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**FAA Technical Center**
Atlantic City International Airport
N.J. 08405

# Alternate Fuels for General Aviation Aircraft with Spark Ignition Engines



Augusto M. Ferrara

June 1988

Final Report

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16. Abstract

This report describes the results of a study into the behavior of several alternate fuels that are under consideration for use in general aviation aircraft engines. The study consisted of a literature search and engine tests using a dynamometer. The literature search identified material compatibility problems and possible solutions to these problems. For the engine tests, a number of gasoline/alcohol blends were prepared using both ethanol and methanol in varying concentrations and the vapor lock behavior was identified. Neat alcohols and methyl-tertiary-butyl ether were also used in the engine and special operational conditions and problems were identified. The engine oil was analyzed during this study with the intent of detecting accelerated wear.

Based on the results of this study, a number of considerations pertaining to the use of these alternate fuels in general aviation aircraft are identified.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| Al | Aluminum |
| Ag | Silver |
| ASTM | American Society for Testing and Materials |
| Avgas | Aviation Gasoline |
| BSFC | Brake Specific Fuel Consumption - lbm/hp-hr |
| BTDC | Before Top Dead Center (Used for Spark Timing) |
| BTU | British Thermal Unit |
| C1 | Methanol |
| C2 | Ethanol |
| $^{o}C$ | Degree(s) Celsius |
| C-172 | Cessna 172 |
| CHT | Cylinder Head Temperature |
| Cr | Chromium |
| Cu | Copper |
| degC | Degree(s) Celsius |
| degF | Degree(s) Fahrenheit |
| DOE | United States Department of Energy |
| EB | Ethanol in Autogas |
| EPA | Unites States Environmental Protection Agency |
| EGT | Exhaust Gas Temperature |
| EP | End Point - $^{o}C$ or $^{o}F$ |
| ERVP | Equivalent Reid Vapor Pressure - psig |
| $^{o}F$ | Degree(s) Fahrenheit |
| FAA | Federal Aviation Administration |
| Fe | Iron |

| | |
|---|---|
| F.I. | Fuel Injected |
| FT | Full Throttle |
| ft-lbf | Foot Pound Force (Typically Torque) |
| gm | Gram |
| GCK | ERVP Determined Using the Gas Chek Kit - psig |
| gph | Gallons per Hour |
| IBP | Initial Boiling Point - $^{o}C$ or $^{o}F$ |
| inHg | Inches of Mercury (Typically Manifold Pressure) |
| $inH_2O$ | Inches of Water (Typically Fuel or Cowling Pressure) |
| hp | Horsepower |
| hr | Hour |
| kg | Kilogram |
| kJ | Kilojoule |
| lbm | Pound Mass |
| MB | Methanol in Autogas |
| Mg | Magnesium |
| mL | Milliliter |
| Mo | Molybdenum |
| MON | Motor Octane Number (dimensionless) |
| mpg | Miles per Gallon |
| MTBE | Methyl-tertiary-butyl Ether |
| N/A | Not Available |
| Ni | Nickel |
| OAT | Outside Air Temperature - $^{o}C$ or $^{o}F$ |
| Pb | Lead |
| pH | Acidity |
| psi | Pounds Force Per Square Inch |

| | |
|---|---|
| psig | Pounds Force Per Square Inch, Gauge Pressure |
| RG | Unleaded Racing Gasoline |
| rpm | Revolutions Per Minute |
| RVP | Reid Vapor Pressure - psig |
| RON | Research Octane Number (dimensionless) |
| SAE | Society of Automotive Engineers |
| Si | Silicon |
| Sn | Tin |
| STC | Supplemental Type Certificate |
| TBA | Tertiary-butyl Alcohol |
| TEL | Tetraethyl Lead |
| 100LL | 100 Octane Aviation Gasoline with a Low Lead Content |
| < | Less Than |

ERRATA

Report No. DOT/FAA/CT-88/05

# ALTERNATE FUELS FOR GENERAL AVIATION AIRCRAFT WITH SPARK IGNITION ENGINES

Augusto M. Ferrara

June 1988

FINAL REPORT

U.S DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration Technical Center
Atlantic City International Airport, N.J. 08405

Change the word seconds to minutes on figures 6, 10, 13, 16, 19, 22.

Page 23, Gas Check Kit should be Gas Chek Kit®.

Released July 1988

## EXECUTIVE SUMMARY

This study was conducted to determine the potential problems associated with the use of alternate fuels in general aviation aircraft with spark ignition engines and to establish reasonable certification criteria. The study is composed of (1) a literature search on the use of alcohol fuels and gasohols, and (2) ground-based testing using an aircraft piston engine with an aircraft fuel system. A number of fuels were tested during the ground-based tests including alcohols blended with gasolines, straight ethanol, straight methanol, unleaded racing gasoline, and methyl-tertiary-butyl ether (MTBE).

An analysis of the literature search identified a number of problem areas. Key concerns are material compatibility, oil compatibility, engine and exhaust component corrosion, volumetric fuel efficiency (i.e., miles per gallon), hard starting, and water solubility. Solutions to many of these problems are identified in the literature, primarily as a consequence of research done by the automobile industry.

The dynamometer portion of this study identified the worst case conditions for vapor lock (i.e., the most likely to result in vapor lock). For gasolines containing alcohols, an alcohol concentration of 15 percent (regardless of alcohol type) takeoff power setting and an initial fuel temperature of 35 to 38 degrees Celsius (95 to 100 degrees Fahrenheit) is the worst case. For fuels which are primarily made of one constituent (e.g., alcohols or MTBE), the worst case for vapor lock is a fuel temperature just below the boiling point of the principal constituent and takeoff power setting. The vapor lock behavior of the gasolines containing alcohols was substantially worse than the vapor lock behavior of unleaded gasolines with the same Reid Vapor Pressure.

The conditions most likely to result in detonation are takeoff power setting, high ambient temperatures, and near stoichiometric fuel-to-air ratios. The detonation that was observed with methanol was particularly severe, and it was probably related to the auto ignition temperature of methanol. Detonation was also observed when switching from a fuel which had a higher energy density (BTU per pound mass (lbm)) than the straight alcohol fuel being tested. With the exception of methanol, the motor octane number was indicative of the probability of incurring detonation in the test engine.

Water/alcohol phase separation was observed during the ground-based tests when using gasolines containing alcohols. This problem was much more severe than indicated by the literature. The amount of phase separation could result in engine stoppage if the fuel system is not redesigned.

A number of material compatibility problems were encountered during the ground-based tests. In general, straight methanol caused the most problems, but problems were observed with all the fuels tested except the racing gasoline. The one problem observed when using MTBE may have been induced by the previous use of methanol.

The use of methanol resulted in an oil compatibility problem when operating the test engine under cool ambient conditions, and the use of methanol generally resulted in more contaminants in the oil. In addition, the fuels containing alcohols do not mix readily with aviation gasoline. This caused periods of rough operation when switching from one fuel to the other.

Up to 15 percent gasoline was added to neat alcohol fuels. This improved cold starting behavior and engine smoothness, though cold starts with methanol still required the use of preheat when the ambient temperature was below 8 degrees Celsius (46 degrees Fahrenheit). Gasoline also acts as a denaturing agent and it should render the flame luminous under most circumstances. Small amounts of denaturing agents did not adversely affect the vapor lock behavior of the fuels.

The oil sump and valve covers were removed when changing from the fuel injected system to the carbureted system and there was no evidence of sludge, varnish buildup, or corrosion.

Attempts to improve the fuel consumption when operating on straight alcohol fuels did result in minor improvements, but these were at the expense of the power developed.

The unleaded racing gasoline appears to behave in a manner similar to unleaded automobile gasoline, and it may be an alternate fuel that can be used in the 91/96 octane engines already in use. MTBE appears to be a viable candidate as a substitute for aviation gasoline if minor modifications are made to the fuel system to compensate for the difference in energy density.

# INTRODUCTION

With the advent of Supplemental Type Certificates (STC) which allow the use of automobile gasoline (autogas) in general aviation aircraft, questions concerning alternative fuels for general aviation aircraft have increased. Possible fuels for the immediate future include gasolines containing alcohols and alcohol fuels. For example, a group of investors have obtained an STC which permits the use of methanol in a Piper Super Cub. The Federal Aviation Administration conducted this study to identify the potential problem areas associated with fuels containing alcohols and to identify the potential benefits associated with using such fuels.

One part of this study consisted of a literature search which reviewed a number of reports dealing with alcohol fuels, gasohols, and material compatibility. The other part consisted of engine tests using a dynamometer, an aircraft fuel system, and an automatic data acquisition system. These tests were designed to investigate several areas where there was no information available, such as the effect of alcohol on the vapor lock behavior of the fuel.

On a time-permitting basis, other fuels were evaluated for their vapor lock and detonation behavior. One such fuel was a commercially available racing gasoline and the other was methyl-tertiary-butyl ether (MTBE), an octane booster used in premium unleaded gasolines.

The results of this work are summarized in this report, and they are presented for use in developing certification standards should these fuels be considered for use in an aircraft.

## BACKGROUND.

The following summaries will provide some information on the significance of the laboratory tests which are used as part of a fuel's specification, and a general description of fuels tested. This information will be useful in interpreting the remainder of this report, though it is not essential.

Much of the information that is contained in the following summaries can be found in the references listed at the end of the report. The bulk of these references were generated by the automobile industry in response to the demands created by the emission and fuel economy standards.

Several notes of interest: The word "gasohol" is a registered trademark of the University of Nebraska Agricultural Products Industrial Utilization Committee that applies to blends of 10 percent anhydrous ethanol in unleaded gasoline. In everyday usage, gasohol has come to mean a blend of any alcohol in gasoline. Throughout this report, gasohol will refer only to 10 percent anhydrous ethanol in unleaded gasoline; the term alcohol blends will mean any mixture of alcohol in gasoline. Cosolvents are those materials which when combined with a substance that is to be dissolved into another increases the solubility of that substance. Also, a neat fuel or a neat alcohol is one which does not contain any special additives or blending agents.

REID VAPOR PRESSURE, FLASH POINT, AND DISTILLATION TESTS. The Reid Vapor Pressure (RVP) is a measurement of the volatility of a fuel. Fuels with a high RVP will have good cold-starting behavior, but will be more prone to vapor

locking when ambient and fuel temperatures are high. In addition, a high volatility fuel will adversely affect the evaporative emissions from the fuel system, thus increasing the demands on the vent system.

The flash point of a fuel is the temperature at which sufficient vapors are released to result in a fire, if an ignition source is present. The higher the flash point, the less likely random sparks from a fuel system will result in a fire. Gasolines have a flash point well below the freezing point of water. This implies a flammable mixture could exist in the fuel tanks whenever gasoline is used. In general, gasoline gives off so much vapor the mixtures in the ullage space are too rich to support combustion. When using neat alcohols, the flash point becomes significant since there will be a flammable mixture in the ullage space of a tank at most ambient temperatures.

The distillation test is a rough measure of the constituents found in the fuel. The broader the range of temperatures measured during the distillation, the greater the number of components found in the fuel. A large percentage of constituents with low boiling temperatures will result in a high volatility fuel. If there is a large percentage of high molecular weight and high boiling point components in the fuel, the viscosity may be too great for use in an engine, the formation of gums and waxy deposits might be a problem, and all the fuel may not vaporize. Any of the above will result in poor combustion characteristics. The typical distillation curve of aviation gasoline (avgas) is relatively flat as compared to autogas, reflecting the more selective nature of the refining process used to make avgas.

The initial boiling point (IBP) of the fuel is determined during the distillation process, and it is the temperature of the gases above the liquid in the distillation flask when the first drop falls from the condenser. The temperature of the liquid in the flask is typically 10 to 15 degrees Celsius hotter than the gases above it. The end point is the temperature of the gasses above the liquid in the distillation flask when the residue begins to decompose. Once again, this is not the temperature of the liquid in the flask.

The American Society for Testing and Materials (ASTM) procedures and equipment requirements for the RVP and distillation tests are outlined in standards D323 and D86, respectively. The flash point can be determined using a number of different ASTM test procedures, depending on the material being tested and the ultimate use. ASTM D56 is being used at the Technical Center to determine the flash point of the test fuels.

OCTANE RATINGS AND PERFORMANCE INDEX. There are four octane rating techniques outlined by the ASTM. These are the research octane number (RON), the motor octane number (MON), the aviation lean octane number, and the aviation supercharge (rich) octane number. The aviation lean number and the MON are related to one another, and the test equipment and procedures are outlined in ASTM Standard D2700. The RON is determined in accordance with ASTM Standard D2699 and the aviation supercharge test is described in ASTM Standard D909.

The RON is a measure of the performance of a fuel under a light duty cycle, such as stop and go traffic in urban conditions where the rate of acceleration is slow and intermittent. The MON has more significance if the fuel is to be used under moderate to heavy conditions, such as long periods of operation at high speeds.

Likewise, the aviation lean rating is applicable when the engine and fuel are subjected to the heavy duty cycles commonly found in the aviation environment. The aviation supercharge rating is applicable when operating conditions are severe and the mixture is kept rich to help suppress detonation.

A number of factors can affect the detonation performance of a fuel in the engine. High operating temperatures and pressures increase the chance of encountering detonation. All of the following design parameters influence the working pressures and temperatures: throttle position, engine speed, ignition timing, valve timing, engine cooling, the compression ratio, and turbocharging. These factors also influence the efficiency of the engine as well, and in general, the greater the efficiency the greater the chance of detonation occurring. Changes in engine condition over time and ambient conditions also affect the onset of detonation and are considered when developing the original design.

The octane of the intended fuel strongly affects the design of the engine. Fuels with a high octane rating will operate under conditions which would result in detonation if a fuel with a lower octane rating is used. Thus, a fuel which is more expensive but has a high octane rating may result in more economical operation as the engine's efficiency is improved. In an aircraft, where weight and cooling drag are important considerations, a high efficiency engine is extremely desirable.

The performance or antiknock index is the average of the RON and MON for that particular fuel. This is the number associated with regular or premium autogas; regular unleaded typically has a performance index of 87 and premium unleaded typically has a performance index of 91.5. The sensitivity is the difference between the RON and the MON and it usually lies in the range of 6 to 10 points. For example, a fuel whose RON is 91 and whose MON is 83 has a performance index of 87 and a sensitivity of 8.

THE NATURE OF GASOLINES: LEADED AND UNLEADED. Gasolines are blends of hydrocarbons that are primarily derived from petroleum by distillation and catalytic treatment. They are the principal source of energy for a broad spectrum of motorized vehicles that use spark ignition engines. The features which make gasolines so desirable are a high energy density and a relatively low cost. In addition, experience in handling and transporting gasolines has resulted in gasoline being a relatively safe fuel despite the inherent danger associated with its use.

The classes of gasoline which are of interest in this study are the unleaded automobile gasolines and the leaded aviation gasolines. The ASTM has published and continuously updates the standards for both types of fuel: autogas specifications are outlined in ASTM standard D439 and avgas specifications are outlined in ASTM standard D910. Table 1 gives brief summary of the differences between the various gasolines.

The octane rating of a gasoline can be affected by a number of different parameters. The base petroleum and the refining procedures are important inputs over which there is limited control so the octane is modified by blending with other fractions or by adding an octane enhancer. Tetraethyl lead (TEL) has been used extensively as an octane enhancer but its use in autogas is currently being phased out. When TEL is used as an octane booster, ethylene-di-bromide is added

TABLE 1. PHYSICAL PROPERTIES OF GASOLINES

| Properties | Unleaded Autogas | 100 LL Avgas | 100 Octane Avgas | 80 Octane Avgas |
|---|---|---|---|---|
| Specific Gravity (15.6°C) | 0.749 | 0.72 | 0.7165 | 0.72 |
| Color | (1) | Blue | Green | Red |
| Heat of Combustion (kJ/kg) | 43,960 | 43,100 | 43,800 | 43,800 |
| Lead Content (mL TEL) | 0 | 2 | 4 | 0.5 |
| Latent heat of Vaporization (kJ/kg approx.) | 350 | 350 | 350 | 350 |
| Distillation (maximum, degrees C) | | | | |
| IBP | 25/35(2) | 43 | 48 | 49 |
| 10% | 50/70 | 75 | 75 | 75 |
| 40% | N/A | 75 | 75 | 75 |
| 50% | 110/121 | 105 | 105 | 105 |
| 90% | 185/190 | 135 | 135 | 135 |
| EP | 225 | 170 | 170 | 170 |
| (3) | N/A | 135 | 135 | 135 |
| RVP (psi) | 15 (max)(4) | 7 (max)<br>5.5 (min) | 7 (max)<br>5.5 (min) | 7 (max)<br>5.5 (min) |
| Octane Rating | | | | |
| Lean | N/A | 100 | 100 | 80 |
| Rich | N/A | 130 | 130 | 87 |
| Performance Index(5) | | | | |
| regular | 87 | N/A | N/A | N/A |
| premium | 90 | N/A | N/A | N/A |

(1) The color depends on the refiner; most often, red is a premium unleaded, straw is leaded, and clear is regular, unleaded.
(2) The values given are the maximum permissible for winter/summer grade fuels.
(3) The minimum value for the sum of temperatures at 10 and 50 percent evaporated is listed.
(4) The RVP for autogas is adjusted seasonally and by region.
(5) The performance index is adjusted for elevation and weather. The values listed are typical of those listed for normal duty cycles in hot weather.

to remove the lead salts that are a product of combustion of the TEL. In aviation gasoline, the proportions of TEL and ethylene-di-bromide are carefully controlled to insure the corrosive side effects of ethylene-di-bromide are kept to a minimum. As TEL is being phased out of autogas, MTBE is coming into use as an octane enhancer. MTBE has good octane blending values which vary, depending on the base fuel and concentration, from 115 to 135 for the RON and 98 to 110 for the MON. (The blending value is the apparent octane rating of the additive when the new octane rating is computed in a linear proportion from the base fuel's octane and the additive's blending value. For example, a base fuel has an octane rating of 78 and the additive has a blending value of 108. They are blended so that the resultant fuel is 90 percent base fuel and 10 percent additive. The resulting blend will be 0.9[78] + 0.1[108] or 81 octane.)

The RVP of autogas is varied according to season and location in an attempt to balance the good cold start behavior of high RVP fuels with the threat of vapor lock during the summer. Avgas has a fixed RVP primarily because an aircraft can go from hot to cold ambient conditions in one flight and because of the reduced atmospheric pressure at altitude. Cold starting in aircraft is enhanced by using a primer to supply fuel in cold weather.

The range of distillation temperatures for avgas is narrower than the range of acceptable temperatures for autogas. The elimination of low boiling point constituents reduces the vapor pressure, and the restriction against the high boiling point constituents increases the stability of the fuel and insures against the fuel freezing at altitude.

Sour fuels result when gasolines are exposed to high temperatures in conjunction with oxygen. Conditions which might result in sour fuels are long-term storage at high temperatures or recirculation through a boost pump with entrained air. The formation of sour fuels is accelerated by dissolved ions, such as copper, and by high concentrations of nitrogen compounds like those found in shale-oil derivatives. Sour fuels contain relatively high concentrations of hydroperoxides which are unstable and highly reactive with many of the components found in fuel systems. They are of interest to this study in that many of the materials which are affected by sour fuels are also affected by alcohols and alcohol blends.

THE NATURE OF METHANOL. Methanol, or methyl alcohol, consists of a carbon atom, four hydrogen atoms, and an oxygen atom ($CH_3OH$), and it is commonly referred to as wood alcohol. It is an odorless and colorless liquid whose physical properties are listed in table 2. Methanol is a highly polar molecule and as such it has a high affinity for water. It is soluble in gasoline but this solubility is affected by temperature and the presence of water.

Methanol can be produced from a number of raw materials, such as natural gas and coal, of which the United States has an ample supply. On a volumetric or weight basis, methanol is less expensive than gasoline, but on an energy basis it is more expensive than gasoline.

Neat methanol has relatively high octane ratings (112 RON and 91 MON), and when blended with gasoline, it increases the octane rating of the fuel. The blending value of methanol ranges from 115 to 150 for the RON and 89 to 120 for the MON, depending on the original composition of the fuel. These high octane ratings will allow fuels to be blended to a desired octane value without using

TEL or other more expensive blending agents. Conversely, the high octane ratings will allow for higher compression ratios which will improve the efficiency of the engine.

TABLE 2. PHYSICAL PROPERTIES OF ALCOHOLS AND MTBE

| Properties | Methanol | Ethanol | TBA | MTBE |
|---|---|---|---|---|
| Specific Gravity (20°C) | 0.796 | 0.7893 | 0.7887 | 0.7405 |
| Heat of Combustion (kJ/kg) | 22,670 | 29,710 | 35,560 | 36,010 |
| Latent Heat of Vaporization (kJ/kg) | 1,173 | 880 | 588 | 310 |
| Boiling Point (°C) | 64 | 78 | 82 | 55 |
| Melting Point (°C) | -98 | -117 | 27 | -108 |
| Octane Rating | | | | |
| Motor | 91 | 89 | N/A | 98 |
| Research | 112 | 106 | N/A | 116 |
| Blending Octane | | | | |
| Motor | 89 to 120 | 89 to 113 | - | 98 to 110 |
| R+M/2 | - | - | 108 | - |
| Research | 115 to 150 | 106 to 136 | - | 115 to 135 |
| RVP (psi) | 4.6 | 2.5 | 3.4 | 7.8 |
| Flash Point (°C) | 11 | 13 | 11 | -25.6 |

Methanol has relatively broad flammability limits (from approximately 50 percent of stoichiometric on the lean side to 410 percent on the rich side) when compared with gasoline. This means that extremely lean mixtures of methanol can be burned in the aircraft resulting in improved fuel efficiency. When this is combined with the high octane rating, it is then conceivable to have very good energy efficiencies.

There are a number of problems associated with the use of methanol as a motor fuel. It is mutually miscible with water, and there is no generally available technique for determining the water content of a given sample of methanol. Methanol is toxic to humans; and it can be absorbed into the bloodstream through the skin, by ingestion, or by breathing its vapors. Once absorbed, it leads to nerve damage and heavy dosages can be fatal. The flame associated with methanol has a low luminous intensity and is difficult to detect in most situations. The environmental impact of large spills would be quite severe, given methanol's affinity for water. The energy density is less than gasoline on either a

volumetric or mass basis; this implies a larger percentage of the usable load will be devoted to carrying the fuel needed for the particular trip.

THE NATURE OF ETHANOL. Ethanol, or ethyl alcohol, consists of two carbon atoms bonded to five hydrogen atoms and an hydroxyl group ($C_2H_5OH$) and is commonly known as grain or drinking alcohol. Like methanol, ethanol is a colorless, odorless liquid and, like methanol, it is a polar molecule which attracts water. For most conditions, it is completely soluble in gasoline. The physical properties of ethanol are listed in table 2.

The principle source of ethanol is the fermentation of agricultural products. While this makes ethanol a renewable resource, it is unlikely that it can be produced in sufficient quantities to replace all of the petroleum products used in transportation (reference 1). This implies that it will be primarily used as a blending agent, petroleum extender, or as a specialty fuel. Currently, untaxed ethanol is more expensive than gasoline.

The blending values for ethanol range from 106 to 136 for the RON and 89 to 113 for the MON. This makes it a relatively good blending agent and it can be used to boost the octane of a gasoline blend, though it is not as effective as methanol in this aspect. The RON and MON of neat ethanol is 106 and 89, respectively.

The flammability limits of ethanol are fairly broad ranging from about 50 percent on the lean side to 330 percent on the rich side of stoichiometric. As with methanol, this means ethanol can be burned in the engine at very lean mixtures, improving the energy efficiency of the fuel.

There are problems with ethanol just as there are problems with using methanol as a motor fuel. It is mutually miscible with water and the actual concentration is difficult to determine accurately. There is the danger of persons intentionally ingesting ethanol intended for use as a motor fuel without considering the differences between liquor (a dilute solution of ethanol in water) and neat ethanol. Large spills may create local environmental problems where the concentration of ethanol is toxic to wildlife. Disposal of the byproducts of fermentation may present additional environmental problems. The flame from an ethanol fire has a low luminous intensity and it may not be visible in daylight conditions. This would make firefighting difficult in case of a spill. The energy density of ethanol is less than gasoline, so greater quantities of ethanol would need to be carried in the aircraft to fulfill flight requirements.

THE NATURE OF TBA, ISOPROPYL, AND HIGHER ORDER ALCOHOLS. TBA, or tertiary-butyl alcohol, is a four-carbon alcohol that is used as a cosolvent for methanol. The physical properties are listed in table 2 along with those of ethanol, methanol, and isopropyl alcohol. Isopropyl or rubbing alcohol is a three-carbon alcohol with the hydroxyl group bonded to the middle of the three carbon atoms. Like TBA, it is used as a cosolvent for methanol and may itself be used as a blending agent for gasolines. The higher order alcohols are those that have greater than four carbon atoms in their structure. They, too, may be used as cosolvents or be incorporated in alcohol blends since they are byproducts of the manufacture of the intended cosolvent.

In general, the greater the number of carbon atoms, the better an alcohol will dissolve into gasoline and the less likely the addition of water will result in phase separation. The greater the number of carbon atoms, the lower the octane blending value associated with that alcohol.

THE NATURE OF MTBE. Methyl-tertiary-butyl ether is a high octane blending agent which has come into general use as the level of TEL found in gasolines is being reduced. MTBE is manufactured from methanol, butenes, and butanes containing isobutenes; and it does not have any of the water sensitivity problems associated with alcohol fuels (reference 2). In general, MTBE behaves like a gasoline in that it is relatively volatile, and it is generally compatible with all the materials that are compatible with gasolines. MTBE is also very lead sensitive in that the addition of small amounts of TEL boosts the octane significantly. As an example, the addition of one gram of TEL increases the MON from about 100 to 115.6 (reference 3). This implies that engines with very high compression ratios can be designed to operate on MTBE, resulting in very good thermodynamic efficiencies. MTBE does have a distinctive bittersweet odor, however, and breathing its vapors will result in a headache after extended exposure. Other significant properties of MTBE are found in table 2.

Since MTBE has such a high octane value and it is manufactured from methanol and other light hydrocarbons (which are in relative abundance or can be manufactured from coal), it represents a middle ground in the field of alternative fuels. The energy density and cost lie between gasolines and alcohol fuels, and it is compatible with many of the existing aircraft fuel system components. For these reasons, MTBE was selected as a potential alternate fuel for general aviation aircraft, and including it in the data base broadened the applicability of the results.

## TEST APPARATUS

The majority of the testing was conducted at the FAA Technical Center at Atlantic City International Airport, NJ. The Technical Center Engine Test Facility was used to conduct the dynamometer tests and the fuel samples were tested in the Technical Center Fuel Laboratory. The octane measurements were conducted by Sun Refining and Marketing, Marcus Hook, Pennsylvania. The oil analyses were conducted by Spectro/Metrics Inc., Atlanta, Georgia.

With the exception of the Reid Vapor Pressure (RVP) test, the test apparatus used in a standardized ASTM test was that described in the ASTM procedures. Below is a description of the modifications the Technical Center made to the RVP apparatus followed by a brief description of the dynamometer installation used to conduct the engine tests.

MODIFIED REID VAPOR PRESSURE TEST.

The RVP apparatus consists of a hot water bath and three bombs. Each bomb consists of a gas chamber, an air chamber, and a pressure gauge (figure 1).

During the early stages of testing with alcohol blends, the Technical Center experienced problems with the Bourdon tubes being obstructed by a water/alcohol mixture which was separating from the alcohol blend. Conversations with personnel at the National Institute of Petroleum and Energy Research (NIPER)

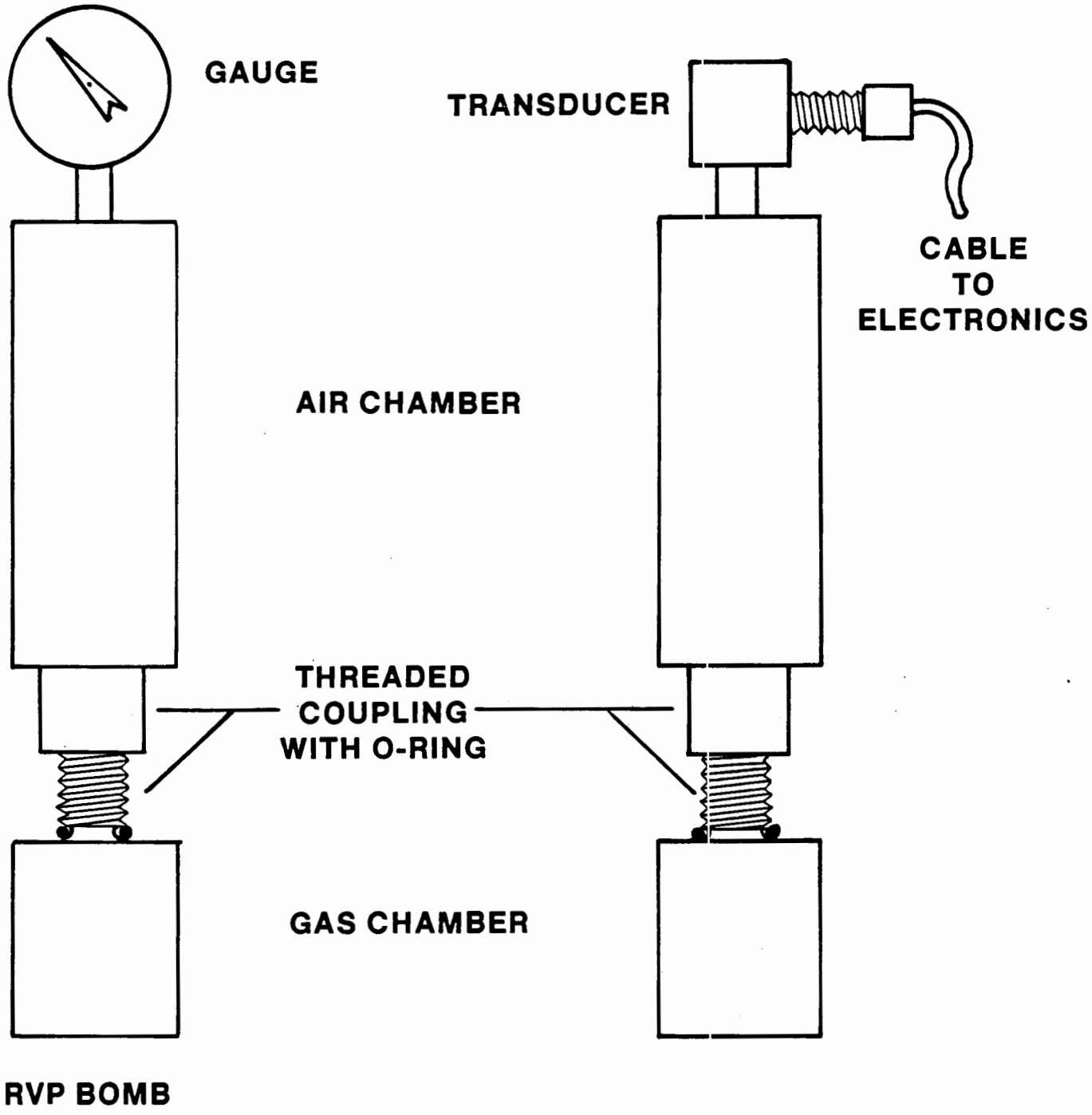



FIGURE 1. REID VAPOR PRESSURE BOMB WITH MODIFICATION

indicated there were two solutions to this problem. The first was to conduct a dry RVP test, whereby the air chamber is heated in the bath with an empty gas chamber attached. This prevents water from entering the air chamber and, in turn, prevents the phase separation noted above. This also distorts the results since the results will no longer include the partial pressure of the water. The second course of action called for replacing the pressure gauge on the bomb with a pressure transducer. Since the transducer would not have the fine openings found in the pressure gauge, the phase separation should not affect the readings. Both of these modification were deviations from the original ASTM D323 specifications, so the results could not be reported as an RVP but rather as an equivalent RVP (ERVP). The Technical Center felt the effect of running a dry RVP would be greater than the effect of replacing the gauge with a transducer.

The RVP apparatus was modified by securing pressure transducers onto the gas chamber, with special attention paid to keeping the internal volume of the assembly the same as with the gauges. The transducers were attached to the electronics needed to calibrate the transducers and to display the reading in engineering units via a wiring harness with a quick disconnect at the transducer itself. This allowed for agitating the bomb without being restricted by the cable. In practice, the cables did not restrict the ability to agitate the bombs and they were left on throughout the duration of the test.

Following modification of the apparatus, three samples of gasoline were tested using both the gauges and the transducers. The difference between the results were within 0.2 pound per square inch gauge (psig) for all three samples as can be seen in table 3. Periodic checks throughout the program confirmed these results.

TABLE 3. REID VAPOR PRESSURE VERSUS EQUIVALENT REID VAPOR PRESSURE

| FUEL IDENTIFICATION | RVP (psig) | ERVP (psig) |
|---|---|---|
| Avgas | 6.5 | 6.6 |
| Autogas | 12.8 | 12.8 |
| Gasohol (10 percent ethanol) | 11.6 | 11.8 |

DYNAMOMETER INSTALLATION.

The Technical Center's dynamometer is an eddy current design with an absorption capacity of 500 horsepower (hp) and a maximum speed of 5,000 revolutions per minute (rpm). A Lycoming O-320 is coupled to the dynamometer. This engine has a compression ratio of 8.5 to 1, and it was operated using both a carburetor and a fuel injection system. Fuel was provided to the engine through a Cessna 172 (C-172) fuel system which was installed in the same relative position as found in the aircraft. The fuel tanks were modified by installing heat exchangers in each tank, and the fuel lines were wrapped with resistance heaters. The selector valve was adapted to a pneumatic actuator which was remotely controlled. Typically, a cool fuel used for recovery from vapor lock was in the left-hand tank and the heated test fuel was in the right-hand tank.

The electronic controls allow the operator to vary either the engine load or engine speed as well as the other parameters listed in table 4. There are separate controls for each side of the fuel system. An important note: the line temperature which is reported is the temperature of the fuel in the line, whereas, the controller maintains the temperature of the outside wall of the fuel line. The difference between these two parameters is a function of the heat transfer characteristics of the line and the fuel flow rate.

TABLE 4. LIST OF CONTROLLED PARAMETERS

| Controlled parameter | Units |
|---|---|
| Engine Speed | RPM |
| or Engine Load | ft-lbf |
| Throttle Position | percent or inHg |
| Mixture Position | percent |
| Cooling Air Pressure | $inH_2O$ |
| Cooling Air Temperature | degrees Celsius/Fahrenheit |
| Combustion Air Temperature | degrees Celsius/Fahrenheit |
| Combustion Air Humidity | percent |
| Oil Temperature | degrees Celsius/Fahrenheit |
| Fuel Temperature, Tank | degrees Celsius/Fahrenheit |
| Fuel Line Temperature | degrees Celsius/Fahrenheit |
| Tank in Use | dimensionless |

The data are recorded by an automatic data acquisition system at a scan rate of from one to 60 scans per minute depending of the test conditions. The parameters which are recorded every scan are listed in table 5.

Any test specific change to the dynamometer installation will be discussed in the Summary of Results.

GAS CHEK KIT.

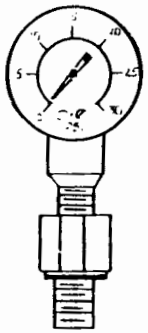
The apparatus provided with the Gas Chek Kit for determining the RVP (GCK is used throughout this report to designate a RVP which is measured with the Gas Chek Kit) is as follows: a tubular stem with internal threads for the gauge, a 0 to 30 psig gauge with a male threaded adaptor for securing to the tubular stem, a 0 to 220 degrees Fahrenheit thermometer, and an insulated cup with a cover that has the appropriate holes for holding the tubular stem and thermometer in place. An eyedropper, a graduated cylinder, and a syphoning tube are also supplied for transferring the sample from the tank to the tubular stem. Figure 2 depicts the apparatus supplied with the Gas Chek Kit.

TABLE 5. DATA RECORDED ON THE DATA ACQUISITION SYSTEM

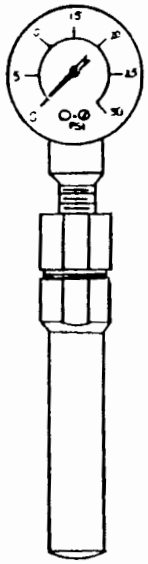
| DESCRIPTION | UNITS |
|---|---|
| Engine torque | ft-lbf |
| Engine speed | RPM |
| Manifold pressure | inHg (absolute) |
| Engine cooling air pressure | in $H_2O$ |
| Fuel pressure at carburetor inlet | in $H_2O$ or psig |
| Oil pressure | psig |
| Event marker, operator triggered | VDC |
| Fuel flow | gph |
| Throttle position | percent |
| Mixture position | percent |
| Tank in use indicator | VDC |
| Carburetor supply air dew point | degC |
| #1 cylinder head temperature | degC |
| #2 cylinder head temperature | degC |
| #3 cylinder head temperature | degC |
| #4 cylinder head temperature | degC |
| Fuel temperature, top of avgas tank | degC |
| Fuel temperature, bottom of avgas tank | degC |
| Fuel temperature, top of autogas tank | degC |
| Fuel temperature, bottom of autogas tank | degC |
| Fuel temperature, avgas line | degC |
| Fuel temperature, autogas line | degC |
| Fuel temperature, sediment bowl | degC |
| Fuel temperature, carburetor bowl | degC |
| Oil temperature | degC |
| Air temperature, carburetor inlet | degC |
| Air temperature, upstream of carburetor | degC |
| Cooling air temperature | degC |
| Air temperature in carburetor area | degC |
| Carburetor supply air temperature | degC |
| #1 exhaust gas temperature | degC |
| #2 exhaust gas temperature | degC |
| #3 exhaust gas temperature | degC |
| #4 exhaust gas temperature | degC |
| Ambient air temperature | degC |
| Engine driven fuel pump pressure | psig |

NOTE: NOT DRAWN TO SCALE

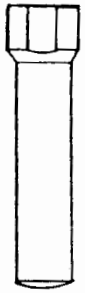
GAUGE UNIT

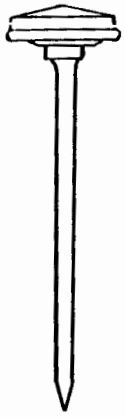


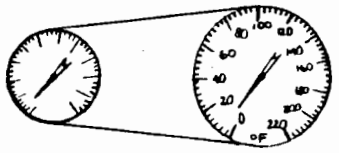
GAUGE HEAD



TUBULAR STEM

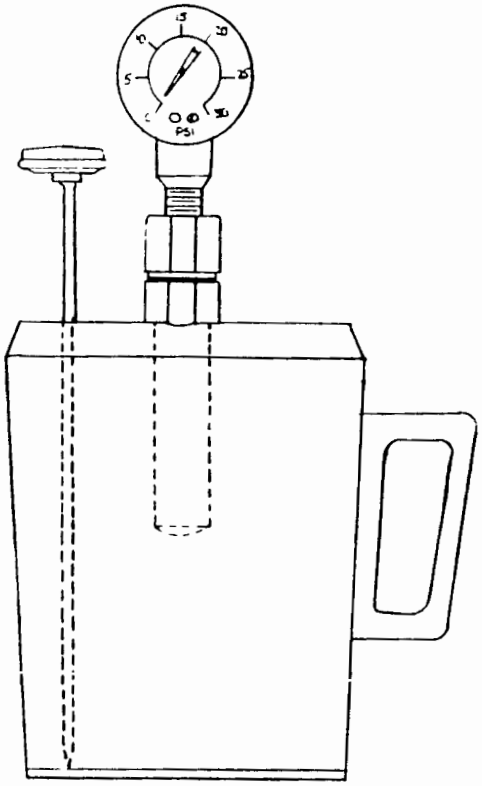






THERMOMETER

ENTIRE UNIT



NOTE: NOT DRAWN TO SCALE

FIGURE 2. RVP APPARATUS PROVIDED WITH THE GAS CHEK KIT

## TEST PROCEDURES

With the exception of the modified Reid Vapor Pressure test, the procedures outlined in the appropriate ASTM standards were followed. The oil sampling procedures were those outlined by Spectro/Metrics Inc.

MODIFIED REID VAPOR PRESSURE TEST.

The Reid Vapor Pressure tests were modified to incorporate the following steps:

Turn on the transducer electronics when the bath heater is turned on. After the bath has reached 100 degrees Fahrenheit, insert the air chambers and allow them to equilibrate to the bath temperature. Remove the air chamber from the bath and set it in a vertical position. Set the zero if necessary. Depress the calibration switch and adjust the calibration reading if necessary. Return the air chamber to the bath and note the slight increase in pressure is indicated. Continue the tests per ASTM D323.

DYNAMOMETER TESTS.

The start procedure was the same for all the runs using the dynamometer. The engine would be started with the dynamometer set to zero load and with the throttle opened slightly. Once the engine was operating, the dynamometer would be switched to the speed control mode and the throttle adjusted accordingly. After allowing the oil to reach approximately 40 degrees Celsius the engine speed was adjusted to 1800 rpm and a magneto check was conducted. If all operations up to this point were acceptable, the run was conducted according to one of the following test procedures: (Whenever these procedures were modified to obtain a specific piece of information, the changes will be discussed in the Summary of Results.)

1. Baseline Tests. Following any major modification to the engine, a baseline run was conducted. These runs consisted of selecting an engine speed and varying the manifold pressure in even increments until full throttle was reached. The engine speed was then increased and the manifold pressured varied (as above) until takeoff power was attained. This test was conducted with the mixture control set to the full rich setting.

When testing with the neat alcohol fuels, the carburetor jets were drilled to increase the fuel flow and the timing was varied to optimize the engine performance. After each of these modifications, a quick performance check was conducted. These tests consisted of setting the engine at takeoff power and recording the power developed. The engine speed and manifold pressure were then adjusted per the list of power settings contained in table 6.

TABLE 6. POWER SETTINGS FOR PERFORMANCE CHECKS

| | | |
|---|---|---|
| 2600 RPM | 27 inHg | Mixture Full Rich |
| 2500 RPM | 25 inHg | Mixture Full Rich |
| 2400 RPM | 24 inHg | Mixture Full Rich |
| 2300 RPM | 23 inHg | Mixture Full Rich |
| 2300 RPM | 23 inHg | Leaned to Peak EGT |
| 2300 RPM | 23 inHg | Leaned to Limit |
| 2200 RPM | 22 inHg | Mixture Full Rich |
| 2100 RPM | 21 inHg | Mixture Full Rich |
| 2000 RPM | 20 inHg | Mixture Full Rich |

The mixture control was varied at the 2300 rpm setting to determine if the jets were large enough to result in a mixture that was richer than stoichiometric and to determine how much the fuel flow could be reduced and maintain stable operations (i.e., lean the mixture until misfire occurs then enrichen the mixture until no misfire is detected.)

At the conclusion of the power optimization sequence for each test fuel, the vapor lock and endurance runs were conducted.

2. Vapor Lock Tests. To determine the vapor lock behavior of a test fuel, the following steps were taken:

Prior to starting the engine, the test fuel tank was drained and filled with the test fuel, and a recovery fuel was placed in the left tank. A sample of the test fuel is drawn from the tank if necessary. The tank heaters were turned on, and the temperature of the fuel in the test fuel tank was raised to the desired temperature. The engine was then started on the recovery fuel.

As the engine warmed, the cowling temperature and pressure were set to 38 degrees Celsius and 2.3 in$H_2O$, respectively. Throughout the run the carburetor inlet temperature was adjusted to maintain 38 degrees Celsius.

Following the magneto check, the fuel flow was set to the lowest idle condition that was stable. The test fuel tank was selected and the instrumentation was monitored for any changes that occurred while operating on the test fuel. If vapor lock did not occur within 5 minutes, the line heaters were turned to a setting of 150, simulating an environment where the lines were exposed to hot engine cooling air. As before, the instrumentation was monitored for any changes. If vapor lock did not occur within 5 minutes, the line heaters were turned to a setting of 250. When vapor lock occurred, as indicated by a decay in engine performance (or if the engine operated for at least 5 minutes with the line heaters set on 250), the recovery fuel was selected and the line heaters were turned off.

The engine speed and throttle were adjusted so that the fuel flow increased in steps of 2.5 gallons per hour (gph) until takeoff power was reached, and the above sequence was repeated for each fuel flow. Following shutdown, a sample of the test fuel was taken and the Reid Vapor Pressure was measured.

3. Endurance Tests. These tests were conducted to accumulate the minimum number of hours needed for an oil analysis to be conducted.

Following the normal start and warmup sequence, the engine was set at the takeoff power setting. This setting was maintained for a minimum of 5 minutes to simulate a climb to altitude. The engine speed and manifold pressure were reduced to a setting which resulted in between 50 and 75 percent power. The mixture would then be set at either best power, best economy, or at the lean limit. All conditions would be maintained for a minimum of 30 minutes and up to 3 hours to simulate the cruise portion of a flight. The power was then reduced to an intermediate setting for a period of time and then reduced to idle to simulate the descent and landing.

GAS CHEK KIT.

The procedure described below is the one provided with the Gas Chek Kit for determining the RVP.

1. Fill the insulated cup to 3/4 full with hot water (greater than 160 degrees Fahrenheit) and place the cover on the cup.

2. Insert the thermometer on the small hole in the cup cover and allow the temperature to drop to about 160 degrees Fahrenheit while performing steps 3 through 5.

3. Obtain a sample of gasoline. (Note: gasoline which has been in a hot area will not give a true result.)

4. Put 3 mL of gasoline into the aluminum tubular stem.

5. Screw the gauge head onto the tubular stem, hand tight.

6. With the water temperature at 160 degrees Fahrenheit place the gauge/stem assembly into the large hole in the cup cover, allowing the aluminum stem to sink full depth into the hot water. The temperature will quickly drop to 155 degrees Fahrenheit and then resume a slow drop.

7. When the water temperature is 150 degrees Fahrenheit, record the gauge pressure reading. This is the equivalent Reid Vapor Pressure reported as GCK.

## SUMMARY OF RESULTS

LITERATURE SEARCH.

The literature search encompassed most of the technical data that were published in the past 13 years. Much of the work in the area of alcohol blends and neat alcohol fuels has been done by the automobile industry and through grants from the Department of Energy (DOE). While there are few direct applications for the developments in the automobile industry, much of this work can be adapted to general aviation aircraft. Below are the highlights of the literature search grouped into a number of broad areas of interest.

MATERIAL COMPATIBILITY. The material compatibility problems begin with the fuel distribution system. Many of the large underground tanks used for storage are fiberglass laminates, and blends containing methanol will attack the material in these tanks (reference 4). While these changes can be lived with, increased maintenance will drive up the cost of providing methanol blends to the end user. Exposing methanol blends to the fiberglass tanks resulted in an increase in the gum content (references 1 and 4). There were no data which indicated if this change in the gum content was large enough to result in operational problems. The addition of methanol with TBA as a cosolvent to gasolines resulted in increased wear rates in the fuel metering pumps (references 5 and 6). The use of standard filter separators with alcohol blends resulted in relatively high fiber counts. This was apparently due to the deterioration of filter elements (reference 7). This indicates similar problems might be encountered in the aircraft fuel filters. The addition of methanol to gasoline appears to reduce the stability of the fuel, implying the long-term storage of methanol blends would be affected (reference 1).

The reaction of the metals currently found in automobile fuel systems to the alcohol blends and neat alcohols ranges from mild to severe. Work conducted at the Southwest Research Institute showed that corrosion of many of the metals found in the existing fuel systems is accelerated with methanol blends (reference 8). The most severe problems were associated with magnesium followed by brass, bronze, copper, and terneplate. A number of corrosion inhibitors were investigated as a part of that study and none provided significant levels of protection for all metals. Studies conducted by the Union Oil Company, the US Army Mobility Equipment Research and Development Command, and others (references 1, 9, and 10) revealed similar problems with metal corrosion when using methanol blends. These studies indicated aluminum would be attacked by the use of methanol. Likewise, an epoxy which was bonded to some metals delaminated (reference 9), and in the case of aluminum, corrosion between the epoxy layer and the aluminum was reported. The formation of rust deposits between the epoxy layer and the metal was more severe when using methanol, and the plugging of filters was traced to the corrosion of the terneplate (references 1 and 6). Exposure of alcohol blends to salt spray and agitation accelerated the corrosion problems with metals (reference 11), and the addition of water to neat methanol accelerated corrosion (reference 1).

Numerous reports dealt with the behavior of select rubbers, similar to those found in the fuel systems of general aviation aircraft, in alcohol fuels. Many of the rubbers that have been used in general aviation aircraft are attacked by either alcohol blends or sour fuels, and typically, fuel blends made with methanol are worse than those made with ethanol (references 9 through 23). Interestingly, the high aromatic content associated with gasolines made from shale oil and with 100LL avgas results in similar problems with many of the existing rubbers (references 24 and 25). A number of factors aggravate the problem of material compatibility, such as high temperature, dissolved copper ions, splashing as opposed to immersion, and high aromatic content (references 15, 16, 20, and 26). Swelling and reductions in tensile strength were worse when select materials were immersed in alcohol blends than when tested with neat alcohol or straight gasoline (references 20, 21, 22, and 23). The concentration of alcohol in the blend also affects the magnitude of the swell and elongation changes (reference 23).

Some of these reports dealt with attempts to develop new materials that could survive in the automobile environment; i.e., a broad range of operating temperatures, high aromatic content, high hydroperoxide content (sour fuel), ethanol blends, methanol blends, and strict requirements governing seeping through the fuel line (evaporative emissions controls). Changes in the concentration of the various rubber compounds, curing process, and fillers improved the performance of some of the existing rubbers used in the fuel systems (references 9, 12, 14, 15, 17, 18, and 19), and new rubbers which are resistant to attack by alcohols or alcohol blends have been developed (references 8, 17, 18, 23, 27, 28). Other reports investigated manufacturing options to reduce the cost while maintaining the performance of parts made with the new generation of elastomers. Some of the manufacturing options which were identified include veneer construction of hoses and jacketing flexible rubbers with thin layers of more expensive, nonporous, rigid rubbers (references 29 and 30).

Cork gaskets shrink badly when exposed to methanol fuels (reference 1). This could present a problem since cork gaskets are still found in a large percentage of the existing fleet of general aviation aircraft. Likewise, methanol fuels will attack the paints commonly found in aircraft (references 1 and 4); and while this may not be a safety item, it will affect the acceptability of methanol fuels from an esthetic and maintenance standpoint.

The use of MTBE as an octane enhancer for unleaded gasolines did not result in any significant material compatibility problems (references 2 and 13). However, the use of neat MTBE may result in the deterioration of Viton (reference 31).

In summary, the material compatibility problems associated with the use of alcohol fuels or alcohol blends and the materials commonly found in the fuel system of the existing fleet of general aviation aircraft presents a major obstacle to using either neat alcohols or their blends without major modification. Much of this is a consequence of the long life of the typical general aviation aircraft. This has resulted in older aircraft with old technology materials comprising a significant percentage of the total fleet.

ENGINE COMPATIBILITY. Alcohol blends will not only affect the power developed but will affect the durability of the engines. Some of the durability changes are the result of the alcohols becoming dissolved in the engine oil and changes in the composition of the exhaust gases. The magnitude of the changes that were reported vary from insignificant to severe.

In cars that were operated on methanol blends, there was a general trend of reduced emissions, which are regulated by the Environmental Protection Agency (EPA), but the emission of aldehydes and organic acids increased (references 1, 32, 33, 34, and 35). In general the reduced emissions could be traced to the fact that the blends resulted in changes in the fuel-to-air ratio (references 1, 4, and 32). The fuel-to-air ratio is affected not only by the alcohol concentration but by the percentage of dissolved water in the fuel. Too much dissolved water resulted in an increase in emissions (reference 35).

Engine wear and maintenance studies were conducted using fleet, chassis dynamometer, and test cell tests. The fleet and chassis dynamometer tests showed there was generally little difference between alcohol blends and unleaded automobile gasoline (references 5, 7, 8, 33, 36, 37, and 38). These tests might

be misleading since they represent either limited mileage or high mileage accumulation rates, which tend to limit the amount of water condensation in the oil, thus minimizing the corrosion problems that could occur in general aviation aircraft. The types of maintenance problems that did increase during fleet tests were associated with material compatibility, corrosion, and the reduced lubricity of the fuels (references 1, 6, 33, 38 and 39). The test cell tests showed there were significant differences between gasolines and the alcohol blends or neat alcohol fuels. In these tests, severe wear and component failures were reported (references 4 and 34). Many of these problems can be traced to the need for improved oil formulations that are compatible with the alcohol fuels, with methanol resulting in more problems than ethanol (references 1, 4, 34, and 38). The high wear rates and oil dilution problems that were reported were aggravated by cold starts (references 1 and 34). There was some evidence that etching of internal engine components would occur when the oil was scraped away and exposed to the blowby gases and liquid fuel which had not evaporated (references 4, 34). It must be kept in mind that many of the conditions established in the test cell tests were designed to aggravate any problem that might occur with these fuels, and the actual operating experience in an aircraft will probably lie between the experiences reported in the fleet tests and those reported in the test cell tests.

The use of neat alcohols will result in fewer deposits in the combustion chamber. This will reduce the need to design the engines to handle the octane requirement increase usually associated with engines that have been operated for a period of time (references 1 and 4).

ENGINE PERFORMANCE. In general, engines that were designed to operate on gasolines performed satisfactorily on the alcohol blends. Engine operations on neat alcohol fuels were satisfactory only after substantial modification.

The volumetric fuel efficiency (i.e., miles per gallon (mpg)) or brake-specific fuel consumption (BSFC), lbm/hp-hr, typically deteriorated with increasing alcohol concentration (references 1, 4, 6, 32, and 33). There were occasional claims of increased volumetric fuel efficiency with the addition of alcohol to gasoline. This can be tied to either engines which were running rich or operating conditions (such as cold weather operations) which normally result in the engine running rich (references 1 and 4). Typically, the energy (or thermodynamic) efficiency improved with increasing alcohol concentration (references 1, 4, and 32). Much of the improvement in energy efficiency could be traced to operating at leaner fuel-to-air ratios while other were the result of modifications to the engine (references 1 and 4). There were limits to how much alcohol could be added before the energy efficiency declined (reference 1). This could be traced to operations at such lean fuel-to-air ratios that the lean misfire limit was approached.

As a consequence of the lower energy density, the BSFC would be higher for the neat alcohol fuels, but changes to the engine which are made possible by the relatively high octane rating of ethanol and methanol (e.g., increase the compression ratio and change the spark timing) could minimize these effects (references 1, 4, and 38). Operations at very lean fuel-to-air ratios are possible when using neat alcohol fuels, since the lean misfire limit with alcohol fuels occurs at lower fuel-to-air ratios (references 1 and 4), and this could be used to further improve energy efficiency but at the expense of power developed. Overall, improvements in engine design would probably result in an increase in

BSFC of 60 percent as compared to an increase of 120 percent if no engine modifications were performed (reference 1).

Because of the higher octane of the alcohol fuels, and methanol in particular, the power developed per engine displacement can be greater (references 4 and 38). This means the size of the engine can be reduced if methanol were used as the fuel. The lower weight would partially offset the increased fuel load; and the reduced frontal area and cooling requirements (as a consequence of greater thermodynamic efficiency) would result in increased cruise speeds, thus improving the fuel consumption somewhat (references 40 and 41). All these steps to further reduce fuel consumption probably would not result in the same or better volumetric fuel consumption for a given flight profile however.

The water content of the fuel affected the power developed and the exhaust emissions, and it served to further boost the octane ratings of the fuel (references 4, 35, and 36). However, it reduced the energy content of the fuel so the gains in thermodynamic efficiency were offset by increased consumption. The addition of too much water to the fuel reduces the power output.

The power developed is only part of the engine performance envelope. The response to transient conditions and the ease of starting are also important considerations. In general, increasing alcohol concentration results in worse transient response though engines with active fuel controls were not affected as badly as those without active controls (references 1, 4, 6, 32, 33, and 39). Cold starting was made worse with increasing alcohol concentration, and engines which were operated on neat alcohol fuels required additives or a separate fuel for starting the engine (references 1, 4, 6, and 38). The addition of fuel preheaters alleviated some of the transient response problem (references 4, 38, and 39).

To optimize the engine performance with alcohol fuels, the spark timing will need to be changed. This is a consequence of the changes in the ignition delay and flame speed that are associated with alcohol concentration, the compression ratio, and the fuel-to-air ratio (references 1, 4, and 39). It is likely that differences between the optimum timing for takeoff power with fuel-to-air ratios close to stoichiometric will be so different from the optimum timing for cruise conditions at very lean fuel-to-air ratios that the use of the current generation of magnetos with fixed timing will be unacceptable.

MISCELLANEOUS OBSERVATIONS. The addition of an alcohol to gasoline increases the total amount of water that can be dissolved in the fuel. The actual amount of water that can be dissolved will vary with the alcohol concentration, the temperature of the fuel, and the aromatic content (references 1, 4, and 35). Changes in any of these parameters either by the addition of another batch of fuel, by absorption of water from the air, or by changes in ambient conditions may result in large quantities of a water/alcohol solution separating from the fuel (references 1, 6, 7, and 11). Possible solutions to this problem are the addition of relatively large phase separators, the use of anhydrous alcohols, co-solvents, or the use of dual fuel systems (references 1 and 4). As an example of the nature of the phase separation problem, it was reported that exposing gaskets to alcohol fuels resulted in removal of the water from the gaskets and this resulted in phase separation (reference 11). It should be noted that if the alcohol is used to boost the octane of the fuel, any phase separation will lower the octane rating of the balance of the fuel. In an area related to the phase

separation problem, it was reported that water which is suspended in gasohols® would not coalesce when passed through filter separators (reference 7).

Alcohols added to gasoline tend to dissolve the gums that had been deposited in the fuel system (references 1, 4, 9, and 10). This can be a mixed blessing. In general, the fuel system will remain cleaner, but the washed gums may be deposited in the filters and the fine metering orifices which are found in the carburetor or fuel injection systems. It was reported that methanol reduces the effectiveness of some of the existing detergents used in automobile gasolines (reference 1), which may tend to further aggravate the buildup of deposits in the filters and fuel metering systems.

The ullage space in the fuel tank will contain fuel-to-air ratios that are within the flammability limits for neat alcohol fuels at ambient temperatures. This problem can be addressed by adding volatile components to the neat alcohol so that the fuel-to-air ratio is always too rich to support combustion. The addition of 10 percent gasoline to the alcohol fuels will result in rich fuel-to-air ratios in the ullage space (reference 16). The addition of gasoline to neat alcohol fuels also addresses other problems which need to be addressed if they are to be widely used. For example, cold start problems are reduced if 12 percent gasoline is added to methanol, and the problems with methanol fires being non-luminous are solved if 15 percent gasoline is added (reference 1). The addition of 15 percent gasoline to methanol also effectively denatures the fuel (reference 1). The addition of 10 percent gasoline to ethanol will address all of the above problems for that fuel.

In general, vapor lock with either straight methanol or ethanol is less severe than with gasoline. The addition of gasoline or other additives used to denature the alcohol, as described above, will adversely affect the vapor lock behavior of the blend (reference 1).

It has been reported that the addition of methanol or ethanol to gasoline will have little effect on the RVP of the fuel, but it will affect the vapor lock behavior of the fuel (references 1, 4, 35, and 42). The addition of cosolvents reduced the vapor lock problem when using methanol/gasoline blends (references 1 and 5) just as they reduce the phase separation problem. The above implies that the RVP is not a good measure of the vapor lock tendency when dealing with alcohol blends. The addition of methanol does affect the temperatures at which the 20:1 and 36:1 vapor-to-liquid ratios occur for the alcohol blends (references 1 and 42), implying these might be better indicators of the vapor lock behavior for these fuels. There are some indications that the percentage of fuel which is distilled below 70 degrees Celsius is related to vapor lock (reference 1).

Reforming methanol into straight hydrocarbons would solve many of the compatibility and distribution problems but this would cost additional energy (reference 1). In the case of the methanol made from coal, the process will result in what is essentially synthetic gasoline derived from coal. Another option reported would be to catalytically reform methanol into hydrogen and methane and then burn these gasses in the engine (references 1, 4, and 43). This results in slightly better energy efficiencies but requires a greater investment in hardware and a possible weight and space penalty which would be unacceptable in a general aviation aircraft.

The addition of methanol to gasoline will probably help reduce the bacterial growth problems that are encountered with straight petroleum distillates (reference 1).

There were several other phenomena reported that will not directly affect the use of alcohol blends in general aviation aircraft but are of interest. For example, there is a slight increase in the total volume when an alcohol is mixed with gasoline. The extent of the swell depends on the concentration of alcohol in gasoline with the maximum swell being about 0.55 percent for ethanol blends containing 12.5 percent ethanol (references 1 and 4).

In summary, the widescale use of neat alcohols will require substantial redesign of the total fuel and engine systems and current material technology can be applied to these designs. As an example of the extent of the design problem, Ford Motor Company used stainless steel fuel system components, nickel plating on the internal parts of the fuel pump, and fuel preheaters in their methanol powered Escorts (reference 38).

DYNAMOMETER TESTS.

The results of the dynamometer tests are broken into broad areas of interest much as the results from the literature search were broken into specific areas of interest. Some of the results will apply to more than the specific area under which they are presented. In those cases, the applicability of the results will be mentioned.

ALCOHOL BLENDS. The dynamometer configuration for this series of tests consisted of a Cessna 172 (C-172) fuel system and the Lycoming IO-320 engine. The engine was equipped with an engine driven pump and a fuel injection system. This configuration was chosen based on the results of the tests done with automobile gasoline (reference 44) which indicated that the use of a fuel injection system resulted in vapor lock sooner than a carburetor system. Also, this configuration was incorporated to expose the maximum number of moving parts to the alcohol blends with an eye on identifying as many operational problems as possible.

The principal control variables for the vapor lock series of tests are the initial temperature of the fuel in the tank, the alcohol concentration, the type of alcohol, and the fuel flow. As outlined in the Test Procedures Section, all of the other variables were fixed at specific values designed to enhance the probability of vapor lock occurring. The initial temperature of the fuel in the tank was varied from 32 to 49 degrees Celsius (90 to 120 degrees Fahrenheit) for this portion of the study.

A number of alcohol blends were prepared using both ethanol and methanol on a weight/weight basis. The ethanol blends were prepared using anhydrous denatured ethanol. The denaturing agents were 1 percent avgas, 1 percent methyl iso-butyl ketone, and 1 percent ethyl acetate. The weight of the denaturing agents was taken into consideration so that the final blends contained the indicated percentage of ethanol and the balance of gasoline. The methanol blends were prepared using TBA as a cosolvent in equal parts with the methanol. Using a 5 percent methanol blend as an example, 5 percent of the final weight will be methanol, 5 percent will be TBA, and 90 percent will be gasoline. The calculations used to prepare the blends are contained in appendix A.

Four ethanol blends were prepared and tested to determine their vapor lock behavior. The results of the vapor lock tests were then compared with the results obtained from the base fuel. Likewise the vapor lock behavior of four methanol/TBA blends were obtained and compared to the base fuel's behavior. The base fuel was the same for all of these tests. The concentrations tested were 5, 10, 15, and 20 percent for both the ethanol series and methanol series. In addition to the ERVP and distillation data, samples of each blend were tested to determine their octane ratings. They were tested using the Gas Check Kit which provides an estimate of the RVP. Figure 3 contains the distillation curves, ERVP, and Gas Chek Kit data for the ethanol blends and figure 4 contains the data for the methanol blends. The data for the base fuel are incorporated into these figures for comparison purposes. The octane ratings and the RVP as determined by Sun Marketing and Refining are listed in table 7.

TABLE 7. OCTANE RATINGS AND RVP DATA FOR THE ALCOHOL BLENDS

| Sample ID | RON | MON | $\frac{R+M}{2}$ | RVP |
|---|---|---|---|---|
| NBF | 96.4 | 86.2 | 91.3 | 12.05 |
| 5% C2 | 97.4 | 86.8 | 92.4 | 12.3 |
| 10% C2 | 98.5 | 87.0 | 92.8 | 12.04 |
| 15% C2 | 99.7 | 87.3 | 93.5 | 12.94 |
| 20% C2 | 101.5 | 87.8 | 94.7 | 12.42 |
| 5% C1 | 98.6 | 87.5 | 93.1 | 13.14 |
| 10% C1 | 100.1 | 88.0 | 94.1 | 13.39 |
| 15% C1 | 102.5 | 88.7 | 95.6 | 13.13 |
| 20% C1 | 105.0 | 89.6 | 97.3 | 12.76 |

C2 - Ethanol
C1 - Methanol

The initial RVP of the alcohol blends was not varied as a part of this study on vapor lock though the effects of changes in RVP and the Gas Chek Kit measurements were considered.

Appendix B contains a tabulation of the data obtained during the vapor lock investigations using the alcohol blends. The data listed are (1) the fuel identification, (2) the initial ERVP, (3) the Gas Chek Kit data, (4) the initial tank temperature, (5) the fuel flow setting, (6) the line heater setting at the time vapor lock occurred, (7) the temperature of the fuel in the line from the tank to the sediment bowl, (8) the sediment bowl temperature, (9) the carburetor bowl temperature, (10) the time to vapor lock or the time at that data point if vapor lock did not occur, (11) the post-test ERVP and (12) the post-test Gas Chek Kit data. As with the autogas study (reference 44) the sediment bowl temperature seemed to be the most consistent indicator of the severity of the vapor lock problem. This is consistent with the observation that vapor formed in the sediment bowl will most likely block the flow of fuel since it is the lowest point in the fuel system. Other useful indicators of the severity of the vapor lock problem are the time it takes for vapor lock to occur and the temperature rise between the tank and the sediment bowl. This last parameter can be

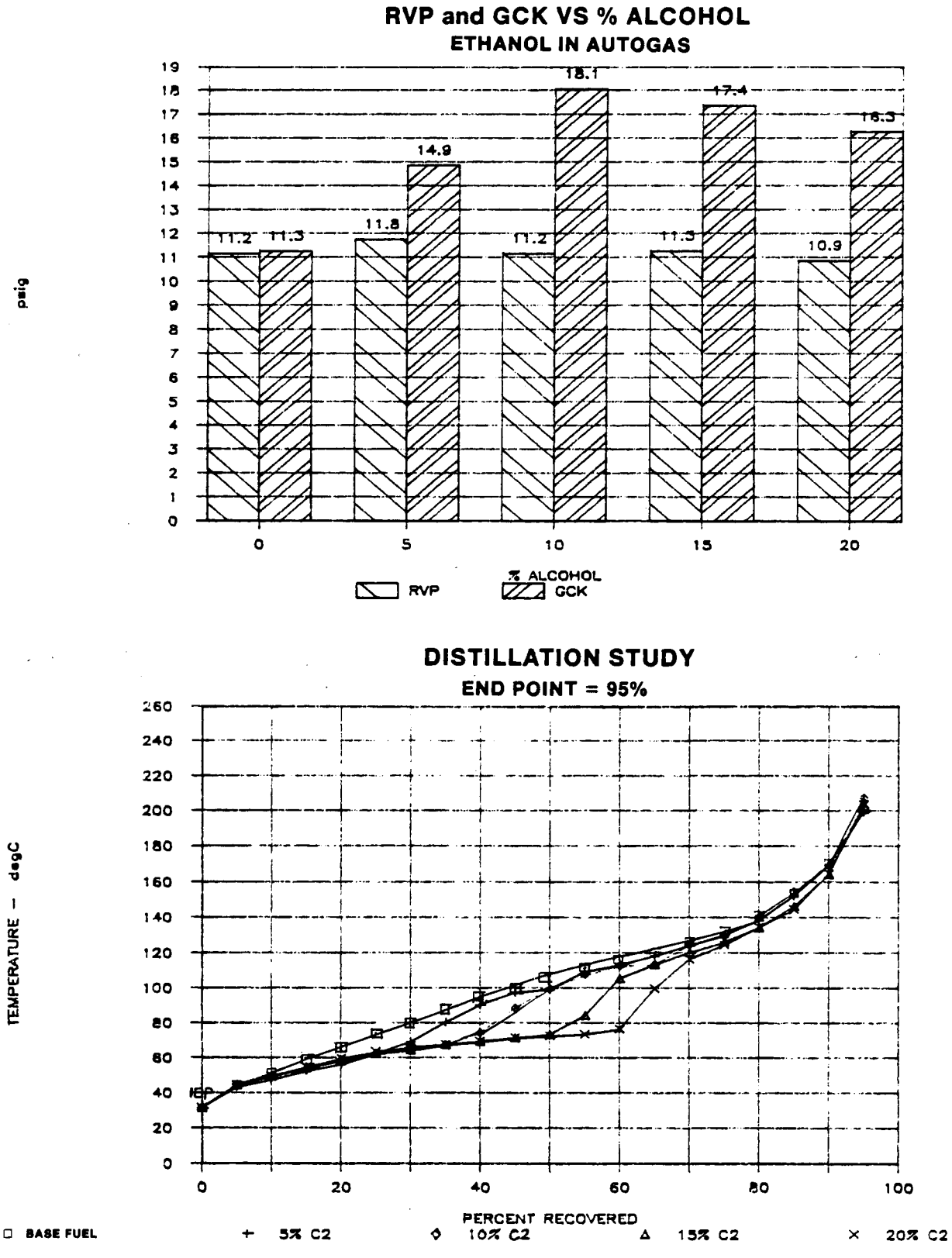



FIGURE 3. RVP AND DISTILLATION DATA FOR ETHANOL BLENDS

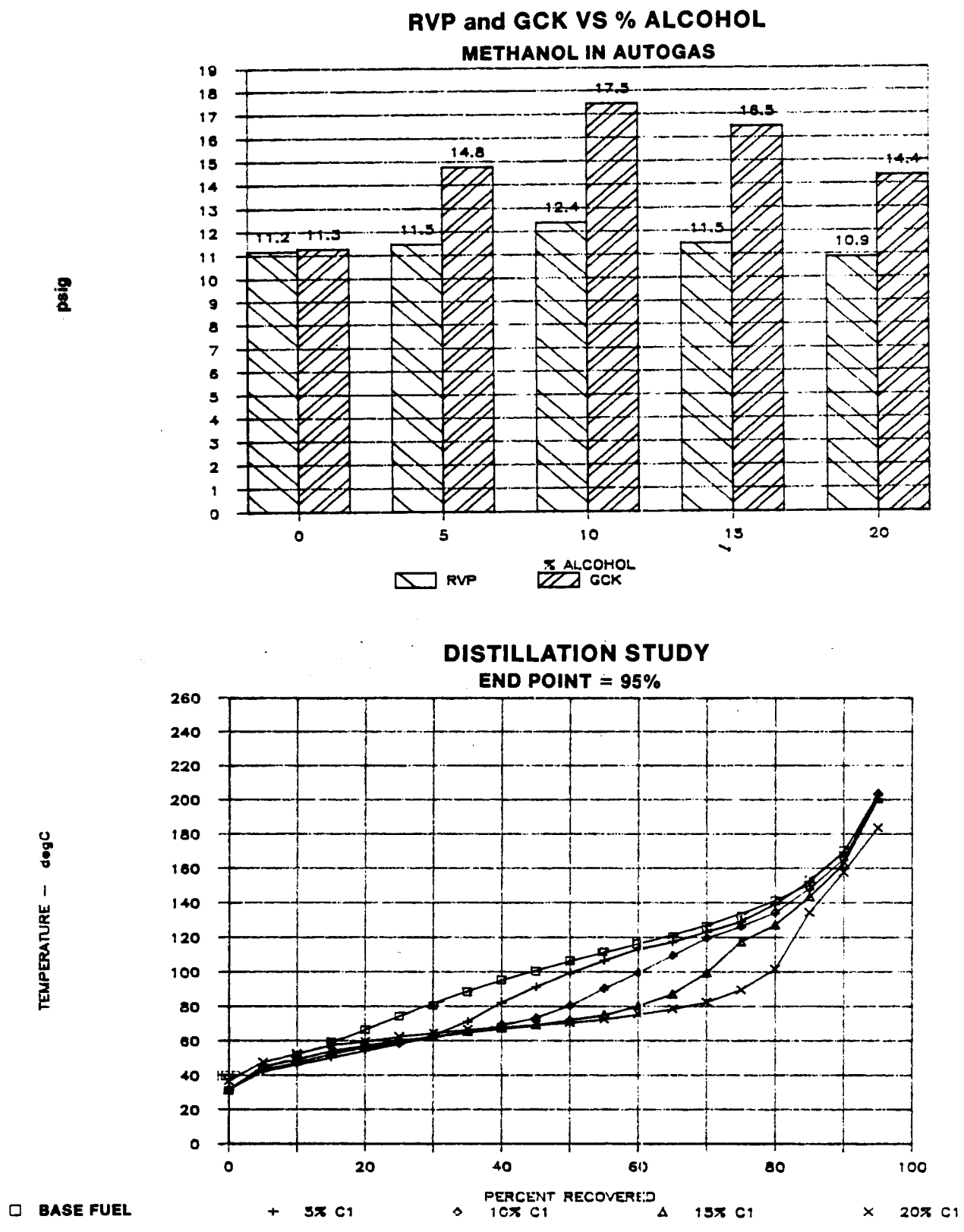



FIGURE 4. RVP AND DISTILLATION DATA FOR METHANOL BLENDS

considered as an indicator of the amount of heat which must be added to the system to result in vapor formation.

From a subjective point of view, the worse case for vapor lock (i.e., most likely to result in vapor lock) with an ethanol blend occurred with a 15 percent blend and an initial fuel temperature in the tank of 100 degrees Fahrenheit (38 degrees Celsius) at takeoff power. Subjectively, the worse case for the blends prepared with methanol occurred with a tank temperature of 100 degrees Fahrenheit and at takeoff power. For the methanol blends, the worse case appeared to lie between the 5 and 10 percent blends. It is significant that the 10 percent methanol blend actually contains 20 percent alcohol (10 percent methanol and 10 percent TBA). The onset of vapor lock was much more rapid with an alcohol blend than with the base fuel, and the alcohol blends in general appeared to be more severe than even the worse case autogas tested in reference 44. These subjective conclusions are supported by an analysis of the data found in appendix B.

Figure 5 shows the average sediment bowl temperature as a function of ethanol concentration. As can be seen, the lowest sediment bowl temperature occurs when the alcohol concentration is 15 percent. Likewise, the average time to vapor lock was the lowest for 15 percent ethanol blend (figure 6). The smallest temperature rise at the time of vapor lock was observed for the 10 percent ethanol concentration; the 15 percent concentration was only slightly higher (figure 7). The anomaly can be attributed to (1) the fact that no data were taken at the 120 degrees Fahrenheit initial tank temperature with a concentration of 15 percent (which tends to lower the average temperature rise), and (2) the fact that the difference between the two points is within the accuracy of the temperature measurements.

The average sediment bowl temperature as a function of initial tank temperature for the ethanol blends is shown in figure 8. In this case the minimum temperature occurs with an initial tank temperature of 32 degrees Celsius (90 degrees Fahrenheit). This might seem to indicate the worse case would occur at the lower temperature until one looks at the average temperature rise between the tank and sediment bowl as a function of initial tank temperature (figure 9). The relatively large temperature rise associated with the 90-degree tank temperature indicates a large amount of heat needs to be added to boil the fuel. The lower rises associated with the tank temperatures above 100 degrees Fahrenheit in figure 9 is offset by the smaller temperature difference between the lower cowl temperature and the fuel in the sediment bowl, which results in less heat being transferred to the fuel. The net effect is for vapor lock to occur more rapidly when the initial tank temperature is 100 degrees Fahrenheit (figure 10).

The average sediment bowl temperature as a function of fuel flow (figure 11) and the average temperature rise as the fuel passes through the system into the sediment bowl as a function of fuel flow (figure 12) tend to indicate the higher the fuel flow the worse the onset of vapor lock with ethanol blends. These trends are not as pronounced with increasing fuel flow as they were when considering the tank temperatures, since the heat available increases with fuel flow (power developed), effectively masking the trend to vapor lock at cooler temperatures with increasing fuel flow. The time to vapor lock is strongly dependent on the fuel flow rate (figure 13) for the ethanol blends. Indeed, for the 100 degrees Fahrenheit/15 percent ethanol blend at takeoff fuel flow, the engine ran only long enough to purge the cool fuel (used to set the point) from the fuel system.

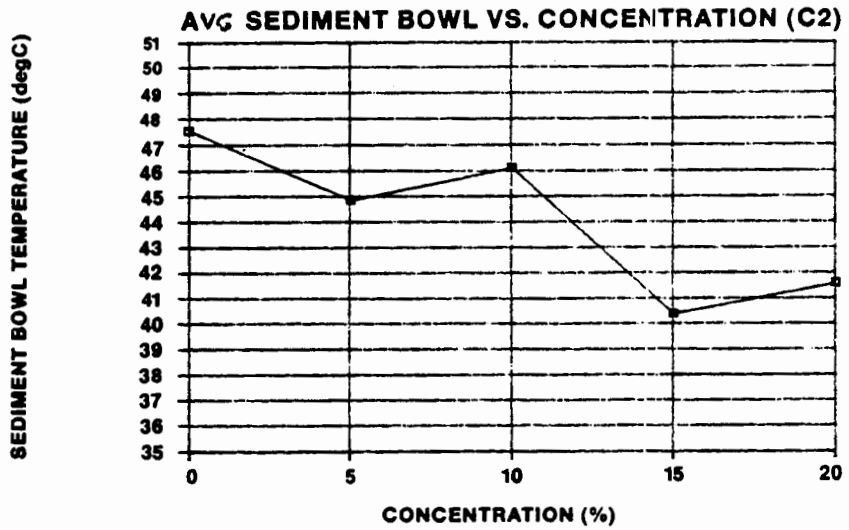



FIGURE 5. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS ETHANOL CONCENTRATION

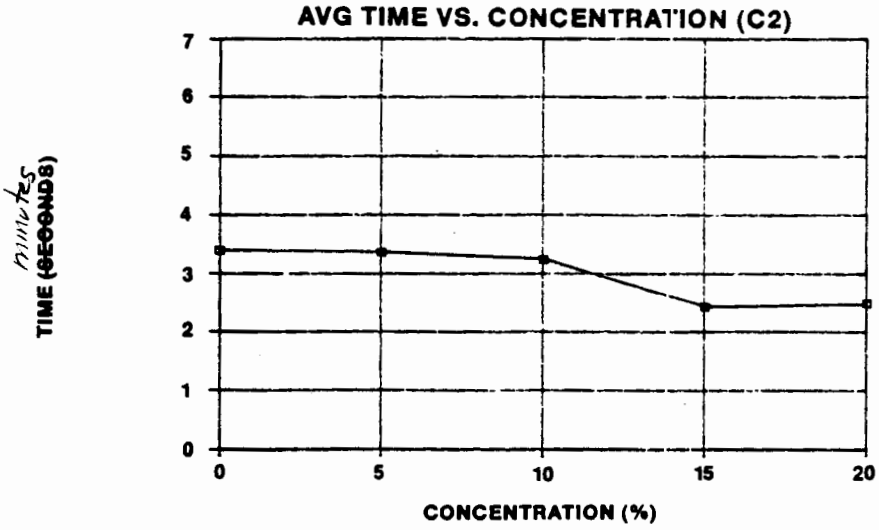



FIGURE 6. AVERAGE TIME TO VAPOR LOCK VERSUS ETHANOL CONCENTRATION

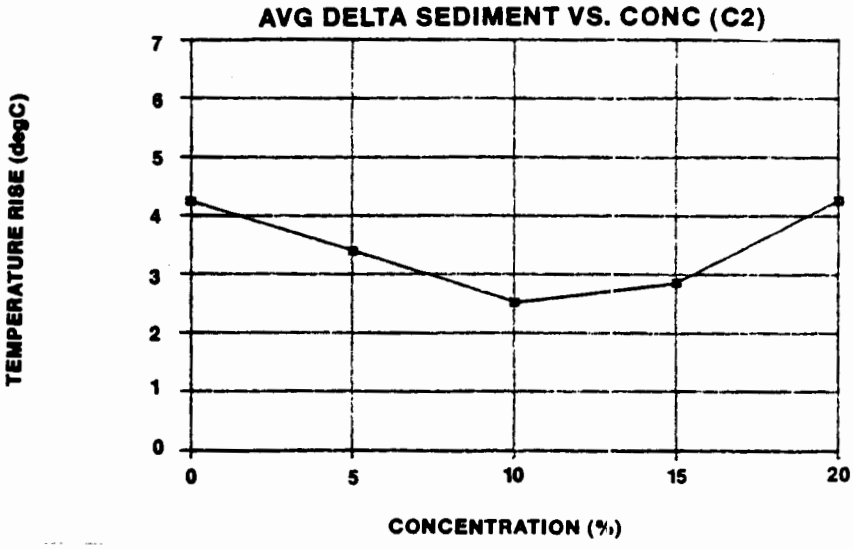



FIGURE 7. AVERAGE TEMPERATURE RISE VERSUS ETHANOL CONCENTRATION

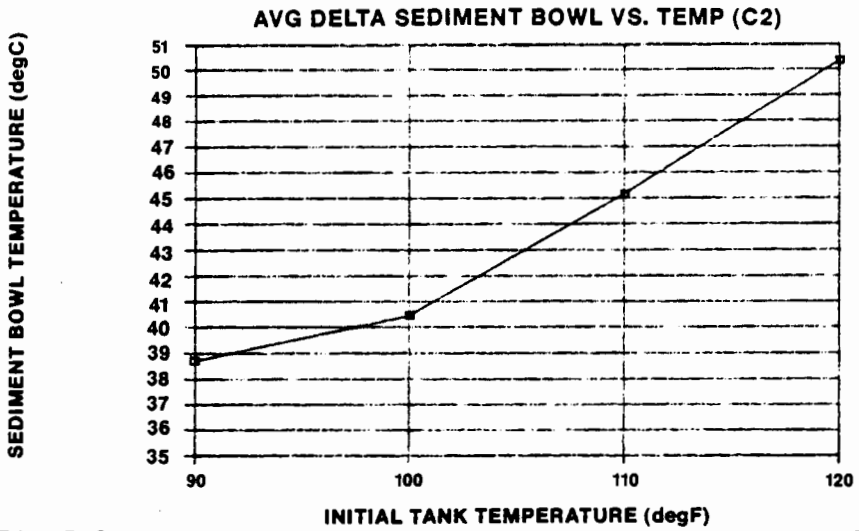



FIGURE 8. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS INITIAL TANK TEMPERATURE FOR ETHANOL BLENDS

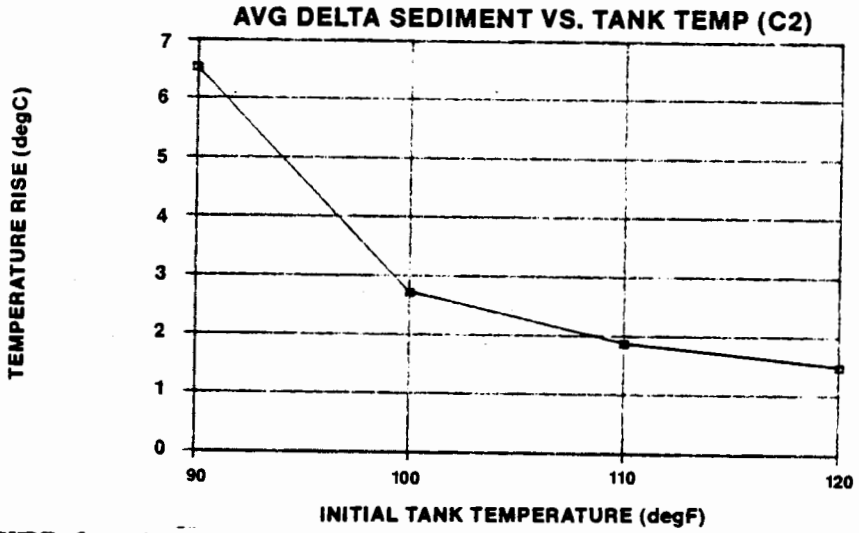



FIGURE 9. AVERAGE TEMPERATURE RISE VERSUS INITIAL TANK TEMPERATURE FOR ETHANOL BLENDS

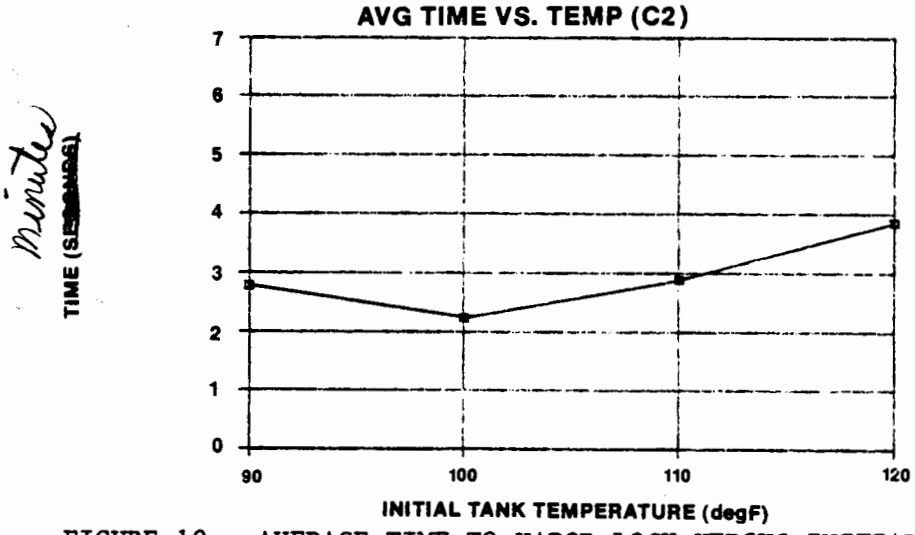



FIGURE 10. AVERAGE TIME TO VAPOR LOCK VERSUS INITIAL TANK TEMPERATURE FOR ETHANOL BLENDS

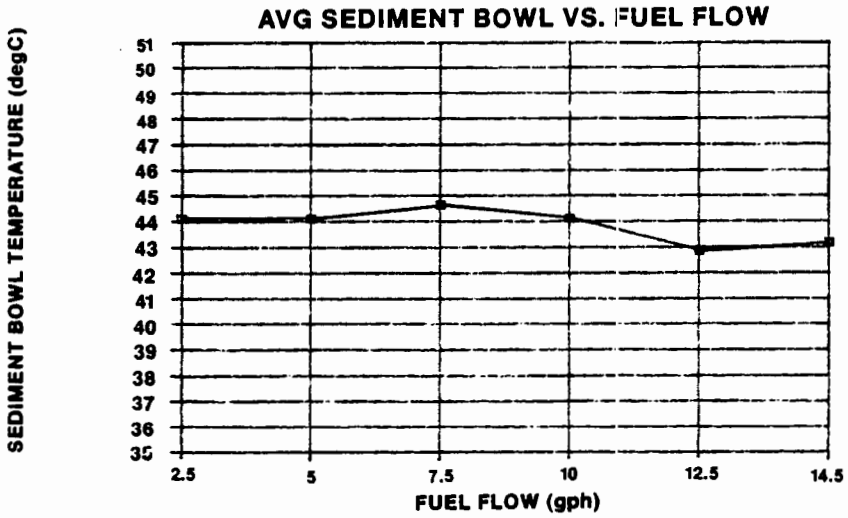



FIGURE 11. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS FUEL FLOW FOR ETHANOL BLENDS

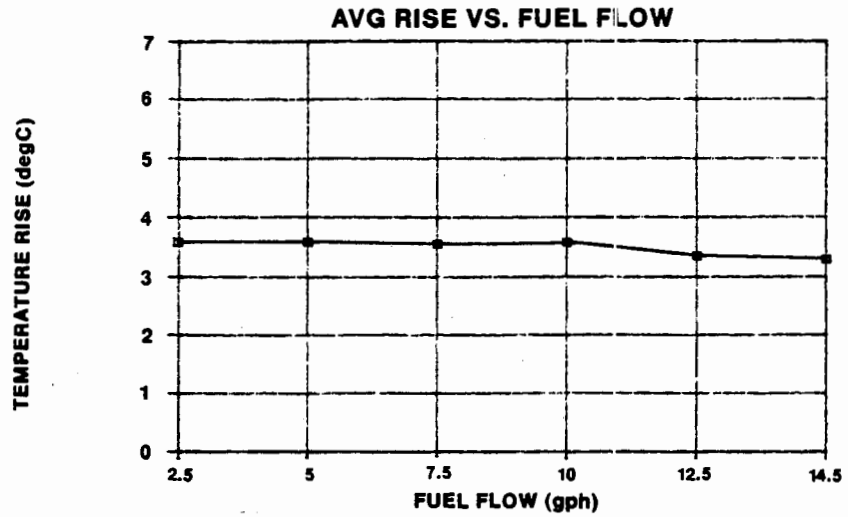



FIGURE 12. AVERAGE TEMPERATURE RISE VERSUS FUEL FLOW FOR ETHANOL BLENDS

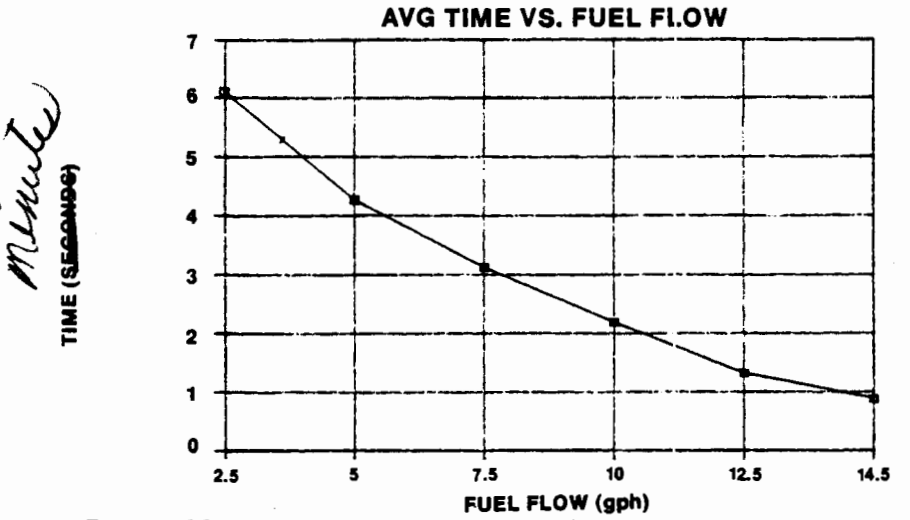



FIGURE 13. AVERAGE TIME TO VAPOR LOCK VERSUS FUEL FLOW FOR ETHANOL BLENDS

The blends made with equal parts of methanol and TBA had similar results. In this case the lowest sediment bowl temperatures and smallest temperature rises as a function of concentration appeared to lie between the 5 and 10 percent blends (figures 14 and 15 respectively). The shortest time to vapor lock was associated with the 5 percent methanol blend, but the general shape of the curve implies the worst case might lie between the 5 and 10 percent blend (figure 16). The analysis of the sediment bowl temperature, the temperature rise, and the time to vapor lock as a function of the initial tank temperature are presented in figures 17, 18, and 19. The general shape of these curves follows the pattern noted with the ethanol blends (figures 8, 9, and 10); which implies the worst case lies with an initial tank temperature of 100 degrees Fahrenheit. The 85-degree Fahrenheit point was run with only the 10 percent methanol blend which resulted in the relatively short time to vapor lock. When this point is compared with the other 10 percent methanol blends, the 100-degree Fahrenheit point is the worst case for this concentration. As with the ethanol blends, the temperature rise is smaller with increasing tank temperature; but the smaller temperature difference between the fuel in the lines and the engine cooling air surrounding it reduces the amount of heat transferred to the fuel, effectively making it more difficult to vapor lock. Figures 20, 21 and 22 show the effects of fuel flow on the average sediment bowl temperature, fuel temperature rise, and time to vapor lock for the methanol blends. The results indicate that the higher the fuel flow, the faster vapor lock will occur.

Based on these results, a short series of tests were conducted on three methanol/TBA blends that were prepared using an unleaded gasoline identified as SBF. The concentrations which were prepared were 5 percent, 7.5 percent, and 10 percent methanol with equal parts of TBA. These samples were tested with an initial tank temperature of 100 degrees Fahrenheit and over the entire range of fuel flows. Table 8 lists the test results for these runs. The average time to vapor lock was 1.4 minutes for the 5 percent and 10 percent blends and 1.0 minute for the 7.5 percent blends, indicating the 7.5 percent methanol blend with equal parts TBA (for a total of 15 percent alcohol) was the worst case. Hence, for a methanol/TBA blend, the conditions most likely to result in vapor lock are takeoff power and 100 degrees Fahrenheit fuel with a concentration of 7.5 percent methanol and equal parts TBA.

A comparison of all the average values for the methanol blends and the ethanol blends that were prepared with the NBF base fuel (table 9) shows that, in general, the methanol blends were slightly more prone to vapor lock than were the ethanol blends. The differences were small however. This agrees with other studies which claim the methanol blends will result in more cases of vapor lock than ethanol blends. This is due to the lower boiling point of methanol when compared with the boiling point of ethanol.

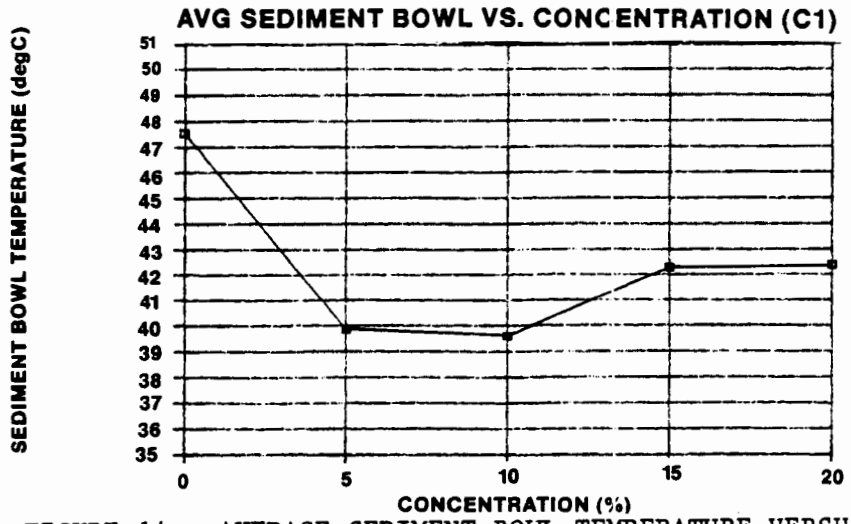



FIGURE 14. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS CONCENTRATION FOR METHANOL BLENDS

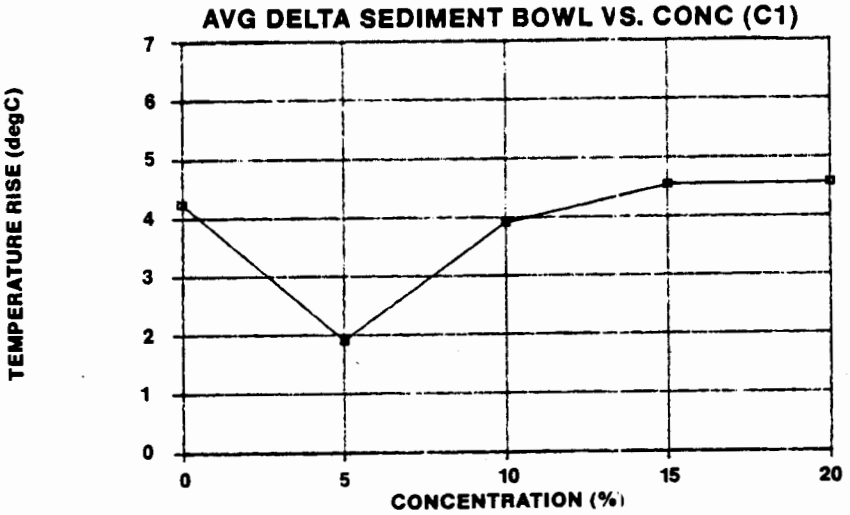



FIGURE 15. AVERAGE TEMPERATURE RISE VERSUS CONCENTRATION FOR METHANOL BLENDS

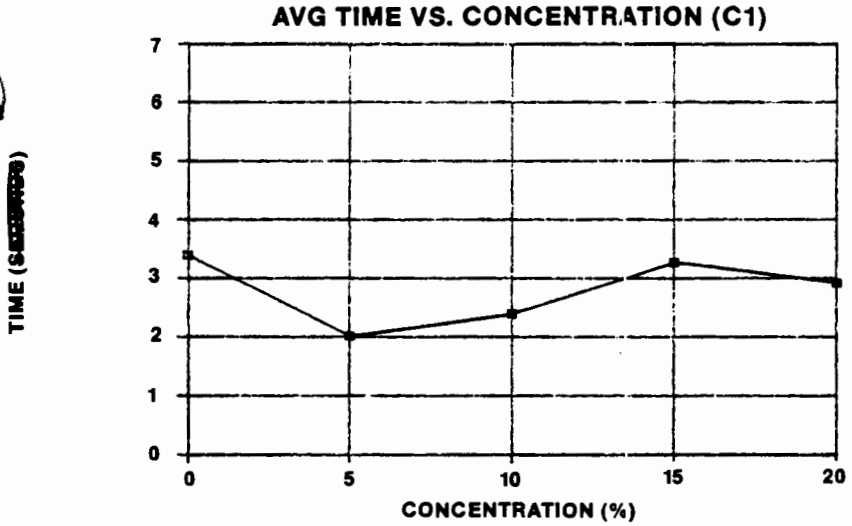



FIGURE 16. AVERAGE TIME TO VAPOR LOCK VERSUS CONCENTRATION FOR METHANOL BLENDS

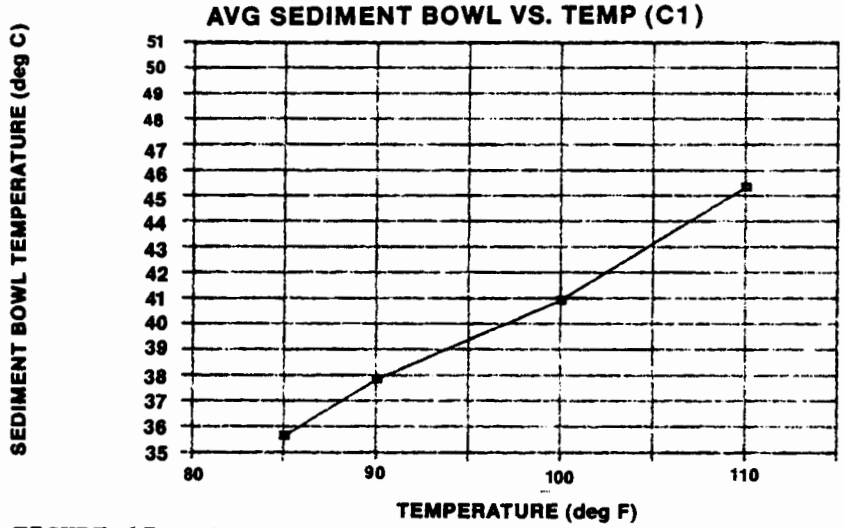



FIGURE 17. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS INITIAL TANK TEMPERATURE FOR METHANOL BLENDS

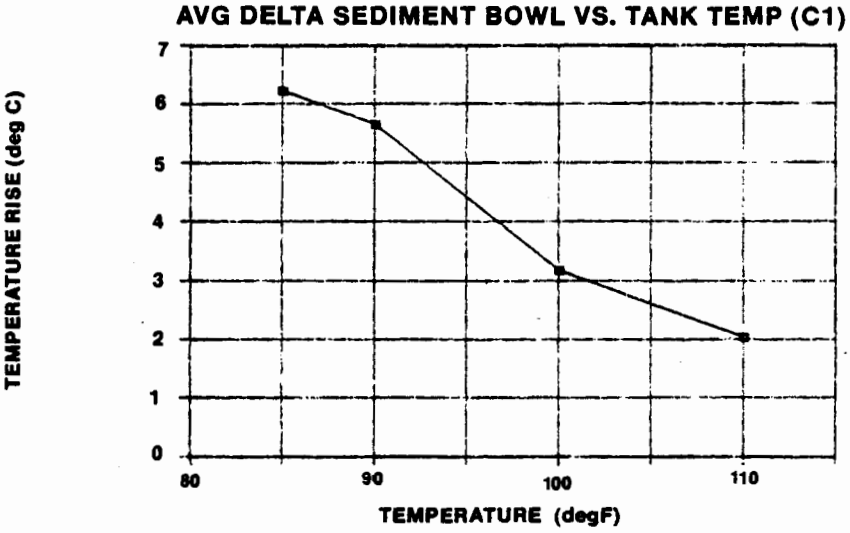



FIGURE 18. AVERAGE TEMPERATURE RISE VERSUS INITIAL TANK TEMPERATURE FOR METHANOL BLENDS

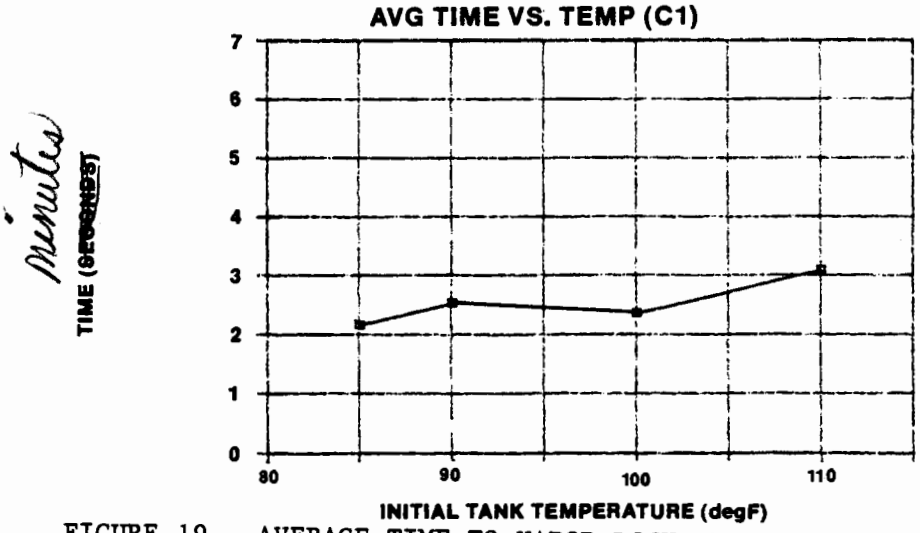



FIGURE 19. AVERAGE TIME TO VAPOR LOCK VERSUS INITIAL TANK TEMPERATURE FOR METHANOL BLENDS

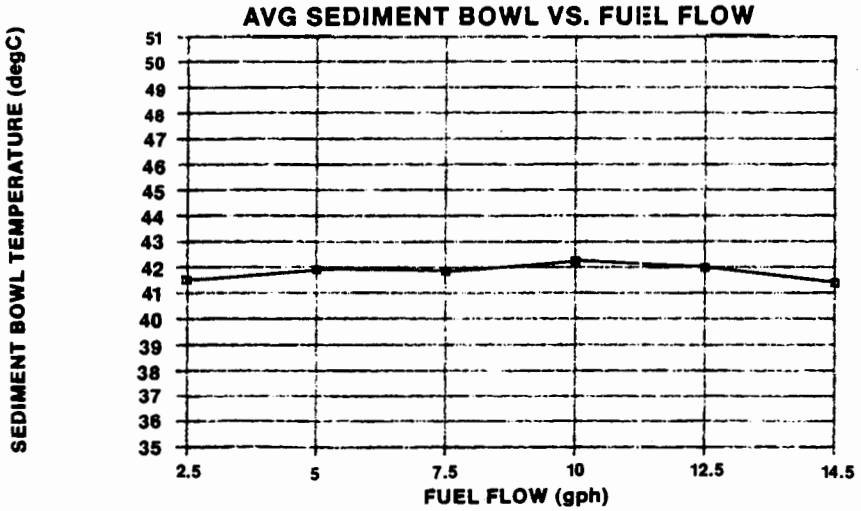



FIGURE 20. AVERAGE SEDIMENT BOWL TEMPERATURE VERSUS FUEL FLOW FOR METHANOL BLENDS

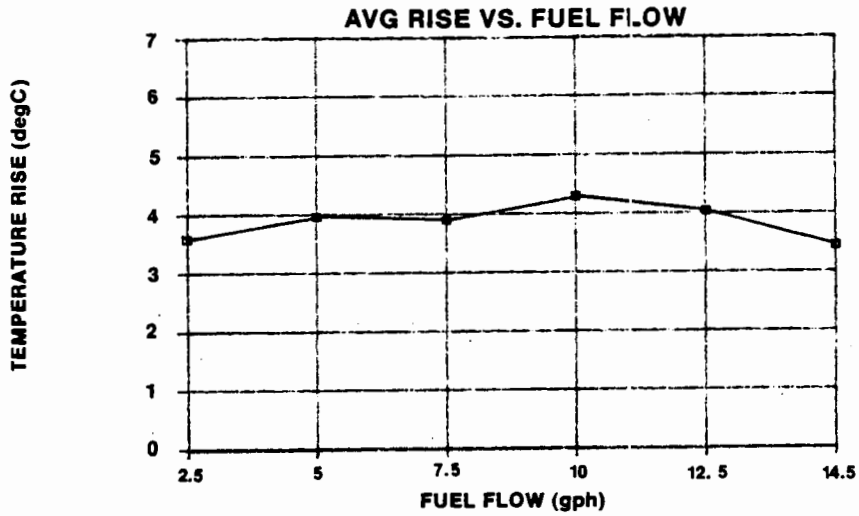



FIGURE 21. AVERAGE TEMPERATURE RISE VERSUS FUEL FLOW FOR METHANOL BLENDS

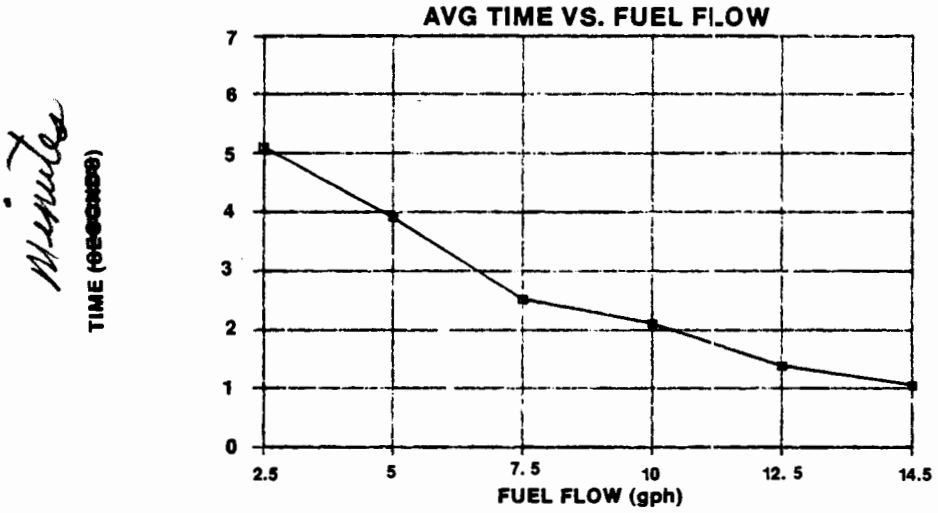



FIGURE 22. AVERAGE TIME TO VAPOR LOCK VERSUS FUEL FLOW FOR METHANOL BLENDS

TABLE 8. TEST RESULTS FOR THE METHANOL/TBA BLENDS PREPARED WITH SBF

| Fuel ID | Initial ERVP (psig) | Initial GCK (psig) | Tank Temp (°F) | Fuel Flow (gph) | Line Heater (°F) | Line Temp (°C) | Sed Bowl (°C) | F.I. Inlet (°C) | Time (min) | Post Test ERVP (psig) | Post Test GCK (psig) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5%-C1 | 11.8 | 19.7 | 100 | 2.5 | 100 | 38 | 42 | 47 | 4.33 | 10.8 | 17.0 |
| 5%-C1 | 11.8 | 19.7 | 100 | 5.0 | 100 | 40 | 41 | 48 | 0.83 | 10.8 | 17.0 |
| 5%-C1 | 11.8 | 19.7 | 100 | 7.5 | 100 | 41 | 41 | 51 | 0.83 | 10.8 | 17.0 |
| 5%-C1 | 11.8 | 19.7 | 100 | 10.0 | 100 | 42 | 42 | 48 | 0.67 | 10.8 | 17.0 |
| 5%-C1 | 11.8 | 19.7 | 100 | 12.5 | 100 | 42 | 42 | 49 | 0.67 | 10.8 | 17.0 |
| 5%-C1 | 11.8 | 19.7 | 100 | 14.5 | 100 | 41 | 42 | 47 | 0.50 | 10.8 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 2.5 | 100 | 40 | 39 | 44 | 2.50 | 10.6 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 5.0 | 100 | 40 | 40 | 46 | 1.00 | 10.6 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 7.5 | 100 | 39 | 40 | 47 | 0.67 | 10.6 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 10.0 | 100 | 38 | 40 | 45 | 0.67 | 10.6 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 12.5 | 100 | 38 | 40 | 45 | 0.67 | 10.6 | 17.0 |
| 7.5%C1 | 10.9 | 19.7 | 100 | 14.5 | 100 | 38 | 40 | 44 | 0.50 | 10.6 | 17.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 2.5 | 100 | 38 | 38 | 43 | 2.83 | 8.1 | 21.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 5.0 | 100 | 39 | 38 | 43 | 1.00 | 8.1 | 21.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 7.5 | 100 | 39 | 39 | 43 | 0.83 | 8.1 | 21.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 10.0 | 100 | 39 | 40 | 43 | 1.67 | 8.1 | 21.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 12.5 | 100 | 38 | 41 | 47 | 1.50 | 8.1 | 21.0 |
| 10%-C1 | 11.6 | 20.5 | 100 | 14.5 | 100 | 38 | 40 | 44 | 0.67 | 8.1 | 21.0 |

NOTES: C1 - Methanol
C2 - Ethanol
GCK - Gas Chek
F.I. - Fuel Injection
All Percentage is on a w/w basis.

TABLE 9. COMPARISON OF THE VAPOR LOCK PARAMETERS FOR ETHANOL BLENDS AND METHANOL/TBA BLENDS MADE WITH NBF

| | Ethanol Blends | Methanol/TBA Blends |
|---|---|---|
| Average Time to Vapor Lock | 2.9 minutes | 2.7 minutes |
| Average Sediment Bowl Temperature | 43.3 °C | 41.1 °C |
| Average Fuel Temperature Rise | 3.3 °C | 3.7 °C |

As with autogas, both the fuel flow indicator and the fuel pressure measurements were useful indicators of the onset of vapor lock. Typically, the fuel flow indicator would begin to give erratic readings, then the pump inlet pressure would begin to fall off. Finally, the pump outlet pressure would begin to drop and the power developed would decrease. The fuel flow meter probably acted as an earlier indicator of vapor lock than either of the pressure measurements, since small bubbles would interrupt the system's optics prior to affecting the pressure readings.

During the course of the runs with alcohol blends, a number of material compatibility problems arose. In general the problems with material compatibility were much worse with the methanol blends than with the ethanol blends. The tank selector was the most troublesome item. When operating on the ethanol blends, the o-rings would swell and the pneumatic selector would not have enough force to push the selector into the detent. With the methanol blends, the problem became so severe the selector had to be replaced. The second selector operated satisfactorily for the balance of the methanol blend runs and operations with neat ethanol (approximately 25 hours), but it was rendered inoperative within a short period of time when operating on neat methanol. The diaphragm of the engine-driven pump (Lycoming part number 6470446, AC Delco part number 40296) began to swell when operating on the ethanol blends, but it continued to operate satisfactorily (approximately 20 hours). Within 2 hours of operation on methanol blends, the diaphragm failed. The pump was replaced with a new design (Lycoming part number 6471426, AC Delco part number 41234), and this pump continued to operate without problems for the balance of the testing with methanol blends, neat methanol, and MTBE. The o-ring in the sediment bowl also swelled in the methanol blends and in neat methanol which resulted in the quick drain staying open after being actuated. If the drain was pushed down, the o-ring would seal. The amount of swell was reduced whenever the fuel being used was changed from one containing methanol to a fuel that did not contain methanol.

The alcohol blends exhibited an unusual phase separation problem during the course of the testing. When this phenomena first occurred, it was thought either the base fuel or the alcohols themselves contained water, but no evidence was found to support this. Additional experience, summarized below, indicates the alcohol blends were absorbing water from the air and from the fuel system itself.

> Typically, a vapor lock sequence would start at a lower fuel flow, then the fuel flow would be increased in even increments. If a data point was repeated after the sequence was finished and the fuel was allowed to age for up to an hour, the second point would tend to vapor lock sooner and at lower temperatures.
>
> The alcohol blends were used in endurance runs to accumulate enough time to have a meaningful oil analysis. During the course of the endurance runs, the fuel flow, then the fuel pressure would begin to decay, and eventually, the engine would vapor lock. This phenomena was markedly more severe on hot humid days than cool dry days.
>
> As the tank was allowed to cool to room temperature following a test where the fuel was maintained at an elevated temperature such as 110 degrees Fahrenheit, the blend would become cloudy; then, over time, a layer of alcohol, water, and gasoline would settle out in the sump. Samples which were heated in sealed containers and then cooled did not exhibit this phenomena. Likewise, the RVP samples of blends which did not have phase separation following the tests would experience phase separation as they were cooled prior to the RVP test.
>
> Finally, if the fuel was allowed to age overnight in the tanks, there would usually be a phase layer in the sump, even if the sumps were drained the previous day.

This phase separation problem appeared to result in corrosion problems in the aluminum tanks. "Before and after" photographs indicated the tanks corroded badly in the short period of time the alcohol blends were used. As with the elastomers, the corrosion problem appeared to be more severe with the methanol blends than with the ethanol blends. The amount of corrosion and pitting seen in the tanks did not appear to change while the tanks contained the neat alcohol fuels. The general appearance of the tanks did change during the neat methanol runs, however, with the aluminum changing from the normal metallic appearance to a light grey, almost white color.

Another solubility phenomena that caused problems was the fact that mixtures of an alcohol blend and 100LL avgas are cloudy and unstable for several minutes following mixing. This appears to be related to changes in the alcohol's solubility as the aromatic content of the fuel changes. Problems associated with this phenomena were ususally encountered when switching from one tank to the other. For example, when switching to avgas following a vapor lock test with an alcohol blend, engine performance would improve slowly at best. After the engine recovered, it would often take up to 5 minutes for the fuel flow indicator to give reliable results. In comparison, recovery on avgas resulted in immediate improvements in engine performance when testing with autogas. This indicates that an aircraft operatng with avgas in one tank and an alcohol blend in the other could experience power interruptions as the tank in use is changed.

Early in the program, the engine ran poorly at the end of a vapor lock test with an alcohol blend, and it would not start for the next vapor lock test. This difficulty was traced to the fuel injection unit's controller becoming air bound. The unit was bled and testing continued. The problem would resurface on a regular basis. It appeared to be more severe if the preceding test was conducted with hot fuel as opposed to room temperature fuel. This indicates the alcohol blends will dissolve more gases than the fuel injection unit in this engine can handle, and the potential for power interruption as a consequence of dissolved gases coming out of solution is a distinct possibility. Indeed, the power developed during some of the endurance runs was affected by air becoming trapped in the fuel injection unit.

As the alcohol blends were heated in the tanks, fuel would be vented overboard through the C-172 tank vents. In general, this problem was worse with the alcohol blends than with the unleaded autogas, and it was not unusual to lose 15 to 20 percent of the initial volume in the tank. This could have a significant impact on the aircraft's range if the flight profile calls for extended operations in high ambient temperatures immediately following refuelling with an alcohol blend.

When operating on alcohol blends, the engine would run at very lean fuel-to-air ratios without misfiring. The power developed would be reduced under these conditions but the operations would otherwise appear normal. Attempts to measure the brake-specific fuel consumption were hampered by the problems associated with the optical fuel flow meter when using the alcohol blends. As the mixture was leaned, the fuel flow indication would become unstable, apparently as a consequence of the internal recirculation in the engine driven pump increasing the fuel temperature.

STRAIGHT ALCOHOLS, FUEL INJECTION SYSTEM. Neat (pure) methanol and the denatured ethanol (3 percent denaturing agents) were tested on the engine using the fuel injection system. The controller of the fuel injection unit limited the fuel flow that could be delivered. With the exception of the idle mixture adjustment, no attempt was made to adjust the settings in the fuel controller for these tests. The neat methanol ran very lean, and as a consequence, the engine misfired badly at idle and would not accelerate beyond 1400 rpm. The denatured ethanol ran well but delivered reduced power as compared to avgas. Once again, this is a consequence of the engine running on the lean side of the stoichiometric fuel-to-air ratio.

An attempt was made to determine if the changes in the spark timing would improve the power developed when using ethanol in this engine configuration. Figure 23 shows the results of this study. Changes in spark timing had a significant effect on the power developed. Advancing the spark timing to 44 degrees before top dead center (BTDC) improved the power developed from 10 to 20 percent over the range tested. The BSFC for the ethanol runs with 44 degrees BTDC timing was compared with the BSFC for avgas with the 25-degree BTDC timing table 10. In general, the BSFC for the ethanol is higher than the BSFC of the avgas, which is expected since ethanol has a lower energy content. The magnitude of the difference is not as great as the energy difference, however. Part of the explanation for this is the fact that the ethanol data are taken at very lean fuel-to-air ratios, whereas the avgas data reflect conditions rich of the stoichiometric fuel-to-air ratio (no effort was made to lean the mixture below 80 percent power as one would normally do in flight). The horsepower used in these calculations is the actual horsepower, not the corrected horsepower. Bear in mind, the power at the individual settings is lower for the ethanol.

TABLE 10. BSFC FOR ETHANOL AND AVGAS IN A FUEL INJECTED ENGINE

| Power setting (RPM/inHg) | Brake Specific Fuel Consumption (lbm/hp-hr) | |
|---|---|---|
| | Avgas | Ethanol |
| 2700/FT* | 0.60 | 0.67 |
| 2600/27 | 0.60 | 0.68 |
| 2500/25 | 0.62 | 0.69 |
| 2400/24 | 0.63 | 0.70 |
| 2300/23 | 0.66 | 0.69 |
| 2200/22 | 0.62 | 0.72 |
| 2100/21 | 0.67 | 0.72 |
| 2000/20 | 0.66 | 0.73 |

*Full throttle

A short vapor lock sequence was conducted using the denatured ethanol in the fuel injected engine. Table 11 shows the results of this study. The denatured ethanol was tested at two initial tank temperatures, 100 and 125 degrees Fahrenheit, and at a number of fuel flows. With the 100-degree Fahrenheit fuel, vapor lock was induced at only the 2.5 gph setting. At the higher fuel flow rates, the line heaters could not add sufficient heat to the fuel to approach the boiling point of the ethanol (78 degrees Celsius). As a consequence, no vapor

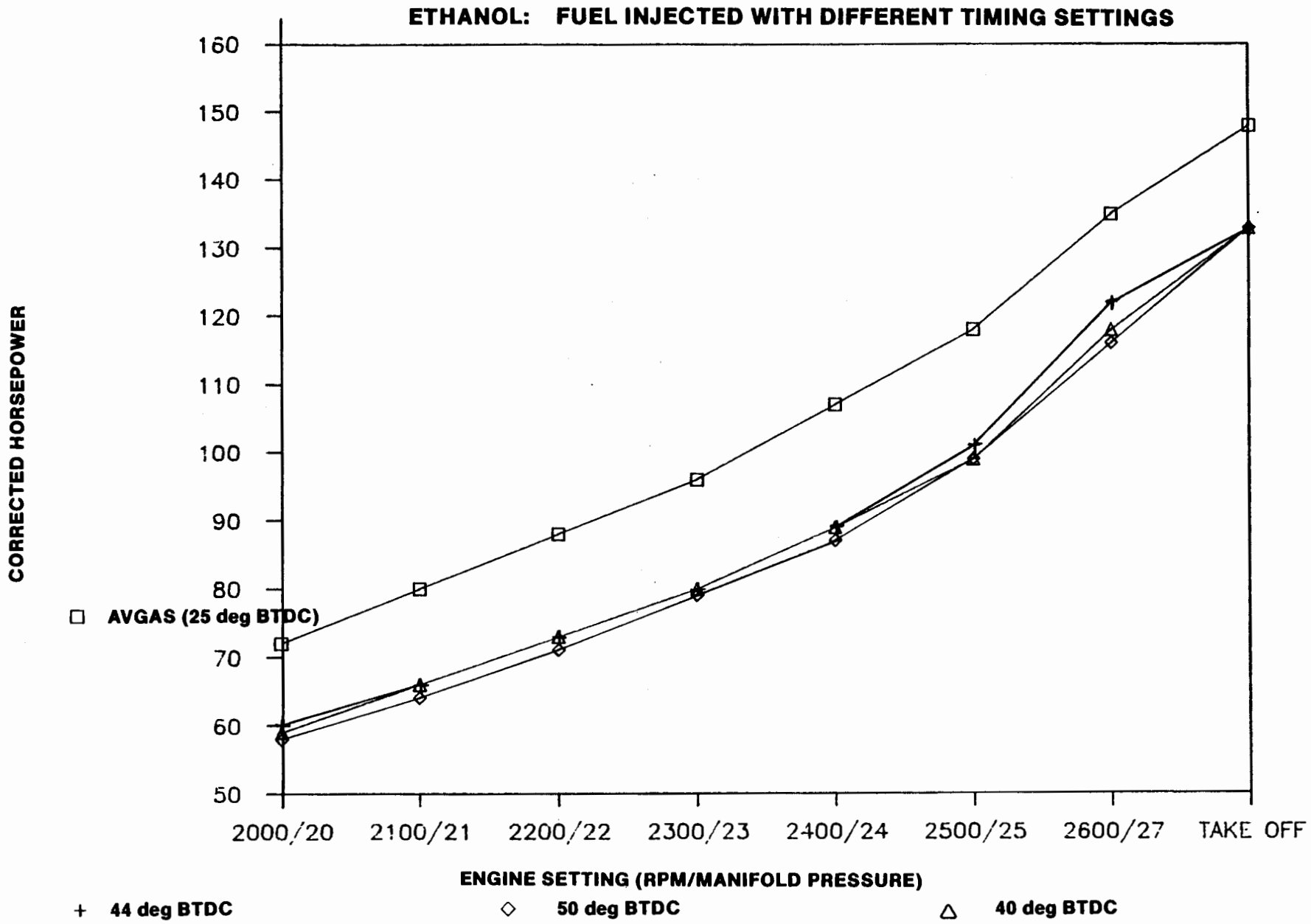



FIGURE 23. POWER DEVELOPED WHEN USING ETHANOL IN A FUEL INJECTED ENGINE

lock was observed. With the 125-degree Fahrenheit initial tank temperature, percolation was observed at the 2.5 and 5.0 gph fuel flow rates. This resulted in periods of unstable running but no power interruption. At the 10 and 14.5 gph fuel flow rates, vapor lock was observed. The sediment bowl temperature was lower than the boiling point of ethanol but not by a significant amount. This was probably a consequence of the reduced pressure in the fuel system as a consequence of the high fuel flows. These tests indicate that ethanol will vapor lock whenever the sediment bowl temperature approaches the boiling point of the ethanol. The hotter the fuel and the higher the fuel flow rate, the easier it is to induce vapor lock.

TABLE 11. VAPOR LOCK BEHAVIOR OF ETHANOL IN A FUEL INJECTED ENGINE

| Initial Tank Temperature (°F) | Fuel Flow (gph) | Line Heater Setting | Sediment Bowl Temperature (°C) | Time at Point (min) |
|---|---|---|---|---|
| 100 | 2.5 | 250 | 77 | 15 |
| 100 | 5.0 | 250 | no VL* | no VL |
| 100 | 7.5 | 250 | " | " |
| 100 | 10.0 | 250 | " | " |
| 100 | 12.5 | 250 | " | " |
| 100 | 14.5 | 250 | " | " |
| 125 | 2.5 | 250 | no VL | no VL |
| 125 | 5.0 | 250 | " | " |
| 125 | 10.0 | 250 | 76 | 11 |
| 125 | 14.5 | 250 | 74 | 6.3 |

*Vapor lock was not observed.

During the course of the vapor lock runs using ethanol in the fuel injected engine, detonation was observed at the higher fuel flow rates. This happened only when setting the point on avgas, then switching from avgas to ethanol. Detonation was not observed when increasing the power setting from idle to a higher power setting using only ethanol. A review of the data showed the engine ran substantially hotter with avgas than with ethanol, and these hotter temperatures induced detonation when switching from avgas to ethanol. The lean mixtures associated with the ethanol probably contributed to the problem.

An attempt was made to run methanol in the fuel injected system by blending it with small quantities of 100LL avgas. Two blends were prepared, one with 5 percent avgas and one with 10 percent avgas. The blend of 5 percent avgas in methanol ran, but hesitation and misfiring were noted. The 10 percent avgas in methanol blend ran substantially smoother, but some hesitation was still noted on acceleration. The power developed when operating on the 10 percent avgas methanol blend was substantially lower than the power developed on avgas. Unlike the neat methanol, the 10 percent avgas methanol blend did successfully restart immediately following an engine shutdown, but it would not start following a cold soak. The ambient temperature for the start following a cold soak was 25 degrees Celsius (77 degrees Fahrenheit). The spark timing for these tests was set at 40 degrees BTDC, and the idle mixture was adjusted to the full rich position.

The hesitation noted during these runs was thought to be due to the lean mixture. Several attempts were made to enrichen the mixture by heating the air going into the fuel injection unit (thus reducing the air density and increasing the fuel-to-air ratio). This not only improved the smoothness of operation but resulted in substantially improved power development, implying the fuel was not completely vaporizing despite the fuel injection unit. A run was made using neat methanol in the fuel injected unit with the inlet air heated to approximately 65 degrees Celsius (150 degrees Fahrenheit). This time the engine ran but the operation was still somewhat rough, reinforcing the opinion that the fuel was not vaporizing completely before entering the combustion chamber (it would not run without heating the inlet air).

During the blending of the 100LL avgas in methanol for these runs, it was necessary to agitate the blend to get the two constituents to mix. Otherwise the avgas would form a layer above the methanol and only gradually diffuse into the methanol.

STRAIGHT ALCOHOLS, STANDARD CARBURETOR. The fuel system on the engine was converted to a carbureted system to investigate the problems which might be encountered with using straight alcohols in a carburetor. A short series of tests were conducted using the standard jet, which is sized for avgas, and the spark timing set at 25 degrees BTDC.

The results for neat ethanol were similar to those when using the fuel injected system, with the power being down somewhat when compared to avgas, but this time significant engine roughness was observed. Heating the carburetor inlet air improved the smoothness of operation and increased the power developed. As the carburetor inlet air was heated, the temperature of the mixture downstream of the carburetor was measured. The temperature of the mixture remained essentially constant as heat was added until the temperature of the inlet air was between 50 and 55 degrees Celsius (122 to 131 degrees Fahrenheit). As the temperature of the inlet air increased to about 50 degrees Celsius, the power developed also increased. Additional heat resulted in the mixture temperature increasing and the power decreasing.

The methanol results using the unmodified carburetor also followed the trend observed with the fuel injected system. Neat methanol would not run even with full carburetor heat. The 10 percent avgas in methanol blend performed satisfactorily though at reduced power. As with neat ethanol, the use of carburetor heat improved the power and the smoothness of operation. The use of full carburetor heat (about 65 degrees Celsius) resulted in the best power in this instance. As with the fuel injected engine, a hot restart with the 10 percent avgas in methanol blend was successful though cold starts could not be made on either neat methanol or the 10 percent avgas in methanol blend.

A sample of neat ethanol with 10 percent avgas was also tested in the standard carburetor. The overall operation of the engine was improved substantially, and as before, the addition of carburetor heat improved the power slightly. The power developed using the avgas-ethanol blend was from 15 to 25 percent higher than the power developed with the neat ethanol. This was still approximately 25 percent lower than the power developed using avgas in the standard carburetor.

STRAIGHT ETHANOL, MODIFIED CARBURETOR. The main jet in the carburetor was replaced with a jet with an area approximately 40 percent larger than the standard jet. This change allowed for the difference in energy content between avgas and ethanol. With the fuel-to-air ratio near stoichiometric, a sequence was initiated to determine what the effects of changes in the spark timing would have on the power developed. Figure 24 shows the power for a range of engine speed and manifold pressures' combinations as a function of ignition timing when using ethanol. The best overall performance was with the 25 degrees BTDC timing which is the standard timing used with avgas. With the timing set at 25 degrees BTDC, the power developed with neat ethanol is within the system repeatability of the power developed with avgas.

The BSFC for the carbureted engine using both avgas and ethanol is tabulated in table 12. The BSFC now reflects the difference in the energy content of the fuel, with the BSFC running approximately 25 percent higher for the ethanol. The mixture is just rich of stoichiometric for both of these sets of data and the spark timing was at 25 degrees BTDC. As with table 10, the actual horsepower was used in these calculations, but in this case the power developed was comparable between these fuels. The differences noted show that the theoretical efficiency gains from running at leaner mixtures with alcohol fuels can be achieved, but they will not eliminate the need to burn more fuel due to the lower energy content. To realize these gains however, the spark timing will need to be optimized for the lean mixtures. Changing the spark timing will result in reduced power available at takeoff, however.

TABLE 12. BSFC FOR ETHANOL AND AVGAS IN A CARBURETED ENGINE

| Power Setting (RPM/inHg) | Brake Specific Fuel Consumption (lbm/hp-hr) | |
|---|---|---|
| | Avgas | Ethanol |
| 2700/FT* | 0.60 | 0.74 |
| 2600/27 | 0.63 | 0.79 |
| 2500/25 | 0.65 | 0.79 |
| 2400/24 | 0.62 | 0.78 |
| 2300/23 | 0.61 | 0.79 |
| 2200/22 | 0.62 | 0.81 |
| 2100/21 | 0.65 | 0.82 |
| 2000/20 | 0.66 | 0.83 |

*Full throttle

During the course of testing neat ethanol with the modified carburetor, several operational difficulties were noticed.

Even though the engine would start on the neat ethanol, it would require a large amount of priming. No attempts were made to conduct a cold start with ambient conditions below 25 degrees Celsius (76 degrees Fahrenheit).

When the engine was cold, the engine would stumble on acceleration. This problem did not occur after allowing the engine to idle for a few minutes.

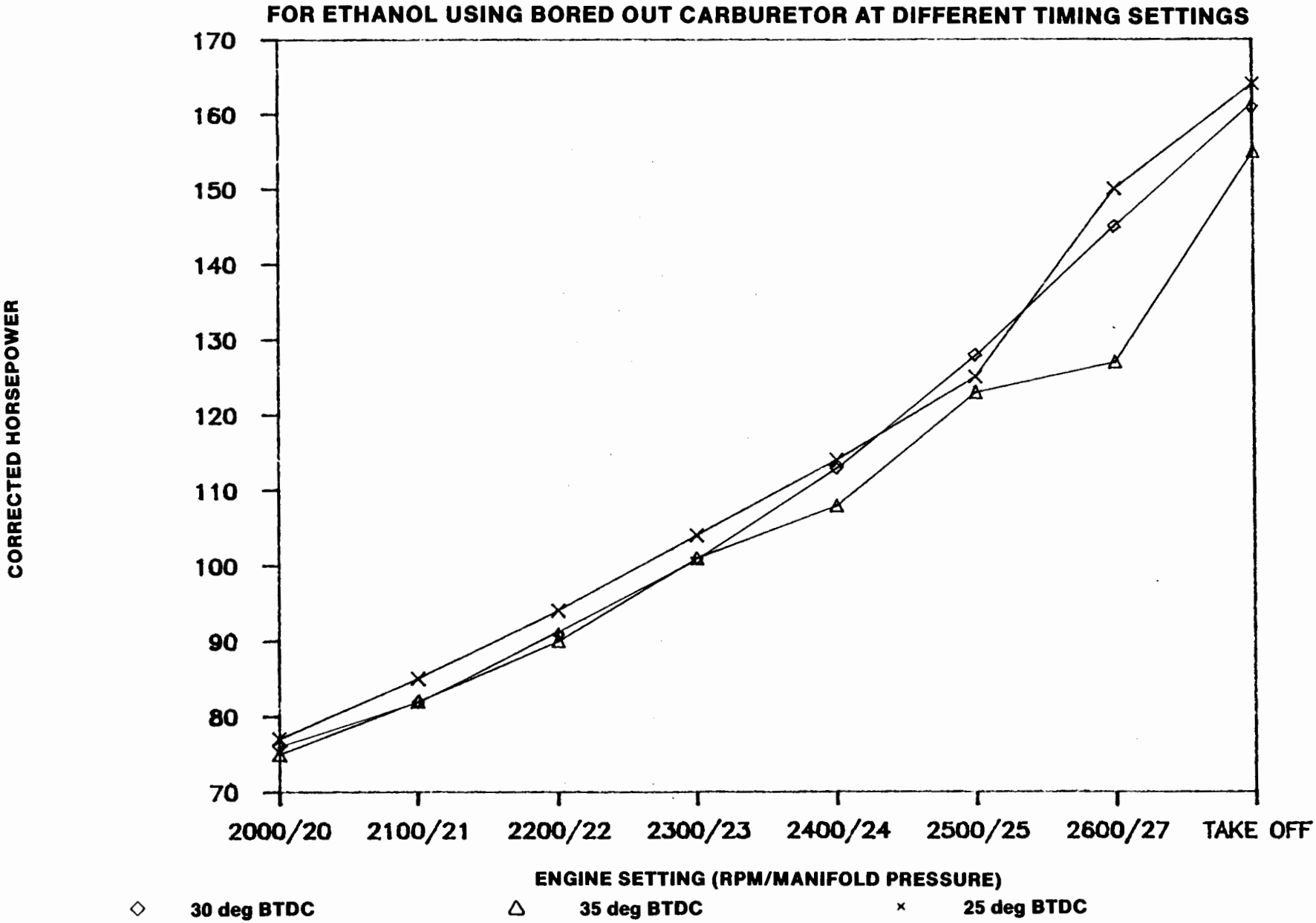



FIGURE 24. POWER DEVELOPED WHEN USING ETHANOL IN A CARBURETED ENGINE

There were large spreads between the exhaust gas temperatures (EGTs) and between the cylinder head temperatures (CHTs) indicating poor fuel distribution. At takeoff power settings, detonation was also noted; once again, the probable cause of the detonation was maldistribution. The temperature spread and detonation problems were reduced by the addition of carburetor heat. Also, the addition of carburetor heat improved the power developed, slightly.

Ten percent unleaded autogas was added to the ethanol for the endurance tests which were used to accumulate enough time for the oil analysis. This appeared to eliminate the problems noted above. In addition, the literature indicated that 10 percent gasoline in ethanol is an effective denaturing agent, it renders the flame luminous, and it prevents the mixture in the ullage space from being within flammable limits under most ambient conditions.

Neat ethanol at 38 and 52 degrees Celsius (100 and 125 degrees Fahrenheit) would not vapor lock when tested on the engine with the modified carburetor. There were minor variations in the pump inlet pressure at the higher fuel flows with the 125-degree Fahrenheit tank temperatures, indicating vapor formation in the fuel system. These variations did not affect the pump output pressure nor the power developed. An attempt was made to induce vapor lock with the 10 percent autogas in ethanol blend using tank temperatures of 32 and 43 degrees Celsius (90 and 110 degrees Fahrenheit). The results were similar to those obtained with neat ethanol.

During the vapor lock tests, the EGT was monitored to determine if it would provide an indication of the onset of vapor lock. When the vapor lock occurred with the fuel injected system, only small changes were observed. No significant changes were noticed during the vapor lock tests with the carburetor. Since the fuel injected engine already ran lean and since the carbureted engine did not vapor lock, these results were not unusual. An attempt was made to determine the extent of the EGT change that would normally be observed when operating on ethanol by adjusting the mixture control. The changes observed did not follow the pattern established with avgas. As the mixture was leaned, a slight increase in EGT was observed. Further leaning did not affect the EGT until the fuel flow was reduced about 10 percent although the torque changed substantially. Leaning to misfire resulted in only small changes in EGT. The maximum EGT recorded was about 50 to 60 degrees Celsius lower than the maximum recorded with avgas or autogas.

During the testing with the modified carburetor to get methanol near the stoichiometric fuel-to-air ratio, ethanol was used as the recovery fuel since avgas would not run at these fuel-to-air ratios. Under these conditions, the fuel-to-air ratio for the ethanol was very rich, and the power was consistently 3 percent higher (about 5 hp at takeoff) than with only slightly rich fuel-to-air ratios. This means, an engine certified on ethanol will be capable of developing more power than one operating on avgas or autogas.

STRAIGHT METHANOL, MODIFIED CARBURETOR. The carburetor was modified to allow methanol to run at stoichiometric fuel-to-air ratios. These modifications included increasing the area of the main jet by 75 percent of the area used with avgas. Even with these modifications the engine would not run with neat methanol. The problem appeared to be maldistribution when using methanol in the carbureted engine. While carburetor heat improved the performance significantly,

it still was not acceptable. As a consequence, a blend of 15 percent unleaded autogas in methanol was used for the balance of the testing with methanol. This blend appeared to improve the performance to satisfactory levels with the exception of cold start problems. The engine needed to be primed with autogas in order to start if the ambient temperature was below 19 degrees Celsius (67 degrees Fahrenheit), and the engine had to be preheated if the ambient temperature was below 8 degrees Celsius (46 degrees Fahrenheit).

The addition of 15 percent autogas to the methanol also resolved several of the other problems associated with the use of neat methanol. It effectively denatures the methanol so that accidental consumption is deterred, it renders the flame luminous, and it results in fuel-to-air ratios in the ullage space that are too rich to support combustion.

The effect of spark timing was investigated once the fuel-to-air ratio was adjusted to be rich of stoichiometric. The results are shown in figure 25, and the optimum spark timing for these conditions was 25 degrees BTDC. This is the same timing used for avgas and ethanol with rich of stoichiometric fuel-to-air ratios. The power developed with the methanol was slightly higher than the power developed using avgas. This could be a consequence of the large temperature drop that occurs across the carburetor, effectively reducing the temperature of the mixture entering the engine.

The BSFC for the 15 percent autogas in methanol fuels is presented in table 13 for both rich and lean fuel-to-air ratios. Avgas data are also presented for comparison purposes. The spark timing for all three sets of data was 25 degrees BTDC, and the actual horsepower was used to make the calculations. In general, the rich methanol data reflect the difference in energy content between methanol and avgas. The lean data show that some of this difference can be compensated for by leaning the mixture, although the results for these power settings are inconclusive. Figure 26 shows the BSFC over a range of cruise power settings. The general trend is toward better BSFC as the engine speed is reduced and the manifold pressure is increased. Much of the scatter in figure 26 is a consequence of trying to set the mixture to just rich of lean misfire; small differences in the fuel flow rate when near the lean limit significantly affect the power developed. The data are more repeatable at the rich setting with the exception of the 1800 rpm full throttle setting. In this case the engine ran rough, probably because of maldistribution. Figure 27 shows the horsepower developed at the same power settings. The horsepower for the lean mixtures is lower than the horsepower for the rich mixtures, so the tradeoff for fuel efficiency will be slower airspeeds. If one is flying into a strong headwind, the slower airspeeds could result in greater fuel consumption. Once again, the spark timing for optimum power with a rich mixture is significantly different than the spark timing for best economy with a lean mixture; and selecting a spark timing to get maximum efficiency will reduce the power available at takeoff power settings.

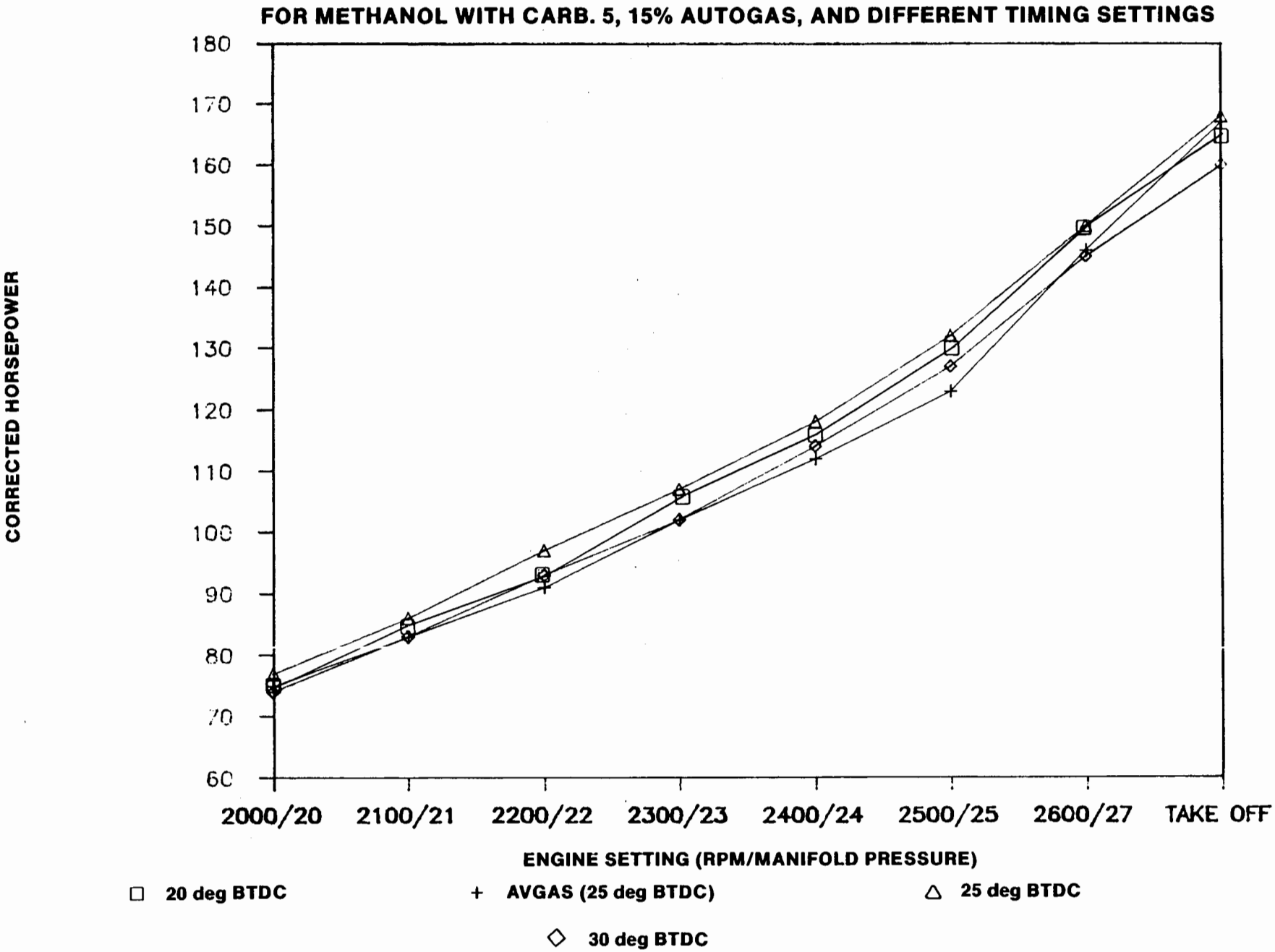
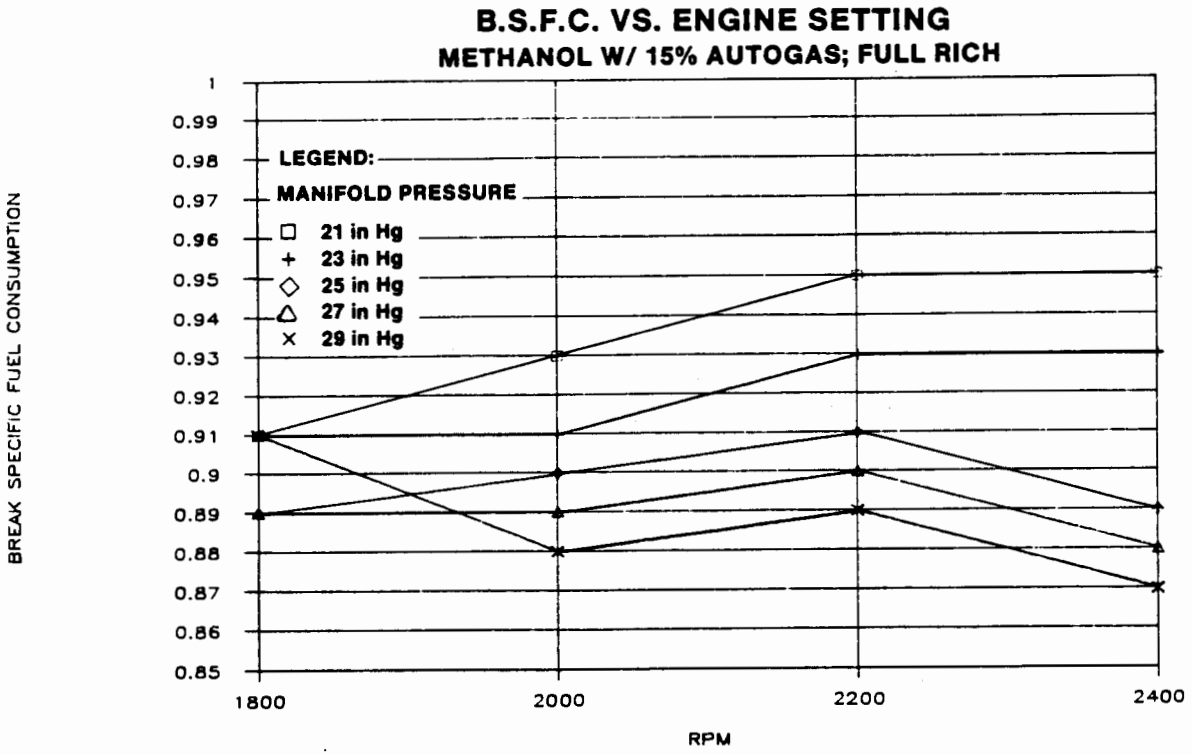



FIGURE 25. POWER DEVELOPED WHEN USING METHANOL IN A CARBURETED ENGINE



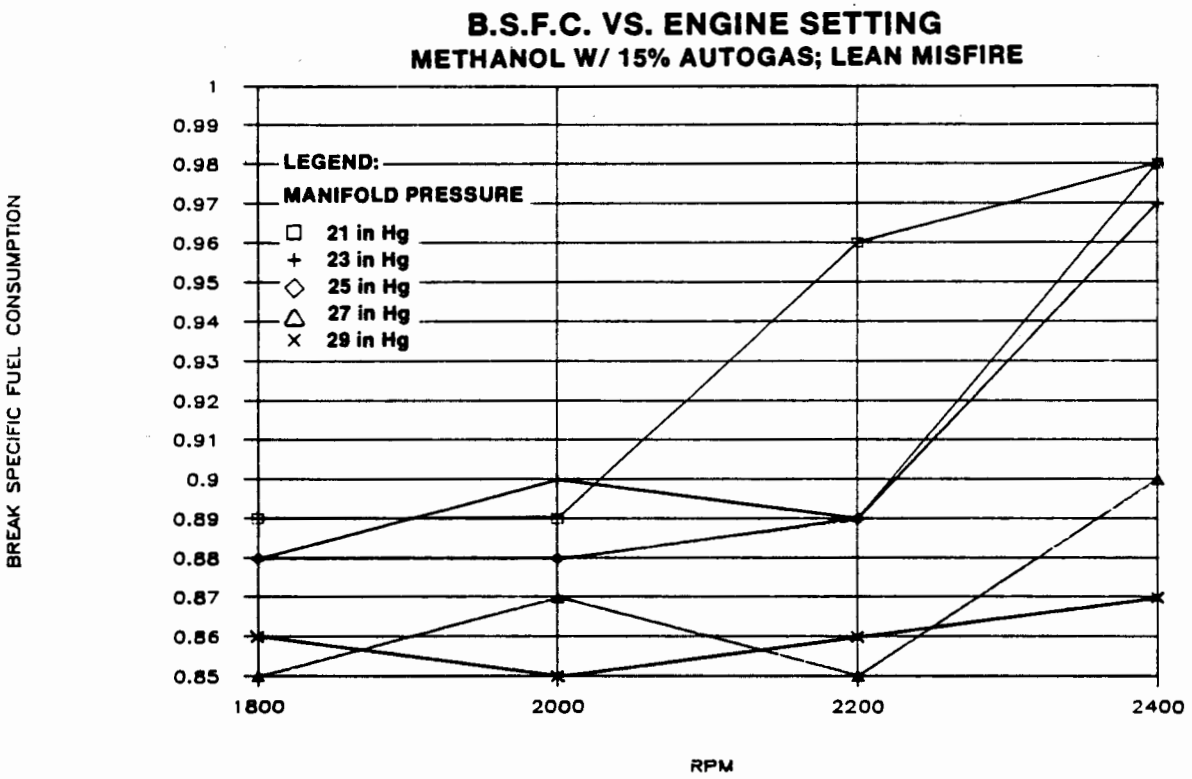
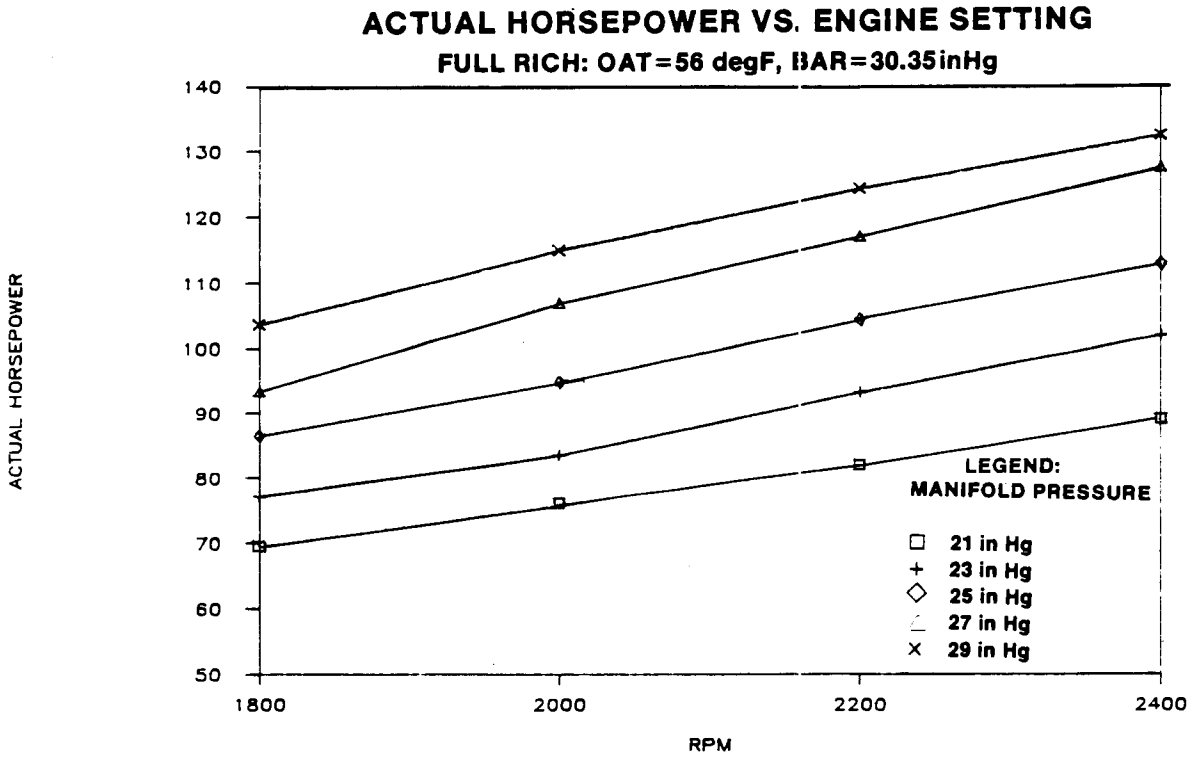




FIGURE 26. BSFC OVER A RANGE OF POWER SETTINGS FOR RICH AND LEAN MIXTURES WHEN USING METHANOL



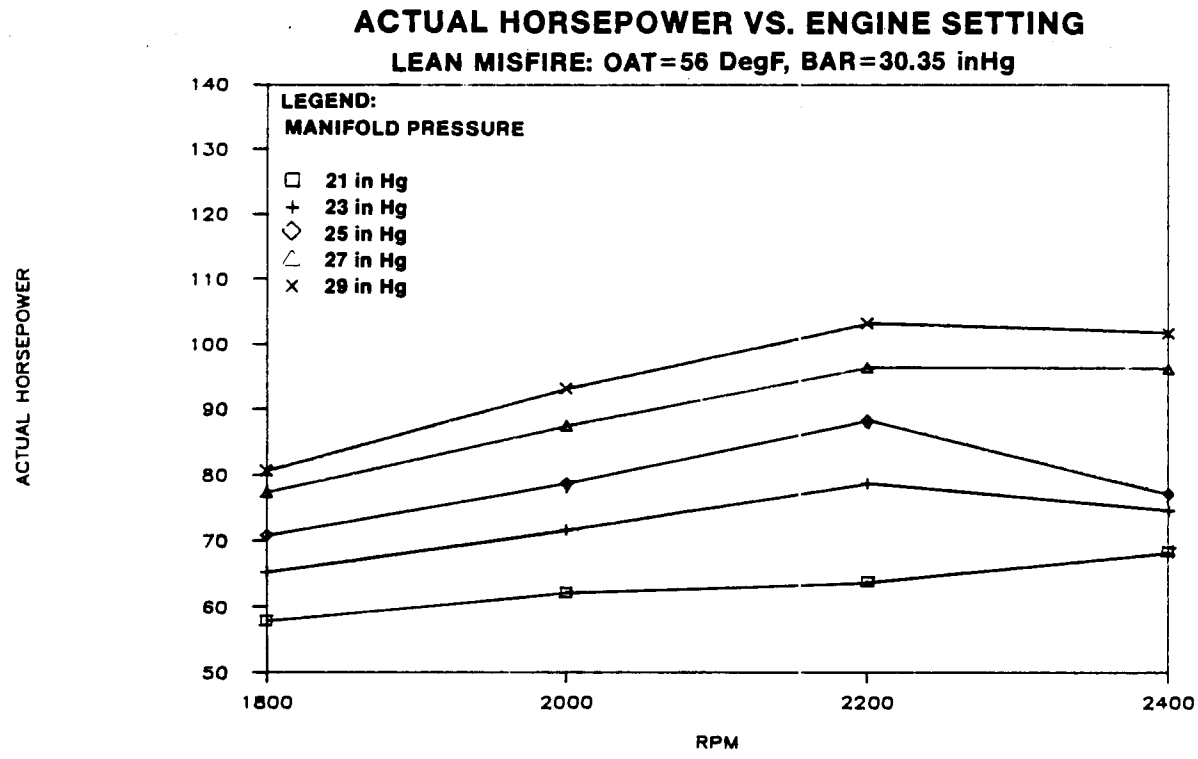




FIGURE 27. HORSEPOWER OVER A RANGE OF POWER SETTINGS FOR RICH AND LEAN MIXTURES WHEN USING METHANOL

TABLE 13. BSFC FOR METHANOL AND AVGAS IN A CARBURETED ENGINE

| Power Setting (RPM/inHg) | Brake Specific Fuel Consumption (lbm/hp-hr) | | |
|---|---|---|---|
| | Avgas | Methanol (rich) | Methanol (lean) |
| 2700/FT* | 0.60 | 0.85 | N/A+ |
| 2600/27 | 0.63 | 0.88 | N/A |
| 2500/25 | 0.65 | 0.89 | N/A |
| 2400/24 | 0.62 | 0.92 | 0.98 |
| 2300/23 | 0.61 | 0.91 | 0.93 |
| 2200/22 | 0.62 | 0.94 | 0.93 |
| 2100/21 | 0.65 | 0.97 | 0.93 |
| 2000/20 | 0.66 | 0.99 | N/A |

*Full throttle
+Not available

A number of vapor lock tests were conducted with the methanol and 15 percent autogas blends. Below 43 degrees Celsius (110 degrees Fahrenheit), vapor lock could not be induced. With the tank temperature at 43 degrees Celsius, vapor lock occurred only at the takeoff power setting and with the line heaters set at 250 (the maximum setting used throughout the program). The sediment bowl temperature under these conditions was slightly lower than the boiling point of methanol. A tank temperature of 49 degrees Celsius (120 degrees Fahrenheit) resulted in vapor lock throughout the range of fuel flows, with vapor lock occurring sooner at the higher fuel flow rates. The sediment bowl temperatures were 10 to 15 degrees Celsius lower than the boiling point of methanol for the higher fuel flow rates, and the pump inlet pressures were high enough to indicate that the vapor lock was not occurring in the sediment bowl with this fuel. The pump outlet temperatures just prior to vapor lock were close to the boiling point of methanol, indicating the fuel was boiling in the pump itself. In general, the power loss with the 15 percent autogas in methanol blend and ethanol fuels was very abrupt. This contrasts with the autogas and alcohol blend (the alcohol blends are primarily gasoline) results, where some misfire preceded power loss. Apparently, once a fuel which is primarily made of one component reaches the boiling point of that component, enough vapor is generated to result in fuel starvation.

When testing the different modifications to the carburetor in order to obtain stoichiometric fuel-to-air ratios with methanol, the engine would be started and set on a data point using ethanol. The CHTs were typically hotter when running on the ethanol fuel than when running on the methanol fuel, and when the methanol fuel was selected, detonation resulted. This was similar to the problems associated with switching to ethanol after setting a point on gasoline.

There was a preignition problem with methanol that was significantly different from the detonation mentioned above. When running at high power settings for extended periods of time and with reduced cooling air pressures, the CHTs would suddenly rise at a rate of approximately 100 to 150 degrees Celsius per minute. Coupled with this sudden temperature rise, the power would drop dramatically. The throttle would have to be reduced to idle settings in order to stop the temperature rise and to stabilize the power being developed. It appears as though some internal engine component reached the spontaneous ignition point for methanol (470 degrees Celsius) and the mixture would begin to burn as it entered

the combustion chamber. A boroscope examination of the engine following the first of these events revealed evidence of thermal damage to the piston top and scuff marks on the cylinder wall. A compression check yielded normal results, so testing was continued without replacing the piston.

During one of the runs to accumulate time on the engine with the 15 percent autogas in methanol blends, the fuel in one tank was freshly blended and the fuel in the other was fuel which had been heated to 49 degrees Celsius for the vapor lock tests. At the cruise power setting, the mixture was set to just rich of the lean misfire limit on the freshly blended fuel. When the tank containing the heated fuel was selected, the engine began to misfire and enriching the mixture improved the performance. This phenomena was probably caused by a combination of the following: as the alcohol fuel was heated it absorbed water, and heating the fuel boiled off some of the gasoline which had been blended with the methanol. Both of these reduce the energy content of the fuel, resulting in a leaner mixture than with the freshly blended fuel.

There was a substantial number of material compatibility problems associated with running neat methanol and the 15 percent gasoline in methanol blends. The neoprene tips on the carburetor needle valve would swell so badly that there would not be enough fuel flow to accelerate the engine out of the idle condition.

As mentioned earlier, the selector valve seized after a relatively short period of operation on methanol, and the tanks showed some evidence of internal oxidation with methanol. The discharge end of the acceleration pump, the main jet, and the idle jets were coated with a white residue at the end of the methanol runs. These areas, which are made of brass, also appeared to be slightly pitted.

A sample of methanol was mixed with 15 percent TBA and this blend was tested in the carbureted engine. The increase in energy density allowed the engine to operate but the performance was still less than satisfactory. Carburetor heat was added to see the effect it would have on the power developed. Figure 28 shows the effect of the carburetor inlet temperature on the horsepower that was developed. The engine speed was 2400 rpm and the manifold pressure was 24 inHg for this set of data. Initially, carburetor heat reduced the power as expected; but when the temperature of the inlet air was raised above the boiling point of methanol, the power began to increase. A plot of the horsepower versus carburetor inlet temperature is also shown for the 15 percent autogas in methanol blend. In this case, the power decreased with increasing inlet temperature throughout the entire range. This implies that the methanol/TBA blend is not fully vaporizing before entering the combustion chamber, resulting in maldistribution and reduced power. This confirms the results noted earlier with the fuel injected engine.

During the course of the endurance runs with methanol, the oil level was checked following every test. On cool days (8 degrees Celsius or cooler), there would be a white foam on the dipstick following each test. This confirms oil compatibility problems that were reported in the literature.

A barrel of 15 percent autogas in methanol was accidentally contaminated with an unknown amount of water during the course of the program. A fuel sample, which was drawn from this barrel, had a white milky appearance and it would not run in the engine. Once again, this highlights the need for improved housekeeping to keep water away from any fuel containing alcohol.

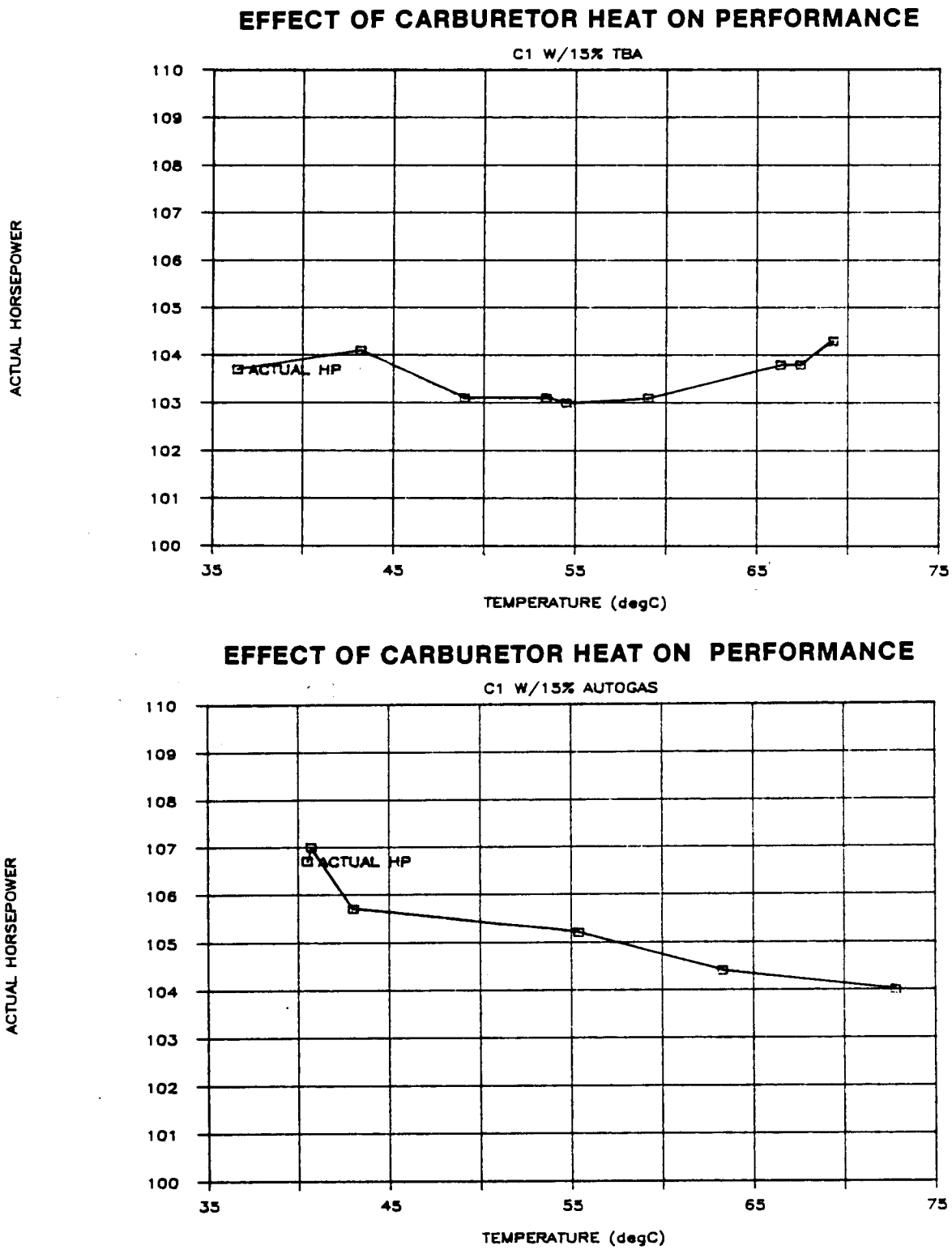



FIGURE 28. HORSEPOWER VERSUS CARBURETOR INLET TEMPERATURE

OTHER FUELS. An unleaded racing gasoline was tested to determine if there was a commercially available, unleaded fuel for use in the engines which were originally certified on 91/96 octane avgas. This might become a concern once the lead is phased out of the automobile gasoline and it is no longer feasible to produce TEL in the limited quantities needed for aviation gasoline production. Table 14 contains the specifications provided by Sun Marketing and Refining. The ERVP measured following delivery was 8.4 psig and the distillation curve following delivery is shown in figure 29. The entire test sequence with this fuel was conducted with the fuel injection system installed on the engine.

The vapor lock sequences conducted with this fuel indicated that its vapor lock behavior was similar to that of normal unleaded gasolines with an RVP of about 8.5 psig, and the conditions most likely to result in vapor lock were 43 degrees Celsius (110 degrees Fahrenheit) fuel temperature and takeoff fuel flows.

Attempts to induce detonation in the engine, while operating on the unleaded racing gasoline, were unsuccessful. The BSFC at cruise power settings and with the mixture set to best power were about 0.45 lbm/hp-hr. No problems with either the elastomers in the fuel system or with engine operations were noted during the tests conducted with this fuel.

MTBE was tested with both the standard carburetor and a modified carburetor installed on the engine. These tests were conducted prior to flight tests using MTBE that were conducted at the National Institute of Petroleum and Energy Research, Bartlesville, OK.

The results with the standard carburetor installed indicated the engine would not detonate, but the cylinder head temperatures ran about 25 degrees Celsius hotter than the recommended maximum CHT. This was a consequence of running the engine lean of peak EGT since the energy content of MTBE is lower than for gasoline. Retarding the timing from the standard setting of 25 degrees BTDC to 20 degrees BTDC reduced the CHTs but also reduced the power by about 5 percent. With the modified carburetor installed, the best power was obtained with the timing set to 25 degrees BTDC.

A vapor lock sequence was conducted. The MTBE would vapor lock whenever the sediment bowl temperature reached the boiling point of the fuel, 55 degrees Celsius (131 degrees Fahrenheit). The hotter the tank, the more likely the fuel would vapor lock; and the greater the fuel flow, the greater the chance of vapor lock. The maximum temperature tested was 43 degrees Celsius. It should be noted that the onset of vapor lock was very abrupt. This was similar to the results obtained with the methanol and ethanol fuels. It appears that once a fuel consisting primarily of a single constituent approaches the boiling point of that constituent, enough vapor is formed to immediately result in power loss. The EGT does not give any indication of a change in mixture nor does the pump outlet pressure. The pump inlet pressure gives some indication of vapor lock but does not give the warning one would receive if operating on a gasoline.

The fuel-to-air ratio was adjusted to near stoichiometric for MTBE by installing the modified carburetor used with methanol, then leaning to obtain the best power. The power developed under these conditions was approximately 6 percent higher than the power obtained with avgas, and the BSFC was 0.57 lbm/hp-hr. This compares favorably with the BSFC figures obtained with avgas. The air-to-fuel ratio at takeoff power, under these conditions, was approximately 10.6 to 1.

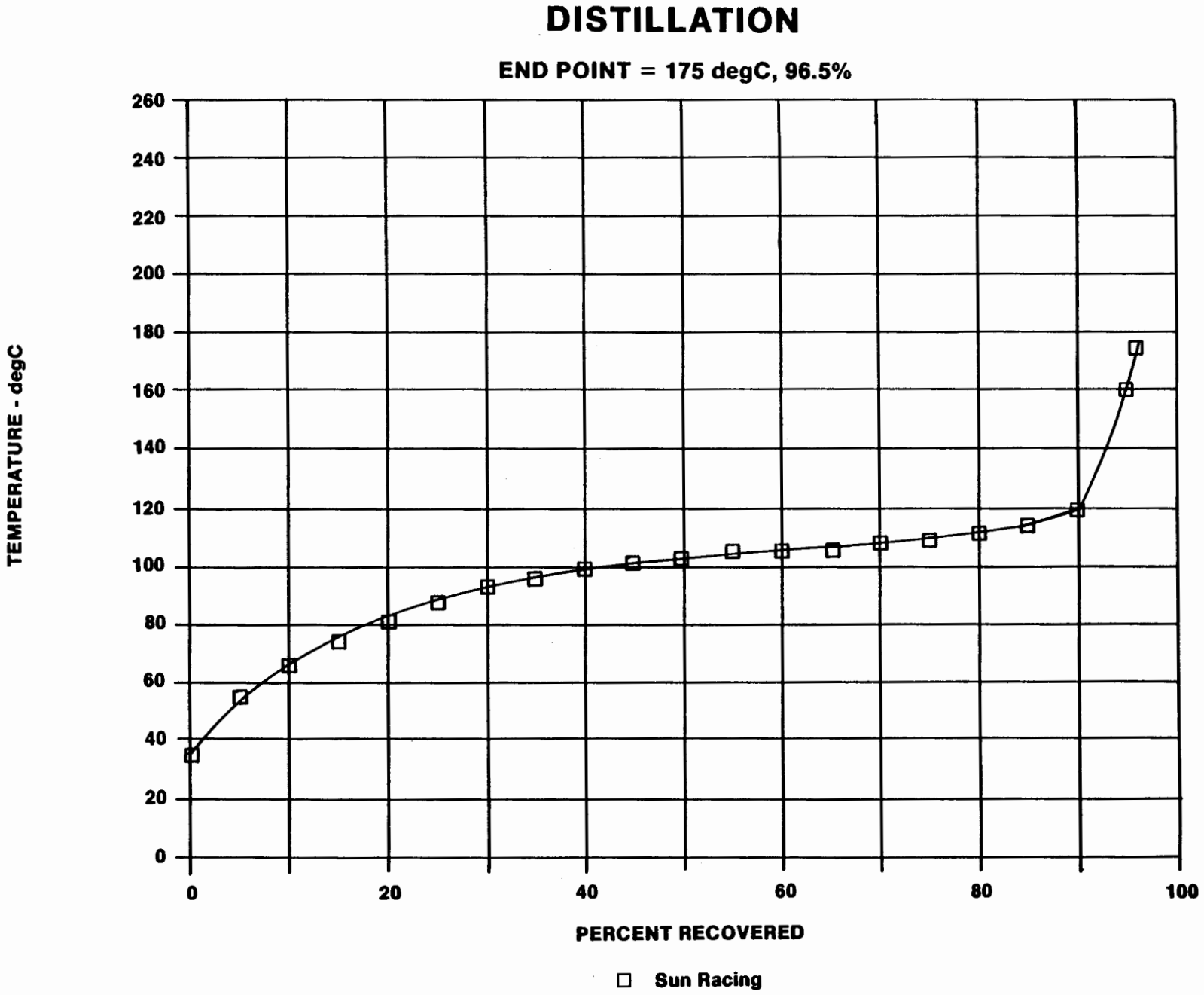



FIGURE 29. DISTILLATION CURVE FOR UNLEADED RACING GASOLINE

TABLE 14. UNLEADED RACING GASOLINE SPECIFICATIONS

| Item | Result | Specification |
|---|---|---|
| API Gravity, ASTM D287 | 57.3 | |
| Research Octane No., ASTM D2699 | 103.8 | |
| Motor Octane, ASTM D2700 | 92.4 | |
| Sensitivity, (R-M) | 11.4 | |
| Octane, (R+M)/2 | 98.1 | 98.0 Min. |
| Reid Vapor Pressure, psi | | |
| ASTM D323 Automated | 9.63 | 9-11 |
| Distillation, ASTM D86 | | |
| Automated | | |
| IBP | 82 | |
| 10% Evap. | 133 | |
| 50% Evap. | 216 | |
| 90% Evap. | 238 | |
| FBP | 389 | |
| Lead, Organic g/U.S. Gal., | | |
| ASTM D3229, D2599 | 0.008 | 0.05 Max. |
| Hydrogen, Wt. %, ASTM D3343 | | |
| Sulfur, Wt. %, ASTM D2622 | | |
| Phosphorus, ppm, ASTM D3231 | | |
| Oxygenates, Vol. % | | |
| Hydrocarbon Composition, | | |
| Vol. %, ASTM D1319 | | |
| Aromatics | | |
| Olefins | | |
| Saturates | | |
| Copper Strip Corrosion, | | |
| Rating, ASTM D130 | | |
| Existent Gum, mg/100 ml, | | |
| ASTM D381 | | |
| Oxidation Stability, Minutes, | | |
| ASTM D525 | | |

The CHTs were slightly higher than those obtained with avgas at takeoff power and with the same cooling air temperature and pressure, but they were still within the limits specified for this engine.

The rubber tip of the needle valve in the carburetor float assembly swelled when exposed to MTBE. This needle valve had been exposed to methanol, and it is uncertain if that affected the amount of swell. The needle valve was replaced with a brass one for the balance of the testing.

OIL ANALYSIS. Table 15 contains the results of the oil analyses. In table 15, the number of hours the engine oil was in use, the principal type of fuel used, the wear material and particulates, and oil condition are tabulated. With the exception of the oil sample taken following the methanol runs, Spectro/Metrics Inc., reported the results as normal. The iron and silicon levels were abnormally high for the sample taken after the methanol runs.

TABLE 15. OIL ANALYSIS RESULTS

| Control | | Wear Materials&Particulates(Dimensionless) | | | | | | | | | | | Oil Condition | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time (hr) | Fuel ID | Al | Cr | Cu | Fe | Pb | Sn | Si | Mg | Mo | Ni | Ag | $H_2O$ % | Diel | Fuel % | Visc SAE | pH |
| 47 | C1 | 24 | 18 | 30 | 188 | 251 | 14 | 19 | 3.6 | 0 | 6.9 | 1.0 | <.05 | 4 | <1 | 45 | 6.3 |
| 22 | C2 | 11 | 11 | 11 | 59 | 327 | 7.1 | 5.5 | 2.7 | 0 | 5.3 | 0.9 | <.05 | 2 | <1 | 44 | 6.5 |
| 20 | C2+C1 | 15 | 11 | 13 | 67 | 544 | 6.8 | 5.2 | 3.3 | 0 | 5.8 | 2.1 | <.05 | 0 | <1 | 37 | 6.9 |
| 29 | MB | 3.4 | 1.7 | 6.4 | 27 | 1579 | 0 | 1.2 | 1.8 | 0 | 1.2 | 1.1 | <.05 | 3 | <1 | 39 | 6.5 |
| 20 | EB | 3.2 | 2.5 | 5.9 | 25 | 260 | 0.6 | 2.2 | 2.2 | 0 | 0.0 | 2.5 | <.05 | 2 | <1 | 42 | 6.7 |
| 12 | MB* | 4.5 | 2.2 | 5.5 | 21 | 460 | 0.3 | 1.1 | 2.0 | 0 | 0.0 | 0.0 | <.05 | 1 | <1 | 39 | 6.7 |
| 16 | EB* | 5.5 | 3.3 | 5.5 | 27 | 437 | 0.6 | 1.6 | 1.5 | 0 | 1.2 | 1.0 | <.05 | 4 | <1 | 42 | 6.7 |
| 24 | RG | 16 | 12 | 16 | 85 | 729 | 4.3 | 3.6 | 1.6 | 0 | 2.5 | 0.7 | <.05 | 4 | <1 | 44 | 6.5 |
| 27 | EB** | 5.0 | 8.7 | 13 | 62 | 524 | 4.1 | 2.0 | 1.9 | 0 | 1.6 | 0.6 | <.05 | 1 | <1 | 42 | 6.6 |
| 20 | EB** | 8.9 | 7.3 | 13 | 49 | 360 | 2.0 | 3.1 | 2.5 | 0 | 2.9 | 2.5 | <.05 | 2 | <1 | 44 | 6.7 |

Diel - Dielectric or Carbon Content
Visc - Viscosity
C1 - Methanol, C2 - Ethanol, RG - Racing Gasoline, MB - Methanol in Autogas, EB - Ethanol in Autogas
< - denotes less than
*Vapor lock sequence, approximately half of the time is on avgas
**Different oil than used for the other data

In general, the lead contained in the oil was higher when operating on fuels containing methanol. Indeed, the MB sample on line four of table 15 was the first time a methanol fuel was run in the engine. An inspection of the engine indicated most of the lead deposits had been scavenged from the cylinder and the exhaust system. By the time the C1 sample (line one of table 15) had been run in the engine, the exhaust system no longer appeared to be coated with any lead deposits.

A comparison of the data obtained following the vapor lock sequences (lines 6, 7, and 8 in table 15) against the data from the endurance runs (lines 3 and 4) indicates there is a trend for the oil to remain cleaner (with the exception of the lead content, as noted above) following the endurance runs. This is contrary to what was expected, since the engine was operated at high power for extended periods of time during the endurance runs and the oil was used for a longer period of time. The most significant difference between the two sets of data is use of 100LL avgas as the recovery fuel during the vapor lock runs. It is likely that the by-products of combustion associated with the TEL found in the avgas are responsible for this increased level of contamination.

The metals found in the oil were higher for the straight alcohol fuels than for the fuels containing gasoline and the methanol was worse than the ethanol. The pH of the methanol sample (line 1) was the most acidic of all the samples tested. This may be related to the white foam that was seen on the dipstick when the methanol fuels were run on cool days.

During the course of switching from the carbureted to fuel injected fuel system, the oil sump and the valve covers were removed from the engine and inspected. These inspections did not reveal any unusual sludge or varnish buildups and there was no evidence of corrosion. It should be noted that the engine was run on MTBE following the incidents where the white foam was observed on the dipstick.

REID VAPOR PRESSURE EFFECTS. The Reid Vapor Pressure is usually considered a useful indicator of the vapor lock tendencies of the fuel. The ERVP measurements made of the alcohol blends (see figures 2 and 3) did not change with alcohol concentration though the vapor lock behavior did. The GCK values did change substantially with alcohol concentration, and the changes tended to reflect the change in vapor lock behavior. Table 16 lists the average time to vapor lock and the average sediment bowl temperature for a number GCK ranges.

TABLE 16. TIME TO VAPOR LOCK AND SEDIMENT BOWL TEMPERATURE FOR GCK RANGE

| Pressure Range (psig) | Avg. Time to Vapor Lock (min.) | Avg. Sediment Bowl Temperature (degC) |
|---|---|---|
| 11 to 12 | 3.40 | 46.58 |
| 14 to 15 | 2.76 | 42.36 |
| 16 to 17 | 2.88 | 41.97 |
| 17 to 18 | 2.41 | 39.98 |
| Above 18 | 3.25 | 46.16 |

In general, the time to vapor lock decreases with increasing GCK and the sediment bowl temperature decreases with decreasing GCK. The exception is the 18-plus point, and there is only one sample in that range so the confidence in those values is limited.

The most significant differences between the Reid Method and the Gas Chek Kit are sample size and temperature. Changing the temperature in the RVP apparatus from 38 degrees Celsius to 65 degrees Celsius used in the Gas Chek Kit results in readings similar to those obtained with the Gas Chek Kit. This implies that for the Reid Method to be an effective indicator of the vapor lock behavior of an alcohol blend, the bath temperature will need to be increased to 65 degrees Celsius.

## CONCLUSIONS

An analysis of the literature identified a number of problem areas which will need to be addressed if fuels containing alcohol are to be used in general aviation aircraft:

1. Material compatibility presents the greatest area of concern. Many of the materials currently found in general aviation aircraft are susceptible to the alcohol-containing fuels. Conversely, many of the materials that have been developed for the automobile industry can be used in general aviation aircraft fuel systems.

2. The long-term effects of using fuels containing alcohols on the lubricating oil is another area of concern which needs to be addressed.

3. Corrosion of the engine and exhaust components is greater when compared to the similar components on engines that used unleaded gasoline. No data comparing alcohol-containing fuels and leaded gasoline were available.

4. The volumetric fuel efficiency (i.e., gallons per hour) is expected to decrease with increasing alcohol concentration, and it is expected to be worse for fuel containing methanol as compared to ethanol and higher order alcohols. This is offset somewhat by the high octane ratings associated with methanol and ethanol, and the fact that alcohols will burn at very lean fuel-to-air ratios.

5. In general, alcohol containing fuels can hold more water in solution than petroleum based fuels, but this feature is highly temperature dependent. Also, alcohol fuels will absorb water from the environment, and this may result in a substantially lower energy content, reduced power output, filtration problems, phase separation, and power interruptions.

6. Hard starting was identified during the literature search as one of the areas of concern. The greater the percentage of alcohol, the greater the problem is expected to be.

7. Alcohol fuels will dissolve many of the gums and residues that build up over time in a fuel system, and these gums may be deposited in filters and fine metering orifices. This may present a problem for aircraft that are using alcohol blends after operating on avgas for a number of years.

The dynamometer tests identified the conditions most likely to result in vapor lock when operating on a gasoline which contains alcohol. These conditions are a fuel temperature in the tank of from 35 to 38 degrees Celsius (95 to 100 degrees Fahrenheit), an alcohol concentration of 15 percent on a weight/weight basis, and takeoff fuel flow. Gasoline blends made with methanol, with TBA as a cosolvent, are only slightly more prone to vapor lock than blends made with ethanol. As

with straight gasolines (reference 44), the hot fuel certification tests for gasolines containing alcohols should be conducted on days when the ambient temperature exceeds 30 degrees Celsius (85 degrees Fahrenheit) and with as high a Reid Vapor Pressure fuel as allowed under ASTM specifications in effect at the time of certification. The certification tests should be conducted when the relative humidity is high, since the absorption of water from the environment increases the probability of vapor lock occurring.

The worse case for vapor lock when using straight alcohols or fuels consisting primarily of one constituent (such as MTBE) is when the fuel is near the boiling point of the principal constituent and at takeoff fuel flow. The boiling point of ethanol is 78 degrees Celsius (172 degrees Fahrenheit), and realistically, the fuel in the tank will never reach this temperature. Results of a temperature survey (reference 45) indicate that the maximum fuel temperature is approximately 46 degrees Celsius (115 degrees Fahrenheit) for white tanks and 52 degrees Celsius (125 degrees Fahrenheit) for black tanks. The use of these temperatures as certification criteria will provide realistic certification tests for straight alcohol fuels.

During the course of testing the alcohol blends, the absorption of water from the air was more of a problem than indicated in the literature, and phase separation was regularly observed. The existing system of using a tank sump and sediment bowl did not provide enough protection to prevent accidental power loss. The rate of absorption appears to be related to the temperature of the fuel and the relative humidity.

The only problem experienced with water contamination of the straight alcohol fuels was the consequence of the accidental addition of bulk water to a methanol fuel which contained 15 percent gasoline. The result was an emulsion which would not run in the test engine.

The motor octane number is indicative of the detonation characteristics of gasoline/alcohols blends in the test engine. If the alcohol is added to the fuel to boost the octane rating, then the loss of the alcohol due to phase separation will lower the octane rating of the remaining fuel. This may result in detonation if the octane rating of the remaining fuel is lower than the engine requirements.

Detonation or preignition was observed with the straight alcohol fuels containing methanol being worse than the ethanol. This was not expected since the octane ratings of the alcohols were higher than the autogas which had been tested previously. Two conditions resulted in detonation or preignition. The first was the consequence of switching from a fuel with a higher energy density to an alcohol fuel. The other occurred when the engine was operated on methanol at near stoichiometric fuel-to-air ratios and at takeoff power.

The metals in the fuel system used during the ground-based tests experienced corrosion when exposed to the alcohol blends. Some of this was a consequence of the corrosive nature of the alcohol/water phase which separated from the gasoline blends. The amount of corrosion was worse using the blends made with methanol than the blends made with ethanol.

The use of straight alcohol fuels may result in severe corrosion problems in the existing fleet of general aviation aircraft. The use of methanol will result in more problems than ethanol.

Many of the synthetic materials found in the fuel system used in these tests were susceptible to attack from gasolines containing alcohol. In general, the blends made with methanol resulted in more problems than the blends made with ethanol. The use of straight ethanol did not result in any problems which were not previously experienced with the gasoline blends. Methanol did result in some severe swelling of neoprene rubber components which eventually restricted the flow of fuel to the engine.

An oil analysis conducted as a part of this study indicates the level of contamination is related to the fuel in use. Methanol resulted in the most contaminants followed by ethanol, gasolines containing methanol, and gasolines containing ethanol. There were indications that the use of methanol would result in unacceptable levels of contamination.

It was extremely difficult to recover from vapor lock when the fuel being studied contained any alcohol. This appears to be related to a solubility problem with avgas. Problems with engine operations may be encountered in flight if one tank contains avgas and the other contains an alcohol blend.

Attempts at optimizing the fuel consumption when operating on straight alcohol improved the fuel consumption somewhat, but they did not result in the gains predicted in the literature. To reach these gains the engine and spark ignition will need to be redesigned specifically for the use of alcohol fuels. Operations just rich of the lean misfire limit may result in engine stoppage when switching tanks, if the fuel in the second tank does not contain a fuel which has the same or higher energy density as the fuel in the first tank.

Up to 15 percent gasoline was added to methanol and 10 percent to ethanol in order to improve the cold starting behavior and engine smoothness. When the ambient conditions were cooler than 8 degrees Celsius (46 degrees Fahrenheit) the engine would not operate on methanol without being preheated. The gasoline acts as a denaturing agent; it will prevent the existence of explosive fuel/air mixtures in the ullage space in the tank; and it will render the flame luminous under most circumstances. These small amounts of gasoline did not adversely affect the vapor lock behavior of the fuels.

The tests indicate MTBE has the potential to be used as a replacement for avgas. Some engine modifications will need to be made to compensate for the lower energy density however.

The unleaded racing gasoline tested performed satisfactorily in the test engine.

Valve seat recession was not measured, and the absence of lead in many of the fuels may result in greater valve-seat wear.

Dissolved air in the alcohol blends may collect in the fuel injection unit and result in power loss.

Fuel venting overboard could result in reduced operating ranges when using alcohol blends.

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# APPENDIX A BLENDING CALCULATIONS

METHANOL CALCULATIONS:

T = weight of TBA
M = weight of methanol
G = weight of the base gasoline
P = desired percentage of alcohol

$$P = \frac{M}{G + M + T}$$

For our purposes M = T so:

$$P = \frac{M}{G + (2\ M)}$$

We know the weight of gasoline and the desired percentage of alcohol so we can solve for the weight of methanol.

$$M = P(G + (2M))$$

$$M - P(2M) = PG$$

$$M\ (1-(2P)) = PG$$

$$M = \frac{PG}{1 - 2\ P} = T$$

EXAMPLE:

We have 210 lbs. of base gasoline and we want 20% methanol in the blended fuel.

$$M = \frac{(.2)210}{1 - 2(.2)}$$

M = 70 lbs of methanol

therefore we add 70 lbs of methanol to the base fuel and 70 lbs of TBA. As a check:

$$\frac{70}{210 + 70 + 70} = .2$$

ETHANOL CALCULATIONS:

E = weight of denatured ethanol
G = weight of the base gasoline
P = the desired percentage of alcohol

The denatured ethanol we are using is 97% ethanol and 3% avgas so:

$$P = \frac{.97E}{G + E}$$

Solving for E:

$$.97E = P(G + E)$$

$$E(.97 - P) = PG$$

$$E = \frac{PG}{.97 - P}$$

Example:
We have 280 lbs of base gasoline and we want 5% ethanol in the blend. The equasion becomes:

$$E = \frac{.05(280)}{.97 - .05}$$

$$E = 15.2 \text{ lbs}$$

Therefore we add 15.2 lbs of tne denatured ethanol to the base gasoline. As a check:

$$\frac{.97\ (15.2)}{280 + 15.2} = .05$$

APPENDIX B ALCOHOL BLEND DATA

| FUEL ID | INIT ERVP psig | INIT GCK psig | INIT TEMP degF | FUEL FLOW gph | LINE HEATER SETTING | AUTO LINE degC | SED BOWL degC | F.I. INLET degC | TIME TO VL min | POST ERVP psig | POST GCK psig |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NBF | 11.2 | 11.3 | 110 | 2.5 | 150 | 58 | 47 | 43 | 6.25 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 5.0 | 150 | 45 | 48 | 53 | 5.50 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 7.5 | 110 | 45 | 49 | 54 | 3.75 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 10.0 | 110 | 45 | 49 | 55 | 2.50 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 12.5 | 110 | 46 | 47 | 48 | 1.00 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 14.5 | 110 | 45 | 47 | 47 | 0.75 | 10.1 | 10.8 |
| NBF | 11.2 | 11.3 | 110 | 2.5 | 150 | 54 | 45 | 44 | 5.83 | 7.7 | 10.9 |
| NBF | 11.2 | 11.3 | 110 | 5.0 | 150 | 43 | 47 | 54 | 5.50 | 7.7 | 10.9 |
| NBF | 11.2 | 11.3 | 110 | 7.5 | 110 | 43 | 47 | 54 | 3.67 | 7.7 | 10.9 |
| NBF | 11.2 | 11.3 | 110 | 10.0 | 110 | 44 | 48 | 55 | 2.67 | 7.7 | 10.9 |
| NBF | 11.2 | 11.3 | 110 | 12.5 | 110 | 45 | 49 | 55 | 1.83 | 7.7 | 10.9 |
| NBF | 11.2 | 11.3 | 110 | 14.5 | 110 | 45 | 48 | 55 | 1.50 | 7.7 | 10.9 |
| 5%-C2 | 11.8 | 14.9 | 90 | 2.5 | 150 | 40 | 43 | 41 | 6.50 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 90 | 5.0 | 150 | 43 | 42 | 47 | 6.00 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 90 | 7.5 | 90 | 33 | 38 | 47 | 3.17 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 90 | 10.0 | 90 | 34 | 39 | 47 | 2.17 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 90 | 12.5 | 90 | 34 | 38 | 46 | 1.50 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 90 | 14.5 | 90 | 34 | 37 | 42 | 0.83 | 10.7 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 2.5 | 150 | 50 | 45 | 40 | 6.00 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 5.0 | 150 | 43 | 46 | 52 | 5.17 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 7.5 | 110 | 43 | 46 | 51 | 3.17 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 10.0 | 110 | 44 | 45 | 47 | 2.33 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 12.5 | 110 | 43 | 45 | 45 | 1.50 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 110 | 14.5 | 110 | 44 | 45 | 45 | 0.83 | 9.1 | 13.1 |
| 5%-C2 | 11.8 | 14.9 | 120 | 2.5 | 150 | 58 | 47 | 41 | 6.33 | 7.7 | 11.5 |
| 5%-C2 | 11.8 | 14.9 | 120 | 5.0 | 150 | 49 | 49 | 53 | 5.67 | 7.7 | 11.5 |
| 5%-C2 | 11.8 | 14.9 | 120 | 7.5 | 120 | 48 | 50 | 54 | 4.00 | 7.7 | 11.5 |
| 5%-C2 | 11.8 | 14.9 | 120 | 10.0 | 120 | 48 | 51 | 55 | 3.00 | 7.7 | 11.5 |
| 5%-C2 | 11.8 | 14.9 | 120 | 12.5 | 120 | 48 | 51 | 53 | 1.33 | 7.7 | 11.5 |
| 5%-C2 | 11.8 | 14.9 | 120 | 14.5 | 120 | 48 | 51 | 50 | 1.17 | 7.7 | 11.5 |
| 10%-C2 | 11.2 | 18.1 | 100 | 2.5 | 150 | 44 | 41 | 41 | 5.83 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 100 | 5.0 | 100 | 38 | 42 | 48 | 3.83 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 100 | 7.5 | 100 | 39 | 43 | 48 | 2.50 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 100 | 10.0 | 100 | 39 | 43 | 48 | 2.00 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 100 | 12.5 | 100 | 39 | 41 | 44 | 1.00 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 100 | 14.5 | 100 | 38 | 40 | 38 | 0.67 | 10.6 | 13.4 |
| 10%-C2 | 11.2 | 18.1 | 110 | 2.5 | 150 | 53 | 46 | 44 | 7.00 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 110 | 5.0 | 110 | 46 | 45 | 51 | 4.00 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 110 | 7.5 | 110 | 44 | 46 | 52 | 3.00 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 110 | 10.0 | 110 | 45 | 46 | 50 | 1.67 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 110 | 12.5 | 110 | 46 | 44 | 45 | 0.83 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 110 | 14.5 | 110 | 46 | 44 | 44 | 0.50 | 9.8 | 14.3 |
| 10%-C2 | 11.2 | 18.1 | 120 | 2.5 | 150 | 56 | 50 | 45 | 6.17 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 5.0 | 150 | 54 | 52 | 56 | 5.67 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 7.5 | 150 | 48 | 52 | 56 | 5.50 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 10.0 | 120 | 48 | 51 | 55 | 3.50 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 12.5 | 120 | 49 | 50 | 53 | 2.17 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 14.5 | 120 | 48 | 49 | 49 | 1.00 | 6.7 | 13.2 |
| 10%-C2 | 11.2 | 18.1 | 120 | 7.5 | 120 | 51 | 52 | 56 | 4.83 | 6.7 | 13.2 |
| 15%-C2 | 11.3 | 17.4 | 90 | 2.5 | 150 | 39 | 42 | 41 | 6.67 | 10.4 | 14.4 |

| FUEL ID | INIT ERVP psig | INIT GCK psig | INIT TEMP degF | FUEL FLOW gph | LINE HEATER SETTING | AUTO LINE degC | SED BOWL degC | F.I. INLET degC | TIME TO VL min | POST ERVP psig | POST GCK psig |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5%-C1 | 11.5 | 14.8 | 110 | 2.5 | 150 | 47 | 43 | 42 | 6.33 | 10.0 | 15.1 |
| 5%-C1 | 11.5 | 14.8 | 110 | 5.0 | 150 | 47 | 44 | 51 | 5.83 | 10.0 | 15.1 |
| 5%-C1 | 11.5 | 14.8 | 110 | 7.5 | 110 | 44 | 45 | 50 | 2.83 | 10.0 | 15.1 |
| 5%-C1 | 11.5 | 14.8 | 110 | 10.0 | 110 | 44 | 45 | 51 | 2.33 | 10.0 | 15.1 |
| 5%-C1 | 11.5 | 14.8 | 110 | 12.5 | 110 | 45 | 45 | 50 | 1.50 | 10.0 | 15.1 |
| 5%-C1 | 11.5 | 14.8 | 110 | 14.5 | 110 | 44 | 44 | 44 | 0.83 | 10.0 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 90 | 2.5 | 150 | 39 | 38 | 42 | 5.83 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 90 | 5.0 | 90 | 34 | 37 | 46 | 2.00 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 90 | 7.5 | 90 | 33 | 36 | 47 | 1.17 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 90 | 10.0 | 90 | 34 | 36 | 44 | 1.17 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 90 | 12.5 | 90 | 34 | 37 | 45 | 0.83 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 90 | 14.5 | 90 | 35 | 36 | 44 | 0.50 | 11.8 | 17.8 |
| 10%-C1 | 12.4 | 17.5 | 100 | 2.5 | 150 | 45 | 42 | 44 | 6.17 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 100 | 5.0 | 100 | 38 | 41 | 49 | 3.83 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 100 | 7.5 | 100 | 39 | 41 | 48 | 2.17 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 100 | 10.0 | 100 | 38 | 42 | 50 | 2.33 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 100 | 12.5 | 100 | 38 | 42 | 49 | 1.50 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 100 | 14.5 | 100 | 38 | 42 | 48 | 1.33 | 9.9 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 2.5 | 150 | 49 | 44 | 44 | 5.67 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 5.0 | 110 | 42 | 45 | 52 | 3.67 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 7.5 | 110 | 44 | 45 | 50 | 2.00 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 10.0 | 110 | 44 | 45 | 50 | 2.50 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 12.5 | 110 | 44 | 45 | 48 | 1.17 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 110 | 14.5 | 110 | 44 | 43 | 45 | 0.67 | 8.6 | 15.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 2.5 | 150 | 38 | 37 | 42 | 5.33 | 11.0 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 5.0 | 85 | 29 | 36 | 45 | 2.22 | 11.0 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 7.5 | 85 | 30 | 35 | 45 | 2.33 | 11.0 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 10.0 | 85 | 31 | 36 | 44 | 1.50 | 11.0 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 12.5 | 85 | 31 | 36 | 42 | 1.00 | 11.0 | 16.1 |
| 10%-C1 | 12.4 | 17.5 | 85 | 14.5 | 85 | 30 | 34 | 40 | 0.67 | 11.0 | 16.1 |
| 15%-C1 | 11.5 | 16.5 | 90 | 2.5 | 150 | 33 | 39 | 41 | 6.00 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 90 | 5.0 | 90 | 33 | 38 | 47 | 3.00 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 90 | 7.5 | 90 | 33 | 38 | 47 | 2.83 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 90 | 10.0 | 90 | 34 | 40 | 49 | 2.17 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 90 | 12.5 | 90 | 34 | 39 | 48 | 1.83 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 90 | 14.5 | 90 | 33 | 38 | 47 | 1.83 | 8.2 | 15.3 |
| 15%-C1 | 11.5 | 16.5 | 100 | 2.5 | 150 | 45 | 42 | 44 | 7.00 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 100 | 5.0 | 100 | 37 | 42 | 51 | 4.25 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 100 | 7.5 | 100 | 37 | 41 | 50 | 3.17 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 100 | 10.0 | 100 | 39 | 43 | 50 | 3.25 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 100 | 12.5 | 100 | 38 | 42 | 50 | 2.00 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 100 | 14.5 | 100 | 39 | 41 | 46 | 1.10 | 10.8 | 16.2 |
| 15%-C1 | 11.5 | 16.5 | 110 | 2.5 | 150 | 47 | 46 | 43 | 6.00 | 8.8 | 14.3 |
| 15%-C1 | 11.5 | 16.5 | 110 | 5.0 | 150 | 46 | 46 | 53 | 5.50 | 8.8 | 14.3 |
| 15%-C1 | 11.5 | 16.5 | 110 | 7.5 | 110 | 43 | 46 | 52 | 3.00 | 8.8 | 14.3 |
| 15%-C1 | 11.5 | 16.5 | 110 | 10.0 | 110 | 44 | 47 | 53 | 2.50 | 8.8 | 14.3 |
| 15%-C1 | 11.5 | 16.5 | 110 | 12.5 | 110 | 44 | 47 | 51 | 2.00 | 8.8 | 14.3 |
| 15%-C1 | 11.5 | 16.5 | 110 | 14.5 | 110 | 44 | 47 | 52 | 1.67 | 8.8 | 14.3 |
| 20%-C1 | 10.9 | 14.4 | 90 | 2.5 | 150 | 38 | 40 | 43 | 7.17 | 9.3 | 15.1 |
| 20%-C1 | 10.9 | 14.4 | 90 | 5.0 | 150 | 34 | 38 | 48 | 5.50 | 9.3 | 15.1 |

| FUEL ID | INIT ERVP psig | INIT GCK psig | INIT TEMP degF | FUEL FLOW gph | LINE HEATER SETTING | AUTO LINE degC | SED BOWL degC | F.I. INLET degC | TIME TO VL min | POST ERVP psig | POST GCK psig |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 15%-C2 | 11.3 | 17.4 | 90 | 5.0 | 90 | 32 | 38 | 47 | 3.00 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 90 | 7.5 | 90 | 33 | 37 | 48 | 2.50 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 90 | 10.0 | 90 | 33 | 38 | 48 | 3.00 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 90 | 12.5 | 90 | 34 | 38 | 49 | 1.83 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 90 | 14.5 | 90 | 34 | 38 | 48 | 1.50 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 90 | 12.5 | 90 | 34 | 38 | 49 | 2.17 | 10.4 | 14.4 |
| 15%-C2 | 11.3 | 17.4 | 100 | 2.5 | 150 | 45 | 41 | 41 | 5.67 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 100 | 5.0 | 100 | 39 | 38 | 41 | 1.83 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 100 | 7.5 | 100 | 39 | 38 | 40 | 1.33 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 100 | 10.0 | 100 | 38 | 38 | 41 | 0.83 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 100 | 12.5 | 100 | 39 | 38 | 39 | 0.50 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 100 | 14.5 | 100 | 38 | 38 | 38 | 0.50 | 10.7 | 14.6 |
| 15%-C2 | 11.3 | 17.4 | 110 | 2.5 | 150 | 46 | 44 | 43 | 5.67 | 7.4 | 13.8 |
| 15%-C2 | 11.3 | 17.4 | 110 | 5.0 | 110 | 43 | 45 | 51 | 3.00 | 7.4 | 13.8 |
| 15%-C2 | 11.3 | 17.4 | 110 | 7.5 | 110 | 43 | 45 | 50 | 2.50 | 7.4 | 13.8 |
| 15%-C2 | 11.3 | 17.4 | 110 | 10.0 | 110 | 44 | 45 | 48 | 1.67 | 7.4 | 13.8 |
| 15%-C2 | 11.3 | 17.4 | 110 | 12.5 | 110 | 44 | 45 | 48 | 1.33 | 7.4 | 13.8 |
| 15%-C2 | 11.3 | 17.4 | 110 | 14.5 | 110 | 44 | 44 | 44 | 0.83 | 7.4 | 13.8 |
| 20%-C2 | 10.9 | 16.3 | 90 | 2.5 | 150 | 43 | 40 | 43 | 6.00 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 5.0 | 90 | 36 | 39 | 48 | 2.33 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 7.5 | 90 | 33 | 39 | 48 | 2.33 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 10.0 | 90 | 34 | 38 | 47 | 1.83 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 12.5 | 90 | 34 | 37 | 48 | 1.00 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 14.5 | 90 | 36 | 38 | 45 | 0.67 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 90 | 12.5 | 90 | 35 | 38 | 47 | 0.83 | 10.2 | 14.3 |
| 20%-C2 | 10.9 | 16.3 | 100 | 2.5 | 150 | 50 | 42 | 44 | 5.83 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 100 | 5.0 | 100 | 37 | 41 | 49 | 3.00 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 100 | 7.5 | 100 | 38 | 42 | 48 | 2.00 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 100 | 10.0 | 100 | 38 | 41 | 48 | 1.50 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 100 | 12.5 | 100 | 39 | 41 | 47 | 1.00 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 100 | 14.5 | 100 | 39 | 41 | 46 | 0.67 | 10.2 | 15.1 |
| 20%-C2 | 10.9 | 16.3 | 110 | 2.5 | 150 | 47 | 45 | 44 | 5.83 | 7.9 | 15.6 |
| 20%-C2 | 10.9 | 16.3 | 110 | 5.0 | 150 | 44 | 46 | 52 | 5.33 | 7.9 | 15.6 |
| 20%-C2 | 10.9 | 16.3 | 110 | 7.5 | 110 | 44 | 46 | 51 | 2.67 | 7.9 | 15.6 |
| 20%-C2 | 10.9 | 16.3 | 110 | 10.0 | 110 | 44 | 46 | 51 | 2.17 | 7.9 | 15.6 |
| 20%-C2 | 10.9 | 16.3 | 110 | 12.5 | 110 | 44 | 46 | 50 | 1.50 | 7.9 | 15.6 |
| 20%-C2 | 10.9 | 16.3 | 110 | 14.5 | 110 | 45 | 45 | 48 | 1.00 | 7.9 | 15.6 |
| 5%-C1 | 11.5 | 14.8 | 90 | 2.5 | 150 | 35 | 38 | 45 | 5.33 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 90 | 5.0 | 90 | 33 | 38 | 47 | 1.67 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 90 | 7.5 | 90 | 35 | 37 | 44 | 1.17 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 90 | 10.0 | 90 | 34 | 37 | 47 | 1.00 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 90 | 12.5 | 90 | 35 | 37 | 45 | 0.67 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 90 | 14.5 | 90 | 36 | 37 | 45 | 0.67 | 11.2 | 14.2 |
| 5%-C1 | 11.5 | 14.8 | 100 | 2.5 | 100 | 39 | 36 | 40 | 2.00 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 5.0 | 100 | 40 | 39 | 45 | 1.50 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 7.5 | 100 | 38 | 39 | 47 | 1.00 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 10.0 | 100 | 37 | 38 | 47 | 1.00 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 12.5 | 100 | 37 | 38 | 46 | 0.67 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 14.5 | 100 | 38 | 38 | 43 | 0.50 | 10.7 | 18.3 |
| 5%-C1 | 11.5 | 14.8 | 100 | 2.5 | 100 | 38 | 40 | 48 | 1.50 | 10.7 | 18.3 |

| FUEL ID | INIT ERVP psig | INIT GCK psig | INIT TEMP degF | FUEL FLOW gph | LINE HEATER SETTING | AUTO LINE degC | SED BOWL degC | F.I. INLET degC | TIME TO VL min | POST ERVP psig | POST GCK psig |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20%-C1 | 10.9 | 14.4 | 90 | 7.5 | 90 | 34 | 40 | 48 | 3.00 | 9.3 | 15.1 |
| 20%-C1 | 10.9 | 14.4 | 90 | 10.0 | 90 | 35 | 39 | 48 | 2.50 | 9.3 | 15.1 |
| 20%-C1 | 10.9 | 14.4 | 90 | 12.5 | 90 | 34 | 38 | 46 | 2.00 | 9.3 | 15.1 |
| 20%-C1 | 10.9 | 14.4 | 90 | 14.5 | 90 | 35 | 38 | 45 | 1.33 | 9.3 | 15.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 2.5 | 100 | 51 | 44 | 41 | 2.33 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 5.0 | 100 | 40 | 43 | 50 | 3.33 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 7.5 | 100 | 38 | 42 | 49 | 2.67 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 10.0 | 100 | 38 | 42 | 49 | 2.17 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 12.5 | 100 | 39 | 42 | 48 | 1.50 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 14.5 | 100 | 39 | 42 | 47 | 1.17 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 100 | 2.5 | 100 | 39 | 41 | 46 | 2.17 | 10.5 | 17.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 2.5 | 150 | 48 | 44 | 45 | 5.83 | 9.4 | 14.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 5.0 | 150 | 45 | 47 | 54 | 5.33 | 9.4 | 14.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 7.5 | 110 | 44 | 47 | 53 | 3.00 | 9.4 | 14.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 10.0 | 110 | 45 | 47 | 52 | 2.00 | 9.4 | 14.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 12.5 | 110 | 45 | 46 | 51 | 1.33 | 9.4 | 14.1 |
| 20%-C1 | 10.9 | 14.4 | 110 | 14.5 | 110 | 44 | 46 | 50 | 1.17 | 9.4 | 14.1 |

NOTES: C1 - Methanol
C2 - Ethanol
GCK - Gas Chek
F.I. - Fuel Injection
All Percentage is on a w/w basis.

APPENDIX C

DISTRIBUTION LIST

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| ADL-4 North | (1) | APS-1 | (1) | ALG-300 | (1) |
| AES-3 | (1) | APA-300 | (1) | ACT-5 | (1) |
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DOT/FAA National Headquarters
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