



Technical Overview of the Effects of Reformulated Gasoline on Automotive and Non-Automotive Engine Performance



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I. Executive summary

Reformulated gasolines (RFGs) are similar to many conventional gasolines in terms of composition, physical and chemical properties, and effects on engine operation. RFG results in lower emissions of ozone-forming and toxic chemicals than typical conventional gasolines.

RFGs are expected to have little or no influence on the incidence of many engine performance concerns and is expected to reduce the incidence of some of those concerns. Any such effects, which at present are hypothetical in nature and have not been confirmed in the field, would be small and would tend to be overwhelmed by normal variations in engine operation, ambient conditions, and fuel quality. Any adverse effects of RFG on engine performance, which are expected to be extremely rare in actual use, could be mitigated or eliminated through relatively simple actions by the engine operator. Furthermore, the potential problems perceived to be associated with RFG use are more likely to be the result of improper engine maintenance, extreme engine operation, operator error, or normal engine wear.

II. Background and benefits of RFG

Congress, through the Clean Air Act Amendments of 1990 (CAAA), required that cleaner-burning gasoline be used in the nine cities with the worst urban ozone problems in the United States beginning in 1995. This gasoline, called "reformulated gasoline" or "RFG", was required to reduce emissions of ozone-forming compounds and air toxics, such as benzene, when compared to gasolines in use in 1990. Urban ozone (smog) is formed through a complex set of chemical reactions involving volatile organic compounds (VOCs), oxides of nitrogen (NOX), and sunlight. Urban ozone irritates human lungs, increases breathing difficulty (particularly for people with asthma, emphysema, or other lung problems), damages crops and other vegetation, and degrades paint, rubber, and other materials.

With the input of the oil and auto industries, state and local governments, oxygenate producers, and environmental

organizations, the Environmental Protection Agency (EPA) designed the RFG program to give the oil industry as much flexibility as possible to produce gasoline which meets these requirements at the lowest possible cost.

In the first phase of the program, from 1995-1999, cars and trucks running on reformulated gasoline should produce 15% less ozone-forming VOCs each mile they are driven. NOX emissions should not increase over 1990 levels. During this time, RFG use will also reduce emissions of cancer-causing air toxics from cars and trucks by 15%. The second phase of the program begins in the year 2000. In this second phase, RFG use should reduce ozone-forming emissions by roughly 25%, and air toxics by about 20% over 1990 levels. NOX should be reduced about 5-7%.

Most programs to reduce pollution from cars and trucks take years until they become fully effective, since it takes time for vehicles with new technology to replace older, dirtier vehicles. Reformulated gasoline, by contrast, reduces pollution from older and newer cars immediately, which helps make RFG one of the most convenient and cost-effective ways to clean the air in polluted cities. As a result, a number of areas have chosen to join the RFG program to help meet their air quality goals.

III. Similarities and differences between reformulated and conventional gasolines

Before discussing EPA's findings regarding the various engine performance concerns, it may be useful to clarify the similarities and differences between reformulated gasolines and conventional gasolines (CG).

A. Fuel parameter ranges

As stated earlier, reformulated gasoline is gasoline that has been "reformulated" to significantly reduce VOC and air toxics emissions, on average, relative to conventional gasoline. The term "reformulated", however, refers to slight changes in the proportion of fuel components in a given fuel, not to extreme measures where fuel components are totally removed or new, untested fuel components are included. RFG fuel parameter values

are well within the ranges of fuel parameter values of existing gasoline as shown in Table 1.

Gasoline has always been composed of a broad range of components in varying amounts. The type and amount of each component affect fuel economy, engine performance, and vehicle emission levels. The reformulated gasoline program does not require the creation of entirely new gasoline blends but merely requires that only lower-emitting gasoline blends be sold in covered areas.

The following table summarizes the properties of various gasolines. Conventional gasoline properties are presented in terms of their average values and the range of values observed in retail gasolines, including those with oxygenates. For comparison purposes, the table also shows the average properties of the most common ethanol blend, which is commonly known as "gasohol" and contains 10% ethanol by volume. The table also shows the average properties of "oxyfuels" (gasolines that meet the requirements of the oxygenated fuels program) and the reformulated gasolines expected to be produced during 1995-1999.

Table 1. Comparison of RFG and Existing Gasoline Compositions

	Fuel Parameter Values (national basis)				
	Conventional gasoline		Gasohol (3.5 wt% oxygen)	Oxyfuel (2.7 wt% oxygen)	Phase I RFG
	Avg ¹	Range ²	Avg	Avg	Avg
RVP ³ (psi)	8.7-S 11.5-W	6.9- 15.1	9.7-S 11.5-W	8.7-S 11.5-W	7.1/8.0-S 11.5-W
T50 (°F)	207	141- 251	202	205	202
T90 (°F)	332	286- 369	316	318	316
Arom (vol%)	28.6	6.1- 52.2	23.9	25.8	23.4
Olef (vol%)	10.8	0.4- 29.9	8.7	8.5	8.2
Benz (vol%)	1.60	0.1- 5.18	1.60	1.60	1.0
Sulf (ppm)	338	10- 1170	305	313	302
MTBE ⁴ (vol%)	--	0.1- 13.8	--	15	11
EtOH ⁴ (vol%)	--	0.1- 10.4	10	7.7	5.7

¹Clean Air Act

²1990 Motor Vehicle Manufacturers' Association survey

³Winter (W) higher than Summer (S) to maintain vehicle performance

⁴Assumes that oxygenates are not present simultaneously in the same blend. If both MTBE and ethanol are present in a given blend, the total oxygenate volume is less than that shown for MTBE.

B. Summary of differences between CG and RFG

Although RFG fuel parameter values are within the ranges of fuel parameter values of existing gasoline, the reformulated gasoline regulations do impose limits on certain fuel parameters in order to achieve the emissions reductions. Specifically, RFG is required to contain oxygen (supplied by 5.7% ethanol or 11% MTBE by volume, on average), to have no more than 1% benzene and to have lower RVP during the summer months than is required in non-RFG areas. The aromatic content of RFG will also be reduced to varying degrees to ensure that air toxics emissions are controlled. Changes in other fuel parameter values will occur primarily as a result of dilution due to the addition of oxygenates. These fuel changes are minor, within the range of existing gasoline, and should have minimal effects on vehicle performance.

C. Specific RFG Fuel Requirements

1. Reid Vapor Pressure (RVP)

RVP is a measure of how quickly fuel evaporates, or volatilizes. A higher RVP fuel volatilizes more quickly than a lower RVP fuel. Higher RVPs are needed under winter conditions to ensure adequate starting ability. However, in the summer, high RVPs are not needed since summer temperatures ensure sufficient volatility. Higher RVP fuels cause higher emissions. For this reason, summer RVPs have been held at lower levels for several years. Under the RFG program, summer RVPs will be reduced even further. This reduction provides the majority of ozone-forming VOC reductions from RFG.

2. Benzene

Benzene is a proven human carcinogen which is present both as a fuel component and in exhaust and evaporative emissions. In RFG, the benzene content of the fuel is limited to roughly 1% (compared to a typical gasoline average of 1.6%). This limit reduces emissions of benzene and provides the majority of the 15% air toxics emission reduction required of RFG.

3. Oxygenates

Reformulated gasoline is required to contain oxygen. This oxygen can come from ethanol or from ethers, such as MTBE, ETBE or TAME. Currently, ethanol and MTBE are the oxygenates predominately used in RFG.

RFG must on average contain 5.7% ethanol or 11% MTBE, by volume. However, a given batch of RFG may contain 4.0 to 10.0% ethanol or 8.3 to 15.0% MTBE, by volume. While every gallon of RFG must contain oxygenate, RFG contains less oxygenate on average than is allowed in conventional gasoline (up to 10% ethanol or 15% MTBE, by volume). However, oxygenate use in CG is highly dependent on economic factors, that is, whether or not it is financially advantageous to produce oxygenated gasoline.

On average, RFG is also expected to contain less oxygen than is found in oxygenated gasoline required in carbon monoxide (CO) nonattainment areas by the CAAA under a separate program from RFG. In those areas, the gasoline must contain at least 7.8% ethanol or 15% MTBE, by volume.

Many of the recent concerns expressed about RFG have centered on the oxygenate portion of RFG. However, considerable in-use experience with oxygenates in gasoline exists which suggests that vehicle performance should, for the most part, be unaffected by RFG. Oxygenates, particularly ethanol and MTBE, have been used as gasoline extenders and octane enhancers in gasoline since the 1970's without notable problems. In the late 1980's, Denver, CO and Phoenix, AZ started the first oxygenated gasoline programs as a means of reducing CO emissions. Oxygenate use increased substantially in 1992 with the start of the federal oxygenated fuel program (for CO control) which was required in some 39 cities across the country.

In 1990, ethanol was present in nearly 7% of the U.S. gasoline pool (usually at concentrations of 10%, by volume) and MTBE was found in nearly 25% of the U.S. gasoline pool (mostly in smaller concentrations than are required in RFG). Today, MTBE has a larger market share in CO nonattainment areas than ethanol, but the choice of oxygenate is highly dependent on local market conditions. Oxygenates are likely to continue to be used in

conventional gasoline, primarily as octane enhancers.

4. Other fuel changes

RFG is expected to have levels of other fuel parameters that are well within the range observed for conventional gasoline. However, gasoline reformulation is likely to result in small shifts in some of these parameters. To reduce toxic air pollutants, RFGs are likely to have lower aromatics levels, on average, than conventional gasolines, which in turn should reduce elastomer deterioration rates and deposit formation. RFGs are expected to have lower olefin levels, which would reduce gum formation and therefore reduce fuel storage and spark plug fouling problems. RFGs are also anticipated to have lower levels of the heaviest gasoline deposits, which in turn should reduce deposit formation and its associated problems. RFGs are almost certain to have lower levels of sulfur, which would also reduce deposit formation, spark plug fouling, engine wear, and corrosion in the exhaust system, particularly when the second phase of the RFG program begins in 2000.

D. Seasonal Variations in RFG Composition

Gasoline composition, in general, varies from winter to summer. For instance, in winter when higher RVPs are required, greater concentrations of the lighter, higher RVP components are needed to ensure vehicle startability and performance. The higher levels of light components tend to dilute the remaining fuel constituents. In the summer, lower RVP requirements cause a small shift in gasoline composition as the concentration of lighter components is reduced. Similarly, in those areas of the country which require oxygenated gasoline in the winter to reduce CO emissions, the addition of oxygenate will tend to dilute other fuel constituents; as oxygenate concentrations are reduced during the summer, gasoline composition will shift slightly.

Although oxygen and benzene requirements must be met year-round, RFG composition will also vary from winter to summer. EPA imposes no constraints on winter RVP levels, so the winter RVPs of conventional and reformulated gasolines are not expected to differ. In CO nonattainment areas, the winter gasoline oxygen

content will generally be the same regardless of whether the area gets conventional or reformulated gasoline. In summer, when the RVP of RFG must be lower on average than for CG, compositional differences between RFG and CG will reflect the oxygen, benzene and RVP requirements of RFG.

E. Comparison of RFG to California reformulated gasoline

California has its own reformulated gasoline program, which began with a wintertime oxygenated fuel program in 1992. The second phase of the California program (CA Phase II) begins in 1996. CA Phase II gasoline has the same oxygen requirement as RFG. It is somewhat more stringent than the federal RFG program because limits are imposed on many more fuel parameters (whereas the Federal RFG program specifies limits only on oxygen, benzene and RVP). Additionally, until the year 2000, California's limits on RVP are more stringent than would be required under the federal RFG program. Beginning in 2000, federal and California RFGs are likely to have comparable RVP levels as the stricter Phase II emission reduction requirements take effect for the federal RFG program.

IV. Overview of RFG-related concerns

Over the last several months, EPA has become aware of a wide range of concerns regarding the effects of RFG on the performance of automotive and non-automotive engines. Citizens, engine manufacturers, and vehicle manufacturers identified three distinct types of concerns: potential engine performance problems, potential fuel-related sources of those performance problems, and concerns regarding the effects of fuel mixtures.

Each of the engine performance concerns raised regarding RFG can be traced to a wide range of causes, most of which are not related to fuel characteristics. Furthermore, these problems have been experienced when using conventional gasoline and hence are not unique to engines running on RFG. The potential engine performance problems investigated by EPA are listed below. Each concern is discussed more fully in Section V.

Potential engine performance problems

- Rough engine operation
- Engine overheating
- Engine fires
- Damaged pistons
- Vapor lock
- Difficulty in starting the engine
- Plugged fuel filters
- Fouled spark plugs
- Fuel leaks

Potential fuel-related sources of performance problems

- Water absorption by the fuel
- Improper fuel storage and handling practices
- Enleanment
- Reduced Motor Octane
- Materials incompatibility

Fuel mixture concerns

- Mixtures of oxygenates
- Mixtures of RFG and CG
- Overblends of oxygenates

In addition, a small reduction in fuel economy is expected when using oxygenate-containing fuels, including RFGs.

This list comprises the many different concerns that engine manufacturers have dealt with for years with regard to fuel quality issues. None of these concerns are new or unique to the RFG program. The potential impact of RFG on these concerns and problems is discussed in the following sections.

V. Assessment of RFG's effect on engine performance

A. Overview of engine technologies

Before discussing the potential impact of RFG on engine performance, it may be helpful to provide a brief overview of the different types of engines and engine technologies in which RFG and conventional gasoline are used.

- Closed loop v. Open loop: A closed loop control system contains an oxygen sensor located in the exhaust stream

which measures the amount of oxygen present and adjusts the amounts of fuel and air brought into the engine to maintain a precise air/fuel ratio. As a result, closed-loop systems automatically compensate for any oxygen present in the fuel in the form of oxygenates. Essentially all automobile engines produced since 1981 use closed-loop systems.

An open-loop system has no such control, and the fuel flow is fixed unless manual adjustments are made to "enrich" the air/fuel mixture by adding more fuel or "enlean" the mixture by adding more air. Open-loop systems will not compensate for oxygen present in the fuel in the form of oxygenates; as a result, open-loop engines will run slightly leaner on oxygenated fuels than on non-oxygenated fuels. Motorcycles, snowmobiles, and most small engines have open loop mechanical systems.

- **4-stroke v. 2-stroke:** A 4-stroke engine, as in an automobile, has 4 piston strokes: intake, compression, power (combustion) and exhaust. In a 2-stroke engine, exhaust and fuel intake occur during the power stroke. The operating cycle is thus completed in 2 piston strokes. Motorcycles, snowmobiles outboard motors, and most portable power equipment (e.g., chainsaws) use 2-stroke engines. Lawn mowers have mostly 4-stroke engines. All gasoline-powered cars and trucks have 4-stroke engines.

Gasoline-fueled engines in widespread use today fall into three broad categories:

- **Two-stroke engines,** all of which are open-loop, comprise the majority of gasoline-powered small engines, such as weed and hedge trimmers, snowblowers, and chainsaws. Essentially all snowmobile engines and some marine engines fall into this category as well. Two-stroke engines typically require lubricating oil to be mixed into the fuel; most operate in a "fuel-rich" manner, meaning that more fuel is introduced into the cylinder than can be burned by the oxygen in the cylinder.

- Four-stroke open-loop engines are used in most lawnmowers, many marine engines, and some older cars and light trucks (particularly those produced prior to the 1981 model year). These engines do not require lubricating oil to be mixed with the fuel. Most of these engines tend to run somewhat fuel-rich.
- Four-stroke closed-loop engines are found in newer (1981 and later) model-year cars and light trucks. These engines use feedback from an oxygen sensor to assure that exactly enough air is available to burn all of the fuel taken in by the engine and do not require lubricating oil to be mixed with the fuel. Most modern four-stroke, closed-loop engines are equipped with sophisticated computer controls to reduce emissions and optimize engine performance.

B. Engine performance concerns

Vehicle performance problems can occur for a variety of reasons. Tracing performance problems to a specific cause is difficult and often impossible. Most of these problems are the result of non-fuel factors such as vehicle age or mileage, operating conditions, or maintenance history. In some cases, performance problems may be related to fuel characteristics. All of the performance problems brought to EPA's attention in connection with RFG have been observed on vehicles using conventional fuel. Furthermore, neither EPA nor the engine manufacturers have been able to link any of these problems definitively to RFG. The data available from automotive and non-automotive engine manufacturers suggest that performance problems directly attributable to RFG are extremely unlikely.

Given these caveats, the remainder of this section focuses on potential RFG-related causes of the engine performance concerns raised in the context of the RFG program.

1. Rough engine operation

Rough engine operation includes stalling, stumbling, rough idle, engine misfire, or engine knocking. Rough engine operation

can occur for a variety of reasons, many of which are not fuel-related. It should be emphasized that these problems' potential fuel-related causes can and do occur when using conventional gasoline.

- Inadequate vapor pressure during start-up can make it difficult to start a cold engine and cause stumbling or stalling until the engine warms up, particularly in older model vehicles. Vehicles since the mid-1980's have been designed to start much more effectively at cold temperatures. Reformulated gasolines will have lower RVPs during the summer months than conventional gasolines, but this difference is not expected to result in greater start-up problems than is the case for conventional gasolines since the RVP levels for reformulated gasoline are still well within the range of conventional gasolines (as discussed earlier in Section III). A consumer experiencing start-up problems should try switching to another gasoline supplier to correct the problem, since RVPs can vary from station to station and from day to day at the same station. Startability problems that persist when using different sources of gasoline may indicate a maintenance problem with the engine.
- As with any gasoline, insufficient fuel octane can result in engine misfire, knock, dieseling, or rough idle as discussed in Section C. Such problems may be corrected by switching to a higher-octane fuel. Rough operation on premium fuel may be an indicator of mechanical or other problems with the engine.

2. Engine overheating

Engine overheating is most commonly the result of problems in the engine's cooling system, operation at extremely high speeds or under extremely high loads, operation in extremely hot conditions, or some combination of the three. However, there are two potential fuel-related contributors to engine overheating, both of which are discussed in greater detail in Section C.

- Some extremely high-performance open-loop engines

(particularly air-cooled snowmobile and high-performance inboard marine engines) supplement the engine's cooling system by running fuel-rich; such engines may experience a small increase in operating temperature due to the enleanment effect of oxygenates or as a result of operation at lower ambient temperatures or lower elevations -- both of which increase the density of the incoming air and therefore enlean the fuel/air mixture.

- If excessive amounts of water are introduced into an ethanol-blended gasoline, the water can separate from the gasoline. This problem is known as "phase separation;" it is extremely rare and is not unique to reformulated gasoline. Phase separation can lead to a range of engine performance problems as discussed in Section C. (Phase separation can also occur with non-oxygenated and ether-containing gasolines but is far less problematic, as discussed in Section C.)

3. Vapor lock

When gasoline vaporizes in the fuel lines, fuel delivery is restricted or prevented, which can result in power loss or engine shutdown. This phenomenon is known as vapor lock. High volatility gasoline and high ambient and engine temperatures can all contribute to vapor lock. Problems with vapor lock have diminished greatly in recent years as EPA has required the use of lower-volatility fuels in the summer and as manufacturers have improved the design of their fuel systems, notably by increasing the use of in-line, high-pressure fuel pumps. The RFG program will further reduce summer RVP levels and thus is expected to further reduce the incidence of vapor lock.

The fuel lines in some non-automotive engines, notably certain high-performance inboard marine engines, are located within an engine compartment that experiences elevated temperatures during normal operation. According to the manufacturers, the fuel lines in such applications can experience temperatures as high as 200-300°F. These temperatures are high enough to vaporize a substantial portion of the fuel. Since most oxygenates vaporize at lower temperatures than most other

gasoline components, fuels containing oxygenates may be somewhat more prone to vapor lock in such applications than non-oxygenated gasolines with the same RVP levels. It should be noted that such problems are hypothetical in nature and have not been reported in the field. Furthermore, any hypothetical vapor lock problems associated with oxygenate-containing gasolines such as RFG will be offset, in whole or in part, by the lower RVP of reformulated fuels. If vapor lock occurs, the operator should turn off the engine and allow the engine, fuel lines, and fuel tank to cool before attempting to re-start the engine.

4. Plugged fuel filters

Plugged fuel filters occur when contaminants block the filter surface, reducing fuel flow through the filter. Contaminants can come from several sources. Of particular relevance to the RFG program is the possibility that improper fuel handling procedures at fuel distributors or retailers could result in contaminants being introduced to fuel tanks during refueling.

Contaminants can also be introduced when certain gasoline constituents, such as ethanol, behave like solvents and remove or dissolve components built up in the fuel tank, fuel lines, or engine and transport them to the fuel filter. The transported material then plugs the fuel filter. For automotive engines, this type of fuel filter plugging is expected to be a concern only in older cars (approximately 1975 vintage) which ran on leaded gasoline and had lacquer build-up in the fuel lines. Newer non-automotive engines may experience fuel filter plugging as well, though for different reasons. Temporary relief from this problem can be obtained by shutting off the engine and allowing some time, perhaps 10 to 20 minutes, to pass. The absence of fuel flow during that time may allow some of the contaminants to fall off the filter, which should restore engine performance for a short period of time. However, the only permanent solution to this problem is to change the fuel filter. Most non-automotive engine manufacturers recommend changing the fuel filter annually as part of normal engine maintenance.

Any gasoline stored for long periods of time can deteriorate, contributing to gum formation which can lead to

plugged fuel filters. If gasoline is not to be used for long periods of time (greater than 1-2 months), it should be drained from the fuel tank or stabilized with a fuel stabilizer.

***Gasoline of poor quality can also cause gum formation. After changing the fuel filter, a higher quality gasoline should be utilized to avoid filter plugging due to gum formation. RFGs are expected to contain lower levels of olefins, the primary gum-forming components in gasoline, and hence are expected to be slightly less prone to gum formation.

5. Fouled spark plugs

Poor quality gasoline or adverse or lengthy storage conditions can result in gum formation, as discussed above. These gums can deposit on spark plugs, thereby fouling them. In general, gasoline containing heavier components or higher levels of olefins would be expected to form gums more readily than gasoline containing less of the heavier components. RFG is expected to contain lower levels of olefins and heavy components than existing gasoline, and thus would be less likely to form gums which could lead to fouled spark plugs. Sulfur deposits can also foul spark plugs; reformulated gasolines are precluded from having sulfur levels in excess of 500 ppm and are expected to contain significantly lower sulfur levels than conventional gasolines (particularly beginning in 2000), which should reduce spark plug fouling. In addition, additives are required in all gasolines for the express purpose of reducing deposits.

6. Engine fires and fuel leaks

Engine fires can result from many different causes. The primary fuel-related cause of engine fires involves fuel leaks resulting from materials deterioration, which is discussed in greater detail in Section C. No confirmed reports have been received linking oxygenates or other components of RFG to engine fires, and neither engine nor engine component manufacturers have indicated that they anticipate any such problems as a result of the RFG program.

7. Damaged pistons

A number of engine problems can result in damaged pistons. Most of these problems are related to normal wear and engine deterioration or extreme operating conditions, such as extended operation at wide-open throttle. Poor fuel quality, such as insufficient octane, can contribute to piston damage, particularly if engine knock or misfire occurs. RFG is not expected to increase fuel-related engine damage beyond the levels experienced with conventional gasolines for most engines. Regardless of whether RFG or CG is used, consumers experiencing engine knock or misfire should consider switching to higher-octane fuel. Knock or misfire that persists even when using premium fuel may indicate problems with deposit formation, engine timing, or other engine problems. Consumers experiencing knock or misfire when using premium gasoline should consult a qualified service technician.

Inadequate engine lubrication can also cause piston or cylinder damage. Most cases of inadequate lubrication involve insufficient engine oil, failure to change engine oil in a timely manner, oil leaks, or other defects in the engine's lubrication system. As discussed in Section C, however, contamination of ethanol-containing gasolines with water can result in phase separation, which in two-stroke engines can result in a loss of lubrication.

Some high-performance non-automotive engines, particularly those used in snowmobiles or marine applications, may be at risk for damaged pistons or other engine damage if the engine runs too hot. The most common causes of this problem involve cooling system defects such as restrictions in air or liquid coolant flow, prolonged operation at maximum power, or unequal fuel distribution in the engine. In addition, running the engine with a leaner-than-normal fuel/air mixture can increase temperatures. A small enleaning effect occurs when such engines are operated in cooler ambient temperatures or when using oxygenated fuels; these effects are discussed in detail in Section C.

C. Potential fuel-related sources of performance problems

After extensive engineering analysis, investigation of citizen complaints, and discussion with engine manufacturers, the following issues were identified as potential fuel-related

contributors to engine performance problems. It should be noted that none of these potential problems have been linked conclusively to real-world engine performance problems; furthermore, none of these potential problems are unique to RFG.

1. Water absorption/phase separation

Non-oxygenated gasolines cannot absorb significant amounts of water. If water is introduced into the fuel tank, it could separate from the gasoline in a phenomenon called phase separation. This phenomenon is extremely rare and is most commonly due to improper fuel storage practices by fuel distributors or retailers or due to the accidental introduction of water by the operator during refueling. Water is denser than gasoline, so if the water separates, it will form a layer beneath the gasoline. Since water does not burn, and since most engines obtain their fuel from the bottom of their fuel tank, most engines will not be able to run once phase separation occurs.

Gasolines containing ethers such as MTBE or ETBE can absorb slightly more water before phase separation occurs. In such circumstances, the ethers remain blended into the gasoline. The situation is more complicated for ethanol-containing fuels. Such fuels can absorb significantly more water without phase separation occurring than either non-oxygenated or ether-containing gasolines. Such fuels can actually help dry out fuel tanks by blending with the water, allowing it to be combusted. However, if too much water is introduced into an ethanol-containing gasoline (including ethanol-based RFG), the water and most of the ethanol -- typically 60-70% of the ethanol present in the original blend -- can separate from the gasoline and the remaining ethanol. The amount of water that can be absorbed by ethanol-blended gasolines without phase separation occurring varies from 0.3 to 0.5 volume percent, depending on temperature. If phase separation does occur, the ethanol/water mixture would be drawn into the engine. Some engines may not be able to operate on this very lean mixture. Other engines may be able to operate on the mixture but may run rough (see the Enleanment discussion below).

For certain two-stroke engines, however, phase separation could lead to more serious problems. In two-stroke engines, the

lubricating oil that is mixed with the fuel will stay in the hydrocarbon phase if phase separation occurs. The engine may be able to operate (albeit poorly) on the ethanol-water phase but will be operating without lubrication and therefore may incur engine damage. (Lubricating oil also can separate from non-oxygenated or ether-containing gasolines, though this problem is rare and is most likely when the oil/gasoline mixture is stored for long periods of time without fuel stabilizers.) Because of the risk of engine damage when operating without proper lubrication, all two-stroke engine manufacturers recommend checking the fuel to assure that phase separation has not occurred.

Some manufacturers expressed concern that ethanol-blended gasolines might absorb water vapor from the atmosphere, leading to phase separation. Such problems are of greatest concern for engines with open-vented fuel tanks that are operated in humid environments, such as marine engines. However, evidence for this phenomenon occurring in the real world is limited at best. States with extensive ethanol programs such as Minnesota have not reported problems with phase separation due to absorption of water from the atmosphere. Limited testing with ethanol blends suggests that the rate of water absorption from the atmosphere is very slow; it requires several months for open-vented marine fuel tanks to accumulate sufficient water to make phase separation possible. Of far greater concern is the accidental introduction of water during fueling or the presence of water in the fuel tank prior to the addition of ethanol-blended gasolines. Ether-blended RFGs are no more susceptible to this problem than non-oxygenated gasolines, so consumers concerned about phase separation may want to restrict their fuel purchases to ether-blended RFGs.

In addition, consumers can prevent phase separation by maintaining full fuel tanks when not in use and by purging the fuel tank of water condensation prior to introducing fuels, particularly ethanol-containing fuels. Certain over-the-counter gasoline additives such as "dry gas" (many of which contain alcohols to keep small amounts of water mixed with the gasoline) may be helpful. If phase separation does occur, the separated fuel should be removed from the tank and disposed of properly. **Citizens should not attempt to re-blend phase-separated gasolines or use it in other engines; instead, they should dispose of the**

fuel properly. Most communities have a household hazardous waste disposal facility that will accept such fuel.

2. Enleanment

Oxygenates enlean the air/fuel mixture by slightly reducing the amount of hydrocarbon in the fuel. For instance, an engine at stoichiometry has an air/fuel ratio of 14.7:1. Gasoline containing 7.8% ethanol or 11% MTBE (the average level required under the RFG program) would enlean the mixture to about 15.15:1. Most newer automobiles are equipped with closed-loop emission systems, which adjust the amount of air to maintain the desired air/fuel ratio. Such vehicles will not experience enleanment or any enleanment-related changes in engine performance.

Open-loop engines (both two-stroke and four-stroke) do not compensate for the oxygen in the fuel and will run slightly leaner when operated on RFG or other oxygenate-containing gasolines. Older, open-loop automobiles have been operated successfully for years on oxygenated fuels and gasohol without difficulty and should not be affected adversely by enleanment. Most non-automotive engines should not experience enleanment-related operational problems. However, the enleanment effect can increase engine operating temperatures for open-loop engines that rely on a fuel-rich air/fuel mixture to supplement other engine cooling mechanisms. A few high-performance engines may require adjustments to their fuel intake systems to compensate for the enleanment effect, as discussed below.

The enleanment effect due to oxygenates is similar in magnitude to the enleanment effect due to operating the engine at lower ambient temperatures or lower elevations (both of which increase air density and enlean the fuel/air mixture). As a result, engines which do not require adjustments to their fuel intake settings when operated at different altitudes or ambient temperature conditions are unlikely to require adjustments for the enleanment effect, though consumers should consult their operator's manual, dealer, or manufacturer for more detailed information. According to snowmobile manufacturers, the adjustment needed to offset the enleanment effect due to oxygenates is roughly comparable to the adjustment needed to offset a 5 to 15 degree Fahrenheit drop in ambient temperature.

Any adjustments for enleanment should be performed carefully; overcompensating for enleanment can create additional engine performance problems and increase emissions. Consumers should consult the manufacturer or a qualified service technician to obtain further information about engine adjustments.

3. Improper fuel handling and storage practices

Improper fuel handling and storage practices by fuel distributors and retailers can create a number of operational problems, particularly for ethanol-blended RFGs. Basic precautions must be followed when introducing ethanol-containing fuels in a fuel distribution system for the first time. Water must be removed from fuel tanks and fuel lines to prevent phase separation. The fuel must be prevented from coming into contact with materials which the fuel might dissolve or otherwise deteriorate, and filters and screens must be in place to remove any foreign material before it reaches consumers' fuel tanks. Failure to do so can result in fuel contamination with fuel system component materials or deposits, which can in turn impair vehicle performance by clogging fuel filters. Both the American Petroleum Institute and the Renewable Fuels Association have guidelines for station operators to follow to prevent problems related to fuel handling and contamination.

4. Reduced Motor Octane

Octane at the pump is determined as the average of the "Research" and "Motor" octane numbers, or " $(R+M)/2$ ". In the past, oxygenates have been used to increase gasoline octane, since oxygenates have higher octanes than many gasoline components. Oxygenates boost research octane to a greater extent than motor octane. As a result, an oxygenated fuel with the same posted octane rating as a non-oxygenated fuel may have a slightly lower motor octane level.

Some non-automotive engine manufacturers have indicated that their engines respond more strongly to motor octane than research octane. These manufacturers have expressed concern that the small reduction in motor octane which could occur as a result of the oxygen content of RFG could result in a slightly higher

incidence of engine performance problems, such as engine knock, misfire, dieseling, or rough engine operation. Over time, these problems can lead to damaged pistons or other engine damage. If knock, misfire, or dieseling occur, it may be helpful to switch to a higher octane fuel. If the problem persists, the engine is most likely suffering from problems unrelated to the fuel and should be examined by a qualified repair technician.

5. Materials compatibility

There are two distinct types of materials compatibility problems. Acute failures occur when a substance causes a part to fail within a very short period of time. Accelerated deterioration occurs when a substance causes a part to fail noticeably faster than would have been the case had the part not been exposed to that substance. Accelerated deterioration can result from corrosion, chemical reactions between the fuel and the affected material, or permeation of the fuel through the material.

New elastomers called fluoroelastomers have been used in automotive and non-automotive engines since the mid-1980s. These newer materials are specifically designed to handle all modern gasolines, including high-aromatic, ethanol-containing, and ether-containing gasolines within these substances' legally permissible levels, without experiencing either of the materials compatibility concerns described above. Fluoroelastomers are far more resistant to permeation and corrosion than were earlier elastomers.

Except for the oxygenates, all of the components found in RFG are natural constituents of gasoline or have been thoroughly tested for materials compatibility. The oxygenates used in RFG have also been tested for materials compatibility, and no acute failures have been noted. Engine and elastomer manufacturers have indicated that even in older vehicles, any materials compatibility or deterioration problems which were encountered would not result in immediate, acute failures of elastomeric components but rather would result in an increase in deterioration rates in-use. Furthermore, these oxygenates have been used for considerable lengths of time in conventional gasolines without resulting in acute materials failures. Ethanol

and other oxygenates have been used in conventional gasolines since the mid-1970s as octane enhancers and fuel extenders, and oxygenated fuels programs have been in place for years in California, Colorado, and dozens of other carbon monoxide nonattainment areas without resulting in higher rates of acute materials failure in the field.

Some materials used in fuel systems tend to degrade over time, such as the elastomeric materials used to make hoses and valves. Degradation can occur for many reasons, such as repeated heating and cooling cycles, normal oxidation by the atmosphere, or corrosion by road salt or other substances. Fuel composition can also affect deterioration rates. For example, aromatics (a natural component of gasoline) can cause some parts to swell. In addition, degradation of some elastomeric fuel distribution and engine components may be accelerated by exposure to oxygenates, particularly ethanol. However, areas covered by the oxygenated fuels programs mentioned above have not reported higher rates of materials degradation or failure than areas receiving conventional gasolines. Furthermore, gasolines with high levels of aromatics accelerate material degradation to a similar degree as oxygenated fuels, yet no greater rate of materials failures has been reported over the past several decades despite substantial increases in aromatics levels in order to maintain desired octane levels.

Permeation of fuel through elastomers can accelerate deterioration. In general, ethanol blends have higher permeation rates through elastomers than ether blends, which have slightly higher permeation rates than non-oxygenated gasoline. The higher permeation rates of oxygenate-containing gasolines are well within safety limits and are not expected to create performance, deterioration, or safety problems. No such problems have arisen during the 15 to 20 years of oxygenate use in the U.S. Furthermore, engines built since the mid-1980s generally use fluoroelastomers, which have far lower permeation and deterioration rates than earlier materials regardless of the oxygenate type and concentration found in the fuel (within legally permitted limits).

In summary, oxygenate-containing conventional or reformulated gasolines are not believed to cause acute materials failures or dramatically accelerated rates of materials

deterioration over time. As older engines are retrofitted with fluoroelastomeric engine components or replaced by fluoroelastomer-equipped newer engines, the potential for oxygenate-related materials deterioration or fuel permeation will continue to decline. As part of normal vehicle maintenance, engine owners should inspect their engine and fuel distribution system for leaks and replace older or leaking components. Owners of pre-1986 engines (both automotive or non-automotive) with degraded elastomers and other engine parts should install modern replacement parts, which are engineered to assure compatibility with all modern gasolines, including oxygenated gasolines.

D. Fuel mixture concerns

1. Mixtures of RFGs with different oxygenates

Questions have been raised regarding the effects of mixing RFGs with different oxygenates in consumer fuel tanks. EPA is not aware of and does not expect performance or driveability problems for vehicles running on mixtures of different RFGs that differ from those which may occur for any RFG and which are discussed above. This expectation is based on several factors:

- Consumers have operated with mixtures of different oxygenates over the past fifteen years as a result of refueling at different service stations without experiencing unusual performance or other problems.
- The potential adverse engine performance effects discussed above are either a function solely of the oxygen content of the fuel (as in the case of enleanment) or are related to the concentration of specific types of oxygenates (as in the case of materials deterioration, water absorption/phase separation, and motor octane levels). None of these effects are functions of the presence of multiple oxygenates.

2. Mixtures of RFG and CG

Conventional gasoline may not be sold in areas covered by

the RFG program. However, the program does not control which gasoline a consumer uses. Thus, a consumer living and driving in an RFG area may purchase CG outside the area yet drive within the area with no penalty. Likewise, consumers living in CG areas are likely, at some point, to fill-up with RFG when in or near an RFG area, particularly since service stations in CG areas near CG/RFG boundaries may be supplied with RFG due to the nature of the fuel distribution system. No unique problems are expected or have been observed from mixtures of RFG and CG. In fact, mixing RFG with conventional gasoline would tend to reduce the risk of the hypothetical effects on engine performance discussed above. Mixtures of RFG and non-oxygenated gasoline would have lower concentrations of oxygen and of individual oxygenates than would be present in RFG alone; mixtures of RFG and oxygenated gasoline would have lower concentrations of oxygen and individual oxygenates than would be present in the oxygenated gasoline alone.

3. Overblends of oxygenates

Concern was expressed that gasoline containing higher levels of oxygenates than legally allowed (overblends) could cause or contribute to vehicle performance problems. While gasoline containing more than 15% MTBE or 10% ethanol (the upper limits currently permitted in either RFG or CG) could cause or contribute to the problems discussed here or to other problems, it is highly unlikely that overblending will occur. First, and foremost, oxygenates volumes above the waived limits are illegal and should not be available in the marketplace. EPA and the States have a range of enforcement programs designed to ensure that gasolines sold commercially meet the legal requirements, and private industry also monitors fuel quality nationwide. Second, oxygenates tend to be more expensive than gasoline, so it would not be economically sound for a fuel producer to overblend. Finally, blending processes at either the refinery or at the terminal have become far more sophisticated and less susceptible to error over the past decade, thereby minimizing overblending (although the risk of accidental overblending can never be eliminated completely). It should also be noted that the risk of overblending is not restricted to areas covered by the RFG program, since oxygenates can be and are blended in conventional gasolines.

E. Fuel economy

The fuel economy of a vehicle running on RFG would be expected to decrease slightly because a portion of the high energy content component (hydrocarbons) is replaced by a lower energy content component (oxygenate). Auto manufacturers' data confirm this and suggest a 1-3% drop in fuel economy. A recent study of the fuel economy of Wisconsin vehicles running on RFG confirms this range (a 2.8% average loss was reported). Other factors such as weather conditions and personal driving habits result in significantly higher fuel economy losses than those attributable to RFG use. In fact, manufacturers indicate that the consumer is unlikely to be able to detect a fuel economy loss which can be solely attributed to RFG.

Citizens have indicated to EPA that they have experienced substantially greater fuel economy reductions when using RFG than when using CG. EPA and the automobile and oil industries have been unable to identify any fuel-related causes for these reported fuel economy decreases. As mentioned above, controlled tests conducted in laboratory and on-the-road settings by EPA and industry consistently show fuel economy decreases in the 1-3% range. Furthermore, the number of gallons of gasoline sold in areas covered by either the oxygenated fuels or RFG programs in their first year of operation has not been substantially larger than the number of gallons sold in the year before these programs began, which tends to confirm the controlled studies discussed above. Nevertheless, EPA is concerned that some citizens may be experiencing greater decreases in fuel economy than expected, either because of some unique characteristic of their vehicles or because of a vehicle-related (as opposed to fuel-related) problem. EPA and industry are continuing to investigate this issue.

VI. Summary of industry-specific non-automotive concerns

EPA discussed RFG-related concerns with manufacturers of non-automotive engines to identify concerns specific to particular industries or products. Most of these concerns do not reflect actual problems encountered with the use of RFG but instead reflect uncertainty on the part of manufacturers about

the precise effects of different gasolines, including RFGs, on their engines. Most non-automotive engine manufacturers' owner's manuals include oxygenated fuels (with the exception of methanol, which is not permitted in RFG) in their list of acceptable or recommended fuels and will not void their warranties if an owner uses oxygenated or reformulated gasoline.

The purpose of this section is to summarize the concerns expressed by manufacturers of engines for different applications. It is not intended to evaluate these concerns, which have been discussed in prior sections of this report.

A. Marine engines

Manufacturers expressed strong concern about water absorption and subsequent phase separation of ethanol-containing gasolines. Phase separation problems can occur in marine engines at a water content of approximately 0.3-0.5% (3000-5000 ppm). Manufacturers recommend not filling a wet tank (i.e., a tank with condensation) and either draining the fuel tank or keeping it full during prolonged storage periods. Manufacturers also indicated that the risk of water absorption from the atmosphere by ethanol-blended fuels in open-vented tanks exposed to high-humidity atmospheric conditions for several months can be eliminated if tanks are kept at least 2/3 full when not in use. It should be noted that Minnesota, which has ethanol blended in the majority of its gasoline, has not reported problems with water absorption from the atmosphere.

Performance-related concerns other than water absorption included cold start and engine hesitation with lower-RVP gasoline. This concern was tempered by manufacturers' acknowledgement that marine engines often operate on heavily-weathered fuel with RVP levels lower than those found in RFG. Manufacturers also expressed concern that high performance engines might lose several percent of peak power due to RFG's lower energy density. Manufacturers did not express concern about detergents.

Marine engine manufacturers did not consider ether-based RFG to present materials compatibility problems. They did not consider ethanol-based RFGs to present difficulties for 1986 and later engines, again because of the use of fluoroelastomeric

components. Manufacturers were somewhat concerned about the effects of ethanol blends in older engines, though they indicated that blends of up to 10% ethanol should not present significant materials compatibility problems.

Manufacturers expressed concern that their engines might lose performance or experience knock when running on RFG since oxygenates tend to boost research octane far more than motor octane. Though posted octane is the average of motor and research octane, their products respond more strongly to motor octane. Since experience with RFG in marine applications will begin with the start of the boating season, no actual cases of poor performance were reported. Manufacturers suggested switching to a higher-octane fuel if knock is experienced.

B. Snowmobiles

Snowmobiles tend to operate with a rich air/fuel mixture. Some manufacturers recommend enriching the air/fuel mixture when using oxygenate-containing gasolines, just as they recommend enriching the mixture to compensate for the enleanment effect of lower temperatures. Enrichment can be accomplished by increasing the carburetor jet size or changing the ROM chip in fuel-injected engines. Water absorption and subsequent phase separation was also a concern, though not to a greater degree than for conventional gasolines. Materials compatibility does not appear to be a significant issue for snowmobile manufacturers as long as oxygenate concentrations are within the waived limits.

Minnesota sponsored a snowmobile race on ethanol blends; participants chose not to make the recommended adjustment yet experienced the same or lower rate of engine failures (damaged pistons) as they had in prior years when running on conventional gasoline (1 blown engine using 10% ethanol vs 1-2 blown engines in a typical year).

C. Motorcycles

Motorcycle manufacturers shared the concerns expressed by other non-automotive engine manufacturers but had no data linking RFG use to specific performance problems. They also expressed

concern about the effect of RFG on cosmetic parts such as highly polished aluminum and painted surfaces. However, auto manufacturers' materials testing results do not indicate adverse affects on automobile non-engine external parts.

D. Other non-automotive 2-stroke engines

Problems were considered most likely to occur in poorly-maintained older products, products in which the once-per-year change in fuel filters had not been performed, or products in which the fuel was not drained during the off-season or had been allowed to sit for more than 30 days (in which cases water absorption and subsequent phase separation is more likely, as well as gum formation). Phase separation is a particular concern for 2-stroke engines because the engine could run too lean, and therefore too hot, and at the same time would be running without lubrication (because the ethanol-water phase would not contain the lubricating oil). However, no performance nor materials compatibility problems attributable to RFG have been reported for small engines. Manufacturers do not anticipate such problems within the waived limits for ethers or ethanol.

E. Other non-automotive 4-stroke engines

No concerns were expressed regarding enleanment, materials compatibility within waived limits, or fuel aging. No enrichment is considered necessary to compensate for oxygen content, except perhaps in the case of snowblowers. However, the available data are not sufficient to demonstrate the need for such adjustments.

VII. Conclusions

RFG is very similar to existing or conventional gasoline: its fuel parameters are well within the range of CG fuel parameters and its oxygenate content does not exceed the oxygenate levels of gasolines oxygenated to reduce CO emissions or conventional gasolines to which oxygenates have been added to increase octane or extend gasoline. As such, engine performance and other problems attributable solely to the use of RFG are not

expected. Discussions with both automotive and non-automotive engine manufacturers have verified this expectation. The engine performance problems reported to date do not appear to be linked to fuel characteristics; instead, they appear to be linked to other conditions, such as operating conditions, normal vehicle wear, or poor maintenance practices. All potential fuel-related problems can occur when using conventional gasolines and can be prevented or addressed, usually with relatively simple consumer actions.

APPENDICES

1. Performance Problems/Possible Solutions
2. References
3. Acronyms/Abbreviations

Appendix 1

Performance Problems/Possible Solutions

	Performance Problem	Fuel-related Possible Cause	Possible Solution ¹
1.	Difficulty starting	Inadequate vapor pressure	Try another brand of gasoline
2.	Engine misfire, knock, dieseling, rough idle	Insufficient fuel octane	Try a higher octane fuel

¹ The possible solutions listed here have been discussed in the main document and should be taken as general guidance. To the best of our knowledge, the possible solutions listed here are reasonable "fixes" for the associated performance problem, however, USEPA assumes no responsibility for actions taken based on these possible solutions. To avoid voiding your warranty, please consult your owner's manual before taking any action. If the indicated problem persists, please contact your dealer.

3.	Engine overheating	<p>-Enleanment effect of oxygenates</p> <p>-Enleanment due to phase separation</p>	<p>-If possible, adjust to enrich air/fuel mixture²</p> <p>-If phase separation has occurred, remove and dispose of separated fuel³, refill tank with new fuel</p> <p>-To prevent phase-separation: maintain full fuel tank; purge tank of condensate prior to introducing fuels; use "dry gas"</p>
4.	Vapor lock--power loss, engine shutdown	High volatility fuel	Try another brand of gasoline

² Adjusting fuel intake settings for vehicles with emissions standards is a violation of Federal law if such adjustments increase emissions beyond permitted levels.

³ Citizens should not attempt to re-blend phase-separated gasolines or use it in other engines; instead, they should dispose of the fuel at a facility equipped to handle hazardous wastes.

5.	Plugged fuel filters	<ul style="list-style-type: none"> -Deposits loosened by "solvency" -Poor quality gasoline -Adverse or lengthy storage conditions 	<ul style="list-style-type: none"> -Change filter -Try another brand of gasoline -Drain fuel tanks prior to long-term storage -If not draining tank, use a fuel stabilizer
6.	Fouled spark plugs	<ul style="list-style-type: none"> -Poor quality gasoline -Adverse or lengthy storage conditions 	<ul style="list-style-type: none"> -Try another brand of gasoline -Drain fuel tank prior to long-term storage -If not draining tank, use a fuel stabilizer
7.	Blown pistons	<ul style="list-style-type: none"> -Poor fuel quality -Insufficient fuel octane 	<ul style="list-style-type: none"> -Try another brand of gasoline -Try a higher octane fuel

Appendix 2

References⁴

- 1) "Cleaner Gasoline Has Come To Your Part of the Country", American Automobile Manufacturer's Association (AAMA).
- 2) Technical Bulletin, "Use of Oxygenated Gasolines in Non-Automotive Engines", Chevron U.S.A. Products Company.
- 3) Technical Bulletin, "Oxygenated Gasolines and Fuel Economy", Chevron U.S.A. Products Company.
- 4) "The Use of Oxygenated Gasoline in Lawn & Garden Power Equipment, Motorcycles, Boats & Recreational Equipment", Downstream Alternatives, Inc. (DAI) Informational Document #941101, November 1994.
- 5) "Changes in Gasoline II, The Auto Technician's Gasoline Quality Guide", Downstream Alternatives, Inc., July 1992.
- 6) "Cleaner Fuels For Cleaner Air, Facts for Motorists Concerning Colorado's Oxygenated Fuels Program", Colorado Department of Health, September 1992.
- 7) Press Release, Portable Power Equipment Manufacturer's Association, March 7, 1995.
- 8) Press Release, Briggs & Stratton Corporation, 1995.
- 9) "Reformulated Gasoline (RFG)", Outboard Service Bulletin, Outboard Marine Corporation, 1995.
- 10) "California Phase II Gasoline Evaluation with Small SI Engines, Reliability Testing Report", Tecumseh Products Company, Engine and Transmission Group, Prepared for California Air Resources Board, November 11, 1994.

⁴ For copies of a reference listed here, please contact the authoring organization directly.

Appendix 3

Acronyms/Abbreviations

AAMA.....American Automobile Manufacturer's Association
CAA.....Clean Air Act
CAAA.....Clean Air Act Amendments of 1990
CG.....Conventional gasoline
CO.....Carbon monoxide
EPA.....U.S. Environmental Protection Agency
ETBE.....Ethyl tertiary butyl ether
ETOH.....Ethanol
Gasohol..Gasoline containing approximately 10% by volume ethanol
MTBE.....Methyl tertiary butyl ether
NOX.....Oxides of nitrogen
Oxyfuel..Oxygenate-containing gasoline for CO nonattainment areas
RFG.....Reformulated gasoline
RVP.....Reid vapor pressure
TAME.....Tertiary amyl methyl ether
T50.....Temperature at which 50% of the fuel will be evaporated
T90.....Temperature at which 90% of the fuel will be evaporated
VOC.....Volatile organic compound