A Literature Review Based Assessment on the Impacts of a 10% and 20% Ethanol Gasoline Fuel Blend on Non-Automotive Engines

Report to Environment Australia

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Orbital Engine Company

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1 EXECUTIVE SUMMARY

This report represents part of the work commissioned by Environment Australia (EA) under tender 34/2002 “Environment Australia Project: ‘Market Barriers to the Uptake of Biofuels – Testing Petrol Containing 20% Ethanol (E20)’”. Specifically, this report satisfies the section of work Section 2.3.4.2 titled “Analysis of Impacts”.

A study has been conducted on the suitability of ethanol/gasoline blend fuels containing 10% and 20% (by volume) ethanol for non-automotive engines. The study has focussed on researching areas of engine operability, engine durability and fuel system durability when the engines were operated on ethanol gasoline blend fuels. The study must be considered in the context of the current non-automotive engine population, which must operate safely, effectively and efficiently on the ethanol blends without retuning/recalibration or other modification. During the execution of the literature search it became apparent that only limited information relating to non-automotive engines and ethanol blend fuels was available, with respect to higher ethanol blends up to 20% no literature was uncovered. Generally manufacturers recommendations allow the use of up to 10% ethanol. The majority of information available was often not specific to a particular engine group (aircraft, vehicle, marine or utility), forcing rather general conclusions.

The addition of ethanol to gasoline increases the available oxygen for the combustion process. The study shows that there will be enleanment of the combusted mixture. The severity of the impact of enleanment depends on the relative richness the engines gasoline calibration. If the original gasoline calibration is lean, then the impact of enleanment has the potential to be significant. Enleanment has the potential to have a detrimental effect on: cold starting; hot operation; cold operation and wide open throttle performance. Depending on the type of engine and its calibration, there is potential for engine damage to occur through enleanment. The propensity for this to occur will increase as the proportion of ethanol blend is increased.
Ethanol gasoline blend fuels volatility characteristics may impact on an engines operational characteristic under hot conditions. The increased volatility of ethanol gasoline blend fuels may result in vapour lock when operating the engine in hot conditions, the impact being difficulty restarting, hesitation and stumbling during acceleration, in certain cases it can be severe enough to cause the engine to cut out completely.

Fuel consumption theoretically increases when oxygenates are blended with gasoline due to the lower energy content of the oxygenated fuel. The theoretical increase in fuel consumption for a 10% and 20% ethanol gasoline blend is approximately 3% and 6% respectively. This increase in fuel consumption, due primarily to the reduction in energy content of the fuel, may be offset somewhat in by the enleanment of the fuel/air mixture.

No specific literature was found on the effect of ethanol blends on the wide open throttle (WOT) performance of non-automotive engines. There is however no reason to believe that the potential impacts on non-automotive engines will be significantly different to those described for automotive engines. From the automotive literature review of WOT performance the level of potential deterioration is likely to be dependent on the gasoline calibration of the engine, with the 20% ethanol gasoline blend fuel giving the worst performance.

The impact of the 10% ethanol gasoline blends (E10) on the wear of engines is quite clear. In general it should be negligible compared to straight gasoline as many of the non-automotive engine manufacturers permit the use of up to E10 in their products. There are some exceptions with those manufacturers outlining steps the user should take to ensure satisfactory performance with an E10 blend. For blends greater than E10 the impact is not clear though manufacturers specifically do not warrant their products should they be operated on ethanol gasoline blends beyond 10%. No literature was uncovered that detailed specific testing of non-automotive engine testing with ethanol gasoline blends of approximately 20% by volume ethanol.

Corrosion of non-automotive engines metallic fuel system components through the use of E10 will in general not be an issue. Many manufacturers permit the use of up to E10 in their engines, however some manufacturers report corrosion of fuel system components in older engines, prior to the mid 1980s. Beyond the E10 ethanol blend fuel it is unclear as to the impact as no literature was uncovered that detailed specific testing with 20% ethanol gasoline blend fuels.

Fuel systems elastomeric and plastic components in modern non-automotive engines are in general compatible with E10 ethanol fuel blends. This is based on the fact that most manufacturers permit the use of ethanol gasoline blend fuels up to 10%. With older engines, manufacturers recommend that the plastic and rubber fuel system components be inspected regularly for leaks and/or deterioration. Beyond the 10% level there was no available literature uncovered by the search that provided clear and detailed scientific experimental data indicating that there would not be a detrimental impact.

The potential for fuel systems deposits to be dissolved by ethanol gasoline blend fuels has been identified by the study. The introduction of ethanol gasoline blend fuels into fuel systems may dissolve some of the fuel system deposits which in turn will clog filters and fuel metering devices. This impact is most likely on older used engines which have seen previous use on straight gasoline.

It is expected that the issues and shortcomings in information for E20 blends identified in this report will be appropriately addressed and reported in due coarse by the execution of the scope of work provided within the Orbital Engine Company tender 34/2002.

One area that will not be covered by the above scope of work but deserves special attention is the area of aircraft and aircraft engines. There are aircraft and aircraft engines in Australia that are approved to use automotive unleaded gasoline. Approval does not include gasoline blended with ethanol.

It does appear that there are guidelines specifying the outlets that should be used for the supply of automotive gasoline for those approved aircraft or aircraft engines. However the potential does exist for inconsistency in fuel quality, to this end aircraft engine suppliers and safety authorities recommend operators scrutinize each fuel batch to determine the fuels overall quality as well as maintaining a heightened awareness for potential fuel leaks throughout the aircraft fuel system. There is also a recommendation to buy fuel from a large supplier while making all efforts to confirm the fuel being bought is as advertised. A further recommendation by an aircraft engine supplier is that operators of such engines and aircraft obtain a simple alcohol test kit allowing the determination for alcohol to be made as this is the only safe way to be sure the fuel is alcohol free.

2 INTRODUCTION

The Commonwealth Government of Australia, represented by Environment Australia (EA), is investigating the effects of ethanol blends in fuel on non-automotive engines. This investigation is to provide information to the Government on the impacts of engines performance, operability and durability from the use of ethanol blends of 10% and 20% by volume with gasoline (E10 and E20). This study will then be used to aid the Government to set the national fuel standards as provided by the *Fuel Quality Standards Act 2000*.

Environment Australia, under the auspices of the Ethanol task force, commissioned an issues paper with the aim of seeking public comment on setting the appropriate ethanol limit in automotive fuel (2). This paper extensively covered the issues related to using ethanol as an automotive fuel. Currently, there is no information available as to the impact of a 20% ethanol gasoline blend on non-automotive gasoline engines. There is manufacturer/OEM (original equipment manufacturer) evidence, as provided in their product operation and service manuals that generally confirms that a 10% ethanol gasoline blend is suitable for the non-automotive gasoline engine population. There are some manufacturers of high output engines requiring modification when using ethanol gasoline blends. There is one notable exception however, aircraft and aircraft engines approved for the use of automotive unleaded gasoline are not approved for use with ethanol gasoline blends.

One of the conclusions that can be drawn from the submissions to the issues paper was the lack of current Australian data on the effects of ethanol blends on the Australian non-automotive engine population. In order to rectify this, Environment Australia has commissioned testing on non-automotive engines and components under tender No. 34/2002.

As part of this tender, Environment Australia requested a study on the available data on ethanol blends and the impacts on engine operation and engine and fuel system durability with blends of 10% and 20% ethanol compared to straight gasoline. The following report is an assessment of the pertinent testing results and available data on the impact of the 10% and higher ethanol blends. This report, in conjunction with the Failure Mode and Effects Analysis (FMEA) report, aims to verify that the scope of work to be performed on the non-automotive engines and component testing (also covered by the same tender using E20 by Orbital Engine Company) is both warranted and sufficient to identify major issues associated with the adoption of higher ethanol blend fuels.

3 ENGINE GROUPS

The focus of the report is on engine operability, engine durability and fuel system durability for non-automotive engines. Non-automotive engines cover a wide range of engine applications. To rationalise the extensive range of applications, four engine groups were defined. The groups were, aircraft, utility, marine and vehicle. Table 1 below illustrates examples of applications in each engine group.

Engine Group	Example
Aircraft	Ultra-light, hovercraft, light air craft
Utility	Line-trimmer, chainsaw, lawn mower, generator, compressors
Marine	Outboards, personal water craft
Vehicle	Snowmobile, motorcycle, all terrain vehicles

Table 1 Example of an engine application within nominated engine groups

Both two-stroke and four-stroke engines are utilised in the engine groups listed in Table 1. It is important to make this distinction since during operation of crankcase scavenged two-stroke engines base engine components are exposed to the fuel air mixture. These components include: crankshaft, connecting rod, piston and seals made from elastomeric materials.

4 FUEL PROPERTY CHANGES WITH ETHANOL ADDITION

The addition of ethanol to gasoline results in changes to the properties of the fuel. When fuel properties change they can affect engine performance in many ways. This includes exhaust and evaporative emissions, fuel economy, operability, full load performance (power) and durability. The extent to which changes in fuel composition affects these engine performance qualities are very dependent on the engine itself, including engine design, fuel system and control system, as well as emissions control equipment.

Table 2 summarises the some of the major properties of gasoline, ethanol, and mixtures of 10% and 20% (by volume) ethanol with gasoline. This is assuming splash blending of the components with no special blend stock for the gasoline component.

Property	Gasoline	Ethanol	10% Ethanol / Gasoline Blend	20% Ethanol / Gasoline Blend[2]
Specific Gravity @ 15.5 °C	0.72 - 0.75	0.79	0.73 – 0.76	0.735 – 0.765
Heating Value (MJ/kg) (BTU/lb)	43.5 18,700	27.0 11,600	41.9 18,000	40.0 17,200
Heating Value (MJ/litre) (BTU/gal)	32.0 117,000	21.3 76,000	30.9 112,900	29.9 109,000
Approx Reid Vapour Pressure @ 37.8ºC (kPa)[1]	59.5	17	64.0	63.4
Stoichiometric Air/Fuel Ratio	14.6	9	14	13.5
Oxygen Content (% by weight)	0.00	35	3.5	7.0

Table 2 – Properties of Gasoline, Ethanol and Gasoline/Ethanol Blends (1); except for [1] (5) and [2] from calculation)

The effect of adding ethanol to gasoline is to oxygenate the fuel. The higher the ethanol blend, the higher the oxygen content in the fuel. Figure 1 shows the linear increase in oxygen as the % of ethanol is increased (5). The increased oxygen in the fuel changes the stoichiometric air/fuel ratio of the fuel. The stoichiometric air/fuel ratio is the chemically correct or theoretical air to fuel ratio which provides the minimum amount of oxygen for the conversion of all the fuel into completely oxidised products. (For a hydrocarbon-based fuel, this means that all the carbon in the fuel is converted to CO_2 and the hydrogen to water, H_2O). If there is no compensation for this change in stoichiometric air/fuel ratio and the engine is operated at the same mass air/fuel ratio, there is, in effect, a change to the mixture strength as the ethanol content in the fuel is increased. Mixture strength is normally referred to in two non-dimensionalised terms. The first is equivalence ratio, which is the ratio of the theoretical stoichiometric air/fuel ratio and the actual air/fuel ratio, ie:

Equivalence Ratio, ϕ = (Stoichiometric A/F Ratio)/(Actual A/F Ratio).

As the mixture becomes more fuel rich (mixture strength increases), the equivalence ratio is increased.

The other term often used is relative air/fuel ratio (or lambda), often expressed as the symbol λ. The relative air/fuel ratio is the inverse of the equivalence ratio; that is:

λ = (Actual A/F Ratio)/(Stoichiometric A/F Ratio)

As the mixture becomes fuel rich, the relative air/fuel ratio is reduced.

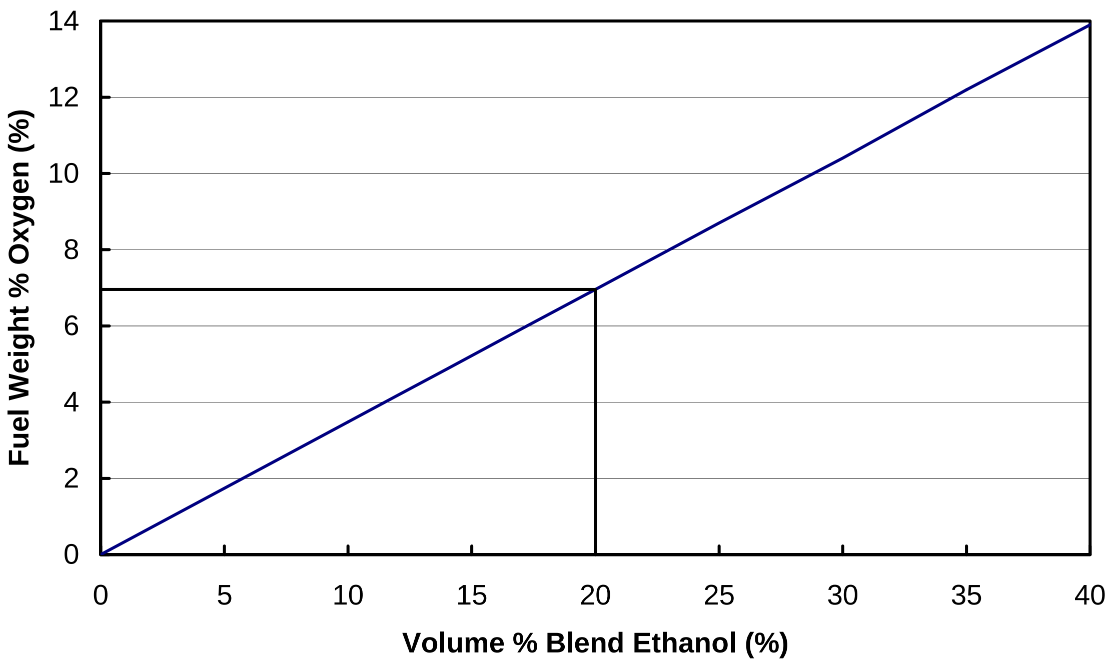

Figure 1 – Oxygen content for ethanol-blended fuels

Figure 2 shows how the mass air/fuel ratio corresponding to stoichiometric (λ=1) mixture strength changes with the addition of ethanol to gasoline. From this figure, it is clearly seen that gasoline has a stoichiometric air/fuel ratio of approximately 14.6:1, while a 20% blend of ethanol and gasoline has a stoichiometric air/fuel ratio of approximately 13.5:1. Also shown in this figure is the fuel metering characteristic line. As a first approximation, it is assumed that most fuel systems (without compensation) will deliver approximately the same volume of fuel (regardless of the fuel composition). This is especially true for electronic fuel injection systems. Therefore, changes in fuel density will change the mass of fuel delivered. As ethanol has a higher density than gasoline, as the ethanol content is increased, the fuel mass is increased for a given injection system setting. By definition, this increase in mass results in a reduction of the mass air/fuel ratio, as is shown by the fuel metering characteristic line. This increase in mass partially compensates (but nowhere near sufficiently) for the reduction in stoichiometric air/fuel ratio as the ethanol content increases (4).

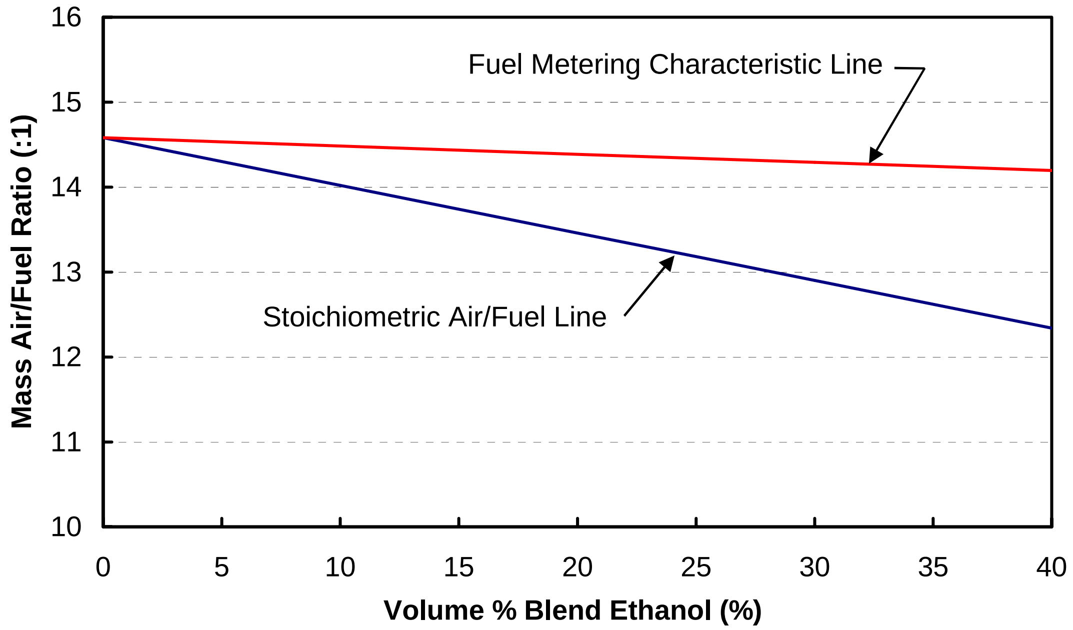

Figure 2 - Stoichiometric air/fuel ratio of ethanol-blended fuel

Figure 3 shows how the relative air/fuel ratio (λ) of the mixture changes with change in ethanol content for a constant volume of fuel delivered. It is assumed that the volume ratio of air and fuel equates to a stoichiometric mass air/fuel ratio, ie $\lambda = 1$ for gasoline only fuel. As the ethanol content increases, the mixture becomes (fuel) leaner for the same volume of fuel delivered, as demonstrated by the increase in lambda. This phenomenon is also often referred to as “enleanment” of the mixture (8).

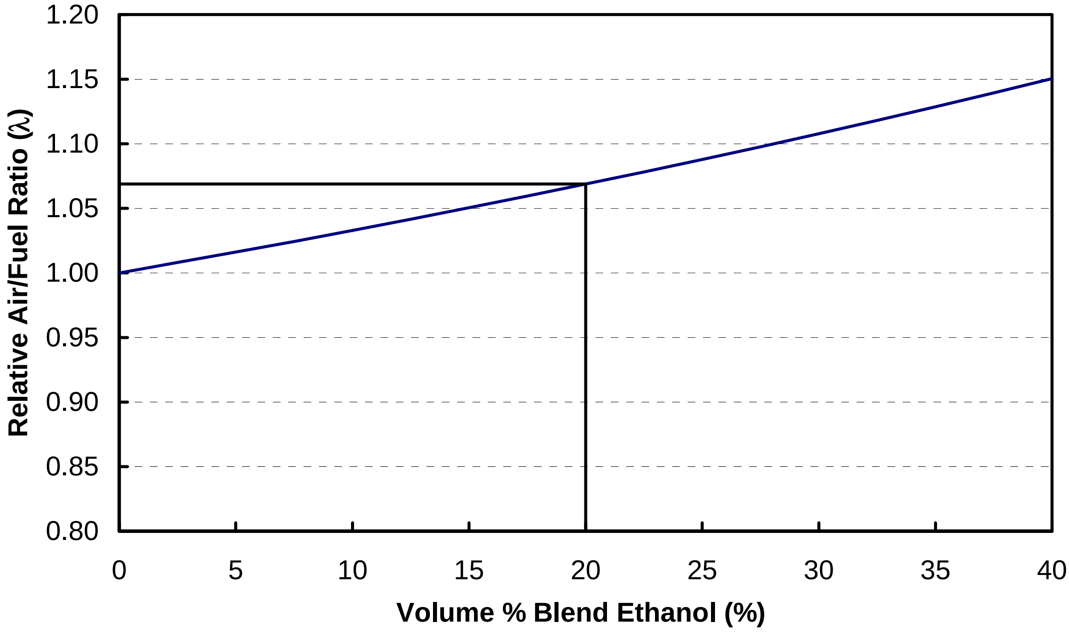

Figure 3 – Relative Air/Fuel ratio (λ) vs ethanol blend for constant fuel delivery volume

At a 20% by volume ethanol blend with gasoline, the enleanment is seen to be approximately 7%. For combustion of homogeneous mixtures, the mixture strength plays a significant role in terms of the “quality” (stability and controllability of the combustion event) and the products of the combustion process.

5 FUEL SYSTEM & CONTROL SYSTEM DEFINITIONS

In general, the fuel system & control system technology employed in non-automotive engines can be described by one the following technology groups:

- Carburetted
- Fuel injected

When considering the impact of changes in fuel properties on emissions and operability, these systems are often described as “open-loop”. Open loop refers to control terminology, with the loop describing the type of control strategy employed. For an open-loop system, the input to achieve a desired output is independent of the actual output.

5.1.1 Open Loop Fuel Delivery Systems

Typical fuel delivery systems are essentially volume flow devices. For a given engine state (airflow), the volume of fuel delivered to the engine will be controlled in order to achieve a desired (target) equivalence ratio for the combustion process. As there is no feedback loop with open-loop systems, the volume of fuel delivered by the fuel system for a given engine condition will remain constant. This means that changes in fuel properties such as density and chemical composition will change the delivered (actual) equivalence ratio for these systems. Generally, these systems are designed to be tolerant to some changes in equivalence ratio, as well as a having a manual mixture strength tuning ability (idle and high speed mixture strength screws for carburettors, or a potentiometer for open-loop electronic fuel injection systems). This is to allow for errors in the system due to deterioration/ageing, environmental conditions (altitude, market fuel etc), and system build tolerances. The addition of ethanol to gasoline changes the density and stoichiometric air/fuel ratio of the fuel. The stoichiometric air/fuel ratio is reduced (including the volume based air/fuel ratio given that ethanol is slightly more dense than gasoline alone), and as such, the mixture strength for a given volume of fuel delivered to the engine, will be reduced, ie enleanment will occur (see Figure 3). The possible effects of this enleanment are discussed in following sections.

5.1.2 Ethanol Addition

The addition of an oxygenate to a fuel effectively results in enleanment of the fuel/air mixture when no compensation is applied. Figure 4 shows the effect on the stoichiometric air/fuel ratio with the addition of ethanol to gasoline. Also shown in this figure is the amount of fuel delivery compensation required (incorporating the change in density of the fuel as ethanol is added) which would need to be provided by the control system to maintain stoichiometric operation of the engine. For a 10% by volume ethanol blend this corresponds to 3.3%, while for 20% ethanol, approximately 7% increase in, fuel injection duration (fuel injection) or fuel metering jet area (carburettor) would be required. Typically non-automotive engines operate on the rich side of stoichiometry.

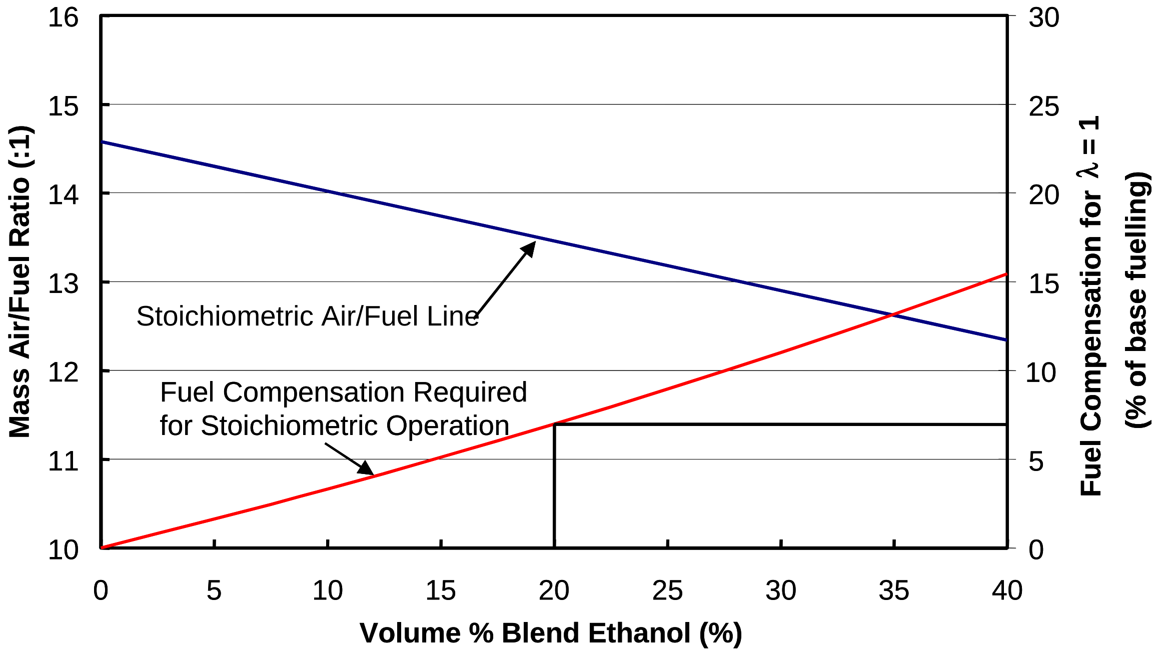

Figure 4 - Air/fuel ratio required for ethanol-blended fuels

6 ENGINE OPERABILITY ISSUES

Engine operability covers a wide range of subjects; some of the more significant are covered in the following sections. Engine operability with respect to cold start as well as hot and cold weather operation. The effects of ethanol blends on fuel quality are discussed in terms of how the engine responds to the changes in the behaviour of the fuel when ethanol is added. The performance of the engine follows and the analysis is formed in terms of the effect that the addition of ethanol has on the octane rating of the base gasoline. The factor of enleanment or “lean shift” is also discussed in terms of the driveability, fuel consumption and the WOT performance of the engine.

Firstly however, fuel quality is covered in terms of the impacts ethanol will have when added to the base gasoline. It is assumed that the ethanol is mixed with normal volatility pump fuel, with unmodified distillation characteristics or make-up.

6.1 Fuel Quality.

Fuel quality can have dramatic effects on engine performance under certain conditions. Two significant issues of fuel quality are those of anti-knock and volatility. Knocking can limit the amount of engine power available and give rise to catastrophic engine damage, while changes to the volatility of the fuel can have significant effects on engine operation (11,11).

6.1.1 Volatility

Fuel volatility can be described by vapour pressure and the distillation curve, each of which is important in understanding what is required from the fuel in terms of satisfying engine operability requirements.

When small amounts of ethanol are added to gasoline, the vapour pressure of the mixture is greater than the vapour pressure of either the gasoline or alcohol alone. The molecules of pure alcohol are strongly hydrogen-bonded, but with small amounts of alcohol in a non-polar material (i.e. gasoline) the hydrogen bonding is much less extensive and the alcohol molecules behave in a manner more in keeping with their low molecular weight. Thus the alcohol becomes more volatile (7).

6.1.1.1 Reid Vapour Pressure

Guibet (13) states that increases in the Reid Vapour Pressure (RVP) of 6 – 8 kPa can be expected with ethanol additions of only 3% to base gasoline with normal volatility. This increase in RVP is confirmed by Owen & Coley (11). The RVP is a measure of the vapour pressure of a liquid as measured by the ASTM D 323 procedure and is commonly applied to automotive fuels. For automotive fuels, the Reid Vapour Pressure (RVP) measured at 37.8 deg C is used to define the fuel volatility (27).

Figure 5 shows RVP of the fuel for different ethanol blend content. The RVP only drops consistently below the gasoline RVP with blends of ethanol greater than 30%.

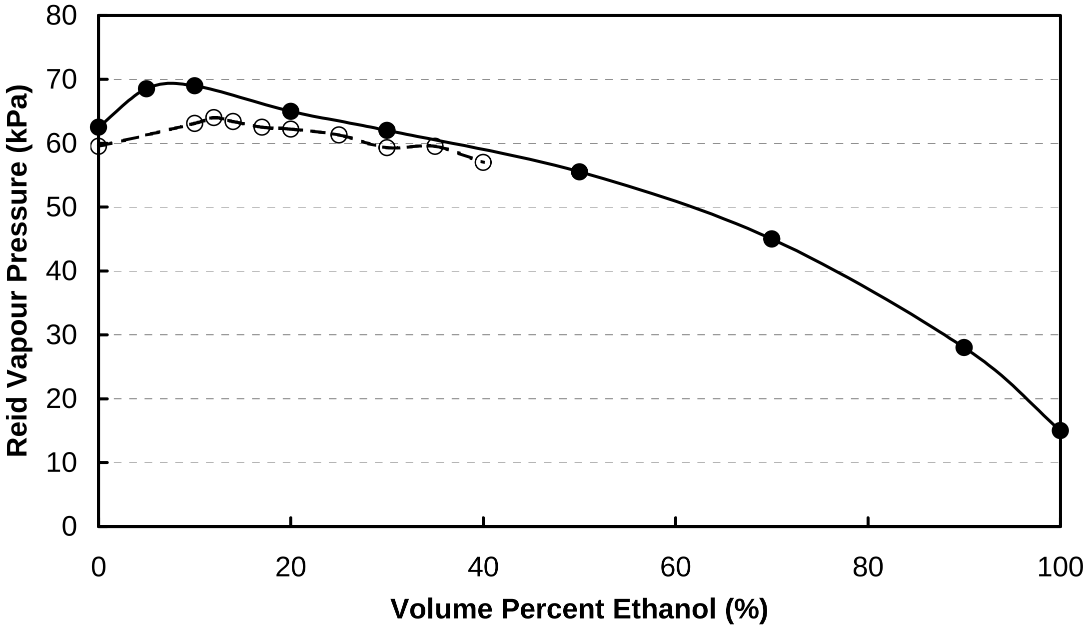

Figure 5 - Reid Vapour Pressure with High Blend Ethanol; solid line ––– Furey & Jackson (7), dashed line – – Guerrieri et al (5).

Table 3 shows the change effect of an addition of 10% and 20% ethanol on the RVP of the base gasoline fuel using data from Owen & Coley.

Volume % Ethanol added	RVP (kPa)
0	62
10	67.3
20	69

Table 3 - Increase in RVP with ethanol addition

6.1.1.2 Distillation curve.

Three regions of the distillation curve are important for the behaviour of a fuel in an engine (11,16). The front end, defined by Owen and Coley (11) as the compounds in the fuel having boiling points up to approximately 70°C, is the first to be distilled over. This controls the ease of starting and the likelihood of hot weather problems such as vapour lock occurring.

The mid-range effectively controls the way the engine runs in cold weather. In particular it has a significant bearing on the warm-up behaviour of the engine in terms of the time taken for the engine to warm-up. Two further important factors are the operational readiness of the hot engine and the behaviour of the hot engine under acceleration. The percentage of the fuel compounds that vaporise at 100°C determines the engines behaviour under the operational conditions just described (11,16,18). The mid point of the gasoline's distillation curve has been used as the principle cold weather driveability control parameter (18).

The final region contains all the heavier compounds. These compounds have a high heat content and are important in improving fuel economy when the engine is fully warmed up. A further requirement on this region is that at a temperature of 180^{o}C, the volume evaporated should be of a significant level so as not to cause dilution of the engine oil through these compounds finding their way into the engine crankcase by passing the piston rings as liquids, (11).

The ASTM D86 Distillation test is also used to define the gasoline volatility, producing a curve similar to that of the base gasoline as shown in Figure 6, (11).

Figure 6 shows the effect of oxygenates on the distillation curve for Indolene HO III fuel with a RVP of 62 kPa (9 psi) from Owen and Coley (11). Considering only the distillation curve for the gasoline, it can be seen that displacing the distillation curve downwards the gasoline will become more volatile and the RVP will increase. Should the distillation curve be displaced upward, the gasoline becomes less volatile with a correspondingly decreasing RVP.

Following (11), it should be noted that weather conditions, particularly ambient temperature, influence the choice of volatility required for satisfactory engine operation. Altitude has a small effect due to the atmospheric pressure influencing the rate of evaporation of the fuel. This is not the case with aircraft that may operate with automotive gasolines, altitude related reductions in atmospheric pressure must be considered, (23). Engines themselves vary significantly in terms of the way they respond to fuel volatility, some being very tolerant while others exhibit severe problems if the fuel volatility is not matched closely to the prevailing weather conditions. The engine application design that is the most important factor in this respect is the proximity of the fuel supply components to hot engine parts.

Clearly, setting the volatility specifications of the fuel is a compromise that is influenced by the prevailing weather conditions, geographical location and the characteristics of the vehicle population, (11).

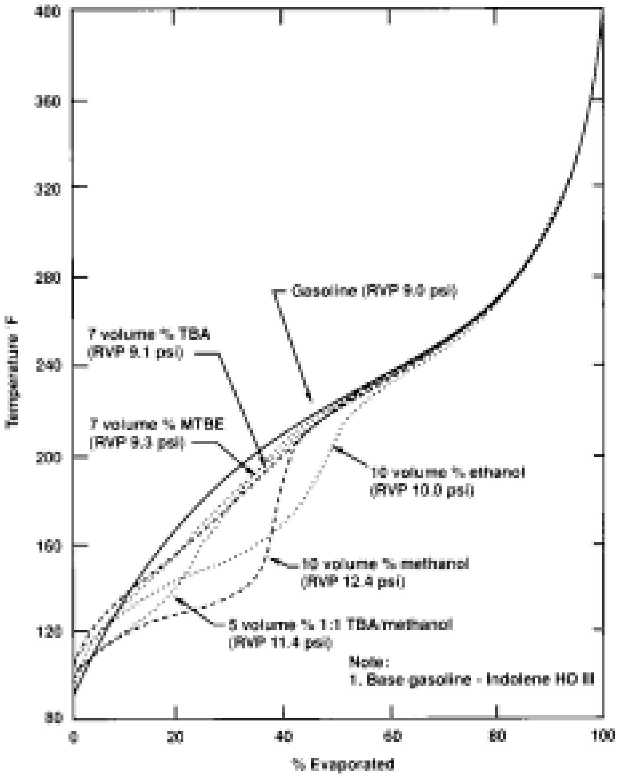

Figure 6 - Effect of Oxygenates on Distillation (11)

Figure 6 shows the effect of adding 10% by volume of ethanol to the base gasoline. Clearly, this results in the front end to the mid region of the curve being heavily distorted in terms of significantly increasing the volatility of the fuel in these regions. Wagner et al. (12) also shows a similar curve to Figure 6 for a 10% ethanol blend and explains that the addition of ethanol into gasoline has significant and curious effects on the volatility of the blend. Further, data from Guerrieri et al. (5) presented as Figure 7 shows the considerable difference in the distillation temperatures for ethanol additions up to 40% by volume to gasoline. Following Figure 7, the effect of 20% ethanol addition to gasoline continues to increase the volatility of the blend as evidenced by further reductions of both the T50 and T90 distillation temperatures. The T50 term is used to denote the temperature at which 50% by volume of the fuel will evaporate, and therefore T90 is the temperature at which 90% of the fuel will evaporate. The reductions seen in T50 and T90 between 10 and 20% ethanol are greater than the reductions from neat gasoline to the 10% ethanol blend, demonstrating a non-linear trend. Beyond the 20% ethanol addition, the T50 distillation temperature remains relatively constant while the T90 distillation temperature continues to fall as ethanol is added up to 40% by volume. For example, the T50 for the gasoline was 103^{o}C, for 10% ethanol the T50 was 89.4^{o}C and for the 20% ethanol blend T50 was 72.8^{o}C.

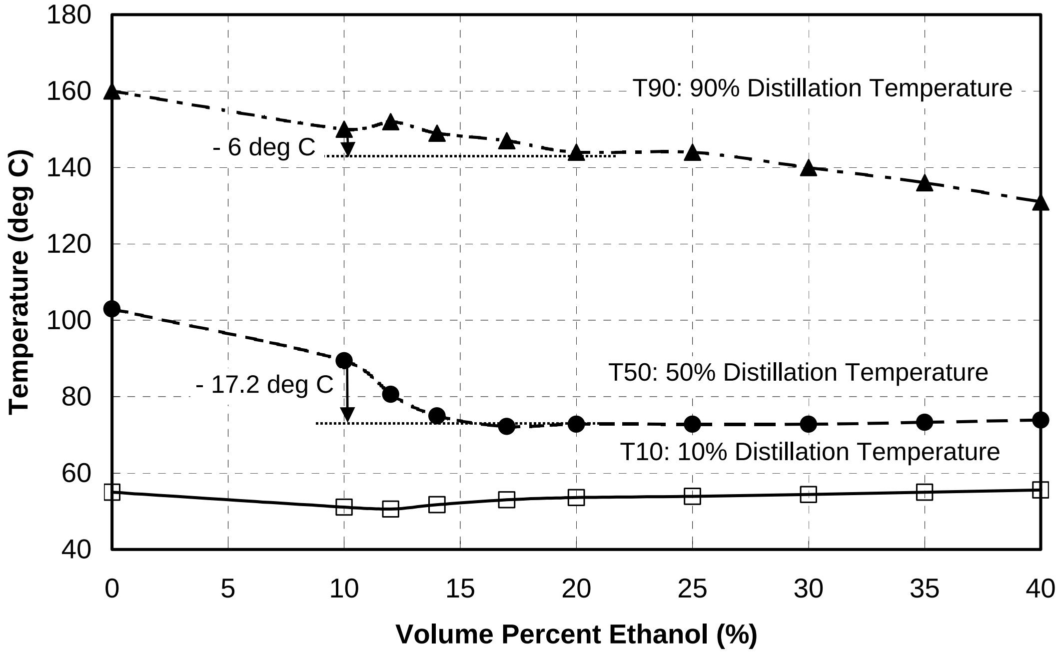

Figure 7 - The distillation temperatures with high blending ethanol (5)

The net affect of the potential for a higher RVP and lower distillation temperature is increased evaporation of the ethanol-blended fuel.

6.1.2 Octane Number

The Research Octane Number (RON) and the Motor Octane Number (MON) as determined by the usual ASTM procedures are used by many authors to indicate that when gasoline is blended with alcohol an increase in the fuel octane occurs over the base gasoline (3,6,11,12,1). There is however, some question as to whether the conventional octane measures of RON and MON give a reliable guide as to the on road octane performance of the fuel when alcohol is blended with gasoline (6). This question is particularly raised when ethanol is blended with gasoline (3,11), though Owen and Coley (11) also state that other work has shown satisfactory correlation between RON, MON and the road octane performance of the ethanol gasoline blend. The on road octane performance is described by the road octane number since it is obtained by testing on the road according to Owen and Coley. To carry out such fuel ratings on the road, the spark timing of the engine is adjusted to find a setting which gives trace knock for the particular fuel and driving mode, whereas when measuring octane requirements through RON and MON, the fuel quality is varied to find the octane level at which trace knock occurs.

Using methanol, which Brinkman et al. (6) suggests gives a comparable effect to that of ethanol, the authors show that the addition of methanol to the base gasoline increases the RON in an almost linear fashion in proportion to the concentration of methanol added, while the MON initially increases and then plateaus beyond approximately 15% addition of methanol by volume, Figure 8 shows this trend. Other authors, (3,12) also show the known trend of increases in RON and MON with addition of ethanol to gasoline. It should be noted that fuel sensitivity increases with the increasing margin between the RON and MON, defined as (RON – MON), by Brinkman et al. and Heywood (19), Figure 8 clearly demonstrates the increase in fuel sensitivity with increasing alcohol content of the fuel. A further trend that can be observed from the reviewed literature is the lower the octane number of the base gasoline, the higher the increase in octane number when ethanol is added. Table 4 shows this trend.

Author	Gasoline	MON	RON	% Ethanol added	MON	RON
Szwarc and Branco (15)	Regular	73	-	20%	81	-
Wagner et al. (12)	Regular	83	92	10%	85	96
Birrell (3)	Regular	-	89	18%	-	97
	Premium	-	97	15%	-	102
Mooney et al. (4)	ULP	-	92.9	30%	-	102.6

Table 4 - Effect of Ethanol Addition on Octane Number

Owen and Coley (11) report on a study where a wide range of oxygenates, including ethanol, were blended with gasoline such that the RON and MON were kept constant. The study showed that with a low level of olefins (10%) in the base gasoline, an improvement to the accelerating knock performance with addition of oxygenate over the base gasoline was found, with a reduction

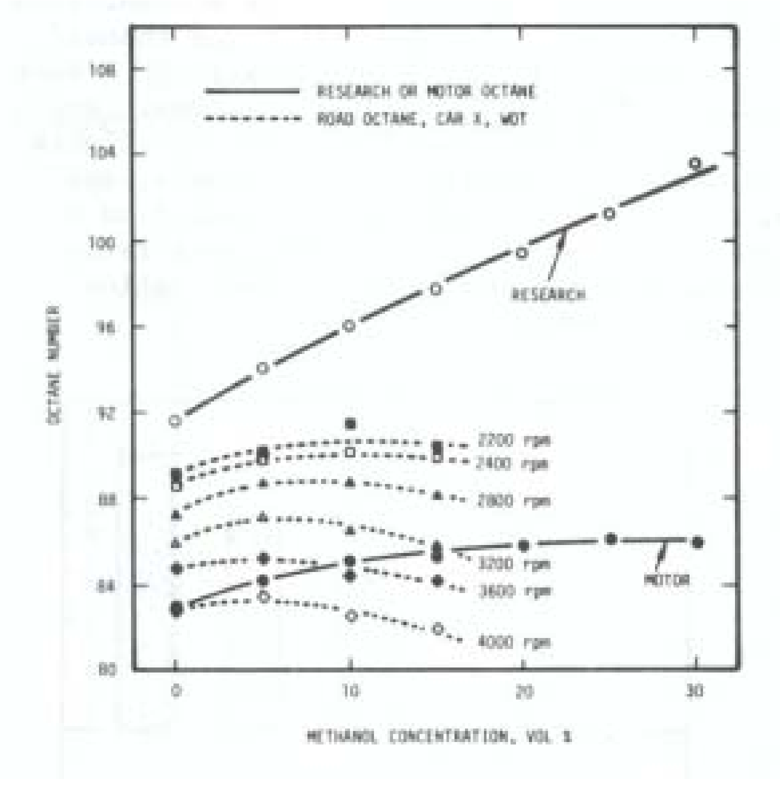

Figure 8- Effect of Methanol Addition on RON and MON (6)

of octane requirement of approximately 0.5 of a point. However, the reverse was true with higher olefin levels (20%). When considering constant speed, ethanol blends gave the worst performance, increasing the octane requirement by approximately 1 point over the base gasoline. The octane requirement can, following Owen and Coley, be defined as the octane number of a reference fuel (any fuel) that gives a trace knock level in an engine on a test bed under specified conditions. Owen and Coley suggest it is only possible to generalise on the effects of oxygenates, as with all octane related work, the actual effect is a function of the engine, the composition of the fuel and the actual test method adopted. Brinkman et al. (6) defines the maximum octane requirement as that occurring at an equivalence ratio of 1.1 corresponding with the maximum brake mean effective pressure. Either side of this equivalence ratio, the octane requirement decreases. Birrell (3) suggests that the equivalence ratio at which maximum knock sensitivity occurs is very close to 1.0 for the engine tested in his paper. Engines differ greatly in the way they respond to octane parameters and in the level of octane quality they require to be clear of knock. It is important for the oil industry to understand the octane requirements of engines under both normal and severe operating conditions so that fuels can be made available to satisfy essentially all engines in a given population regardless of the operating conditions, (11).

6.1.3 Enleanment.

The detail of why enleanment occurs in an engine when ethanol is blended with gasoline is described in section 4. The affects of enleanment have been reported by a number of authors in terms of the impact on the vehicle driveability, (6,11,1). Brinkman et al. (6) suggest that for carburetted vehicles, the effect of enleanment will be strongly linked to the calibration of the carburettor. If the exhaust emissions requirements for the engine tested have been met by a lean calibrated carburettor, further enleanment due to the ethanol blend would seriously deteriorate the operation of the engine. Owen and Coley (11) also suggest this is the case. On the contrary, engines with a rich calibration may not be subject to deterioration of operation. Palmer and Lang (17) state that for a given oxygenate type, oxygenate concentration alone had no detectable effect on engine operation while the most important factor was reported to be volatility. The authors did not provide any indication on the calibration of the carburettor, however based on the other literature it could be assumed the calibration was rich.

A report on off-road engines by the United States Environmental Protection Agency (EPA) (29) states that the addition of oxygenates to gasoline has the effect of enleaning the air/fuel mixture slightly on engines that do not adjust or optimise the air/fuel ratio (open loop engines). Fuel metering components are sized to deliver an air/fuel mixture that optimises power output, fuel economy and durability. Engine manufacturers are aware of the air/fuel ratio sensitivity of their engines and in some cases, they recommend alterations to certain engine models when using oxygenated gasoline. If an engine operates at an air/fuel mixture of that is significantly leaner than it is designed for, it is highly probable that it will run at a somewhat higher temperature, leading to concerns that engine damage could result. Virtually all off-road engines are two-stroke and usually operate at air/fuel ratios that are rich enough to not be affected by the addition of oxygen. Though the author does not specifically state the level of oxygen addition, it seems likely to be of the order of that available from a 10% ethanol blend fuel as the reference is from the United States where a maximum 10% ethanol blend is allowable under regulations. Some manufacturers of recreational vehicles, such as snowmobiles, offer recommendations for modifying engines when operated on oxygenated fuels. Consumers are advised to consult their owner's manual or servicing dealer to determine the manufacturers recommended course of action, (26,29).

The effect of enleanment on Mercruiser inboard marine engines (four stroke cycle engines) operating on 10% ethanol gasoline blends is described as a slightly leaner running engine. Should the engines be in unaltered condition and the fuel system in good operating condition the enleanment should not cause any problems, (30).

6.2 Engine Operability

Essentially, the operation of an engine is directly affected by the volatility and octane number of the fuel. These two factors are also of most importance to the refiner as controlling them is costly (15). An engine with good operating characteristics will accelerate smoothly without stumbling or hesitating, will idle evenly and will operate at constant speed and load without surging. The remainder of this section considers the effect of fuel properties on engine operation.

6.2.1 Cold Start

Cold startability is highly dependant on the fuels ability to vaporise effectively at low temperatures and provide an ignitable mixture at the time of ignition. Owen and Coley (11) state that for alcohol blends, cold starting depends on the vaporisation of the gasoline front end (more volatile fractions). However, when alcohol is present, the vapour contains a greater concentration of alcohol than would be expected based on the vapour pressure of the alcohol or it's concentration in the gasoline. Together with ethanol's higher heat of vaporisation than for hydrocarbons, more heat is required to vaporise the blends containing them. Effectively, the mixture suffers from enleanment due to the higher concentration of alcohol. All these factors indicate cold starting difficulties on vehicles operating with alcohol blends, and test work confirms this, (11).

Johnson (28) reports that aircraft engines operating on aviation gasoline (avgas) fuels blended with ethanol are not guaranteed to start in cold conditions as it is not certain that the blend will be rich enough in gasoline to facilitate an engine start in cold weather. Formal cold starting experiments are planned by the Renewable Aviation Fuels Department (the research area of Baylor University's Department of Aviation Sciences) to understand this issue. It must be noted that automotive gasoline can only be used in approved aircraft and engines, within these applications the cold starting issues may occur as a result of ethanol blends.

During execution of the literature search no other information relating to the cold starting of non-automotive engines and ethanol blend fuels was found.

6.2.2 Hot Operation

When gasoline vaporises prematurely in the fuel system, i.e., upstream of the carburettor jets or fuel injectors, operability problems may occur. The likelihood of the gasoline vaporising will depend on engine design, ambient temperature, ambient pressure and fuel volatility. Due to the higher vapour pressure of ethanol-blended fuels, the incidence of vapour formation in the fuel system is more likely than for gasoline fuels.
Excessive front-end volatility can cause poor hot weather engine operation as described by Owen and Coley (11). According to the authors this is mostly due to vapour lock arising from the increased volatility of the ethanol blend as described in section on the distillation curve, 6.1.1.2.

Typical hot weather engine operating problems can be classified as follows, (27):

- Carburettor percolation
- Vapour lock
- Carburettor foaming

Carburettor percolation occurs when the fuel in the carburettor float bowl boils either during or after a hot soak condition. An engine experiences a hot soak condition when the engine load is reduced or the engine is shutdown after a period of operation at high engine load allowing the heat of the engine to soak back into the fuel system. Engine and fuel system component temperatures are elevated during the hot soak. During the carburettor percolation event, fuel is forced into the inlet manifold through the carburettor vent or jet system, this may give rise to an over rich mixture which can lead to poor hot restarting or persistent engine stalling, (27).

Vapour lock occurs when fuel vaporises in fuel supply lines preventing the carburettor float bowl/fuel system being replenished with fuel. Fuel typically vaporises in the fuel supply to the fuel pump preventing the pump from delivering an adequate fuel supply. Vapour lock causes poor restarting, hesitation and stumbles during acceleration, it can be severe enough to cause the engine to cut out completely. The problems presented by vapour lock are generally due to the mixture being too lean as a result of excessive vapour formation, (27).

Carburettor foaming occurs when the fuel rapidly boils as it enters a hot carburettor generating foam. The foam cannot support the weight of the fuel float, which sinks allowing more fuel into the carburettor promoting malfunction of the engine as excess fuel is forced through the metering and vent systems causing the engine to run excessively rich. The resulting potential engine malfunctions are poor hot restarting, hesitation and stumbling under acceleration of the engine, (27).

A general description of the outcome of vapour lock with respect to non-automotive engines is given in (26). The publication goes on to state that some manufacturers are concerned that oxygenated gasoline will aggravate the vapour lock problems through volatility increases commensurate with the addition of ethanol to gasoline.

Aircraft engines achieve very high engine operating temperatures during takeoff due to the high engine loading required to get the aircraft airborne. The high engine operating temperatures cause heat to soak back into the fuel system. These conditions along with the reducing ambient pressure accompanying an increasing altitude and the use of automobile gasolines containing ethanol promote the potential for vapour lock, (23). Johnson (28) describes the potential vapour lock problem for aircraft and how the fuel volatility factors are used to prevent most vapour lock problems in flight.

6.2.3 Cold Operation

It is well known that engine operability deteriorates as the ambient temperature decreases. Satisfactory engine operation is most critical during the period the engine is warming up. When a single point injection or carburetted engine is cold and the ambient temperature is low, a large portion of the fuel can be present in the inlet manifold as a liquid film. It is this lack of vaporisation that gives rise, for example, to a hesitation before a burnable mixture reaches the cylinders at the start of an acceleration. The uneven idle or surging during steady state operation in carburettor or single point injection engine may be caused by maldistribution of fuel between the cylinders. This can be another reason for stumble during acceleration, (11).

Ambient temperature and humidity in combination with the ethanol fuel blend having a higher heat of vaporisation may lead to icing. Icing is the condition where ice forms, from water vapour in the air, within the engine inlet system or on carburettor surfaces. In extreme conditions icing in the engines inlet tract could occur resulting in loss of performance or engine stalling. Figure 9 illustrates the combination of ambient temperature and humidity that may result in icing (27). Icing has the potential to affect performance of engines with carburetted fuel systems. Fuel injection virtually eliminates icing since fuel is delivered into the inlet port rather than vaporised at the carburettor.

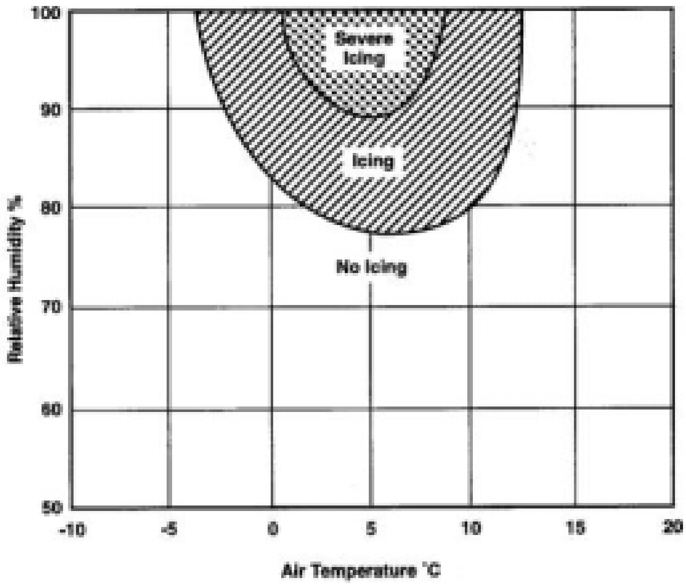

Figure 9 – Ambient conditions conducive to icing (27)

6.3 Engine Performance

Engine performance or engine behaviour during part load and full load (WOT) operation in terms of fuel quality and fuel properties are presented in relation to fuel consumption and WOT performance.

6.3.1 Fuel Consumption

Fuel consumption theoretically increases when oxygenates are blended with gasoline due to the lower energy content of the oxygenated fuel. This increase in fuel consumption, due to the reduction in energy content of the fuel, may be offset somewhat by the enleanment of the fuel/air mixture (open loop fuel control) (11). Table 5 shows the change in fuel economy (on a fuel volume basis) based on the fuel energy loss as the ethanol content is increased. Table 5 contains fuel economy information as the reference is of automotive origin. The change in heat of combustion is relevant to this report.

Ethanol Percentage	Average Heat of Combustion (BTU/Gallon)	Change in Heat of Combustion (%)	Average Fuel Economy (mpg)	Change in Fuel Economy (%)
0	115,650	-	22.00	-
10	112,080	-3.10	21.25	-3.41
12	111,130	-3.91	20.92	-4.90
14	110,500	-4.45	20.90	-5.00
17	109,660	-5.18	20.63	-6.23
20	108,550	-6.14	20.48	-6.91
25	106,510	-7.90	20.13	-8.50
30	104,860	-9.33	20.00	-9.09
35	102,750	-11.15	19.57	-11.05
40	104,270		15.64	

Table 5 – Heat of combustion and Fuel economy for various Ethanol blends (5)

Results of a study performed by Arapatsakos (20) on a two-stroke outboard engine show increased fuel consumption through the use of ethanol-blended fuels as shown in Figure 10. Figure 10 illustrates a volume based minimum fuel consumption increase of 3.2 and 6.4% for 10 and 20% ethanol blend fuels respectively, comparing favourably with predictions in Table 5. It is expected that this trend would follow for the remaining engine groups.

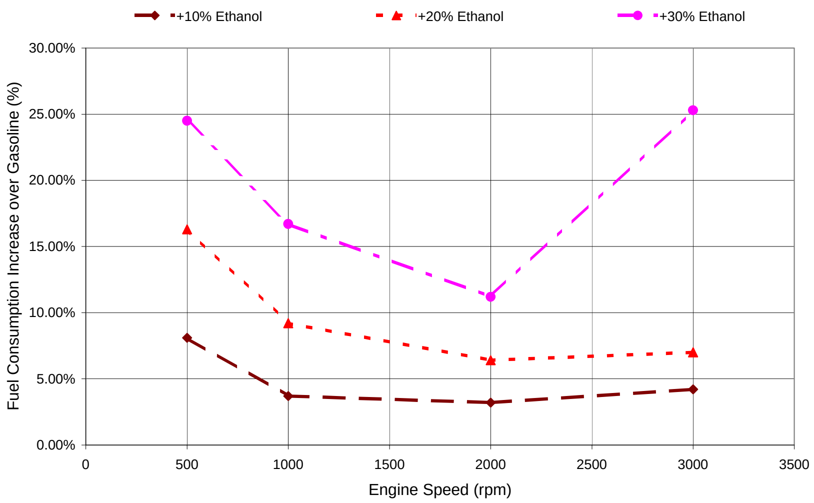

Figure 10 – Volume based percentage fuel consumption change using ethanol-blended fuels (20)

6.3.2 WOT Performance

To consider the effect of ethanol blend fuels on an engines WOT performance there are several factors to consider:

- Increase in the RON and MON, potentially providing the engine with an increased knock limit.

- Increase in the oxygen content of the blend, introducing enleanment, potentially reducing the knock limit and increasing exhaust gas temperatures of the engine.

During execution of the literature search limited information relating ethanol blend fuels and the WOT performance of non-automotive engines was found.

The following information is of automotive background and is equally applicable to non-automotive spark ignition gasoline engines.

Birrell (3) performed a series of tests devised to study the relationship between spark timing required for the onset of knock and two ethanol blend fuels. Four types of fuels were used and the engine was operated under wide open throttle (WOT) conditions at engine speeds of 1000, 2000 and 4000 rpm. Table 6 shows the fuels used. Fuel 1 was used as the baseline and for the three engine speeds tested, the knock limited spark timing for each of the speeds was determined and represents the datum. The knock limited spark timing at each engine speed was re-optimised for each of the other three fuels, 2,3 & 4.

Table 7 shows the approximate differences in the knock limited spark timing at each speed for the three other fuels when referenced to Fuel 1, the premium grade gasoline. It is clear from the testing and the author makes the statement that the knock resistance of the engine tested is seen to be reduced by the use of the ethanol blends with only the 1000 rpm test speed reflecting the RON increase attributed to the ethanol addition. According to Heywood (19), this behaviour is typical of fuel with high sensitivity, where the region of knock occurs at the higher engine speeds.

Fuel Type	**Designation**	**RON**
Premium Grade Gasoline	Fuel 1	97
Premium Grade Gasoline + 15% Ethanol	Fuel 2	102
Regular Grade Gasoline	Fuel 3	89
Regular Grade Gasoline + 18% Ethanol	Fuel 4	97

Table 6 - Fuels used by Birrell (3)

Engine speed (rpm)	**Change in spark timing relative to Fuel 1, ^{o} crank angle**		
	Fuel 2	**Fuel 3**	**Fuel 4**
1000	+10	-15	+2
2000	+1	-14	-4
4000	-10	-4	-8

Table 7 - The variation of spark timing with fuel (3)

Within Birrell's (3) testing the question of the effect of enleanment on the knock performance of the ethanol blends was addressed. Fuels 1 & 2 were compared at the engine speed of 4000 rpm by altering the fuel delivery by adjustment of the main carburettor jet, thereby allowing testing at various equivalence ratios. The author suggests that when operating at the same equivalence ratio as the unadjusted main jet when using Fuel1, the reduction in anti knock performance of Fuel 2 was not as pronounced. The authors graph indicates the change in spark timing was approximately –9 degrees crank angle compared with –10 degrees crank angle when no adjustment to equivalence ratio was made.

The experience of Brinkman et al. (6) is similar with that reported by Birrell, though not as pronounced. Figure 8 shows the effect of adding methanol to gasoline in varying percentages from 5 to 15 on the road octane number of the fuels tested by Brinkman et al. The authors determined the road octane number by using the CRC Modified Borderline technique. It is clear from Figure 8 that after 2800 rpm, the road octane number for the alcohol blends with more then 5% alcohol was reduced below that measured for the base gasoline. Brinkman et al. also note the potential effect of enleanment; however do not specifically test to determine the enleanment effect. They do however conclude that with a 10% methanol blend, knocking would be slightly decreased.

Joseph and Grogan (10) report that there was a need to adjust the ignition timing of approximately 10 vehicles in the very significant fleet of vehicles run within their experiment. The authors offer no conclusive judgement as to whether or not the 15% ethanol blend caused the timing problems. They do however make mention of the increased octane rating of the blend over the base gasoline.

6.4 Discussion

The issue of enleanment for utility engines seems clear, in that generally these engines have carburettor calibrations that are rich and therefore capable of operating with up to a 10% ethanol gasoline blend. In general, manufacturers of the utility products confirm this, indicating that using ethanol gasoline blends of up to 10% is acceptable. Downstream Alternatives Inc. (21) have collated utility (nominated as power equipment by Downstream Alternatives Inc.) engines manufacturer recommendations contained in their owners manuals confirming that ethanol gasoline blends of up to 10% is acceptable.

In terms of the marine engine group, a similar situation exists as for the utility engines. Downstream Alternatives Inc. in their collated review of owners manuals indicate that ethanol gasoline blends up to 10% is acceptable. Further, Mercury Marine (31) though not recommending the use of gasoline containing alcohol, specify that should only gasoline containing alcohol be available the gasoline must not contain more than 10% ethanol. Some manufacturers recommend various methods of enriching the fuel flow when operating their products on oxygenated fuels, (32).

The engine group of vehicle in general falls into a similar situation, (21). Again, there is however exceptions with some manufacturers recommending various methods of enriching the fuel flow when operating their products on oxygenated fuels, (32).

No specific detail of the potential effects due to enleanment of a 20% ethanol gasoline blend was found during the literature search, the theoretical implication is however clear, further enleanment will occur. Depending on the engines calibration, enleanment has the potential for causing significant deterioration of engine operation as well as engine damage to certain engines. Based on manufactures recommendations up to 10% ethanol gasoline blends is acceptable and by implication blends greater than should not be used.

Within the area of operability covering cold start and cold operation, there was no literature uncovered for the engine groups of utility, marine and vehicle that specifically dealt with these areas of concern with respect to ethanol content in gasoline. In terms of hot operation, only one publication was found which stated that some manufacturers are concerned with the hot operation of non-automotive engines in terms of vapour lock and hot restarting based on the increases in volatility brought about by the addition of ethanol to gasoline. It is believed that these areas of operability are far more significant for automotive products due to the reliance on and the cost of the automobile relative to non-automotive products.

In terms of engine performance, in general it seems that the fuel consumption of the engines will increase in a similar ratio to the reduction in energy content due to the particular ethanol content the fuel blend. For a 10% and 20% ethanol gasoline blend fuel, the potential increase in fuel consumption is approximately 3% and 6% respectively.

The potential impacts arising through the use of ethanol gasoline fuel blends on the WOT performance of engines has been reviewed. With respect to non-automotive engines, limited literature was found which only outlined the potential impacts based on the gasoline engine calibration. There is however no reason to believe that the potential impacts on non-automotive engines will be significantly different to those described for automotive engines within section 6.3.2 of this report.

The test program to be performed by Orbital aims to address the issues discussed and provides information for marine and utility engine groups through testing outboard and utility engines. The test program includes testing of: hot and cold starting; WOT operation; fuel consumption and operability assessment. WOT operation of engines utilising ethanol gasoline blend fuels is particularly important since the literature search revealed limited information on this topic for non-automotive engine applications. During testing both 10% and 20% ethanol gasoline blend fuels will be used.

Within the testing program, the volatility and octane number of the fuel utilised for all testing will be managed by measuring the fuel parameters that define the fuel quality. This includes the base fuels used to which the ethanol is added. A quality procedure has also been determined ensuring that the actual ethanol blend contains very close to 10 and 20% by volume ethanol

The aircraft engine group requires a separate discussion. Within this engine group there are engines or aircraft that the flight manual specifies unleaded automotive gasoline with a minimum octane rating of 90 RON as approved fuel for the aircraft. Within Australia, standard unleaded automotive gasoline satisfies the minimum 90 RON requirement as does premium unleaded automotive gasoline. The Skyfox C25 and C25N aircraft, (33), for example is certified to operate on 90 RON unleaded and premium unleaded automotive gasoline, however the approval does not appear to include that the two approved gasolines should be blended with ethanol of any percentage.

ROTAX a manufacturer of two cycle aircraft engines provide a warning on the use of alcohol gasoline fuel blends, (34). Service information detailing the use of automotive fuel in the ROTAX two cycle aircraft engine provides the following warning, “Oxygenates (alcohol additives) are to be avoided, any volume over 5% cannot be used. Testing for alcohol (content) is the only safe way to be sure your fuel is o.k. for use in your ROTAX.”

7 ENGINE DURABILITY

Engine manufacturers will test their products on various durability test cycles to ensure satisfactory operation of the engine over the design life. Upon passing the durability testing to the manufactures standards, the manufacturer can be relatively certain the engines are capable of meeting their customer's expectations and warrant them accordingly. Should the engine be operated with fuels and oils not meeting the manufacturers specifications, questions are then raised in relation to the engine being able to meet the manufacturers durability standards.

Issues related to the potential engine durability degradation have been raised, with various stakeholders having differing views, (1). The following sections review the literature related to studies undertaken to identify the potential engine durability impacts of using ethanol gasoline blends in engines.

7.1 Wear on Engines and Lubrication

Various studies investigating wear on engines using ethanol-blended fuels have been performed on four-stoke and two-stroke engines. The majority of work on four-stroke engines is of automotive background.

There have been studies completed on the metal to metal wear differences due to the impact of using alcohol and alcohol gasoline blends. The evidence reported by Black (9) is that ethanol blends offer less lubrication to metal parts. The same paper also reports that should long cranking periods be required to start the engine, metal to metal contact occurs due to the alcohol washing away the lubrication film. It should be noted that though it is not clear, this might be based on straight alcohol fuels.

Testing reported by Owen and Coley (11) expressed some concerns as to whether the use of alcohols in fuel would increase engine wear, with the authors indicating that oxygenate additions allowing a 3.5% increase in oxygen level would not require specially formulated lubricants.

Crankcase scavenged two-stroke engines have the additional complication of the air/fuel and oil mix interacting with the base engine components (crankshaft, connecting rod, seals, bearings and piston for example). By design and functional requirements the base engine components have critical bearing surfaces that require satisfactory lubrication to reduce wear. Manufacturers consider lubricity of fuel oil mixes an issue for engines using ethanol gasoline blend fuels although limited information available indicate otherwise (24, 25,29). A field evaluation of two-stroke engines running 10% ethanol gasoline blend fuel by Kasperson and Reynolds (24) on a number of utility engines indicated that satisfactory engine durability was possible. A lubricity test was performed which indicated that lubricity was improved using ethanol-blended fuels. Upon completion of the testing the engines were disassembled and inspected. One observation made was the greater incidence of ring sticking for test engines with high hours of operation, 200-400 hours.

Crankcase scavenged two-stroke engines may also experience loss of lubrication by the oil separating out of the fuel oil mix. This may occur through unsuitable oil formulation or the ethanol separating from the gasoline (phase separation). Phase separation may occur if the water content of the fuel exceeds a threshold value. Should the engine start and run when phase separation has occurred the engine will not be lubricated, a situation presenting the greatest potential for engine damage, (26).

7.2 Deposit Formation

Various studies investigating deposit formation on engines using ethanol-blended fuels have been performed on four-stoke and two-stroke engines. The majority of work on four-stroke engines is of automotive background.

Four-stroke engines may experience intake system deposits (ISD). ISDs are the deposits discussed in any significant detail by the various authors of the literature reviewed. In particular, deposits on the back of the intake valve is referenced as the area of most concern. This concern is clear due to the intake valve and seat area presenting the flow restriction point in the intake tract of modern engines.

Intake system deposits are reported by (13,14) to be more prevalent with fuels containing alcohol. The authors (14) explain that gasoline contains two types of additive packages to control deposits. The two different additive packages are formulated to control deposits on the pintle of the fuel injector to ensure accurate fuel metering and to control the deposits on the surfaces of the intake system, particularly the intake valve, to ensure the engines charge airflow is not compromised. Their detailed testing has shown that adding 10% by volume neat ethanol to gasoline with adequate ISD additive increased intake valve deposits by more than 350%. This is not only due to the dilution effect but also due to an antagonistic effect since neat ethanol blended at 10% by volume with gasoline without ISD additive increased intake valve deposits by 37% over the gasoline base without ISD additive. Increasing the ISD additive by 50% over the normal concentration in gasoline was found necessary with 10% ethanol blends in order to achieve the same deposit control as with normal ISD additive levels in gasoline. Some of the experiences reported by (14) are confirmed by (11). Firstly that intake system deposits have been found in the intake valve area, and also includes the intake manifold area; and secondly that the deposits can be controlled with higher additive levels than would be required for gasoline only (11).

Crankcase scavenged two-stroke engines may experience detrimental deposits in the piston ring land area as documented by Kasperson and Reynolds (28). The piston ring land deposits tended to cause ring stick, where the piston ring becomes stuck in the pistons ring groove. These ring land deposits are common in engines operating on gasoline; solvents and detergents in the fuel and oil control the severity of the deposits.

7.3 Phase Separation

Water of up to a concentration of 50 ppm at ambient temperatures will remain in solution with gasoline causing no fuel system related problems. Ethanol has an affinity for water and should the water content of an ethanol gasoline blend increase, phase separation or de-mixing is likely to occur. This process is temperature dependent occurring more readily at lower temperatures with lower ethanol content and therefore more readily at higher temperatures with higher ethanol content, (13). The temperatures mentioned are in the ambient temperature range.

Aircraft engines typically operate at engine loads above 65% of full load; under these conditions the engines may experience severe damage through phase separation. Aircraft engines, as reported by Johnson (32), may switch from operation on the gasoline phase to the ethanol-water phase of the separated fuel, such transition causes power surges, dynamometer testing has shown this to cause severe engine damage.

Chevron (26) note that should phase separation occur in the fuel supply to a two-stroke engine it is likely that lubricating oil will not be present in the ethanol-water phase. Should the engine start and run on the ethanol-water phase this presents the greatest potential for engine damage through lack of lubricant. Four-stroke engines will tend to stall or exhibit poor operability as a result of water contamination or phase separation.

7.4 Discussion

The issue of non-automotive engine durability while operating on ethanol gasoline blend fuels beyond 10% ethanol is not adequately addressed by available literature. Some confidence in engine durability can be gained by the fact that the majority of manufacturers allow the use of 10% ethanol gasoline blend fuels. A field investigation performed using production utility engines using 10% ethanol-gasoline fuel indicated that satisfactory engine durability was possible.

Non-automotive four-stroke engines may experience Intake system deposits (ISD). ISDs are fuel-based deposits that typically form on the back of the inlet valve. Literature available on this issue is based on automotive engines. The severity of ISDs may be controlled by additive packages in the fuel blend.

Phase separation may result in damage to two-stroke engines through loss of lubrication. When ethanol gasoline blend fuel undergoes phase separation it is expected that the oil will remain in the gasoline phase. Should the engine start and run on the ethanol-water phase the engine will not receive lubrication and damage will most likely result. Two-stroke engines utilising oil injection systems are immune to this effect.

To address the lack of non-automotive engine durability data related to engine operation with 20% ethanol gasoline fuel blends, Orbital will undertake testing on engines taken from the marine and utility engine group. Comparative testing will occur with three of each type of engine one running on gasoline, the second on E10 and the third E20. The planned durability cycles for the engine types is based on the specific manufactures recommendations for the product in terms of the actual cycle and appropriate length. Evaluation of the engines will be based on making accurate measurements and recordings of internal engine components before and after the engine durability exercise. The measurements and recordings have been targeted to clearly reveal a wear situation as well as reveal potential differing deposit behaviour.

For aircraft with approval to use unleaded automotive gasoline, should an ethanol gasoline fuel be used, phase separation has the potential to cause severe engine damage. Within this engine group there are engines or aircraft that the flight manual specifies unleaded automotive gasoline with a minimum octane rating of 90 RON as approved fuel for the aircraft. Within Australia, standard unleaded automotive gasoline satisfies the minimum 90 RON requirement as does premium unleaded automotive gasoline. The Skyfox C25 and C25N aircraft, (33), for example is certified to operate on 90 RON unleaded and premium unleaded automotive gasoline, however the approval does not appear to include that the two approved gasolines should be blended with ethanol of any percentage.

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8 FUEL SYSTEM DURABILITY

The stable performance of the fuel system for an engine is of paramount importance to ensure the engine will be able to meet its intended design features, performance or customer satisfaction and safety requirements. Should a modified fuel, not considered during the design phase of the fuel system be introduced to the fuel system, it is likely the fuel system may not perform as intended for the design life of the fuel system. The following sections present the findings of a review of the available literature on the impacts of ethanol blends on fuel systems and their components.

8.1 Corrosion of fuel systems components

A limited amount of literature was available regarding corrosion of non-automotive engine fuel systems using ethanol-blended fuels. Limited confidence is gained by the fact that the majority of engine manufacturers currently allow the use of 10% ethanol gasoline fuel blends (21). Some manufacturers report corrosion of metallic fuel system components when gasoline oxygenated with alcohol was used in older engines. Apart from prolonged storage, this does not appear to be a concern with late model engines. These corrosion problems may be aggravated by phase separation, where the alcohol-water phase tends to be more corrosive than the alcohol gasoline blend, (26). Johnson (28) also suggests corrosion is aggravated by the occurrence of phase separation of ethanol gasoline blend fuels.

Metals at risk of corrosion by ethanol-blended fuels are: steel; zinc die-castings and aluminium fuels system components. The addition of ethanol to gasoline accelerates the corrosion of steel due to the increased water content and presence of organic acids (27).

8.2 Perishing of fuel systems components

Generally it is expected that modern non-automotive engine fuel systems materials are suitable for up to 10% ethanol gasoline fuel blends, as engine manufacturers allow the use of up to 10% ethanol blend fuel (21,29). During the early to mid 1980s in the United States, a number of manufactures of non-automotive gasoline engines did find it necessary to upgrade some of the materials used in their products fuel systems. The current belief is that manufacturers now use upgraded materials that largely are unaffected by properly formulated oxygenated fuels, again as evidenced by the manufacturers fuel recommendation comments which now permit the use of such properly formulated fuels, (35). Further, responsible aftermarket suppliers such as Walbro Engine Management Corp. a major supplier of carburettor rebuild kits and other parts, has indicated that Walbro parts are resistant to alcohol related decomposition as long as the volume of alcohol is within legal limits, being 10% by volume. During the testing of 10% ethanol gasoline fuel blends undertaken by Kasperson and Reynolds (24), the authors reported a compatibility problem where the fuel line of one product was visibly more swollen than the control unit operating on gasoline only. The Mercruiser company (31), manufacturers of marine inboard four stroke gasoline engines and stern drives suggest that their product range produced after 1987 should be compatible with 10% ethanol gasoline fuels however, products produced before 1987 should have the plastic and rubber fuel system components inspected regularly for leaks and/or deterioration. Some manufacturers recommend frequent inspection of the fuel system for leaks and deterioration of elastomeric parts when operating their older engines on oxygenated gasoline, (26).

No non-automotive specific literature was available with respect to ethanol gasoline fuel blends exceeding 10%.

8.3 Fuel system deposits

Owen and Coley (27) report increases in gum and deposit formation during ethanol gasoline blend fuel storage and use, which have the potential to affect all engine groups. Ethanol gasoline blend fuels also increase the solubility of gasoline fuel deposits lending to the release of gum bound debris followed by blockage of filters and fuel metering components. Gum formation during equipment storage is a particular concern for equipment that does not get used on a regular basis. The majority of engine manufacturers recommend draining unused fuel from equipment or adding a fuel stabilising additive that prevents oxidation prior to storage of equipment (21). The solvent action of the oxygenated fuel may dissolve some of the fuel system deposits which will clog filters of inboard marine engines. Changing fuel filters more frequently until the fuel system has cleaned itself is recommended, (30).

8.4 Discussion

A limited amount of literature was available regarding fuel system durability of non-automotive engines utilising ethanol-blended fuels. Engine manufacturers generally allow the use of fuel blends with up to 10% ethanol; indicating modern engines are capable of durable operation with up to 10% ethanol gasoline blend fuels. Use of blends with beyond 10% ethanol is clearly not recommend by manufacturers. For products that were manufactured before the mid 1980s, manufactures recommend that frequent inspection of the plastic and rubber fuel system components is followed to ensure the potential deterioration of these components is discovered as early as possible.

The addition of ethanol to gasoline has the potential to accelerate the corrosion of fuel system components due to the increased water content and the presence of organic acids. Phase separation of ethanol gasoline blend fuels may lead to more aggressive corrosion of metal fuel system components.

Increased gum formation is a result of blending ethanol with gasoline, however, the ethanol in blended fuels tends to dissolve gasoline gums allowing the release of gum bound debris that may block filters and fuel metering components. Ethanol gasoline blend fuels are also noted to produce gums during storage and use of fuel stabilising additives is recommended to reduce gumming and fuel oxidation.

Only testing of representative components along with long-term durability and testing with the E20 ethanol blend can provide accurate information of the possible impact, as no information was uncovered during the literature search for an E20 blend.

To address the lack of data, Orbitals test plan follows two avenues in which data for gasoline as well as 10% and 20% ethanol gasoline blends will be gathered.

- Engine durability testing of marine and utility engines in which the status of the durability engines fuel systems will be recorded prior to and upon completion of the durability exercise providing comparison data for evaluation of potential corrosion and perishing behaviour.
- Complementing the durability exercise is a fuel system component materials compatibility test program in which actual fuel systems component materials are immersed into the three fluids at elevated temperature for an extended time period. Continuous monitoring of the immersed materials during which changes in, for example, volume and weight are monitored and recorded providing the necessary data for the evaluation of the potential for corrosion and perishing behaviour.

9 CONCLUSIONS

A study on the suitability of ethanol/gasoline blend fuels containing greater than 10% (by volume) ethanol for non-automotive engines has been performed. The study was aimed at specific areas of engine operability, durability and fuel system durability while operating on high ethanol blend fuels. During the execution of the literature search it became apparent that only limited information relating non-automotive engines and ethanol blend fuels was available. The majority of information available was often not specific to a particular engine group (aircraft, vehicle, marine or utility groups). The available data needs to be considered in the context of the current population of non-automotive gasoline engine, which must operate effectively and efficiently on the higher ethanol blends without the need for retuning/recalibration or other modification. As there is only limited and non-specific information available for higher ethanol blends, the detailed testing program, which is to be undertaken as part of tender 34/2002, is warranted.

Ethanol, an oxygenate, when blended with gasoline increases the available oxygen for the combustion process. The study shows that there is enleanment of the combusted mixture for those engines operating with open loop fuelling systems. The severity of the impact of enleanment depends on the richness of the engines gasoline calibration. If the original calibration is lean, then the impact of enleanment is likely to be significant. Enleanment has the potential to have a detrimental effect on: cold starting; hot operation; cold operation and wide open throttle performance.

The increased volatility of ethanol blend fuel may result in the detrimental effect on engine operation in hot conditions through vapour formation within the fuel system. Vapour lock is the most likely hot condition effect due to the increased volatility. The vapour lock condition generally causes poor engine restarting, hesitation and stumbles during acceleration and can be severe enough to cause the engine to cut out completely. In terms of operation of engines under cold conditions no information was uncovered describing the impacts that a 20% ethanol gasoline blend will have on the engine population.

Fuel consumption theoretically increases when oxygenates are blended with gasoline due to the lower energy content of the oxygenated fuel. For 10% and 20% ethanol gasoline blends the theoretical increase in fuel consumption is approximately 3% and 6% respectively. This increase in fuel consumption, due to the reduction in energy content of the fuel, may be offset somewhat by the enleanment of the fuel/air mixture.

The effect of ethanol blends on the WOT performance of non-automotive engines was not uncovered due to the lack of literature available on this subject. There is however no reason to believe that the potential impacts on non-automotive engines will be significantly different to those described for automotive engines. From the automotive literature review of WOT performance included in this report, the level of potential deterioration is likely to be dependent on the gasoline calibration of the engine, with the 20%

ethanol gasoline blend fuel giving the worst performance and increasing the possibility of engine damage through overheating and the potential onset of knock.

The impact of a 20% ethanol blend on engine wear in non-automotive engines in the Australian non-automotive engine population is unclear. No literature was uncovered that dealt with ethanol blends exceeding 10% ethanol. The only valid conclusion that can be drawn is that further testing is required to obtain data to provide an indication of the potential impact.

Non-automotive four-stroke engines are expected to experience intake system deposits (ISD) in the same manner as automotive four-stroke engines operating on ethanol gasoline blend fuels. ISDs may have an effect on engine performance and fuel economy. Increasing the treat rate of the additive used in conventional gasoline fuels may control the severity of ISDs when using ethanol-blended fuels. Two-stroke engines may also experience deposit related issues when operating on ethanol blends. The literature related to non-automotive engines appears to be very limited and only related to the E10 blend. With respect to the potential impacts of an E20 blend, the only valid conclusion that can be drawn is further testing is required to obtain data to provide an indication of the potential impact.

Many non-automotive engine manufacturers recommend the maximum ethanol content of 10% in gasoline is safe to use in their engines produced after the mid 1980s. Many of these manufacturers also recommend that their products produced prior to the mid 1980s should have their fuel systems regularly inspected for deterioration of plastic and rubber components should an ethanol gasoline blend fuel have been used. The potential for corrosion and perishing of fuel system components increases with increasing ethanol content in gasoline. There was no literature uncovered that dealt with the impacts of higher ethanol blends on the aspects of fuel system component corrosion and perishing though it is clear that manufacturers do not recommend the practice. To provide an indication of the potential impact of higher ethanol blends, further testing is required.

The literature reviewed indicates a significant potential for ethanol gasoline blends to increase the solubility of gasoline fuel deposits with the release of gum bound debris followed by blockage of filters and fuel metering components. This action is not specific to either the E10 or E20 blend though may occur earlier with the E20 blend with its higher ethanol concentration. This action is likely to be more prominent on the older engines that have operated on gasoline only for some time.

The use of aircraft/aircraft engines approved to use automotive unleaded gasoline of which there are examples in Australia deserves special attention. Two examples are the Skyfox C25 and C25C aircraft along with certain ROTAX two cycle engines (for use in ultralight aircraft) both are approved to operate on automotive unleaded gasoline of a particular octane rating. Approval does not include gasoline blended with ethanol. It does appear that there are guidelines specifying the outlets that should be used for the supply of automotive gasoline for those approved aircraft or aircraft engines. However the potential does exist for inconsistency in fuel quality, to this end aircraft engine suppliers and safety authorities recommend operators scrutinize each fuel batch to determine the fuels overall quality as well as maintaining a heightened awareness for potential fuel leaks throughout the aircraft fuel system. There is also a recommendation to buy fuel from a large supplier while making all efforts to confirm the fuel being bought is as advertised. A further recommendation by the aircraft engine supplier is that operators of such engines and aircraft obtain a simple alcohol test kit allowing the determination for alcohol to be made as this is the only safe way to be sure the fuel is alcohol free.

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11 ACRONYMS AND TERMINOLOGY

A/F Ratio	Air Fuel Ratio
Avgas	Aviation gasoline
BTU	British Thermal Unit (heat energy unit)
CO_2	Carbon Dioxide
CRC	Coordinating Research Council
E10	Ethanol gasoline blend with 10% by volume ethanol
E20	Ethanol gasoline blend with 20% by volume ethanol
EPA	Environmental Pollution Agency (United States of America)
FMEA	Failure Mode and Effects Analysis
gal	gallons
H_2O	Water
ISD	Intake System Deposits
kg	kilograms
kPa	kilopascals
lb	pounds (mass)
MJ	Mega Joule (energy)
MON	Motor Octane Number
mpg	miles per gallon
OEM	Original Equipment Manufacturer
psi	pounds per square inch
RON	Research Octane Number
rpm	revolutions per minute (engine speed)
RVP	Reid Vapour Pressure
SAE	Society of Automotive Engineers
T50	Temperature at which 50% evaporates
T90	Temperature at which 90% evaporates
WOT	Wide Open Throttle

% used in reference to ethanol is % v/v
% used in reference to oxygen is % m/m