature of the fuel vapors and dispensed fuel. At low dispensed fuel temperatures, the fuel vapor content of the vapor space that is replaced is lower than it is at higher temperatures because of the cooling effect on the vapor in the fuel tank.

In automotive applications, the carbon canister is sized not only to capture diurnal emissions, but refueling, hot soak, and running loss emissions as well. With an engine purge, the canister would effectively capture running loss emissions and hot soak emissions because the canister would presumably be nearly empty after a short period of operation. For the canister to be effective at collecting refueling emissions, it would need to be purged before the refueling event. However, even without a purged canister, refueling emissions could be minimized by matching the geometry of the fuel fill opening to the fuel pump nozzle. By minimizing the open space in the fuel fill opening around the nozzle, less air will be entrained which will minimize vapor generation during the refueling event. This will not help control the expulsion of vapor that is displaced by liquid fuel.

5.5.2 Refueling Spitback/Spillage

Installed fuel systems on boats are typically open vented. The exception to this is PWC which have sealed fuel tanks with pressure relief valves, largely to prevent spillage of fuel during operation. For larger boats, fuel spillage during operation is less of an issue; however, it is common for fuel to be lost to the environment during refueling or shortly thereafter.[179,180] There are several mechanisms that lead to fuel loss due to a refueling event. These mechanisms include restrictions in the fill neck, fuel flowing out the vent line, and expansion of fuel in the tank.

The American Boat and Yacht Council (ABYC) has a voluntary refueling standard designed to help prevent fuel from backing up the fill neck during a refueling event.[181] This test requires that no fuel back up the fill neck when a fuel tank in a boat is filled from 25 to 75 percent full at a fill rate of 9 gallons per minute. This test is apparently designed to make sure that the fill neck does not have a restriction that may cause fuel to back up the fill neck during refueling. To prevent fill from backing up the fill neck, fill necks are typically made of large diameter hose which is reinforced to prevent kinking. In addition, the fuel fill opening is typically positioned higher than the vent line. This test does not consider fuel overflow that may occur from filling a marine tank to 100 percent full. In addition, the full rate may be too low to require a design that would work in typical in-use situations. One survey on 19 marinas saw a range of 8 to 25 gallons per minute for gasoline fill nozzles with an average of 14 gallons per minute.[182]

The most common refueling spillage today is overflow out the vent line. Typically the vent line is the path of least resistance for fuel overflow. Boats typically do not have a mechanism that prevents fuel tanks from filling all the way to the top. In fact, the fill and vent hose are attached to the top of the fuel tank and are often filled with fuel in addition to the tank. Because the vent hose exits the boat lower than the fill neck opening, the tank can be filled until fuel begins to exit through the vent hose. In addition, fuel may expand in the fuel tank when cool fuel is pumped into the fuel tank on a warm day. This expansion can cause additional fuel overflow out the vent line.

A number of devices have been produced to help control fuel spillage during refueling. These devices include liquid/vapor separators, combination deck fills and vents, and fuel flow monitoring systems. A study was performed by Boat US Foundation to evaluate the effectiveness of several of these systems which are currently available on the market.[183] The results of this study are discussed below.

Liquid/vapor separators are valves that are installed in the fuel line. The typical design is for the valve to contain a ball that rises when liquid fuel reaches it which closes the vent to liquid fuel. As the tank fills, fuel backs up the fill neck, allowing the automatic shut-off on the nozzle to stop the fuel flow. The study found that these systems typically worked best at lower fuel fill rates and that the larger units were more effective. The effectiveness of the larger units was probably because they essentially included a reservoir, allowing extra room for fuel expansion. For the smaller units, the testing consistently showed fuel backing up the fill neck too quickly for the automatic shut-off valve to engage and fuel spit back out of the deck fill.

In a vented deck fill design, the vent line is routed back to the top of the fill neck. The intent is that the fuel surging out of the vent line would return to the fill neck and back to the tank. The study found that the combination vented deck fills significantly reduced spitback/spillage, but still needed to be used with some caution. One issue was that even when the fuel came back up and shut off the nozzle, pressure in the fuel tank would cause fuel to continue to rise in the line and spill onto the deck. Another manufacturer has a similar device except that a clear section of tubing that redirects the fuel overflow from the vent line to the fill neck. The operator only attaches this tubing during refueling. Because the tubing is clear, the operator can see when the fuel is coming out of the vent and can manually slow down or stop the fuel flow.

Fuel flow monitoring systems are designed to keep track of fuel usage by measuring fuel flowing to the engine. The study did not present definitive results for the use of flow meters to accurately refuel the tank without overfill.

Where a carbon canister is used in the vent line for diurnal vapor control, it would be important to include a device to prevent liquid fuel from entering the canister. This device could take the form of a floating ball valve, limited flow orifice, or other liquid/vapor separation mechanism. In addition, this device could be positioned in such a way as to prevent the tank from filling all the way to the top. For instance, the vent fitting could reach down into the fuel tank. Leaving a vapor space in the fuel tank would give room for fuel in the tank to expand.

In automotive applications, carbon canisters have been used for many years in vehicles that also meet fuel spit-back standards set by EPA. In typical automotive fuel systems, the fuel shut-off on the nozzle is tripped before the fuel comes back out the fill neck. It is common to have a narrow tube parallel to the fill neck reach into the fuel tank at the desired peak fill level of the tank. The narrow tube connects to the fill neck near the top where the small hole on the nozzle would be. When fuel splashes on this small hole, the vacuum draw is broken and the shut-off device is triggered. Fuel travels up the narrow tube more quickly than up the fill neck and triggers the nozzle shut-off well before fuel spit-back can occur.

At least one company is developing a similar design for use in boats. Testing has been performed on one system by an independent laboratory that also performs ABYC and Coast Guard tests for the marine industry. During the testing, a fuel tank was filled 30,000 times, using this fuel system configuration, without any spillage.[184] Also, this fuel system configuration creates a vapor space in the top of the tank which allows fuel to expand during heating, thereby preventing fuel spillage due to expansion of the fuel in the tank.[185] This system has since been modified to be adaptable to any fuel tank with a fuel sending unit based on the standard SAE 5-hole pattern. The updated system was tested using a similar methodology as in the Boat US study discussed above and underwent 25,000 refueling events at 15 gallons per minute without experiencing any spills.[186] Pictures and video of this system are included in the docket.

5.6 Evaporative Emission Test Procedures

This section discusses test procedures for measuring fuel line permeation, fuel tank permeation, and diurnal emissions.

5.6.1 Hose Permeation Testing

We propose for hose permeation to be measured at a temperature of 23 ± 2°C using the weight loss method specified in SAE J30.[187] In this method, one end of a specified length of hose is connected to a metal reservoir while the other end is plugged. Test fuel is then added to the reservoir at a volume high enough to ensure that the hose is filled with fuel. Once any air bubbles have been removed from the hose, the reservoir is sealed and the entire system is weighed. Permeation is determined by weighing the system every 24 hours and noting the weight loss. After each weighing, the fuel is mixed by inverting the assembly, then returning it to its original position.

We are proposing two modifications to SAE J30 that are consistent with our current requirements for recreational vehicles and highway motorcycles. First, the test fuel must be ASTM Fuel C[188] (50 percent toluene, 50 percent iso-octane) blended with 10 percent ethanol. This fuel is known as CE10 and is commonly used in industry standards and test procedures such as in SAE recommended practices. Section 5.4, and Appendix 5D presents permeation data for several hose constructions and materials used in hose constructions on fuels with and without ethanol. As shown in this data, adding ethanol to the test fuel significantly increases permeation. Standard recommended practice for hose testing uses Fuel C, or some blend of Fuel C and either ethanol or methanol. This test fuel is generally more aggressive than standard gasoline. Although hoses are not generally exposed to Fuel C in use, the level of the standard was based on testing using Fuel C and Fuel C blends. In addition, most of the test data on low permeation hose presented in this Chapter is based on fuel CE10. For these reasons, we believe that it is appropriate to allow Fuel CE10 for hose testing.

The second modification is that the hose must be preconditioned by filling the hose with fuel and soaking long enough to ensure that the permeation rate has stabilized. We are proposing a soak period of 4 weeks at 23 ± 5°C. If a longer time period is necessary to achieve a stabilized permeation rate for a given hose design, we would expect the manufacturer to use a longer soak period (and/or higher temperature) consistent with good engineering judgement. For instance, thick-walled marine fuel hose may take longer to reach a stable permeation rate than thinner-walled hose used in Small SI applications.

Alternatively, for purposes of submission of data at certification, permeation could be measured using alternative equipment and procedures that provide equivalent results. To use these alternative methods, manufacturers would have to apply to us and demonstrate equivalence. Examples of alternative approaches that we anticipate manufacturers may use are the recirculation technique described in SAE J1737,[189] enclosure-type testing such as in 40 CFR part 86, or weight loss testing such as described in SAE J1527.[190]

Coast Guard standards for marine fuel hoses (33 CFR part 183) cite SAE recommended practice J1527[191] which, among other things, includes test procedures for measuring permeation from marine fuel hoses. In this test procedure, a short section of hose is attached to a nonpermeable container (i.e. metal fuel can) and plugged. Fuel is added to the container and the mass of the entire unit is measured every 24 hours for 15 days and the peak fuel loss is determined. This testing is performed at 23 ± 2°C on both reference fuel “C” for the version of the SAE standard referenced in 33 CFR part 183. However, SAE J1527 was revised in 1993 to include permeation standards for hoses tested on a fuel blend with 15 percent methanol. This test procedure is simple; however, it is sufficient for marine hoses because they have high permeation rates ranging from 100 to 600 $g/m^2/day$ depending on the hose class and the fuel used.

Recommended practice for automotive fuel tubing is defined in SAE J2260.[192] The permeation requirements in this standard are one to two orders of magnitude lower than those defined for marine hoses. These permeation requirements are based on the same fuels as the revised SAE J 1527, but at a much higher temperature (60°C). At 60°C, permeation rates for a given material may be 16 times as high or higher than at 23°C based on the rule of thumb that permeation doubles for every 10°C increase in temperature. SAE J2260 refers to the permeation test procedures in SAE J1737.[193]

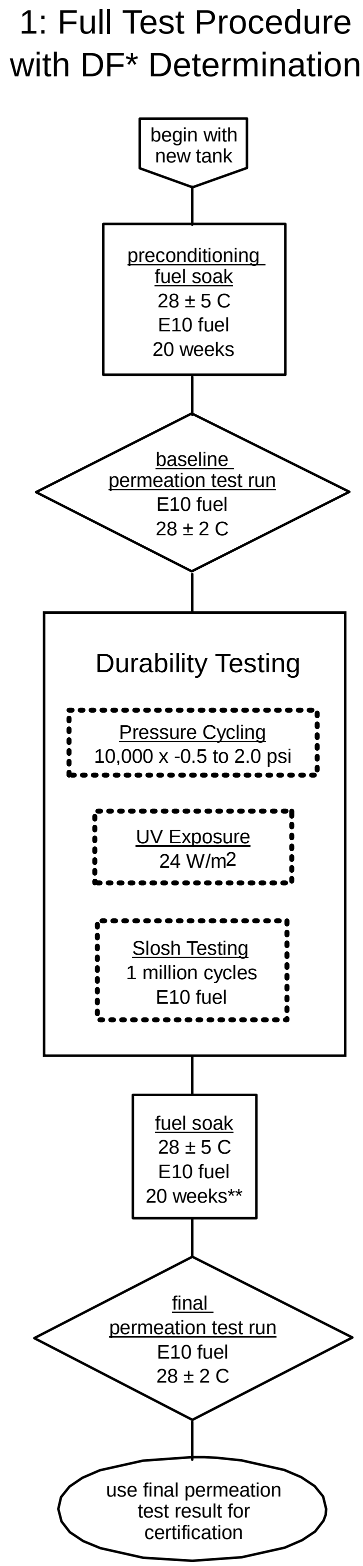
The procedures in SAE J1737 were designed to measure the low permeation rates needed in automotive applications to meet EPA evaporative emission requirements. There was concern that the weight loss measurement, such as used in SAE J1527, was not sensitive enough to measure these low permeation rates. In addition, this procedure requires exposing the material to be tested for hundreds of hours, depending on the material and fuel, to reach a steady-state permeation rate. In this procedure, fuel is heated to 60°C and circulated through a tube running through a glass test cell. Nitrogen around the tube in this test cell is used to carry the permeate to activated charcoal canisters. The canisters are weighed to determine their capture. Because the canister is much lighter than the reservoir/hose in the SAE J1527 configuration, a much more accurate measurement of the permeation loss can be made.

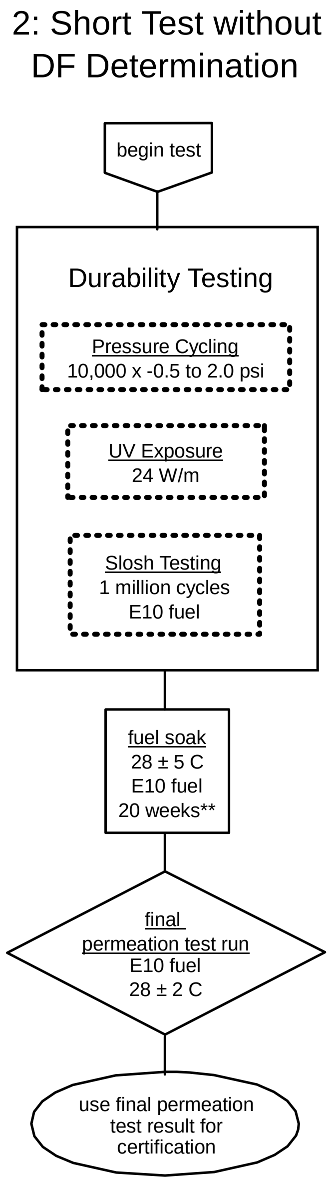
Some manufacturers of low permeability product are finding that as their emission rates decrease, they need more refined test procedures to accurately measure permeation. These manufacturers are finding that the weight of the charcoal canisters are much higher than the permeate being measured. As an alternative to the gravimetric approach used in the above two procedures, even very low permeation emissions can be measured by a flame ionization detector and a SHED. As discussed earlier, SHED testing is generally used to measure evaporative emissions from whole automobile systems as well.

5.6.2 Fuel Tank Permeation Testing

We are proposing to apply a similar fuel tank permeation test procedures to Small SI equipment and Marine SI vessels as we currently use for recreational vehicles. This testing includes preconditioning, durability testing, and permeation measurement. The proposed differences in the test procedure compared to recreational vehicles are minor and are intended to simplify the testing. For instance, the durability testing would be performed during the preconditioning soak period prior to the weight loss testing rather than testing the tank twice; once before durability testing, and once after. Figure 5.6-2 provides flow charts for this testing compared to the recreational vehicle test which includes the calculation of a deterioration factor.

Figure 5.6-2: Flow Chart of Fuel Tank Permeation Test with and without a Deterioration Factor (DF) Determination





** The deterioration factor (DF) is the difference between the baseline and final permeation test runs in the full test procedure. In future tests, the first 3 steps would be performed, then a DF could be applied to determine the final test result.*

*** The length of "soak" during durability testing may be included in the fuel soak period provided that fuel remains in the tank. Soak periods can be shortened to 10 weeks if performed at 43* ± 5 C

For the purpose of this testing, “fuel tank” includes the fuel cap and other components directly mounted to the tank that become part of the barrier for the fuel and vapor. During testing, fittings and openings in the fuel tank intended for hose connections (or petcock) would be sealed with an impermeable plug. An opening containing a fuel petcock could also be plugged with an impermeable fitting because this is an opening to the fuel hose which will be required to meet permeation standards. In many installed marine fuel tanks, the fuel cap is not directly mounted on the fuel tank. Instead, the fuel cap is usually linked to the fuel tank by a fill neck hose. In this case, the fill neck opening in the fuel tank may be sealed with an impermeable plug during permeation testing.

5.6.2.1 Durability Testing

Prior to the weight loss test, the fuel tank must be preconditioned to ensure that the hydrocarbon permeation rate has stabilized. Under this step, the fuel tank must be filled with a 10 percent ethanol blend (E10), sealed, and soaked for 20 weeks at a temperature of 28 °C ± 5 °C. Once the permeation rate has stabilized, the fuel tank is drained and refilled with E10, sealed, and tested for a baseline permeation rate. The permeation rate from the fuel tank is determined by measuring the weight difference the fuel tank before and after soaking at a temperature of 28 °C ± 2 °C over a period of at least 20 weeks. The soak periods could be shortened to 10 weeks if performed at 43 °C ± 5 °C. The durability testing described below may be performed during the soak period. During the slosh testing, a lower tank fill level, consistent with the proposed slosh test, would be acceptable.

To determine a permeation emission deterioration factor, we are proposing three durability tests: slosh testing, pressure-vacuum cycling, and ultra-violet (UV) light exposure. The purpose of these deterioration tests is to help ensure that the technology is durable and the measured emissions are representative of in-use permeation rates. For slosh testing, the fuel tank is filled to 40 percent capacity with E10 fuel and rocked for 1 million cycles. The pressure-vacuum testing contains 10,000 cycles from -0.5 to 2.0 psi. The slosh testing is designed to assess treatment durability as discussed above. These tests are designed to assess surface microcracking concerns. These two durability tests are based on a draft recommended SAE practice.[194] The third durability test is intended to assess potential impacts of UV sunlight (0.2 µm - 0.4 µm) on the durability of the surface treatment. In this test, the tank must be exposed to a UV light of at least 0.40 W-hr/m^2 /min on the tank surface for 15 hours per day for 30 days. Alternatively, it can be exposed to direct natural sunlight for an equivalent period of time in exposure hours.

The order of the durability tests is optional. However, we require that the fuel tank be soaked to ensure that the permeation rate is stabilized just prior to the weight loss test. If the slosh test is run last, the length of the slosh test may be considered as part of this soak period. Where possible, the deterioration tests may be run concurrently. For example, the fuel tank could be exposed to UV light during the slosh test. In addition, if a durability test can clearly be shown to not be appropriate for a given product, manufacturers may petition to have this test waived. For example, a fuel tank that is only used in vehicles where an outer shell prevents the tank from being exposed to sunlight may not benefit from UV testing.

After the durability testing, once the permeation rate has stabilized, the fuel tank is drained and refilled with fresh fuel, sealed, and tested for a final permeation rate. The final permeation rate from the fuel tank is determined using the same measurement method as for the baseline permeation rate. The final permeation rate would be used for the emission rate from this fuel tank. The difference between the baseline and final permeation rates could be used to determine a deterioration factor for use on subsequent testing of similar fuel tanks.

5.6.2.2 Test Fuel

As discussed in Chapter 3, about 30 percent of fuel sold in the U.S. contains ethanol and this percentage is expected to increase to about 45-50 percent in 2012 and later. We are proposing the use of E10, which is a blend of 90 percent certification gasoline (as specified in 40 CFR 1065.210) blended with 10 percent ethanol for permeation testing of fuel tanks. As an alternative, we are proposing that ASTM Fuel C blended with 10 percent ethanol (Fuel CE10) may be used. Fuel CE10 is commonly used in industry standards and test procedures such as in SAE recommended practices.

5.6.2.2.1 Effect of ethanol on fuel tank permeation

Most plastic nonroad fuel tanks today are made out of high-density polyethylene (HDPE) or cross-link polyethylene (XLPE). For Small SI and Marine SI markets, plastic is much more widely used than metal for fuel tank constructions. For HDPE, E10 fuel has little effect on permeation emissions and may even result in slightly lower emissions according to one study.[195] We tested three 0.5 gallon Small SI fuel tanks for permeation using both certification gasoline and E10 and found a slight increase in permeation due to ethanol. ARB also tested several Small SI fuel tanks on both gasoline and ethanol blends [196,197,198,199] and saw a small increase in permeation. Permeation data was collected on two XLPE marine fuel tanks on E10. The measured permeation rates were within the range of data from other XLPE marine fuel tanks tested on gasoline presented earlier in Table 5.3-1. This data is presented in Table 5.6-1.

Table 5.6-1: Effect of Ethanol on Permeation for HDPE Fuel Tanks

Material	Test Equipment	Tank gallons	Test Temp(s)	gasoline [g/m^2/day]	E10 [g/m^2/day]	Increase in Permeation
HDPE	material sample	NA	40˚C	90*	69*	-23%
HDPE	Small SI fuel tanks (EPA Testing)	0.5	29˚C	11.5	13.9	21%
		0.5		11.4	13.7	21%
		0.5		11.2	14.4	28%
HDPE	Small SI fuel tanks (ARB Testing)	0.25	18-41˚C	11.6	13.6	18%
		0.25		10.7	11.6	7%
		0.25		12.5	11.4	-9%
		0.25		9.9	10.3	4%
		0.25		9.2	10.3	12%
		0.5		12.7	14.8	17%
		3.9		4.8	5.0	4%
XLPE	marine tanks (EPA testing)	12	29˚C	**	7.5	minimal
		12			8.5	

*ASTM Fuel C was used as gasoline (50% toluene, 50% isooctane). Units are per mm of thickness

** See Table 5.3-1 for data on similar tanks tested on gasoline.

Although E10 does not have a large effect on permeation through polyethylene, it does have a large effect on most other materials used in fuel systems, especially those designed for low permeation. This is supported by the data presented in Appendix 5D of permeation rates for several fuel system materials on fuel C, CE10, and C15. In addition, ethanol is commonly blended into fuels in-use and alcohol fuels may be used more in the future in an effort to use alternative energy sources. Therefore, we are proposing E10 as a test fuel to ensure that the proposed permeation standard will be met on in-use fuels.

A recent study found that permeation from automotive fuel systems increased significantly when gasoline containing ethanol was used compared to gasoline without ethanol.[200] In this case the ethanol fuel was specifically blended to achieve two weight percent oxygen. This test fuel represents California reformulated fuel and contains 5.7 percent by volume ethanol. Table 5.6-2 presents the test results at 29°C. The average increase in permeation due to using E5.7 was 60 percent. Presumably, this effect would have been higher on E10. Because most of the fuel tanks are metal, the effect is largely due to fuel hose/tubing permeation. The highest effect of ethanol in gasoline on permeation probably occurs when 10-30 percent ethanol is blended into the gasoline. We are just beginning a contract for testing to study permeation rates at various ethanol fuel blends as part of our on-highway inventory modeling efforts.

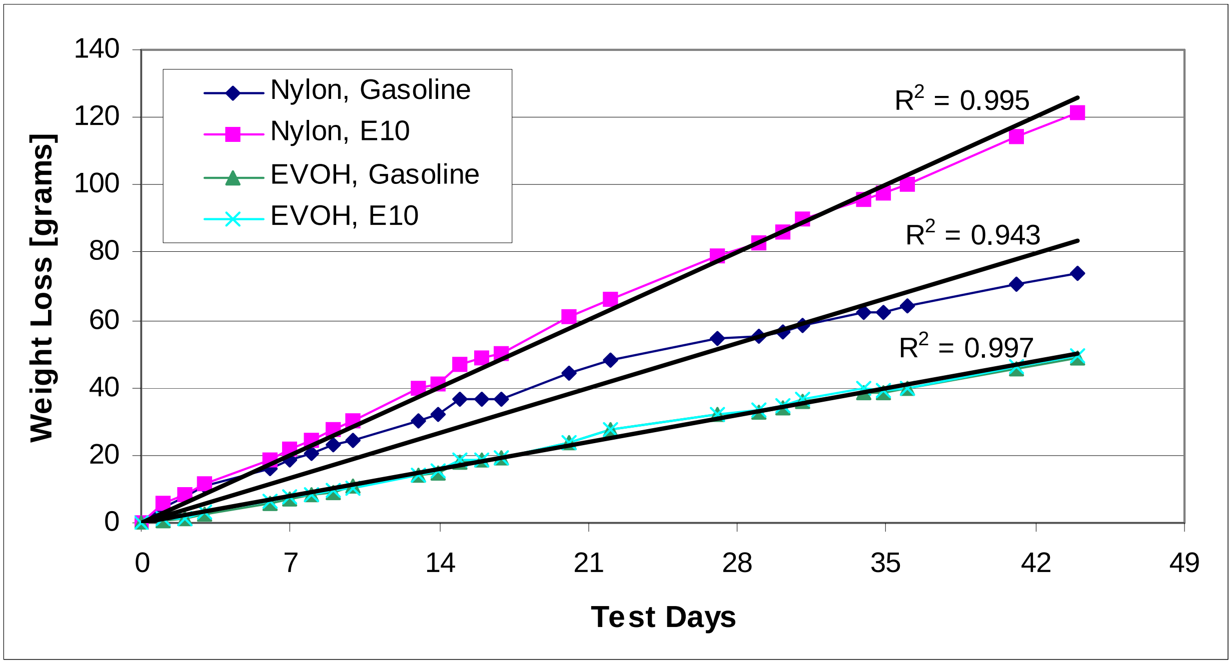
Table 5.6-2: Effect of Ethanol on Permeation from Automotive Fuel Systems

Fuel System	Fuel Tank	Gasoline	E5.7	Increase
2001 Toyota Tacoma	Metal	10	32	220%
2000 Honda Odyssey	Plastic (enhanced evap)	19	53	179%
1999 Toyota Corolla	Metal	11	57	418%
1997 Chrysler Town & Country	Plastic (enhanced evap)	40	66	65%
1995 Ford Ranger	HDPE	348	342	-2%
1993 Chevrolet Caprice Classic	Fluorinated HDPE	94	137	46%
1991 Honda Accord LX	Metal	39	100	156%
1989 Ford Taurus GL	Metal	28	73	161%
1985 Nissan Sentra	Metal	73	177	142%
1978 Olds Cutlass Supreme	Metal	73	139	90%

One significant finding with the above study was that switching from one fuel to another affects the permeation rate within a few weeks. Although operating on gasoline with ethanol changes the fuel tank material in such a way that permeation increases, this effect is reversible when gasoline is used in the fuel tank for a long enough period of time. This study found that the permeation rate at 40°C typically approached a stabilized level within 1 to 2 weeks of switching from one fuel to another.

To investigate the potential effects of fuel switching, we tested two pairs of 6.6 gallon portable marine fuel tanks. These fuel tanks used the barrier platelet technology discussed above. The first pair used nylon as a barrier material which is highly sensitive to ethanol while the second pair used EVOH which is much less sensitive to ethanol. All four tanks were soaked on E10 fuel, then the fuel was drained and replaced for testing. For each pair, one tank was tested on EPA certification gasoline and the other was tested on E10 fuel (10 percent ethanol, 90 percent gasoline). We continued the test for more than six weeks to observe the effects of fuel switching on the permeation rates. The results suggest that switching to gasoline significantly reduces the permeation rate for the nylon barrier tanks, but has no significant effect on the fuel tanks using EVOH as a barrier. Note that the nylon tanks had permeation rates near the proposed standards when soaked and tested on gasoline, but have much higher permeation rates when tested on E10. This data is presented in Figure 5.6-1. The R-squared values for linear fits to the data are also presented. The fuel tank with a nylon barrier that experienced fuel switching had a lower R-squared value than the other fuel tanks.

Figure 5.6-1: Effect of Fuel Switching on Permeation from Barrier Platelet Fuel Tanks



Fuel tank permeation data on both gasoline and E10 fuel were presented earlier in this chapter for nylon handheld tanks, fluorinated and sulfonated Small SI tanks, portable tanks with non-continuous nylon barrier platelets, and rotationally molded tanks with a nylon inner barrier. This data is repeated here in Table 5.6-3 to better focus on the effect of ethanol on fuel tank permeation. As shown by this data and the previous discussion, ethanol in the test fuel tends to increase permeation. However, the effect of ethanol on permeation appears to be highly variable depending on the materials or surface treatments used in constructing the fuel tank.

Table 5.6-3: Permeation Rates on Gasoline and E10 for Barrier Fuel Tanks

Permeation Control	Capacity [gallons]	Gasoline [g/m^2/day]	E10 [g/m^2/day]	% Increase
nylon 6	0.24	0.34	0.42 0.48	32%
nylon 6, 33% glass	0.05	0.62	1.01 1.12 0.93	65%
nylon 6, 30% glass	0.06	1.45	2.2 2.5	60%
nylon 6, 30% glass	0.06	1.30	1.4 2.1	37%
fluorination	0.5	0.56 0.62 0.22	0.43 0.62 0.62	19%
sulfonation	0.5	2.5 2.7 2.2	3.9 4.2 2.9	49%
non-continuous nylon platelets	2.0	3.7	6.8	84%
Rotomolded with PA11 liner*	1mm barrier thickness	0.17 0.24 0.12	0.91 0.72 0.78 0.81	350%

* based on testing for California (California Phase II gasoline and fuel CE10)

5.6.2.2.2 Effect of CE10 versus E10 on fuel tank permeation

As discussed above, we are proposing to allow the use of fuel CE10 as an alternative to E10 for fuel tank permeation testing. The primary fuel, E10 is representative of in-use fuel and is consistent with the certification fuel used for recreational vehicles. However, fuel CE10 is widely used by industry for materials testing. Data presented earlier in this chapter suggests that permeation is generally significantly higher on fuel CE10 for fuel hoses. We were therefore interested in the effect of fuel CE10 versus E10 on fuel tank permeation. We tested several fuel tanks and found that permeation was only slightly higher on CE10 than E10 for most of the fuel tanks tested.

To study the effects of CE10 versus E10 on permeation, we used fuel tanks that had been previously tested on fuel E10. All of these tanks were drained and refueled with fresh test fuel. Most of the tanks were filled with fuel CE10; however, with some exceptions, one of each tank type was filled with fresh E10 for comparison. These fuel tanks were then preconditioned by soaking them for 12 weeks with the new test fuel. Note that all of the test tanks had been soaking with E10 fuel for more than a year (and in some cases multiple years) prior to beginning this preconditioning soak. Following the soak period, each tank was drained, refilled with fresh fuel, and sealed. Permeation was measured over two weeks at 29˚C. The fuel tanks were weighed on each weekday during this period.

Table 5.6-4 presents the results of this testing. In most cases, emissions were only slightly higher on CE10 than E10. The exceptions were the nylon 6 and the acetal copolymer fuel tanks which showed much higher permeation on CE10. However, the permeation rates for these fuel tanks were still below the proposed standard when tested on fuel CE10. The fuel tank with a continuous EVOH barrier was well below the proposed standard on fuel CE10. No comparison was made to E10 results for this technology.

Table 5.6-4: Permeation Rates on Gasoline and E10 for Barrier Fuel Tanks

Permeation Control	Capacity [gallons]	E10 [g/m^2/day]	CE10 [g/m^2/day]	% Increase
nylon 6	0.24	0.69	1.4 1.2	90%
HDPE	0.5	12.5	13.3 13.5	7%
fluorination	0.5	0.41	0.49 0.52	21%
sulfonation	0.5	3.1	4.2 2.9	16%
non-continuous platelets (4% nylon)	6.6	4.5	5.3	16%
non-continuous platelets (2% EVOH)	6.6	3.0*	3.3	10%
non-continuous platelets (4% EVOH)	6.6	2.2	2.3	6%
non-continuous platelets (6% EVOH)	6.6	1.3	1.4	6%
continuous EVOH barrier	5.6	--	0.05 0.01	NA
acetal copolymer	0.8	0.25	0.55 0.65	140%

* based on previous testing (presented earlier in this chapter)

5.6.2.3 Reference Tank

In cases where the permeation of a fuel tank is low, and the sample tank is properly sealed, the effect of air buoyancy can have a significant effect the measured weight loss. Air buoyancy refers to the effect on air density on the perceived weight of an object. As air density increases, it will provide an upward thrust on the fuel tank and create the appearance of a lighter tank. Air density can be determined by measuring relative humidity, air temperature, and air pressure.[201]

One testing laboratory presented data to EPA on their experience with variability in weight loss measurements when performing permeation testing on portable fuel tanks.[202] They found that the variation was due to air buoyancy effects. By applying correction factors for air buoyancy, they were able to greatly remove the variation in the test data. A technical brief on the calculations they used is available in the docket.[203]

A more direct approach to accounting for the effects of air buoyancy is to use a reference fuel tank. In this approach, an identical fuel tank to that being tested for permeation would be tested without fuel in it and used as a reference fuel tank. Dry sand would be added to this tank to make up the difference in mass associated with the test tank being full of fuel. The reference tank would then be sealed so that the buoyancy effect on the reference tank would be the same as the test tank. The measured weight loss of the test tank could then be corrected by any measured changes in weight in the reference tank. The California Air Resources Board has proposed this approach for measuring portable fuel tank emissions, and they refer to the reference tank as a "trip blank."[204]

5.6.2.4 Engineering Design-Based Certification

Fuel does not permeate through metal and automotive style EVOH barrier tanks have very low permeation through the walls of the tank. We are proposing to allow design-based certification for metal tanks and co-extruded high-density polyethylene fuel tanks with a continuous ethylene vinyl alcohol barrier layer. The EVOH barrier layer would be required to be at least 2 percent of the wall thickness of the fuel tank.

To address the permeability of the fuel cap, seals, and gaskets used on metal and co-extruded tanks, we are proposing that the design criteria include a specification that seals and gaskets that are not made of low-permeation materials must have a total exposed surface area less than 1000 mm^2. A low-permeation material would have a permeation rate not more than 10 $g\text{-}mm/m^2/day$ at 23°C on CE10 fuel as tested under the procedures specified in SAE J2659.[205] A metal or co-extruded fuel tank with seals that meet this design criterion would reliably pass the standard.

5.6.3 Diurnal Emission Testing

The proposed test procedure for diurnal emissions is to place the fuel tank in a SHED[6], vary the temperature over a prescribed profile, and measure the hydrocarbons escaping from the fuel tank. The final result would be reported in grams per gallon where the grams are the mass

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[6] Sealed Housing for Emission Determination

of hydrocarbons escaping from the fuel tank over 24 hours and the gallons are the nominal fuel tank capacity. The proposed test procedure is based on the automotive evaporative emission test described in 40 CFR part 86, subpart B, with modifications specific to marine applications. If we were proposing diurnal emissions standards for Small SI applications, the test procedures would be similar and would be based on a 72-96°F temperature profile.

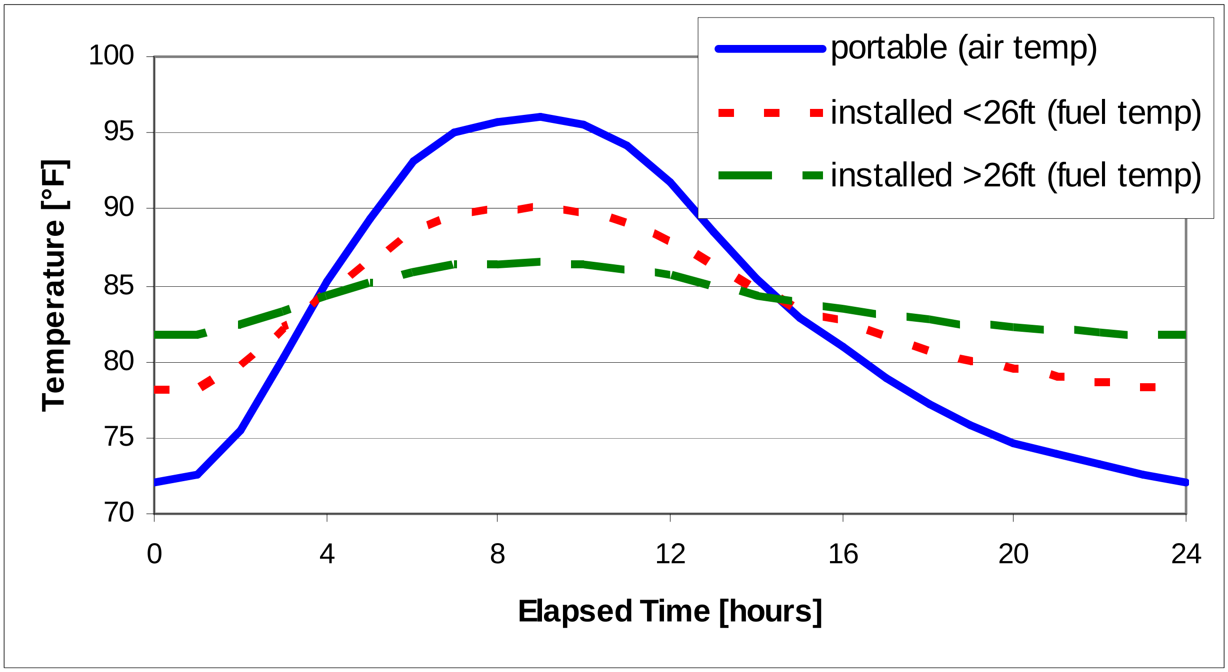
5.6.3.1 Temperature Profile

We are proposing that portable marine fuel tanks would be tested over the same 72-96°F (22.2-35.6°C) temperature profile used for automotive applications. This temperature profile represents a hot summer day when ground level ozone emissions (formed from hydrocarbons and oxides of nitrogen) would be highest. This temperature profile would be for the air temperature in the SHED.

For installed marine fuel tanks, we believe that the fuel temperature profile observed in the tank would have a lower variation in temperature due to the inherent insulation provided by the boat hull. Data discussed earlier in this chapter, and presented in Appendix 5A, suggest that the fuel temperature in an installed marine tank would see a change in temperature less than that of ambient air. Based on this data, the fuel temperature change in boats stored on trailers would be expected to be about half of ambient. For boats stored in the water, the fuel temperature change would be expected to be about 20 percent of ambient. Based on discussions with industry, we use a boat length as a surrogate for determining if a boat is a trailer boat. We are proposing to consider a boat below 26 feet (7.9 m) in length as a trailer boat and larger boats as being primarily stored in the water.

To account for the differences between ambient and fuel temperature, we are proposing a test temperature profile of 78-90°F (25.6-32.2°C) for marine fuel tanks installed in boats less than 26 feet in length. For larger boats, we are proposing a test temperature profile of 81.6-86.4˚F (27.6-30.2˚C). These test temperature profiles would be based on fuel rather than ambient temperature. Figure 5.6-3 presents the three temperature profiles over 24 hours. Numerical values are presented in Appendix 5E.

Figure 5.6-3: Proposed Diurnal Temperature Profiles



The automotive diurnal test procedure includes a three day temperature cycle. The purpose of this test length is to ensure that the carbon canister can hold at least three days of diurnal emissions without vapor breaking-through the canister. For vessels using carbon canisters as an evaporative emission control strategy, we are proposing a multiple day cycle here as well so that the passive purging can be observed. In the automotive test, the canister is loaded, then purged during an engine test prior to the first day of testing. Because we are anticipating canisters on marine applications to be passively purged we are proposing a different approach. Prior to the first day of testing, the canister would be loaded to full working capacity, then run over the diurnal test temperature cycle to allow one day of passive purging. The test result would then be based on the highest recorded value in the following three days.

For fuel systems using a sealed system (or sealed-system with pressure relief), we do not believe that a three day test would be necessary. Prior to the first day of testing, the fuel would be stabilized at the initial test temperature. Following this stabilization, the SHED would be purged and a single diurnal temperature cycle run. Because this technology does not depend on purging or storage capacity of a canister, multiple days of testing should not be necessary. Therefore, we are proposing a one-day test for the following technologies: sealed system without pressure relief, sealed system with a pressure relief valve, sealed bladder fuel tanks, sealed fuel tanks with a volume compensating air bag.

5.6.3.2 Test Fuel

Consistent with the automotive test procedures, we are proposing that the test take place using certification gasoline with a vapor pressure of 9.0 RVP. We are not proposing to require ethanol to be blended into the test fuel. Although ethanol has a significant effect on permeation, it would not be expected to affect diurnal emissions except in that it may affect fuel vapor pressure.

Diurnal emissions are not only a function of temperature and fuel volatility, but of the size of the vapor space in the fuel tank as well. Consistent with the automotive procedures, we are proposing that the fill level at the start of the test be 40 percent of the nominal capacity of the fuel tank. Nominal capacity of the fuel tank would be defined as the volume of fuel, specified by the manufacturer, to which the fuel tank can be filled when sitting in its intended position. The vapor space that normally occurs in a fuel tank, even when "full," would not be considered in the nominal capacity of the fuel tank.

5.6.3.3 Tank Configuration

Personal watercraft and other installed marine fuel tanks are typically equipped with a vent line. As shown above, this vent line can impact the emissions determined over the test procedure because it largely restricts diffusion losses. Therefore, for open vent marine fuel tanks that are designed with a connection for a vent line, we propose that the be equipped with a one meter fuel line to more accurately reflect real world emissions. This should only be necessary for baseline configurations.

The majority of marine fuel tanks are made of plastic. Even plastic fuel tanks designed to meet our proposed standards would be expected to have some amount of permeation. However, over the length of the diurnal test, if it were performed on a new tank that had not been previously exposed to fuel, the effect of permeation on the test results should be insignificant. For fuel tanks that have reached their stabilized permeation rate (such as testing on in-use tanks), we believe that it would be appropriate to correct for permeation. In such a case, we propose that the permeation rate could be measured from the fuel tank and subtracted from the final diurnal test result. The fuel tank permeation rate would have to be stabilized on the 9 RVP test fuel used for the diurnal test and measured either over the diurnal temperature cycle or at a constant temperature (28 ± 2°C). This test measurement would have to be made just prior (within 24 hours) to the diurnal emission test to ensure that the permeation rate does not change prior to the diurnal test. In addition, the test fuel would need to remain in the fuel tank between the permeation and diurnal tests to ensure a stable permeation rate. The fuel tank could be emptied to change test fuels and test set ups; however, this period would not be allowed to exceed one hour. As an alternative to stabilizing the permeation rate prior to testing, the permeation could be measured immediately before and after the diurnal test, and the lower permeation rate used to correct the diurnal test results. In this case, the test fuel would not be removed after the diurnal test, and the second permeation test would begin within 8 hours of the end of the diurnal test.

5.6.3.4 Carbon Canister Engineering Design

We are proposing to allow design-based certification as an option to performing the above test. For vessels using a carbon canister to control diurnal emissions, it is important to ensure that the canister design is sufficient to achieve the proposed standards. The following discussion outlines the requirements that would be necessary to ensure adequate canister design. These design parameters and their associated test procedures are largely based on our understanding of current industry practices for marine grade carbon.[206]

5.6.3.4.1 Carbon canister capacity

In a passive purge system, the storage capacity of the carbon canister must be properly matched to the fuel system. Ideally, the canister would be large enough to take full advantage of the passive purge caused by cooling of the fuel tank. By creating more open sites in the canister, greater vapor collection is possible during the next heating event. If a canister is undersized, then the vessel would not likely meet the proposed standards. On the other hand, after a certain point, increasing the size of the canister offers little additional emission control. Once the system reaches a stabilized purge/load condition, the emission reduction potential is based on the portion of the canister that purges and loads rather than the full volume of the canister.

The storage capacity of a carbon canister is based both on the volume of the canister and the working capacity of the carbon. Butane working capacity (BWC) is a measure of the vapor storage capacity of the carbon and is expressed in units of mass of butane per unit of volume. We are proposing that the BWC of the carbon be at least 9 g/dL based on the test procedures specified in ASTM D5228-92.[207] Under this test procedure, butane vapor is fed through a carbon sample at a specified rate, until the mass of the carbon sample reaches equilibrium. The butane is then purged off with dry air. BWC of the carbon sample is calculated from the difference in the measured mass of the carbon sample before and after the purge.

Using the ASTM test procedure, the BWC represents the full saturated capacity of the canister and not the amount of vapor that the canister will hold before breakthrough occurs. Under the EPA automotive test procedure in 40 CFR 86.134-96, the canister capacity is based on the amount of butane loaded in the canister until 2 grams of breakthrough is measured. However, we are proposing to use the ASTM procedure because it gives a repeatable measure that is currently used by industry. The design standard of 9 g/dL is based on this test procedure and therefore accounts for the differences in the ASTM and existing EPA automotive procedure.

Based on the data presented earlier in this chapter, we are proposing that the volume of the carbon canister must be a minimum of 0.04 liters of carbon per gallon of fuel tank capacity for fuel tanks installed in boats less than 26 feet in length. For larger boats, the fuel temperature may be less affected by diurnal temperature swings for two reasons. First, these fuel tanks would be in larger vessels which are more likely to be stored in the water and therefore, subject to smaller temperature fluctuations. Second, these fuel tanks would likely be larger and have larger thermal inertia in the fuel which may lead to lower temperature fluctuation. Therefore, for fuel tanks installed on boats greater than or equal to 25 feet, we are proposing a design minimum volume of 0.016 liters of carbon every gallon per gallon of fuel tank capacity.

5.6.3.4.2 Carbon humidity resistance

In a marine environment, the carbon may be exposed to more humid air, on average, than in land-based applications such as cars and trucks. Traditional carbons used in automotive applications can adsorb water, thereby closing sites off to hydrocarbons. With active purge and carbon heating during refueling vapor collection, the water vapor is easily purged off the carbon. Under this proposed rule, we are basing the design specification on a passive purge canister design and are not requiring onboard refueling vapor recovery. Therefore, we believe that the carbon should be resistant to moisture in the air. In the in-use program discussed above, marine grade carbon was used that was developed specifically for high humidity applications.[208]

We proposing design-based certification requirements for humidity resistance based on the specifications of the humidity-resistant carbon used in the in-use demonstration program. This carbon meets a moisture adsorption capacity maximum of 0.5 grams of water per gram of carbon at 90 percent relative humidity and a temperature of 25±5˚C. This limit is based on a test procedure where dried carbon is exposed to water vapor and the pressure in the sample chamber is controlled to achieve the correct partial pressure of the water to achieve the desired relative humidity. The adsorption of water in the carbon is calculated based on the reduction in pressure in the sample chamber. More detail on this test procedure is available in the docket.[209]

5.6.3.4.3 Carbon durability

Another issue that has been raised with regard to canister use in marine applications is the durability of the canister under the shocks that can be observed on a marine vessel. Automotive applications see shocks and vibration as well and the carbon is protected by packing it under pressure in the canister. To address the concern of carbon durability, however, we are proposing to include a carbon strength requirement. This strength requirement is consistent with the specifications for the carbon used in the in-use test program described above, which was designed to have a higher hardness value and lower dust attrition rates than typical automotive carbons.

The industry procedure for carbon pellet strength is to determine the average pellet size in a sample of carbon before and after a pan hardness test. Pellet size is determined by separating the carbon by size using sieves. The pan hardness test involves shaking the carbon in a pan with steel balls over a fixed period of time. The pellet strength is determined by taking the ratio of the average pellet size of the carbon before and after the pan and ball attrition test. We are proposing a pellet strength of at least 85 percent. The proposed test procedure is ASTM D3802-79[210] with two variations. First, as discussed above, hardness is defined as the ratio of mean particle diameter before and after the attrition test. Second, the attrition test would use twenty ½" steel balls and ten ¾" steel balls rather than fifteen of each as specified in ASTM D3802-79. These proposed variations on the ASTM procedure reflect common industry practice for pelletized carbons in contrast to the original test procedure which were intended for granular carbons.[211]

5.6.3.4.4 Canister design

The design of the canister itself is important in building an effective and durable carbon canister system. The canister should be made of a material that is compatible with the application. For instance, the material should be fuel resistant and durable. Where a flame test is required by the Coast Guard, the material should be able to pass this test on its own or with a protective cover. In addition, the canister material must have good structural integrity at temperatures that it would be exposed to in a boat. If the material changes in dimension at temperature, that flexing may loosen the carbon packing, allowing the carbon to move and eventually deteriorate. The canister should be installed in the boat in such a way that undue stress is not placed on the canister. It should also be properly constructed so that there are no leaks in the canister.

The canister must be packed in such a way that the carbon does not move inside the canister in-use. If the carbon were able to move, it would eventually break down under vibration. Over time the carbon could deteriorate into dust which could eventually escape from the canister. This is not an issue with a carbon canister that uses a properly designed and installed volume compensator. The basic design of a volume compensator is that compression is held on the carbon bed with a spring. A mesh or foam cover is used on the volume compensator that will allow air to pass through, but will hold the carbon pellets in place.

The carbon should be packed into the canister in such a way that there is a consistent size of carbon pellets throughout the canister. If the carbon settles in the storage hopper, it would be possible for some canisters to be filled largely with the smallest diameter carbon pellets (or dust) which would increase the pressure restriction of the canister. Also, if the carbon is not packed properly when placed into the canister, it could later settle leading to a volume reduction of the carbon that is too large for the volume compensator to address.

The carbon canister design must allow for a proper flow path of vapor and air through the carbon bed. In current carbon canister designs, an air gap is typically installed upstream of the carbon bed. Flow directors may be molded into this air gap. The purpose of the air gap is to allow the vapor or purge air to disperse and flow through the entire carbon bed. Even with a small air gap, the vapor will disperse because it will attempt to follow the path of least resistance through the canister. Without the air gap, the flow could be predominately in the center of the carbon (or wherever the intake hose connection is located).

The geometry of a carbon canister can affect the effectiveness of the control system. For instance, a long, narrow canister will have higher efficiency than a short wide canister. This is because some breakthrough can occur if the pathway is too short for the flow of vapor. Based on one study, the effectiveness of the carbon canister increases notably until a length to diameter ratio of about 3.5 is achieved.[212] At higher ratios, less of an impact on efficiency was observed. At too high of a length to diameter ratio, significant back pressure may occur in the system.

5.6.3.4.5 Integration with Fuel System

It would be important that a carbon canister system be appropriately integrated into the fuel system. For instance, the canister would need to be positioned in the vent line, and potentially a liquid separation valve added, to ensure that liquid fuel would not reach the canister during refueling. We would also expect the fuel system design to minimize spit-back out of the fill neck during refueling. A design that caused fuel to stream out the fill neck during refueling, even with a fuel nozzle shut-off mechanism, would not be acceptable.

5.7 Impacts on Noise, Energy, and Safety

The Clean Air Act requires EPA to consider potential impacts on noise, energy, and safety when establishing the feasibility of new emission standards for marine vessels.

5.7.1 Noise

In this case, we would not expect evaporative emission controls to have any impact on noise from Small SI equipment or marine vessels because noise from the affected parts of the fuel system is insignificant.

5.7.2 Energy

We anticipate that the proposed evaporative emission standards will have a positive impact on energy. By capturing or preventing the loss of fuel through evaporation, we estimate that the lifetime average fuel savings would be about 1.2 gallons for an average piece of Small SI equipment and 31 gallons for an average boat. This translates to a fuel savings of about 44 million gallons for Small SI equipment and 26 million gallons for Marine SI vessels in 2030 when most of the affected equipment used in the U.S. would be expected to have evaporative emission control.

5.7.3 Safety

As part of the development of this proposed rule, EPA performed a technical study on the safety of emission control technology for Small SI equipment and Marine SI vessels.[213] The conclusions of this study are presented below. Although the study focuses on equipment with engines less than 37 kilowatts, the conclusions drawn for marine apply to boats with larger engines as well as ABYC, USCG, UL, and SAE requirements do not distinguish between engine sizes.

EPA has reviewed the fuel hose and fuel tank characteristics for NHH and HH equipment and evaluated control technology which could be used to reduce evaporative emissions from these two subcategories. This technology is capable of achieving reductions in fuel tank and fuel hose permeation without an adverse incremental impact on safety. For fuel hoses and fuel tanks, the applicable consensus standards, manufacturer specific test procedures and EPA requirements are sufficient to ensure that there will be no increase in the types of fuel leaks that lead to fire and burn risk in use. Instead, these standards will reduce vapor emissions both during operation and in storage. That reduction, coupled with some expected equipment redesign, is expected to lead to reductions in the risk of fire or burn without affecting component durability.

We also conducted a design and process Failure Mode and Effects Analyses (FMEA) comparing current Phase 2 and Phase 3 compliant engines and equipment to evaluate incremental changes in risk probability as a way of evaluating the incremental risk of upgrading Phase 2 engines to meet Phase 3 emission standards.[214] This is an engineering analysis tool to help engineers and other professional staff on the FMEA team to identify and manage risk. In a FMEA, potential failure modes, causes of failure, and failure effects are identified and a resulting risk probability is calculated from these results. This risk probability is used by the FMEA team to rank problems for potential action to reduce or eliminate the causal factors. Identifying these causal factors is important because they are the elements that a manufacturer can consider reducing the adverse effects that might result from a particular failure mode.

Our FEMA evaluated permeation and running loss controls on nonhandheld engines. We found that these controls would not increase the probability of fire and burn risk from those expected with current fuel systems, but could in fact lead to directionally improved systems from a safety perspective. Finally, the running loss control program being proposed for nonhandheld equipment will lead to changes that are expected to reduce risk of fire during in-use operation. Moving fuel tanks away from heat sources, improving cap designs to limit leakage on tip over, and requiring a tethered cap will all help to eliminate conditions which lead to in-use problems related to fuel leaks and spillage. Therefore, we believe that the application of emission control technology to reduce evaporative emissions from these fuel hoses and fuel tanks will not lead to an increase in incremental risk of fires or burns and in some cases is likely to at least directionally reduce such risks.

EPA has reviewed the fuel hose and fuel tank characteristics for marine vessels and evaluated control technology which could be used to reduce evaporative emissions from boats. With regard to fuel hoses, fuel tanks, and diurnal controls, there are rigorous USCG, ABYC, UL, and SAE standards which manufacturers will continue to meet for fuel system components. All of these standards are designed to address the in-use performance of fuel systems, with the goal of eliminating fuel leaks. The low permeation fuel hoses and tanks needed to meet the Phase 3 requirements would need to pass these standards and every indication is that they would pass.

Furthermore, the EPA permeation certification requirements related to emissions durability will add an additional layer of assurance. Low permeation fuel hoses are used safely today in many marine vessels. Low permeation fuel tanks and diurnal emission controls have been demonstrated in various applications for many years without an increase in safety risk. Furthermore, a properly designed fuel system with fuel tank and fuel hose permeation controls and diurnal emission controls would reduce the fuel vapor in the boat, thereby reducing the opportunities for fuel related fires. In addition, using improved low permeation materials coupled with designs meeting USCG and ABYC requirements should reduce the risk of fuel leaks into the vessel. EPA believes that the application of emission control technologies on marine engines and vessels for meeting the proposed evaporative emissions standards would not lead to an increase in incremental risk of fires or burns, and in many cases may incrementally decrease safety risks in certain situations..

APPENDIX 5A: Diurnal Temperature Traces

Figure 5A-1: Temperature Trace for Personal Watercraft on Trailer

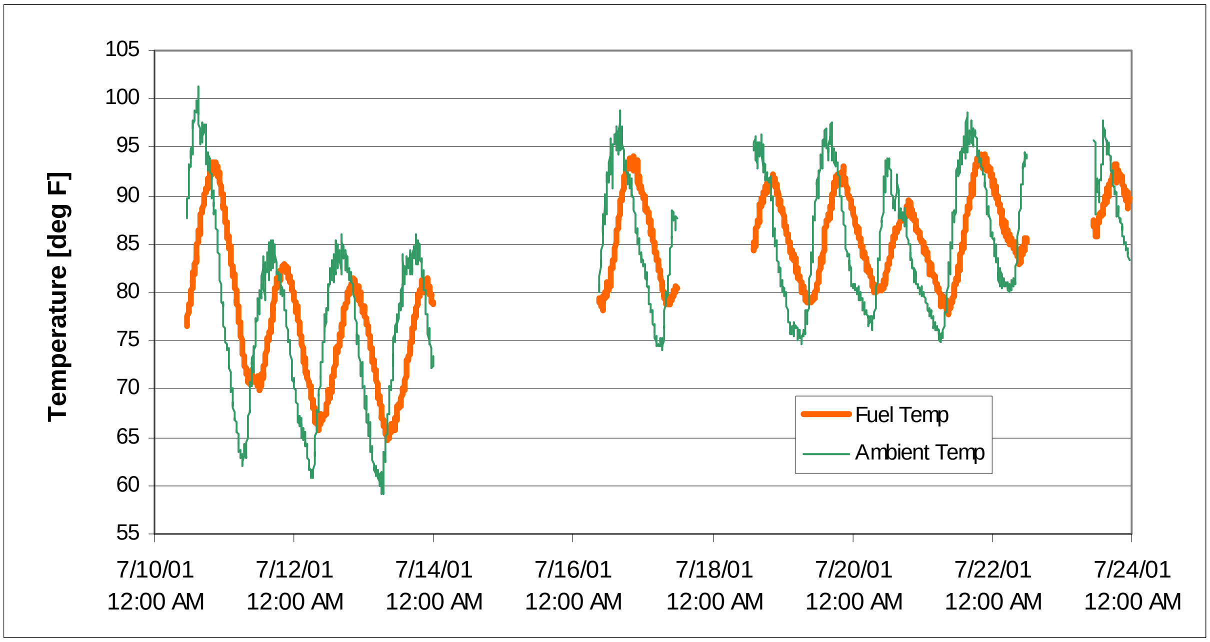


Figure 5A-2: Temperature Trace for Jet Boat on Trailer

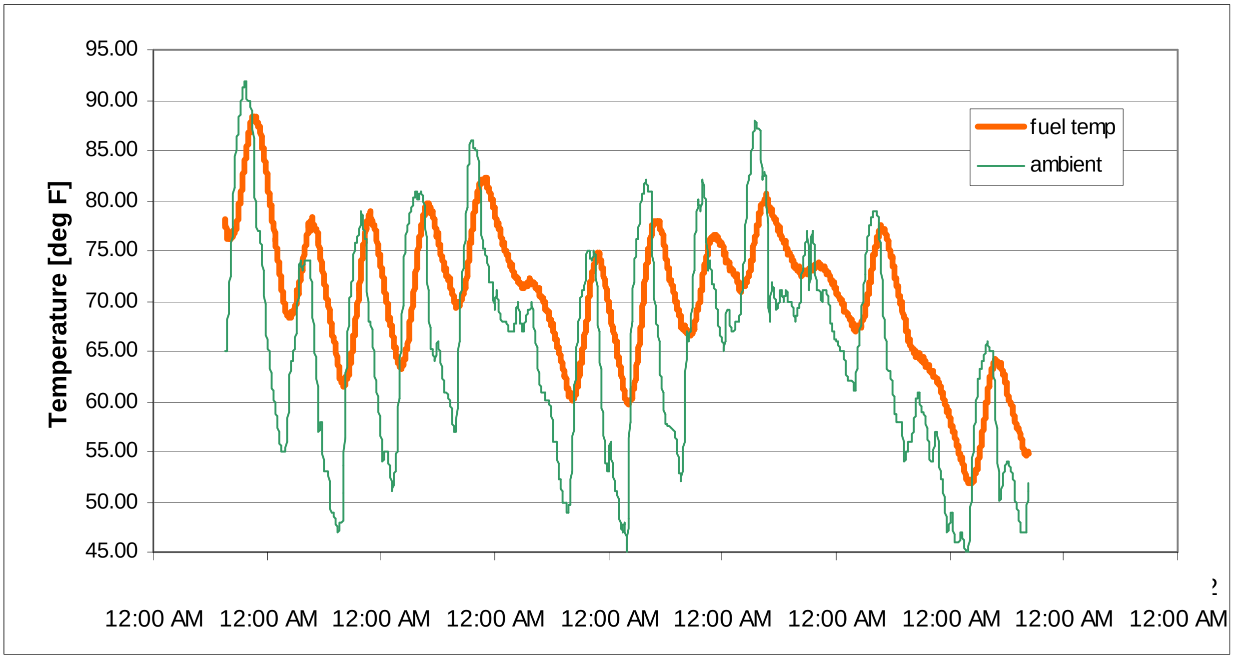


Figure 5A-3: Temperature Trace for Runabout on Trailer

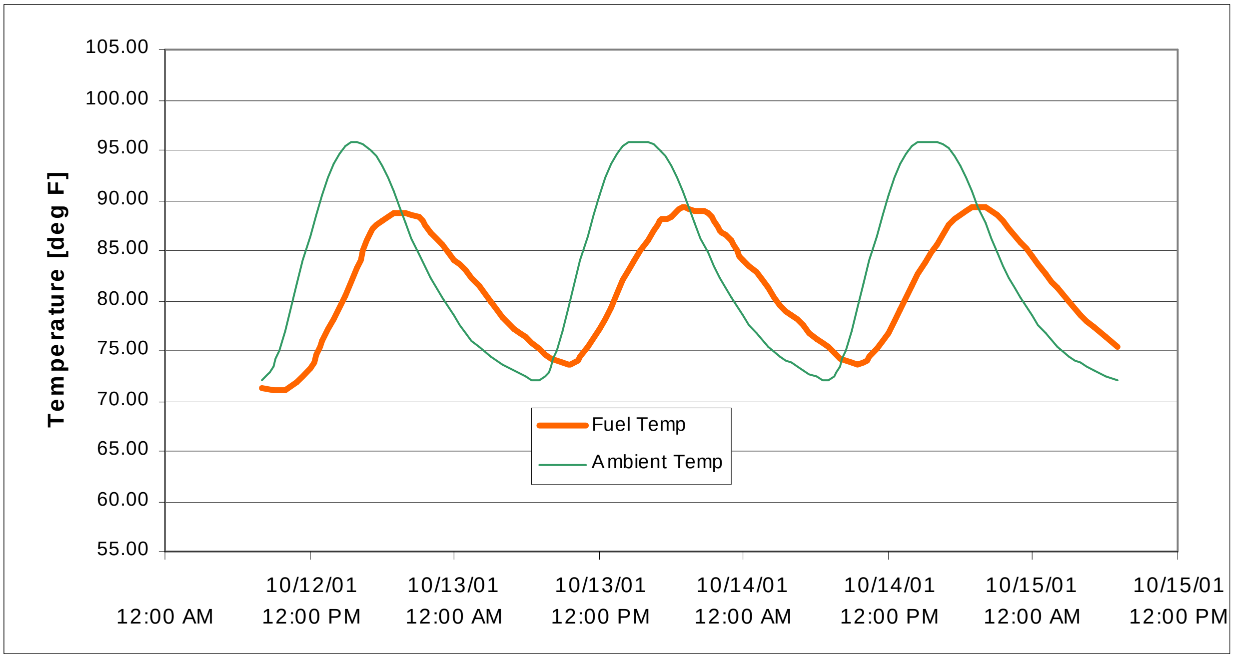


Figure 5A-4: Temperature Trace for Jet Boat on Trailer

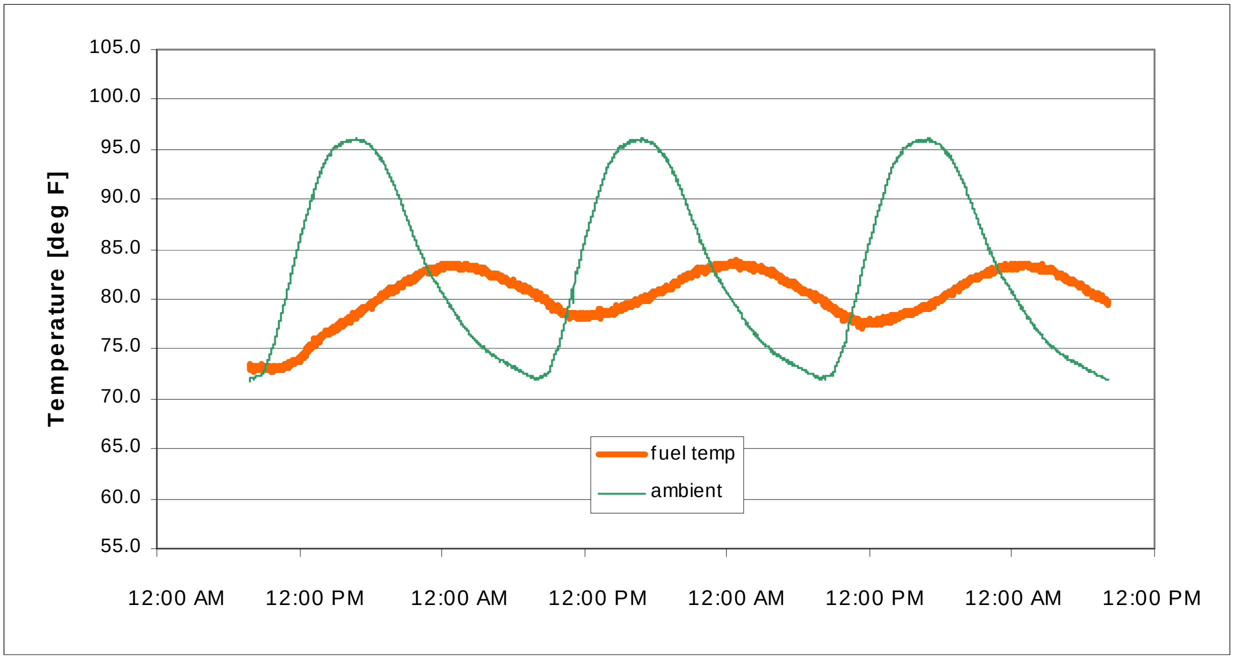


Figure 5A-5: Temperature Trace for Runabout in Water

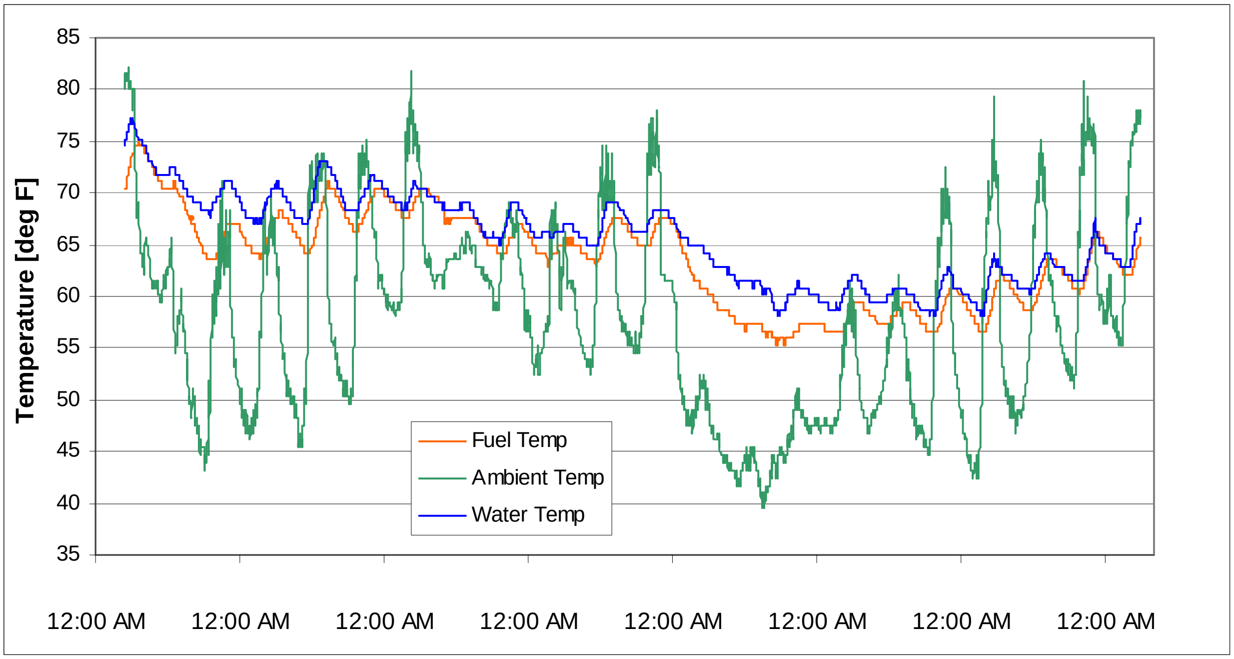
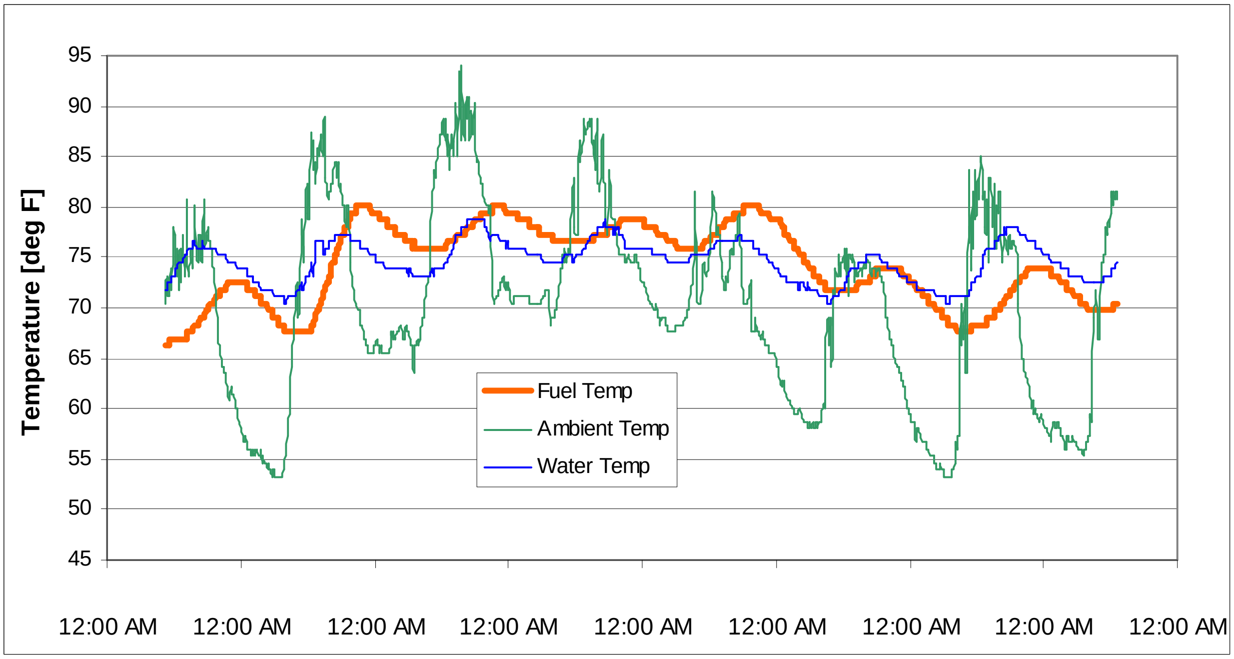


Figure 5A-6: Temperature Trace of Deckboat in Water



APPENDIX 5B: Emission Results for Small SI Equipment Fuel Tanks Showing Effect of Venting on Diffusion

5B.1 Diffusion Effects from Variable Temperature Diurnal Testing

Figure 5B-1: Diurnal/Diffusion Test Results for BM Metal Fuel Tank (2 Labs)

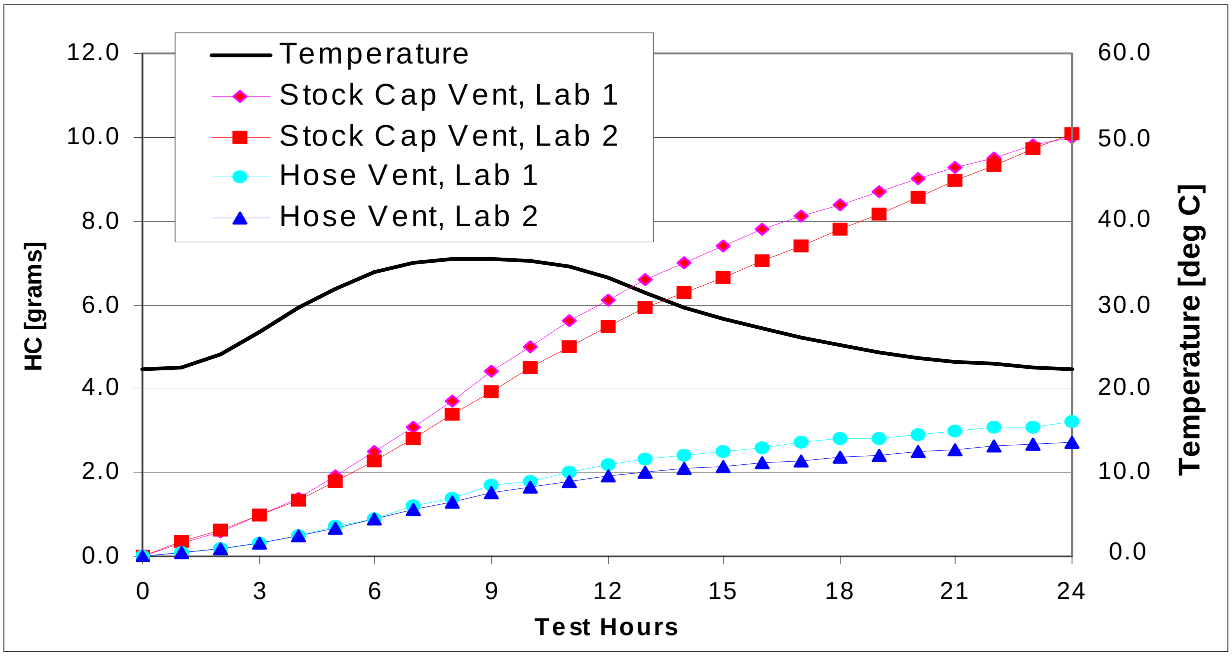


Figure 5B.1-2: Diurnal/Diffusion Test Results for BP Plastic Fuel Tank

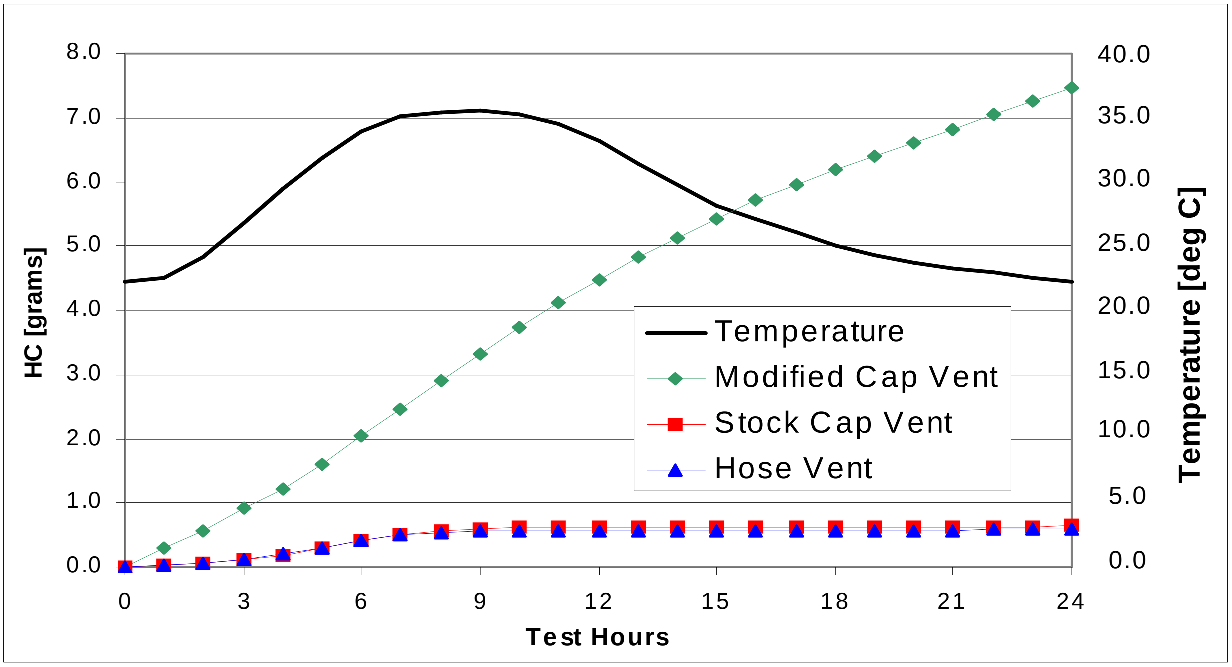


Figure 5B.1-3: Diurnal/Diffusion Test Results for HP Plastic Fuel Tank

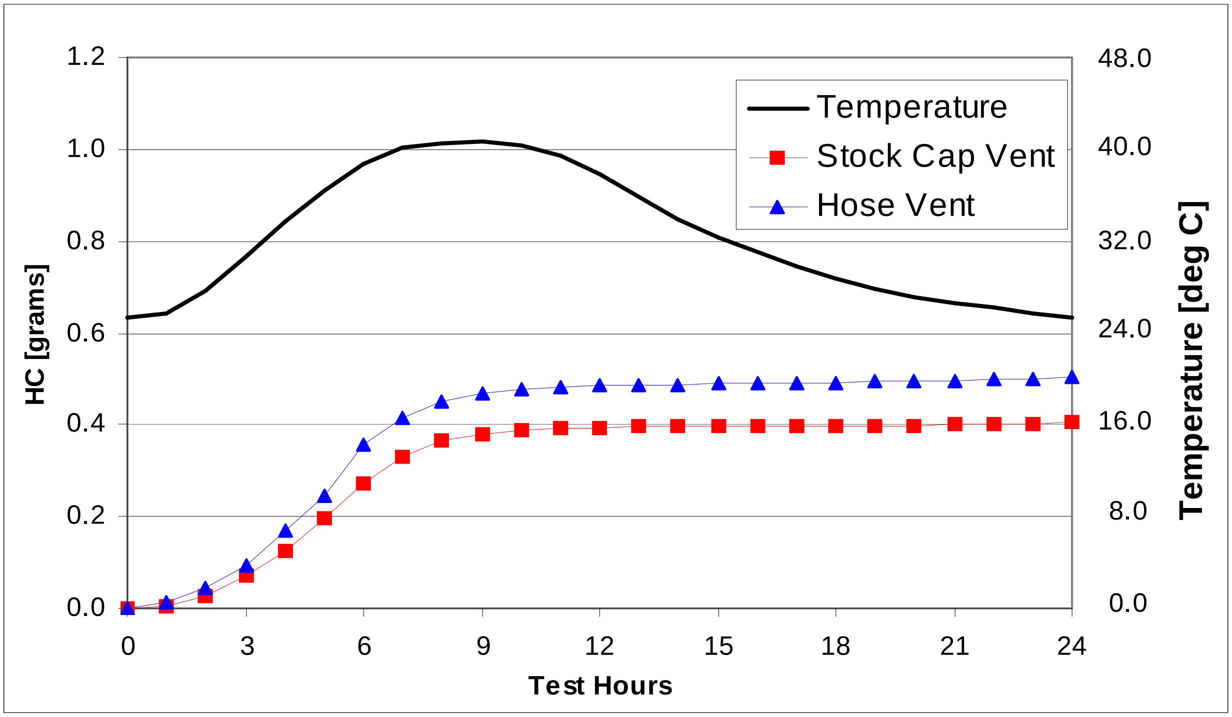
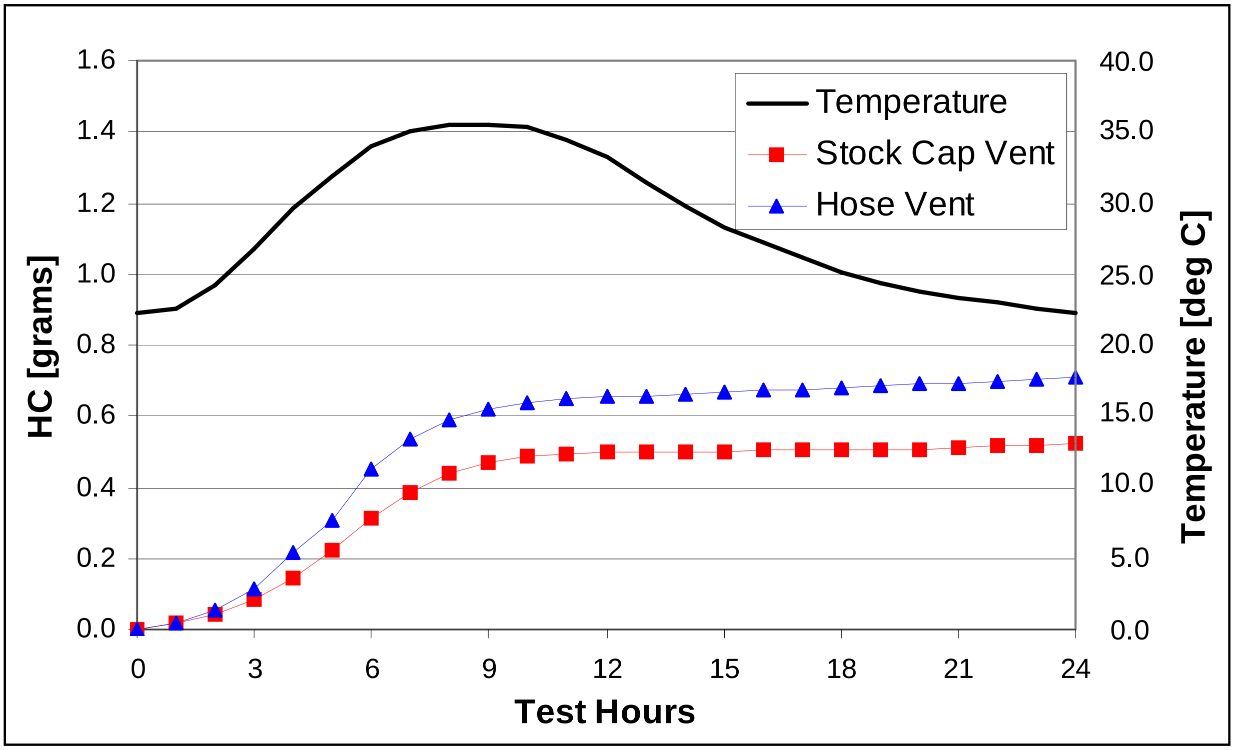


Figure 5B.1-4: Diurnal/Diffusion Test Results for TP Plastic Fuel Tank



5B.2 Isothermal Results for Small SI Equipment Fuel Tanks Showing Effect of Venting on Diffusion

Figure 5B.2-1: Isothermal Diffusion Test Results for BM Metal Fuel Tank

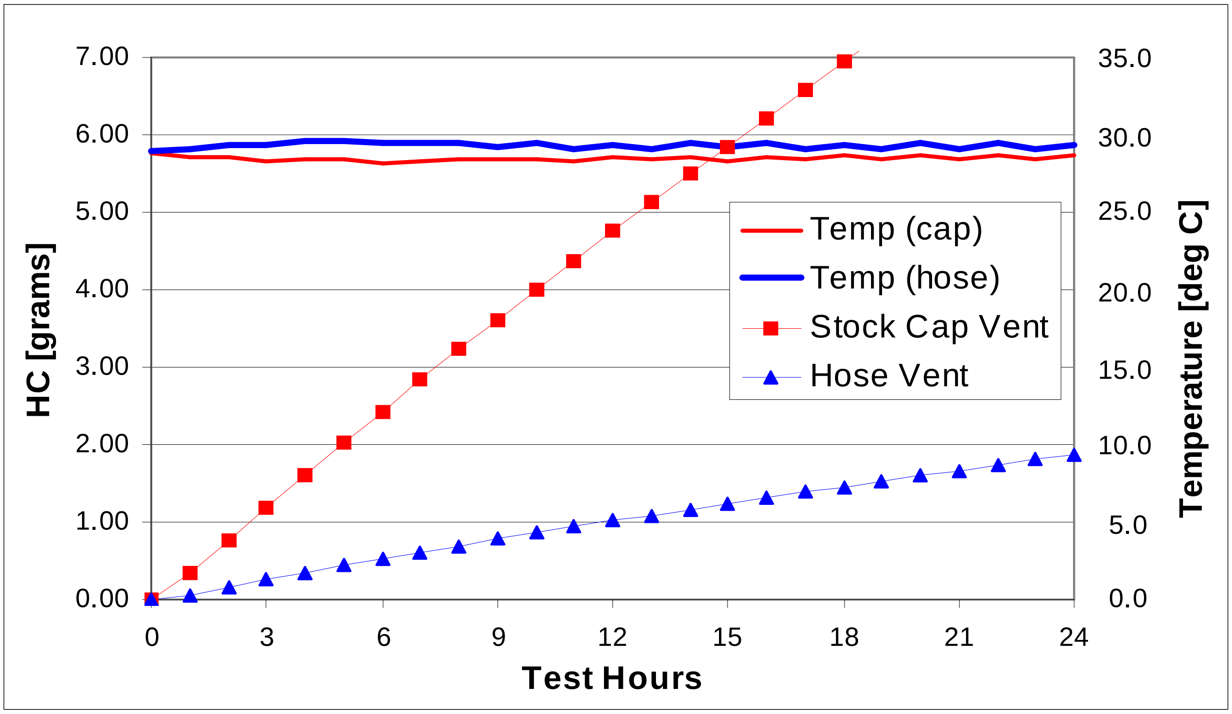


Figure 5B.2-2: Isothermal Diffusion Test Results for BP Plastic Fuel Tank

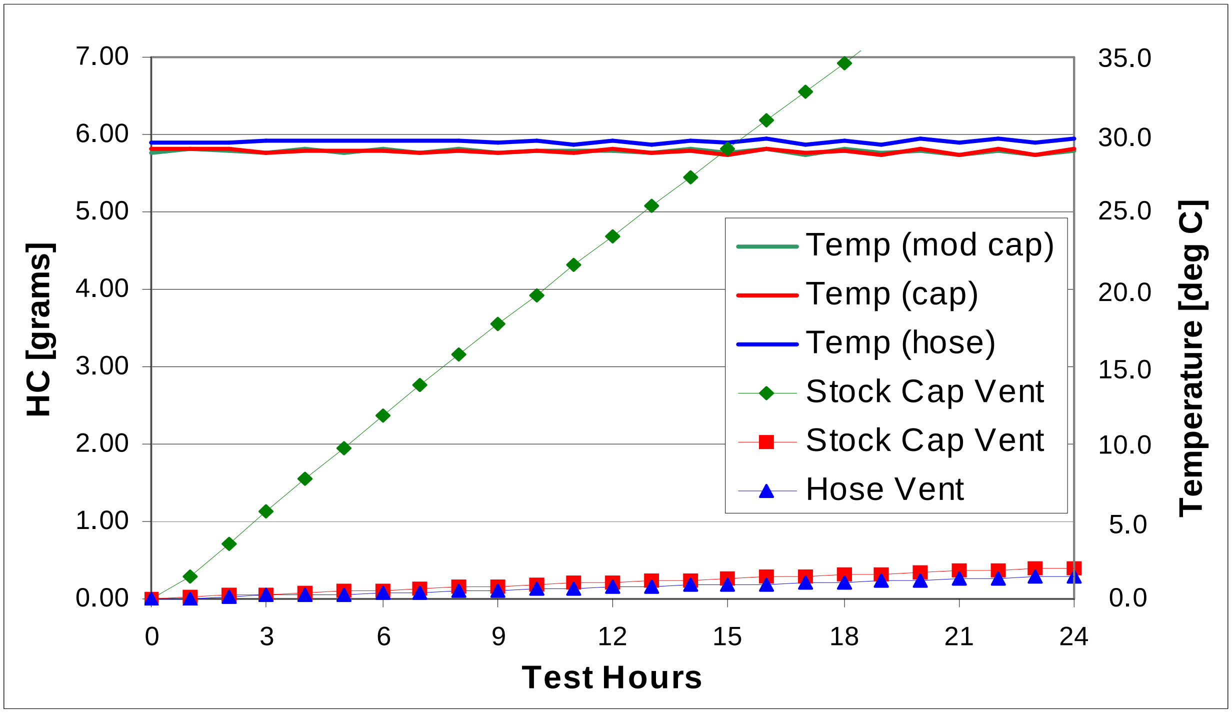


Figure 5B.2-3: Isothermal Diffusion Test Results for HP Plastic Fuel Tank

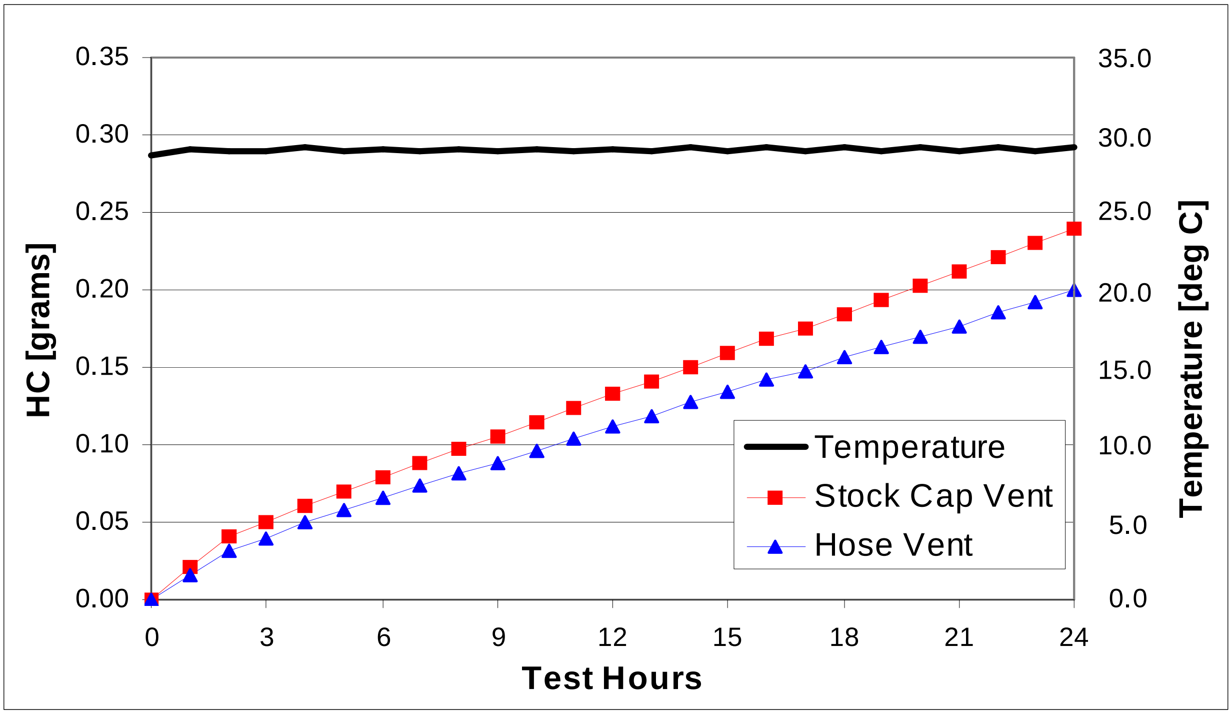
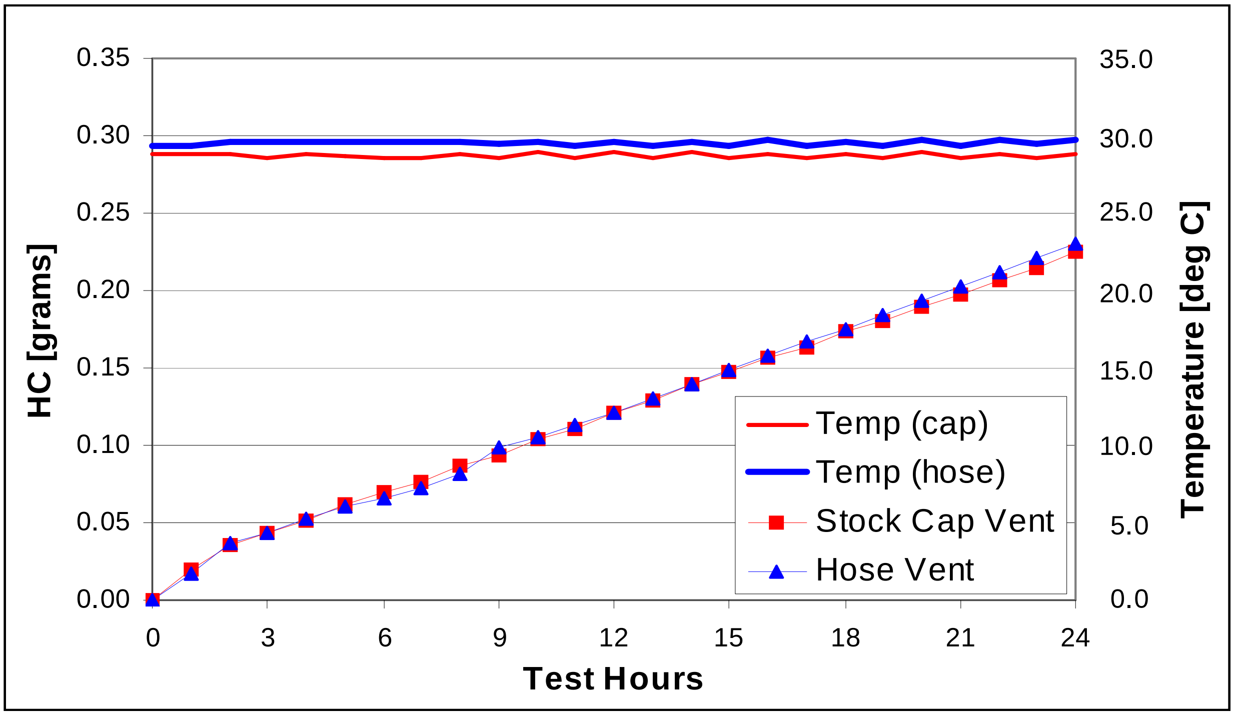
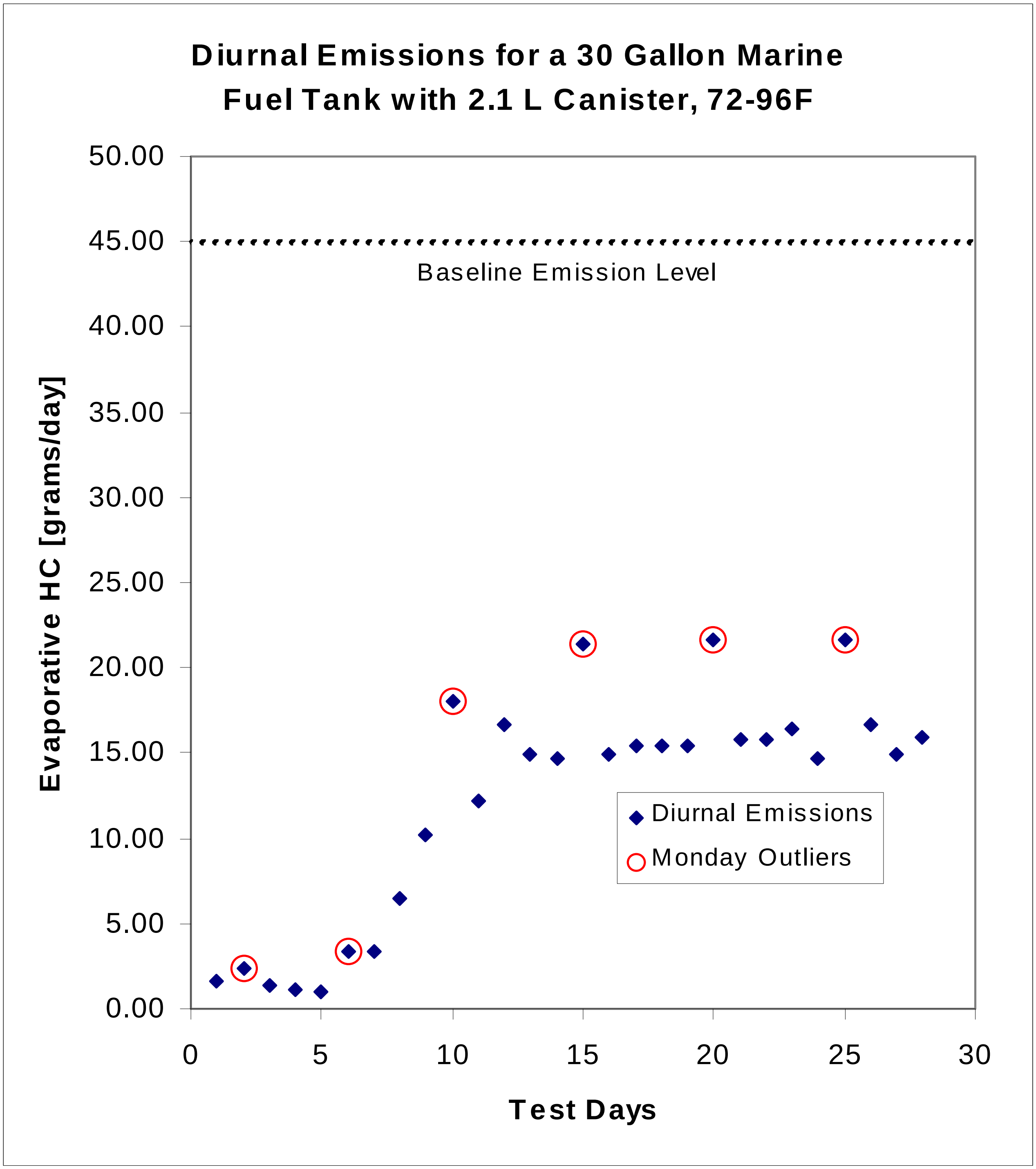


Figure 5B.2-4: Isothermal Diffusion Test Results for TP Plastic Fuel Tank



APPENDIX 5C: Diurnal Emission Results: Canister and Passive-Purge



APPENDIX 5D: Material Properties of Common Fuel System Materials

This appendix presents data on permeation rates for a wide range of materials that can be used in fuel tanks and hoses. The data also includes effects of temperature and fuel type on permeation. Because the data was collected from several sources, there is not complete data on each of the materials tested in terms of temperature and test fuel. Table D-1 gives an overview of the fuel systems materials included in the data set. Tables D-2 through D-3 present permeation rates using Fuel C, a 10 percent ethanol blend (CE10), and a 15 percent methanol blend (CE15) for the test temperatures of 23, 40, 50, and 60°C.

Table 5D-1: Fuel System Materials

Material Name	Composition
ACN NBR	acrylonitrile
Carilon	aliphatic poly-ketone thermoplastic
Celcon	acetal copolymer
CFM	fluoroelastomer
CO	epichlorohydrin homopolymer
CR	polychloroprene polymer
CSM	chlorosulfonated polyethylene
E14659	fluoropolymer film
E14944	fluoropolymer film
ECO	epichlorohydrin-ethylene oxide copolymer
ETER	epichlorohydrin-ethylene oxide terpolymer
ETFE	ethylenetetrafluoroethylene, fluoroplastic
EVOH	ethylene vinyl alcohol, thermoplastic
FEB	fluorothermoplastic
FEP	fluorothermoplastic
FKM	fluorocarbon elastomer
FPA	copolymer of tetrafluoroethylene and perfluoroalkoxy monomer
FVMQ	fluorovinyl methal silicone rubber (flourosilicone)
GFLT	fluoroelastomer
HDPE	high-density polyethylene
HDPE	high density polyethylene
HNBR	hydrogenated acrylonitrile-butadiene rubber
LDPE	low density polyethylene
NBR	acrylonitrile-butadiene rubber
Nylon 12	thermoplastic
PBT	polybutylene terephthalate, thermoplastic
PFA	fluorothermoplastic
Polyacetal	thermoplastic
PTFE	polytetrafluoroethylene, fluoroplastic
PVDF	polyvinylidene fluoride, fluorothermoplastic
THV	tetrafluoroethylene, hexafluoropropylene, vinyledene fluoride

Table 5D-2: Fuel System Material Permeation Rates at 23°C by Fuel Type [215,216,217,218,219,220]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
HDPE	35	–	35
Nylon 12, rigid	0.2	–	64
EVOH	–	–	10
Polyacetal	–	–	3.1
PBT	–	–	0.4
PVDF	–	–	0.2
NBR (33% ACN)	669	1028	1188
HNBR (44%ACN)	230	553	828
FVMQ	455	584	635
FKM Viton A200 (66%F)	0.80	7.5	36
FKM Viton B70 (66%F)	0.80	6.7	32
FKM Viton GLT (65%F)	2.60	14	60
FKM Viton B200 (68%F)	0.70	4.1	12
FKM Viton GF (70%F)	0.70	1.1	3.0
FKM Viton GFLT (67%F)	1.80	6.5	14
FKM - 2120	8	–	44
FKM - 5830	1.1	–	8
Teflon FEP 1000L	0.03	0.03	0.03
Teflon PTFE	–	–	0.05
Teflon PFA 1000LP	0.18	0.03	0.13
Tefzel ETFE 1000LZ	0.03	0.05	0.20
Nylon 12 (GM grade)	6.0	24	83
Nitrile	130	635	1150
Silicone Rubber	–	–	6500
Fluorosilicone	–	–	635
FKM	–	16	–
FE 5620Q (65.9% fluorine)	–	7	–
FE 5840Q (70.2% fluorine)	–	4	–
PTFE	0.05	–	0.08*
ETFE	0.02	–	0.04*
PFA	0.01	–	0.05*
THV 500	0.03	–	0.3

* tested on CM20.

Table 5D-3: Fuel System Material Permeation Rates at 40°C by Fuel Type [221,222]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
Carilon	0.06	1.5	13
EVOH - F101	<0.0001	0.013	3.5
EVOH - XEP380	<0.0001	–	5.3
HDPE	90	69	71
LDPE	420	350	330
Nylon 12 (L2101F)	2.0	28	250
Nylon 12 (L2140)	1.8	44	–
Celcon	0.38	2.7	–
Fortron PPS SKX-382	–	0.12	–
Celcon Acetal M90	–	0.35	–
Celanex PBT 3300 (30% GR)	–	3	–
Nylon 6	–	26	–
Dyneon E14659	0.25	–	2.1
Dyneon E14944	0.14	–	1.7
ETFE Aflon COP	0.24	0.67	1.8
m-ETFE	0.27	–	1.6
ETFE Aflon LM730 AP	0.41	0.79	2.6
FKM-70 16286	11	35	–
GFLT 19797	13	38	–
Nitrile	–	1540	3500
FKM	–	86	120
FE 5620Q (65.9% fluorine)	–	40	180
FE 5840Q (70.2% fluorine)	–	12	45
THV-310 X	–	–	5.0
THV-500	0.31	–	3.0
THV-610 X	–	–	2.1

Table 5D-4: Fuel System Material Permeation Rates at 50°C by Fuel Type [223]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
Carilon	0.2	3.6	–
HDPE	190	150	–
Nylon 12 (L2140)	4.9	83	–
Celcon	0.76	5.8	–
ETFE Afcon COP	–	1.7	–
FKM-70 16286	25	79	–
GFLT 19797	28	77	–

Table 5D-5: Fuel System Material Permeation Rates at 60°C by Fuel Type [224,225,226,227]

Material Name	Fuel C g-mm/m^2/day	Fuel CE10 g-mm/m^2/day	CM15 g-mm/m^2/day
Carilon	0.55	7.5	–
HDPE	310	230	–
Nylon 12 (L2140)	9.5	140	–
Celcon	1.7	11	–
ETFE Afcon COP	–	3.8	–
FKM-70 16286	56	170	–
GFLT 19797	60	130	–
polyeurethane (bladder)	285	460	–
THV-200	–	54	–
THV-310 X	–	–	38
THV-510 ESD	6.1	18	35
THV-500	–	11	20
THV-500 G	4.1	10	22
THV-610 X	2.4	5.4	9.0
ETFE 6235 G	1.1	3.0	6.5
THV-800	1.0	2.9	6.0
FEP	0.2	0.4	1.1

APPENDIX 5E: Diurnal Test Temperature Traces

Table 5E-1: Temperature vs. Time Sequence for Proposed Diurnal Testing

Test Time* [minutes]	Portable Fuel Tanks SHED Air Temperature		Installed Fuel Tanks Boat < 26 feet (7.9m) Fuel Temperature		Installed Fuel Tanks Boat ≥26 feet (7.9m) Fuel Temperature	
	Fahrenheit	Celsius	Fahrenheit	Celsius	Fahrenheit	Celsius
0	72.0	22.2	78.0	25.6	81.6	27.6
60	72.5	22.5	78.3	25.7	81.7	27.6
120	75.5	24.2	79.8	26.5	82.3	27.9
180	80.3	26.8	82.2	27.9	83.3	28.5
240	85.2	29.6	84.6	29.2	84.2	29.0
300	89.4	31.9	86.7	30.4	85.1	29.5
360	93.1	33.9	88.6	31.4	85.8	29.9
420	95.1	35.1	89.6	32.0	86.2	30.1
480	95.8	35.4	89.9	32.2	86.4	30.2
540	96.0	35.6	90.0	32.2	86.4	30.2
600	95.5	35.3	89.8	32.1	86.3	30.2
660	94.1	34.5	89.1	31.7	86.0	30.0
720	91.7	33.2	87.9	31.0	85.5	29.7
780	88.6	31.4	86.3	30.2	84.9	29.4
840	85.5	29.7	84.8	29.3	84.3	29.1
900	82.8	28.2	83.4	28.6	83.8	28.8
960	80.9	27.2	82.5	28.0	83.4	28.5
1020	79.0	26.1	81.5	27.5	83.0	28.3
1080	77.2	25.1	80.6	27.0	82.6	28.1
1140	75.8	24.3	79.9	26.6	82.4	28.0
1200	74.7	23.7	79.4	26.3	82.1	27.9
1260	73.9	23.3	79.0	26.1	82.0	27.8
1320	73.3	22.9	78.7	25.9	81.9	27.7
1380	72.6	22.6	78.3	25.7	81.7	27.6
1440	72.0	22.2	78.0	25.6	81.6	27.6

* Repeat as necessary

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