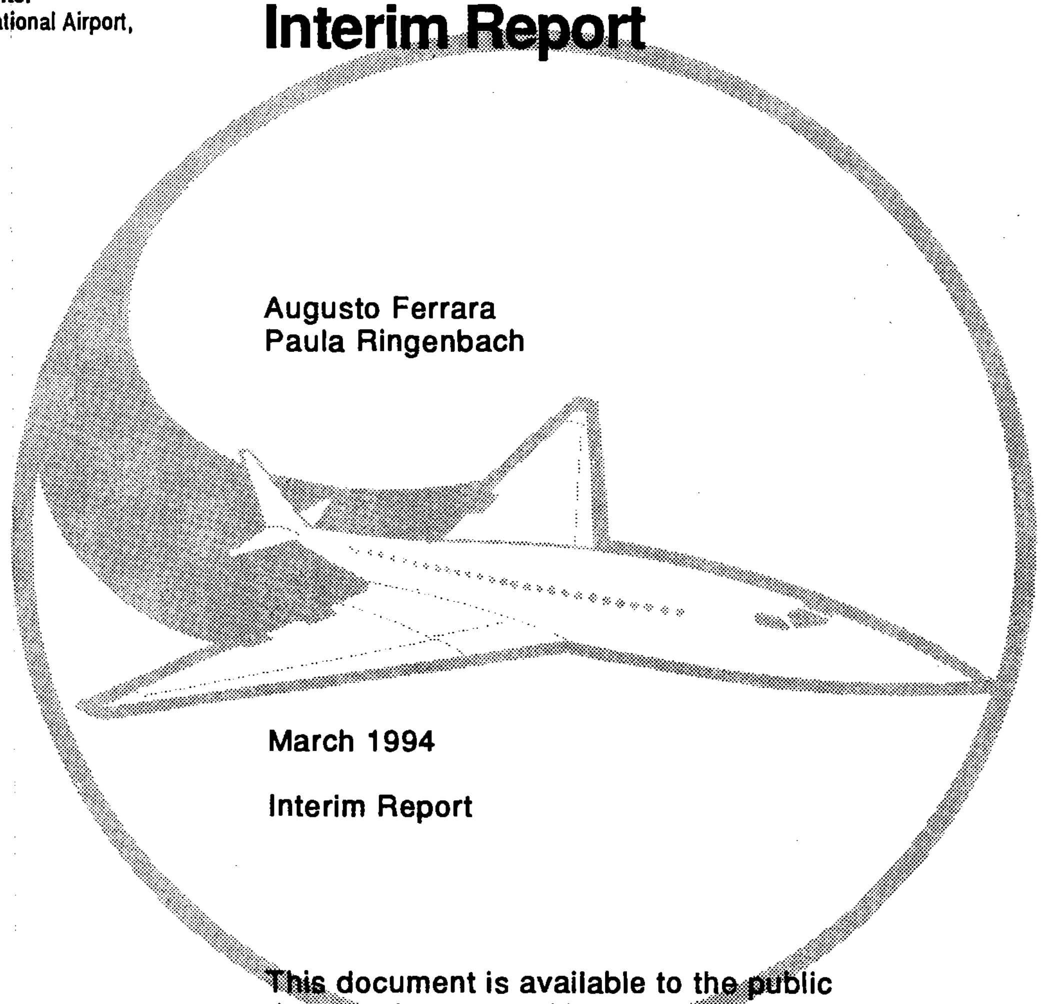
DOT/FAA/CT-93/65

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

Unleaded AVGAS Program Interim Report



Augusto Ferrara
Paula Ringenbach

March 1994

Interim Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-93/65	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle UNLEADED AVGAS PROGRAM INTERIM REPORT		5. Report Date March 1994
		6. Performing Organization Code
7. Author(s) David Atwood, Galaxy Scientific Corp. Augusto Ferrara/Paula Ringenbach, FAA Technical Center		8. Performing Organization Report No.
9. Performing Organization Name and Address Galaxy Scientific Corporation 2500 English Creek Avenue Pleasantville, NJ 08232		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		13. Type of Report and Period Covered Interim Report
		14. Sponsoring Agency Code ACD-210
15. Supplementary Notes		

16. Abstract

The Federal Aviation Administration (FAA) Technical Center has performed extensive research toward finding an unleaded replacement for the current leaded aviation gasoline for general aviation aircraft. Described in the report are testing procedures, results to date, and future testing plans. The tests include vapor lock behavior, performance, endurance, detonation analysis, material compatibility, storage stability, volatility, emissions, water miscibility, and flight testing. The volatility tests include Reid Vapor Pressure, distillation, and vapor to liquid ratio tests. The endurance tests involved periodic checks of cylinder wear, particularly valve seat wear, leak downs to determine cylinder compression loss, and oil analysis.

A variety of unleaded automobile gasolines with a large range of vapor pressures and experimental ultra-low lead aviation gasoline were tested. Special blends were prepared to obtain high octane ratings. The additives that were tested include Methyl Tertiary-Butyl-Ether (MTBE), Methylcyclopentadienyl Manganese Tri-carbonyl (MMT), Methyl Tertiary-Amyl-Ether (TAME), and Ethyl Tertiary-Butyl-Ether (ETBE).

Two different dynamometers and three engines were utilized. One dynamometer was of the eddy current design and the other was of the water brake type. Two of the engines were Lycoming IO320's and the other was a Continental TSIO360.

17. Key Words Unleaded Aviation Gasoline, Gasoline, Avgas, Vapor Lock, Piston Engine, Reid Vapor Pressure, Vapor-to-Liquid Ration, Knock, Detonation, Material Compatibility. Water Contamination, MTBE, ETBE, MMT, Engine Wear Measurements	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgments:

The FAA Technical Center would like to acknowledge the following individuals and organizations for their support of the Unleaded Avgas Program:

- Roger Gaughan and John Fowlks of Exxon Research and Engineering Company, for their assistance with conducting the knock surveys, for providing standard reference fuels, and for conducting audible knock ratings on the Technical Center's test engines.
- Dick Fullerton (retired) and Jim McKeman of Textron Lycoming for providing the vibration knock detection system and training on the use of the system.
- Richard Riley and Don Burnett of Phillips Petroleum for conducting the analysis of the ring groove deposits and samples of methyl tertiary amyl ether (TAME).
- Jack Muzako and Fred Barnes of Chevron, USA, for providing samples of test fuels.
- Jim Wheelock and Ron Wilkinson of Teledyne Continental Motors for conducting the engine tear down and analysis of the TSIO-360 engine used in this study.
- Chris Dumont of the FAA Technical Center for conceiving the numerical technique that was used to rate knock severity.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ASTM	American Society for Testing and Materials
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
ETBE	Ethyl Tertiary Butyl Ether
GAMA	General Aviation Manufacturers Association
MMT	Methylcyclopentadienyl Manganese Tri-carbonyl
MON	Motor Octane Number
MTBE	Methyl Tertiary Butyl Ether
RVP	Reid Vapor Pressure
TAME	Methyl Tertiary Amyl Ether
VLR	Vapor-to-Liquid Ratio

Executive Summary

The FAA Technical Center is conducting extensive research on the development of an unleaded aviation gasoline. This work will result in data to be used in the development of certification criteria and during the transition period from leaded to an unleaded aviation gasoline. The Congress has mandated this work as a follow on to the implementation of the requirements of the 1990 Clean Air Act Amendments.

The results presented in this report summarize the work that has been completed as of September, 1993. Several phases of the program are still underway and flight testing is planned for the summer of 1994. The principle results to date include:

- The use of ethers as octane boosters does not affect the volatility of the resulting blend. The current hot fuel certification criteria apply to fuels that are prepared with ethers.
- The use of ethers increases the power developed slightly, but the resulting increase in power does not offset the lower energy density of the resulting blend. The fuel consumption could increase as much as 5 percent when compared to the current leaded aviation gasoline.
- There is some evidence that the use of unleaded gasolines will increase valve seat wear, especially in older engines. The data indicate that new material specifications can address this issue.
- Preliminary testing indicates that the use of MMT (a manganese based octane enhancer) may result in harmful engine deposits. Tests are planned to confirm this observation.
- The Technical Center has confirmed that the use of an in-cylinder pressure transducer results in the same knock rating as the existing system of vibration pickups. The electronic systems detect the onset of knock sooner than the audible rating technique. At limiting conditions, all three systems result in the same knock rating. This is important for future cross correlation studies.
- The Technical Center has developed a numerical technique for determining the onset of knock when using in-cylinder pressure measurements. This removes the subjective nature of current knock rating systems and reduces the need to train personnel as octane raters.
- There are no significant material compatibility concerns associated with the use of either MTBE or ETBE as octane enhancers. The addition of ETBE may result in some oxidation stability concerns.
- Water contamination does not result in phase separation when using ethers as an octane blending agent.
- A motor octane number of 98 or higher will be difficult to attain using ethers as the sole octane blending agent. This value is the goal identified by GAMA in a position paper to ASTM.

[illegible]

1. INTRODUCTION.

The 1990 Clean Air Act Amendments call for the removal of lead from all motor gasolines by the end of 1995. This law also required engine manufacturers to certify their engines for operations on unleaded gasolines by 1992. At the request of the General Aviation Manufacturers Association (GAMA), the US EPA has ruled that aircraft engine manufacturers were not required to certify production engines on unleaded fuels by 1992. This ruling does not affect the 1995 deadline for removing lead from all fuels, and to date, there is no indication as to how the EPA will rule on this issue. Even if the EPA exempts aviation gasolines, the anticipation is that the economics of providing special handling and facilities for aviation fuels will render leaded aviation fuels uneconomical. As an example, burning waste oil from engines that operate on leaded fuels may soon be impossible. In light of this and in response to a request from the Congress, the FAA has begun research toward developing an unleaded aviation gasoline.

The research conducted by the FAA is primarily intended to address certification issues such as vapor lock behavior and engine performance. The research plan also calls for developing a data base to be used by the concerned organizations in addressing their particular needs. The FAA is cooperating with the engine manufacturers, the airframe manufacturers, user groups, the oil industry, and the American Society of Testing and Materials (ASTM) in performing this research.

This report describes preliminary results from the FAA Technical Center's studies on engine performance, vapor lock behavior, fuel volatility, engine wear, detonation analysis, material compatibility, fuel aging, and water contamination. Also described are future plans for emissions testing, flight testing, material compatibility, engine performance, engine wear, and detonation analysis to be performed at the Technical Center. The results from a number of tests conducted at the FAA Technical Center on the effectiveness of several octane enhancers are also presented.

1.1 BACKGROUND.

Due to the use of high octane additives, the unleaded test fuel has less energy than existing aviation gasoline (i.e., a lower energy density). In theory, certain operating conditions allow for the recovery of the lost energy by operating at a more efficient configuration (hence the term recovery). For example, the use of oxygenates should allow for operations lean of stoichiometric fuel-to-air ratios, and in theory these operations should be more efficient than operations rich of stoichiometric fuel-to-air ratios.

The American Society of Testing and Materials specifies several different octane ratings, which measure the fuel's resistance to knock for different duty cycles. The motor octane number (MON) indicates performance under a heavy duty cycle, and the Technical Center used the MON for reporting purposes. The Aviation Lean Rating can be calculated from the MON. The Aviation Rich Rating depends on the energy density of the fuel, and it is not considered repeatable for oxygenated fuels. The Technical Center used oxygenated fuels throughout this program, so the Aviation Rich Rating is not reported.

There are a number of techniques used to correct the power generated at ambient conditions to the standard conditions. For example, Lycoming has developed a rigorous correction routine which includes factors such as friction losses, vapor pressure, and the back pressure on the exhaust system. Correcting the data with the Lycoming routine involves looking up data on charts, and the volume of data generated during this program prevented the regular use of the more rigorous correction routines. The Technical Center used a modified Society of Automotive Engineers (SAE) routine which reports the net horsepower developed. At takeoff power settings, this value is typically ten horsepower less than the figure reported under the more rigorous correction routines.

The Reid Vapor Pressure (RVP) is the standard method for measuring the volatility of a gasoline. The accuracy of the RVP is ± 6.7 kPa (1 psi), and the addition of alcohols affects the accuracy of the RVP. Because of this, the Technical Center investigated the use of the vapor-to-liquid ratio (VLR) as a technique for measuring the volatility of its test fuels.

The Technical Center uses metric units in accordance with federal law. English units are presented in parentheses.

2. TESTING PROCEDURES/RESULTS.

2.1. VAPOR LOCK/VOLATILITY.

The addition of alcohol to gasoline adversely affects the volatility and water solubility of the resulting fuel. Like alcohols, the high octane ethers used in this program contain an oxygen atom, and program sponsors expressed concern about volatility issues. While the literature indicated that the use of ethers would not affect overall volatility or water solubility, the data in the literature did not specifically address volatility in aircraft applications. Since this concern affected the development of high octane unleaded gasolines and the use of oxygenated automobile gasolines in aircraft with autogas Supplemental Type Certificates (STCs), it was the first technical issue addressed in this program.

A Lycoming IO320 engine was mounted on a test stand and run on different fuel blends. The use of a normally aspirated, fuel injected engine allowed for comparison with previous tests conducted at the Technical Center. The base fuels consisted of two unleaded automobile gasolines, 100LL avgas and an experimental ultra-low lead aviation gasoline. One of the automobile gasolines had a RVP of 69 kPa (10 psi) and a MON of 84.5. The other had a RVP of 97 kPa (14 psi) and a MON of 89. The experimental ultra-low lead avgas had a RVP of 47 kPa (6.8 psi) and a MON of 100.8. The blending agent studied in the vapor lock runs was MTBE.

The load on the engine was provided by an eddy current dynamometer. The cooling air and the induction air temperatures were regulated to 38 °C (100 °F).

Vapor lock tests were performed on the automobile gasolines containing concentrations of 0, 5, 10, 15, 20, 25, and 30 percent by weight MTBE, on the 100LL avgas containing 0 and 15 percent by weight MTBE, and on the experimental ultra-low lead avgas containing 15 percent MTBE. The ultra-low lead avgas contained 0.5 ml of tetra ethyl lead (TEL) per gallon, and it contained 15 percent MTBE. For each test fuel blend, tank temperatures of 32, 38, 44, and 49 °C (90, 100, 110 and 120 °F) and fuel flow rates of 10, 20, 30, 40, 50, and 60 liters per hour were tested.

The procedure consisted of heating the test fuel to the desired temperature and taking a pretest fuel sample from the test tank. The manifold pressure and rpm were adjusted to obtain the desired fuel flow rate. The fuel line temperature was set to the tank temperature. The fuel line temperature was raised after five- and ten-minute periods to 66 °C (150 °F), and 121 °C (250 °F) respectively. Increasing the fuel line temperature at the five and ten minute marks causes the light ends (constituents with low boiling temperatures) to be distilled out in the fuel line resulting in vapor formation and an increased potential for vapor lock. If vapor lock occurred or the run lasted fifteen minutes, then the next fuel flow rate was set and the fuel line temperature was reset to the tank temperature. The procedures were repeated until all of the fuel flow rates were tested. After the engine was shutdown a post test fuel sample was taken from the test tank. These tests followed the same format as was used in previous testing at the Technical Center (reference 1) .

Figure 2.1.1 shows vapor lock occurring after roughly 5 minutes and 40 seconds of run time, during a typical test. This was just after the fuel line temperature was increased to 66 °C (150 °F) at the five-minute mark. When vapor lock occurs, the power, the fuel flow rate, and the inlet and outlet fuel pressures at the fuel pump drop, and the sediment bowl temperature and the fuel line temperature increase rapidly.

The sediment bowl temperature and the time to vapor lock values are useful indicators of the tendency to vapor lock. Table 2.1.1 shows the average sediment bowl temperature and time to vapor lock as a function of fuel flow rate. These values include data for the different tank temperatures and MTBE concentrations for both automobile gasolines and for each given fuel flow rate. The values show that the faster the fuel flow rate the shorter the time it takes to reach vapor lock and the lower the temperature of the fuel in the sediment bowl when vapor lock occurs. These results are consistent with the data presented in reference 1.

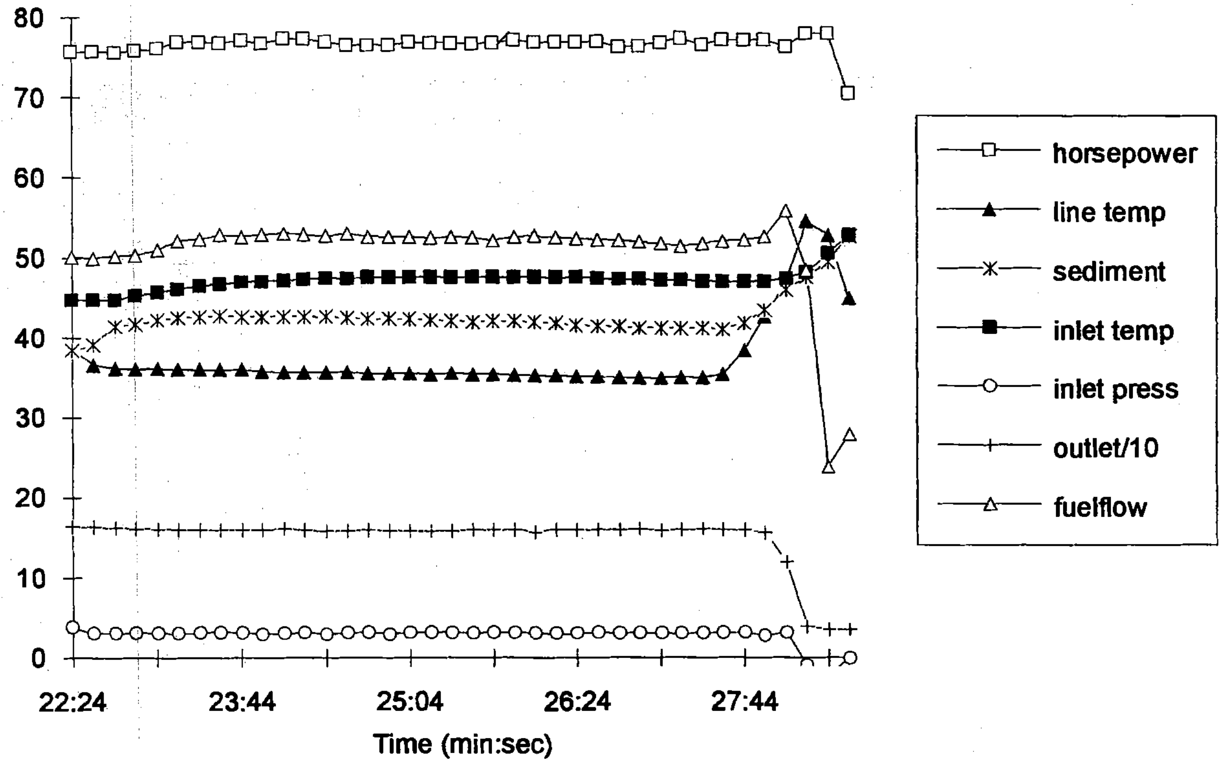


Figure 2.1.1. Effect of Vapor Lock on Fuel System Parameters.

Table 2.1.1. Average Sediment Bowl Temperatures and Average Times to Vapor Lock for Given Fuel Flow Rates.

Fuel flow rate (L/Hr)	Sediment bowl temperature at vapor lock (°C)	Time to vapor lock (min.)
10	68.1	13.29
20	53.5	10.30
30	54.1	9.53
40	53.8	8.83
50	53.1	8.55
60	52.9	7.62

Table 2.1.2 shows the data for each concentration of MTBE. The values in the table are averages of the sediment bowl temperatures at vapor lock and the times to vapor lock for the different combinations of fuel flow rate, base fuel, and tank temperature. The data shows that the addition of MTBE did not result in adverse vapor lock behavior and that the behavior is independent of the MTBE concentration over the range tested.

The relationship between the tank temperature and the time it takes to vapor lock is shown in figure 2.1.2. The values in the figure are averages for both of the automobile gasolines, for different concentrations of MTBE, and fuel flow rates for each given tank temperature. The graph demonstrates that the average time to vapor lock decreased as the tank temperature was increased up to 44 °C (110 °F). Above the 44 °C tank temperature the average time to vapor lock increased as the tank temperature was increased. Thus the shortest time to vapor lock occurred at the 44 °C (110 °F) tank temperature.

Table 2.1.2. Average Sediment Bowl Temperatures and Average Times to Vapor Lock for Different Concentrations of MTBE.

Concentration of MTBE (% by weight)	Sediment bowl temp. at vapor lock (°C)	Time to vapor lock (min.)
0	55.7	9.97
5	56.4	10.02
10	56.0	9.92
15	55.6	9.54
20	56.7	9.59
25	55.0	9.03
30	56.0	9.74

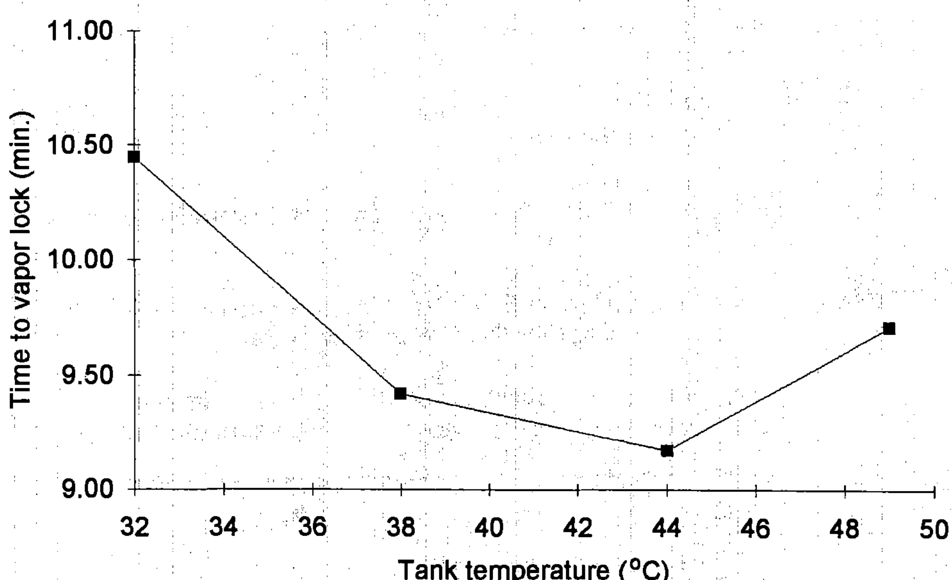


Figure 2.1.2. Effect of Initial Fuel Temperature on Vapor Lock Behavior.

This behavior is explained by reviewing the results from the distillation, RVP, and vapor-to-liquid ratio tests. The Reid Vapor Pressure, distillation, and vapor-to-liquid ratio (VLR) tests were performed on all the base fuels and fuel blends that were used in the vapor lock testing. These tests were also performed on the pretest and post test samples that were heated to different temperatures during the vapor lock runs. The RVP and distillation tests were performed as per ASTM specification. The VLR tests were performed using a Graebner VLR tester. Typical distillation data for the unheated fuels are presented in figure 2.1.3. The RVP and VLR for the pretest (heated) samples are presented in figures 2.1.4 and 2.1.5.

Figure 2.1.3 demonstrates that the addition of MTBE resulted in a slight flattening of the distillation curve by raising the initial boiling point and lowering the end point. Overall the changes noted in the distillation curves are not large enough to adversely affect the vapor lock performance of the test fuels, and they reflect the small changes that resulted from MTBE concentration in RVP (figure 2.1.5).

In order to explain the behavior observed during the vapor lock testing (figure 2.1.2), start with the distillation curve. When distilling a fuel sample, a slight increase in temperature above the initial boiling point results in a large increase in the quantity distilled. Similarly, when the fuel in the tank is heated above 44 °C, a large amount of light ends (constituents with low boiling temperatures) are lost. This results in less vapor formation in the fuel line, reducing the chance of vapor lock. It should also be noted that the initial boiling point as defined by ASTM is the temperature of the gasses above the liquid in the flask. Technical Center experience shows that the boiling temperature of the liquid lies near 43 °C (108 °F).

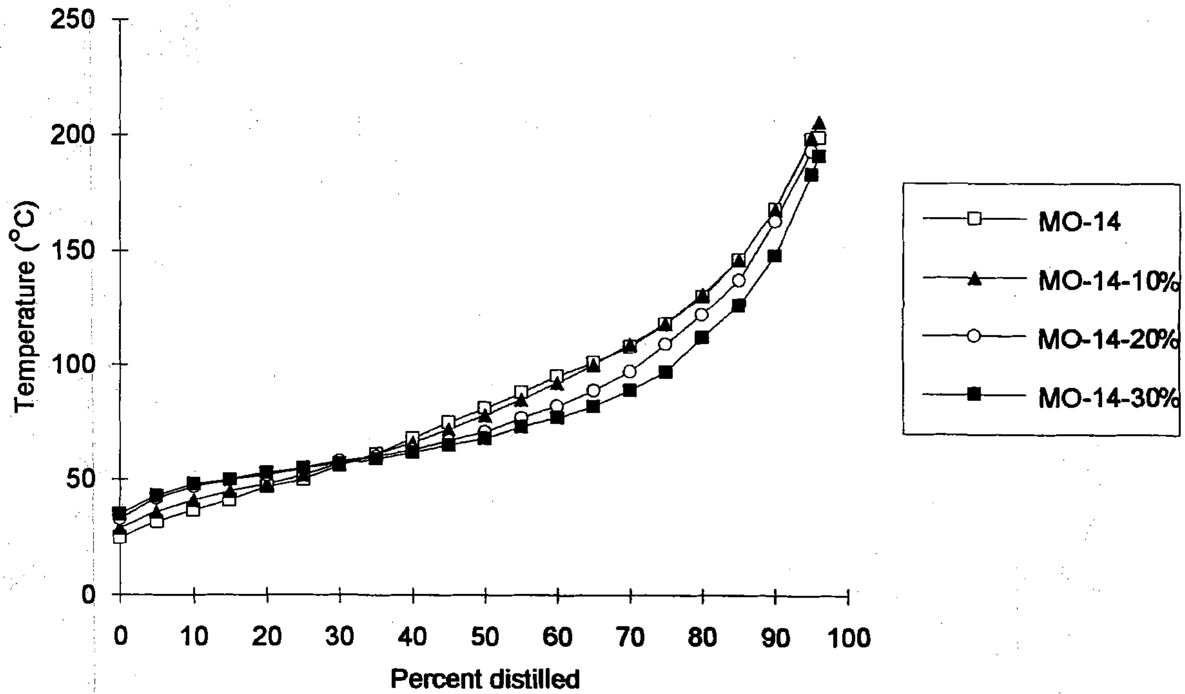


Figure 2.1.3. Distillation Curves as a Function of MTBE Concentration.

Figure 2.1.4 shows the RVP curve, for each tank temperature, as a function of MTBE concentration. The RVP decreased slightly as the fuel temperature increased. As noted earlier, the RVP test is plus or minus 7 kPa (1 psi), and this masks some of the temperature effect. The large shift in RVP between the 44 and 49 °C tank temperatures (110 and 120 °F) reflects the loss of the high volatility components as the fuel is heated above 44 °C. The graph also shows that the concentration of MTBE has a small effect on the RVP of the blend, over the range of concentrations tested.

Figure 2.1.5 shows the effect of heating the fuel on the VLR curves. For this figure, the VLR curves for all the pretest fuel samples were averaged together. Note that there was a large shift in the VLR curve

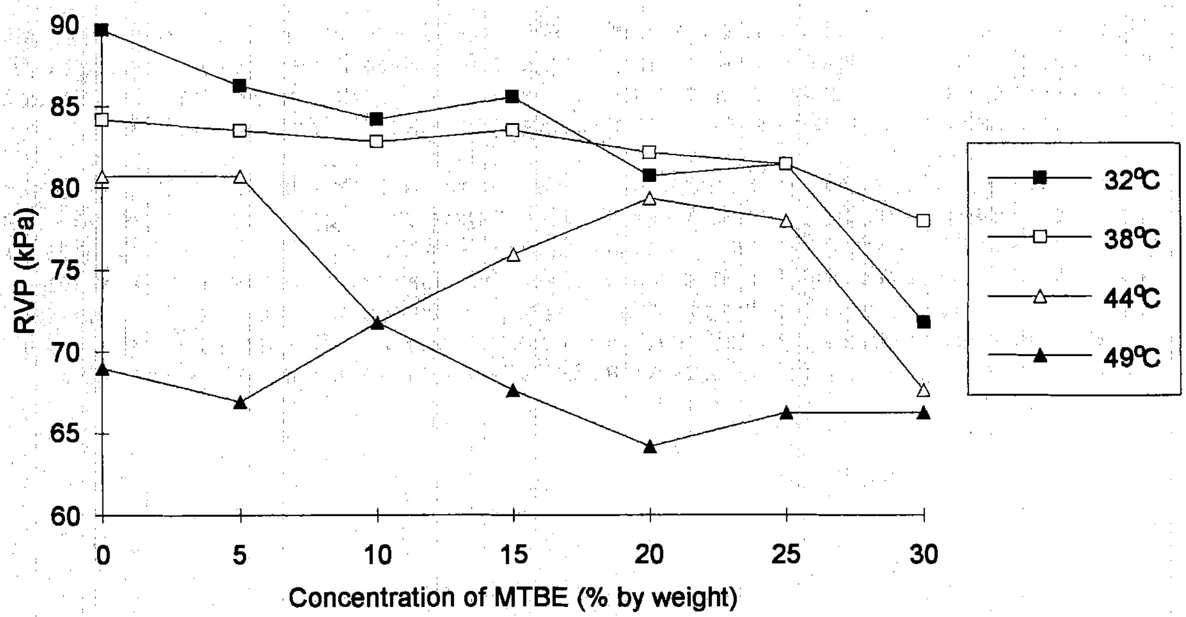


Figure 2.1.4. Effect of MTBE Concentration on RVP.

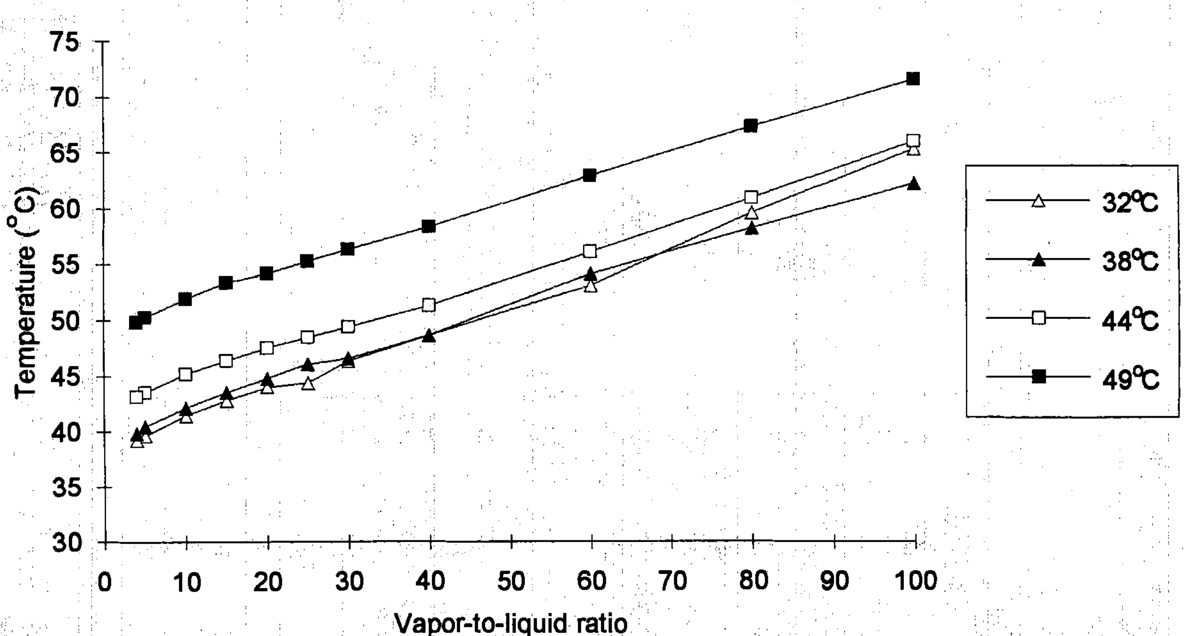


Figure 2.1.5. Vapor-to-Liquid Ratio as a Function of Tank Temperature.

between the 44 and 49 °C (110 and 120 °F) tank temperatures. This indicates that for initial tank temperatures above 44 °C, a much higher temperature is needed to generate the same amount of vapor. This is the same effect noticed in figures 2.1.2 and 2.1.4, and it is a consequence of losing the high volatility components as the fuel is heated above 44 °C.

In summary, for temperatures at 44 °C (110 °F) and below, the closer the initial temperature is to 44 °C the faster vapor lock will occur. At this temperature, the distillation curves show that the temperature of the fuel needs to increase only slightly to generate enough vapor to cause vapor lock. Any increase in fuel flow rate, for a given initial temperature, results in an increase in turbulence and agitation of the fuel in the fuel line. This causes a greater formation of vapor and a shorter time to vapor lock. Since the fuel is heated for a less amount of time, the sediment bowl temperature will also be lower. For temperatures above 44 °C, the light ends that are distilled out results in the lowering of the vapor pressure and hence increases the time to vapor lock. The net result is that the most severe condition for vapor lock occurs when the fuel in the tank is close to 44 °C, and the engine is at takeoff power.

The addition of MTBE tends to shift the VLR curves upward as is seen in figure 2.1.6. These data are for blends made with a 97 kPa (14 psi) motor gasoline. The changes noted are relatively small however, and they further indicate that the addition of MTBE to the fuel will not adversely affect the vapor lock behavior of the fuel. Indeed the curves tend to indicate the vapor lock behavior will improve with MTBE concentration, which was the observed behavior for the fuels blended from the 97 kPa (14 psi) motor fuel.

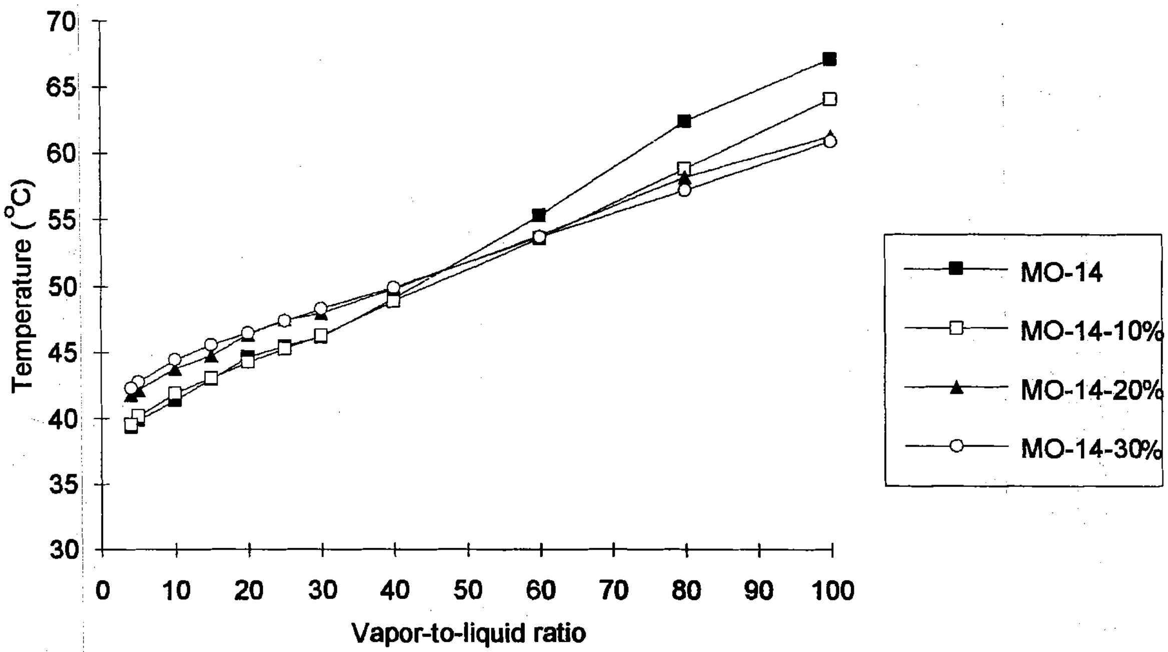


Figure 2.1.6. Effect of MTBE Concentration on VLR.

Correlation tests were performed to investigate the relationships between the RVP, the VLR 40 temperature, the VLR 60 temperature and the characteristics of vapor lock behavior. Table 2.1.3 shows that the best correlation was found between the VLR 40 temperature and the time to vapor lock. Excellent correlations were also found between the VLR 60 temperature, the RVP, and the time to vapor lock. Very good correlations were also found to exist between the RVP, the VLR 40 temperature, the VLR 60 temperature, and the sediment bowl temperature at vapor lock.

Figure 2.1.7 shows that for each concentration of MTBE the VLR 40 temperatures were found to be approximately equal to the average sediment bowl temperatures at vapor lock. As noted before, the VLR 40 temperature was found to have good correlation with another indicator of vapor lock, the average time to vapor lock. This suggests that the VLR 40 temperature is a good measure of the vapor lock behavior of the fuel.

Table 2.1.3. Correlation Coefficients (r^2) Between Lab Tests and Indicators of Vapor Lock.

	RVP	VLR 40 Temp.	VLR 60 Temp.
Time to vapor lock	0.95	0.98	0.96
Sed. bowl temp. at vapor lock	0.93	0.91	0.89

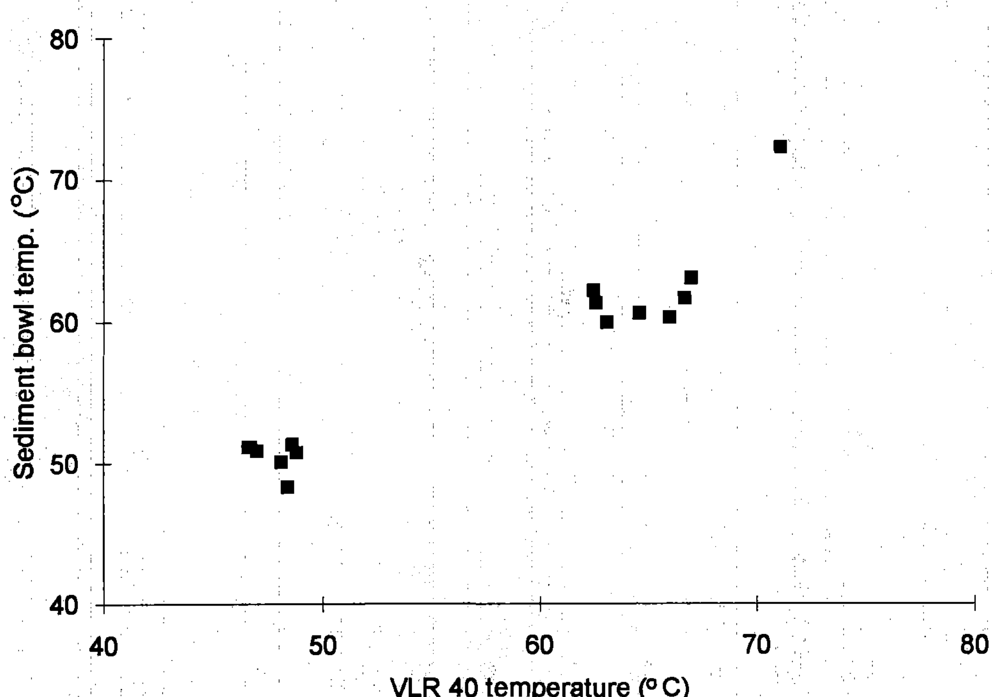


Figure 2.1.7. Correlation Between Sediment Bowl Temperature at Vapor Lock and VLR 40 Temperature.

2.2 POWER BASELINES.

Power baselines were performed using MO1087 (an automobile gasoline with an RVP of 69 kPa), MO14 (an automobile gasoline with an RVP of 96 kPa), 100LL avgas (with and without 15 percent MTBE), and an experimental ultra-low lead avgas. The MO1087 and the MO14 fuels contained MTBE percentages ranging from 0 to 30 percent in 5 percent increments. The experimental ultra-low lead fuel contained 0.5 ml TEL/gal and 15 percent MTBE. The engine settings included manifold pressures ranging from 500 mmHg (≈20 inHg) to full throttle in 50 mmHg (2 inHg) increments and the rpm ranged from 2000 to 2700 in increments of 100 rpm. The mixture was set on full rich. The procedures consisted of setting the rpm and manifold pressure combination and allowing the engine to stabilize. After one minute the next combination of manifold pressure and rpm was then set, and the procedure was repeated. Each combination of rpm and manifold pressure was tested. A manifold pressure of 500 mmHg (20 inHg) could only be obtained for rpm settings of 2300 and lower.

The comparative baseline test sequence consisted of operating the engine at power settings representative of normal aircraft operations, as found in table 2.2.1, and measuring the engine's performance on both avgas and test fuel prior to selecting the next power setting. Using this sequence removes the small variations that occur when selecting the power setting and it makes for easier comparisons. This sequence was also used in an attempt to determine if operating at lean fuel-to-air ratios could result in recovery. In this case, the operator adjusted the mixture to lean misfire and then enriched the mixture to obtain smooth operations prior to taking data.

Prior to each run, wet bulb and dry bulb temperatures were taken and the barometric pressure was recorded. Unless noted otherwise, all performance data was corrected to standard day conditions. Takeoff power for the Lycoming IO320 engine was found to be approximately 160 horsepower, in agreement with the manufacturer's specification, when corrected using the Lycoming correction factors and accounting for friction losses. All of the power data in this report, unless otherwise noted, was corrected using SAE correction factors and does not account for friction losses. This would explain any discrepancy between the takeoff power values in this report and the manufacturer's specified takeoff power.

Table 2.2.1. Manifold Pressures and Engine Speeds for Comparative Baselines.

Manifold Pressure (mm Hg)	Engine Speed (rpm)
500	2000
525	2100
550	2200
575	2300
600	2400
625	2500
650	2600
675	2700
FT*	2700

*Full Throttle

Initially, there was some concem that fuels containing MTBE might be incompatible with 100LL avgas. To investigate this possibility, the Technical Center blended 15 percent MTBE into 100LL. Several sets of baseline tests were conducted using both neet and blended fuels. In addition, the Technical Center evaluated an experimental ultra-low lead avgas provided by a member of the ASTM Future Fuels for General Aviation Task Group. Table 2.2.2 shows the averaged data for all runs and power settings with these fuels.

The results indicate that the power developed increases slightly and the BSFC decreases slightly when comparing the 15 percent MTBE blend to 100LL. In addition the power and BSFC show similar trends with the ultra-low lead test fuel. The ultra-low lead contained MTBE to offset reduction in lead content. These tests are with the mixture control set at the full rich position, so the fuel flow is not compensated for the energy density of the fuel.

During operations on the test fuels with MTBE, it appeared as though the MTBE acted as a lead scavenger in that the spark plugs and exhaust system appeared to have fewer deposits. The oil analyses during this time frame showed an elevated lead level in the oil, but the amount of lead was within normal limits. When operating on the test fuels, there were no indications of stumbling or other operational difficulties.

Table 2.2.2. Average Power and BSFC for Avgas, Avgas with 15% MTBE, and an Ultra-Low Lead Avgas.

	Power (kW)	BSFC (L/kW·Hr)
100LL	76.91	0.5849
100LL with 15% MTBE	77.08	0.5492
Ratio vs. 100LL	1.002	0.939
Ultra-Low Lead	76.92	0.554

The Technical Center then investigated the effect of concentration on the power developed and the BSFC. Figure 2.2.1 shows the averaged data for the baseline tests which were conducted using motor fuel blended with MTBE (all the concentrations are weight/weight). The base fuel for these tests was a motor gasoline with a RVP of 70 kPa (10 psi) and a MON of 84.5.

In this figure the power developed is divided by the power developed on the base fuel (without MTBE), as are the brake specific fuel consumption (BSFC) and the measured energy density of the test fuels. As before, these tests are conducted with the mixture control at the full rich position, so the fuel flow is limited by the system configuration and no compensation is made for energy density.

As figure 2.2.1 shows, the power gradually increases with MTBE concentration. This is apparently a result of operating at leaner fuel-to-air ratios as the energy density of the fuel decreases. At 30 percent MTBE, the test engine developed approximately 2 percent greater power than was developed with the base fuel. Since the power developed increases and the fuel flow is held constant, the BSFC decreases. In these tests, the measured BSFC is approximately 3 percent lower on the fuel with 30 percent MTBE. The average power and BSFC for the neet motor fuel is 74.327 kW, and 0.571 kg/kW Hr, respectively. The exhaust system configuration had been changed slightly from the original baseline tests so the power developed is not directly compatible with the baseline tests conducted with avgas.

The Technical Center attempted to evaluate the effect of MTBE concentration (energy density) on the power developed and BSFC, when the mixture control was adjusted to obtain the best power setting and the lean to just rich of the misfire limits. For these tests, the comparative baseline sequence was used. This allowed for more direct comparison and eliminated some of the variables that could affect the results.

The results from the lean to just rich of the misfire limit did not show a significant pattern. This is a consequence of small changes making large differences in the power developed, when one operates the engine near the lean limit. In fact, many points showed a higher BSFC than was measured using full rich operations. At the time of these tests, the Technical Center did not measure the oxygen concentration of the exhaust, which would have made the results more accurate.

These results were disappointing since the Technical Center had hoped to identify an operating condition where some recovery could be obtained. The identification of such an operating condition could have been used to offset the expected reduction in energy density of the unleaded avgas.

Table 2.2.3 shows the results from the tests where the mixture control was adjusted to obtain best power. The base fuel for this test sequence was a motor gasoline with a RVP of 97 kPa. In this case, the

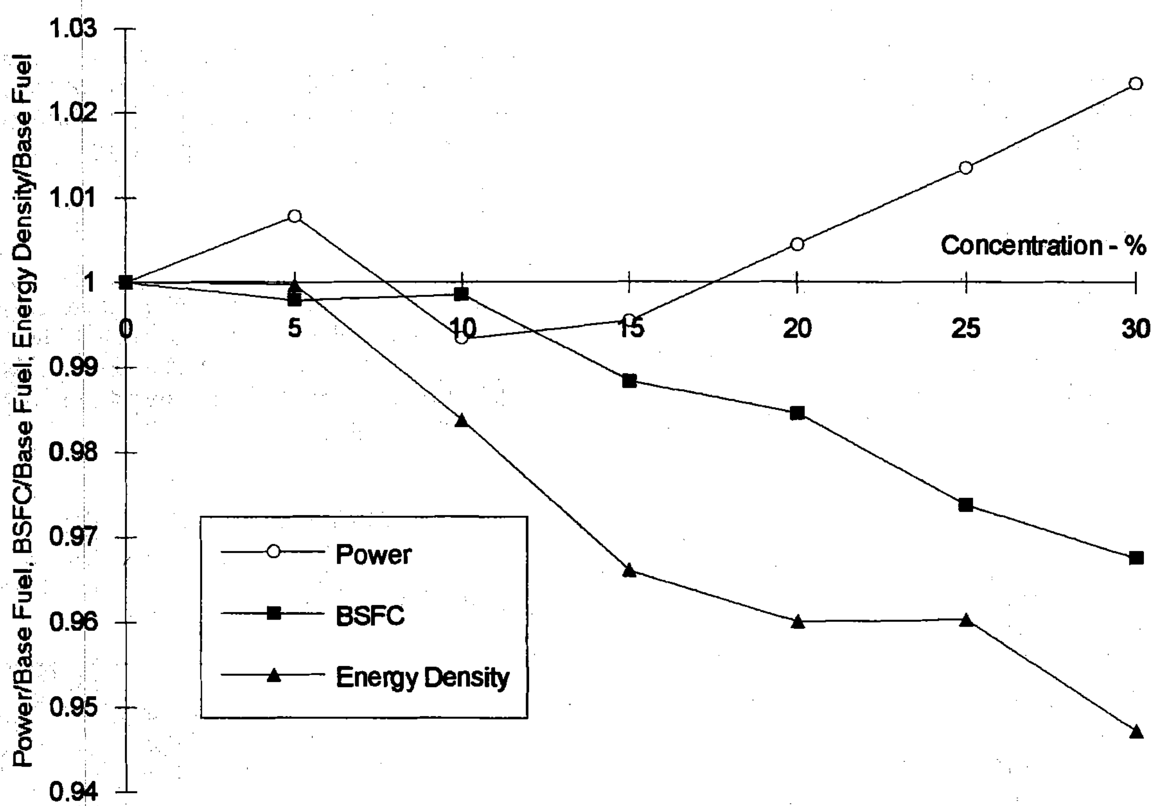


Figure 2.2.1. Ratio of Power, Energy Density, and BSFC for Various MTBE Concentrations.

Table 2.2.3. Results from Leaning Experiments.

Conc. (%)	Power (kW)		BSFC (L/kW-Hr)		Energy Density	BSFC
	Avgas	Blend	Avgas	Blend	Ratio	Ratio
5	72.767	73.559	0.526	0.562	0.99	1.068
10	68.935	69.684	0.534	0.535	0.979	1.002
15	72.538	73.136	0.536	0.561	0.969	1.047
20	71.216	72.883	0.576	0.592	0.958	1.028
25	73.411	74.758	0.549	0.594	0.948	1.082
30	72.17	72.531	0.551	0.588	0.937	1.067

averaged data for the comparative baselines are presented. The power developed is not corrected to standard day conditions. For these test results, the avgas data which was taken on the same day as the blend data, is presented for comparison purposes. The calculated energy density ratio (blend/avgas) and the measured BSFC ratio are presented for the various concentrations.

For the 10 percent concentration, insufficient fuel remained to test at the takeoff power setting so the average for that power setting is lower than the others. The other variations are a consequence of operating under different ambient conditions.

The power developed is greater when operating on the blends containing MTBE as opposed to avgas, with the average power increase being on the order of 1 percent. This result is consistent throughout the range of concentration and mixture control settings, though the cause of this improved performance is unclear at this time. This increase in power only slightly offsets the lower energy density of the fuel.

2.3 ENDURANCE.

Endurance tests were performed on a Continental TSIO360 engine and a Lycoming IO320 engine both connected to a water brake dynamometer. Two fuel blends were utilized for these tests. The first fuel contained 70 percent aviation alkylate, 30 percent MTBE, 0.1 g MMT/gal and had a MON of 94.9. The second fuel contained 70 percent aviation alkylate, 30 percent MTBE, no MMT and had an MON of 95.6. The following table shows the test sequence for the TSIO360 engine.

Table 2.3.1. Endurance Test Sequence for the Continental TSIO360 Engine.

TEST DURATION Hrs.	NUMBER OF TESTS	TIME Hrs.	POWER SETTING	RPM	TORQUE Ft·Lbf
0.5	10	5	50%	2225	248
0.5	10	5	60%	2365	280
0.5	10	5	65%	2435	294
0.5	10	5	70%	2490	310
0.5	10	5	75%	2550	324
2.5	4	10	MAXIMUM BEST ECONOMY		
2.5	4	10	MAXIMUM CONTINUOUS		
1.5	50	75	MAXIMUM CONTINUOUS		
0.08	180	14.5	TAKEOFF		
0.08	180	14.5	MAXIMUM CRUISE		
	Total time:	150			

The tests were performed using the worst case scenario. The oil and cylinder head temperatures were kept as close to the manufacturer's allowable maximum as possible.

The cylinders, pistons, rings, valves, and spark plugs were inspected periodically for metallic deposits, particularly manganese. Valve degradation measurements were taken initially and after every twenty hours of run time. Oil samples were taken at the 50-hour and 100-hour marks and sent to an independent lab for analysis. After every 50 hours, a leak down was performed. These wear measurements were also performed any time that they were needed. All of the valve degradation measurements and leak downs were performed on the engine while it was cold.

The TSIO360 engine was run for 102 hours at power settings listed in table 2.3.1, and it was operated for a total of 144 hours. The results of the wear tests are presented in table 2.3.2. When reviewing the table, delta 20 is the wear over the past 20 hours of operation. Similarly, delta 50 is the wear since the last measurement. Delta 70, delta 90, and delta 110 are the wear measurements since the initial measurement and the time listed above.

Table 2.3.2. Wear Analysis for the Continental TSIO360 Engine. All Valve Measurements are in Inches.

Hours	Intake Valve						Exhaust Valve					
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 5	Cyl 6
31.1	0.72	0.715	0.722	0.735	0.729	0.719	0.739	0.715	0.714	0.703	0.685	0.727
55	0.7195	0.714	0.7225	0.739	0.728	0.716	0.739	0.701	0.698	0.688	0.681	0.724
delta 20	0.0005	0.001	-0.0005	-0.004	0.001	0.003	0	0.014	0.016	0.015	0.004	0.003
leak down	69/80	56/80	32/80	68/80	71/80	69/80	69/80	56/80	32/80	68/80	71/80	69/80
102	0.719	0.714	0.723	0.733	0.729	0.715	0.738	0.673	0.627	0.609	0.584	0.651
delta 50	0.0005	0	-0.0005	0.006	-0.001	0.001	0.001	0.028	0.071	0.079	0.097	0.073
delta 70	0.001	0.001	-0.001	0.002	0	0.004	0.001	0.042	0.087	0.094	0.101	0.076
leak down	45/80	38/80	56/80	37/80	3/80	66/80	45/80	38/80	56/80	37/80	3/80	66/80
124.1	0.721	0.714	0.725	0.734	0.727	0.716	0.710	.0655	0.684	0.57	0.552	0.604
delta 20	-0.002	0	-0.002	-0.001	0.002	-0.001	0.028	0.018	-0.057	0.039	0.032	0.047
delta 90	-0.001	0.001	-0.003	0.001	0.002	0.003	0.029	0.060	0.030	0.133	0.133	0.123
leak down	20/80	24/80	0/80	0/80	0/80	0/80	20/80	24/80	0/80	0/80	0/80	0/80
132.3			0.744						0.7535			
144	0.719	0.714	0.744	0.7335	0.728	0.716	0.6885	0.639	0.745	0.555	0.544	0.5675
delta 20	0.002	0	0	0.0005	-0.001	0	0.0215	0.016	0.0085	0.015	0.008	0.0365
delta 110	0.001	0.001	-----	0.0015	0.001	0.003	0.0505	0.076	-----	0.148	0.141	0.1595
leak down	45/80	32/80	76/80	0/80	0/80	0/80	45/80	32/80	76/80	0/80	0/80	0/80

The table shows the large amount of exhaust valve seat wear that occurred between the 31- and the 55-hour mark, especially in cylinders 2, 3, and 4. At the 100-hour mark all six cylinders had poor compression. All cylinders, except for cylinder 1, showed appreciable wear of the exhaust valve seats. The exhaust valve in cylinder 5 was lapped for better compression after it was discovered that it had a leak down of 3/80. It was also discovered that the exhaust valves in cylinders 3, 4, 5, and 6 were worn into their seats. The loss of compression was due to valve seat wear and stuck rings.

At the 125-hour mark, four of the six cylinders showed leak downs of 0 over 80 while the other two cylinders had leak downs of 20 and 24 over 80. The cylinders were then removed and cleaned. Upon tear down of the engine it was found that a dark brown substance clogged the ring lands causing them to stick. This material was scraped out and sent to the Phillips Petroleum Company for analysis. Analysis of the scrapings are shown in table 2.3.3. Manganese was found to comprise the largest percentage by weight of the material. The analysis also found a large amount of iron.

Cylinder 3 was replaced at the 132-hour mark because the exhaust valve had worn through the seat. The exhaust valve in cylinder 1 was found to be wearing at a normal rate. It was later learned that this cylinder was cast in 1973 while the others were cast in 1968. In 1972 the manufacturer increased the hardness of the materials used in the cylinders for the purpose of operation on 100LL avgas. This suggests that there may be reason for concern about operating an engine with parts made prior to 1972 on unleaded fuels.

Oil consumption was approximately one quart per 3-hour run. Oil consumption rose to 4 quarts per 3-hour run due to oil blowby in the crank case. It was later found that the increased oil consumption was caused by stuck rings.

Table 2.3.3. Analysis of the Ring Groove Scrapings.

Element	Atomic Number	Weight %	Standard Error
Aluminum	13	0.150	0.020
Silicon	14	0.100	0.000
Sulfur	16	0.400	0.020
Chromium	24	0.110	0.010
Manganese	25	0.590	0.030
Iron	26	0.560	0.030
Nickel	28	0.058	0.005
Copper	29	0.090	0.007
Cadmium	48	0.059	0.005
Zinc	50	0.090	0.007
Lead	82	0.450	0.030

Both of the oil analyses suggested that normal wear was occurring. The engine was shipped to Teledyne Continental where it was disassembled. No appreciable wear was found in the bearings or other components. The endurance runs were aborted after 144 hours due to valve seat wear and stuck rings.

Pictures were taken of the inside of the cylinder. The cylinder head, piston head, and valve heads were covered with an orange powder which the FAA, the engine manufacturer, and oil representatives considered to be manganese dioxide. The material found in the ring grooves was a dark brown. It is thought that the manganese dioxide powder absorbs the oil which slows the oil flow and allows coking. The coke then plugs the ring ports and causes sticking. Automobiles do not show the same effect since they have lower operating temperatures and their oils contain detergents.

Endurance tests were also performed on the Lycoming IO320 engine which was used in the vapor lock tests, some power baseline tests, and the detonation tests. The engine was run on an unleaded autogas containing 0.1 g MMT/gal and 30 percent MTBE to determine if the operation on MMT would result in stuck rings and/or unusual wear. Initial inspection of the cylinders using a boroscope did not expose any unusual wear. Valve degradation measurements were taken initially and at the end of the test. There was only enough of the fuel containing MMT for thirteen hours of engine run time and therefore only one power setting was used: 75 percent power, 2500 rpm and 278 Nm (205 Ft·Lbf) of torque, with the mixture leaned to peak EGT. The wear analysis can be seen in table 2.3.4.

The discrepancy in the leak down in cylinder 1 was probably due to the fact that the valves were staked at the 13-hour mark but not at the 0-hour mark. The test was not run long enough to make any determinations about potential wear problems resulting from operation on MMT. The compression loss in cylinder 3 was due to exhaust valve leak. Upon tear down of the cylinder it appeared that there was carbon buildup on the valve seat which resulted in a poor valve seat.

Endurance tests were also performed on a Lycoming IO320 engine run only on unleaded fuels containing MTBE. The fuels did not contain MMT nor TEL. The engine had been previously overhauled and the only tests performed on it prior to the endurance tests were four hours of power baselines for the break-in period, knock mapping of three power points, and an octane rating. All operations were conducted using unleaded fuels. The endurance tests were performed to evaluate a Lycoming engine for valve seat wear and to obtain data on octane requirement increase. The results from the wear measurements and compression checks are shown in table 2.3.5.

Table 2.3.4. Valve Seat Wear and Compression Checks for the Lycoming IO320 Engine Run on an Unleaded Avgas Containing 30% MTBE and 0.1 g MMT/gal. All Values are in Inches.

Hours	Intake Valve				Exhaust Valve			
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 1	Cyl 2	Cyl 3	Cyl 4
0	0.572	0.572	0.602	0.581	0.564	0.565	0.573	0.572
Leak down	66/80	78/80	60/80	78/80	66/80	78/80	60/80	78/80
13	0.571	0.572	0.602	0.581	0.562	0.565	0.573	0.571
delta 13	0.001	0	0	0	0.002	0	0	0.001
Leak down	74/80	78/80	22/80	74/80	74/80	78/80	22/80	74/80

While the endurance test sequence is still underway for the Lycoming IO320 engine, the preliminary results indicate that valve seat wear will not be a problem. The initial high rate of wear in cylinders 1 and 3, are probably the consequence of normal engine break-in.

Table 2.3.5. Wear Analysis for the Overhauled Lycoming IO320 Engine Run on an Unleaded Avgas Containing 30% MTBE and No MMT. All Values are in Inches.

Hours	Intake Valve				Exhaust Valve			
	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Cyl 1	Cyl 2	Cyl 3	Cyl 4
0	0.566	0.553	0.570	0.592	0.600	0.556	0.661	0.586
Leak down	71/80	74/80	77/80	72/80	71/80	74/80	77/80	72/80
20	0.569	0.554	0.556	0.592	0.5615	0.555	0.598	0.584
delta 20	-0.003	-0.001	0.014	0	0.0385	0.001	0.063	0.002
Leak down	70/80	78/80	76/80	78/80	70/80	78/80	76/80	78/80
40	0.569	0.554	0.556	0.592	0.559	0.553	0.597	0.580
delta 20	0	0	0	0	0.0025	0.002	0.001	0.004
delta 40	-0.003	-0.001	0.014	0	0.041	0.003	0.064	0.006
Leak down	78/80	78/80	76/80	76/80	78/80	78/80	76/80	76/80
60	0.569	0.554	0.555	0.592	0.556	0.553	0.599	0.580
delta 20	0	0	0.001	0	0.003	0	-0.002	0
delta 60	-0.003	-0.001	0.015	0	0.044	0.003	0.062	0.006
Leak down	75/80	78/80	78/80	75/80	75/80	78/80	78/80	75/80

The FAA Technical Center is in the process of acquiring ETBE to be blended in unleaded gasoline and to be used in future endurance tests.

2.4 DETONATION.

The Technical Center had a number of goals in conducting the knock tests. The first goal was to demonstrate that the three primary systems used by the industry resulted in similar knock ratings. The three systems are in-cylinder pressure measurements, vibration pickups that are externally mounted and the signal is viewed on an oscilloscope by a trained observer, and audibly rating knock (typically used in the automobile industry). This is important for future certification work. The next goal was to octane rate several typical engines and to develop a knock requirement increase profile for these engines. This would give the FAA confidence in the octane rating specified for the upcoming unleaded fuel. The last issue was to develop confidence in several techniques that could be used to reduce the octane requirement if a particular engine could not be made to operate satisfactorily on the unleaded aviation gasoline.

The Lycoming IO320 engine, which was used in the vapor lock, endurance and power tests, and an overhauled Lycoming IO320 engine were knock mapped and octane rated. Piezoelectric transducers were flush mounted in each cylinder and vibration pickups were attached to each spark plug. Figure 2.4.1 shows an approximate cylinder cross section with the approximate transducer location. The piezoelectric transducers were connected to charge amplifiers which were then connected to a personal computer.

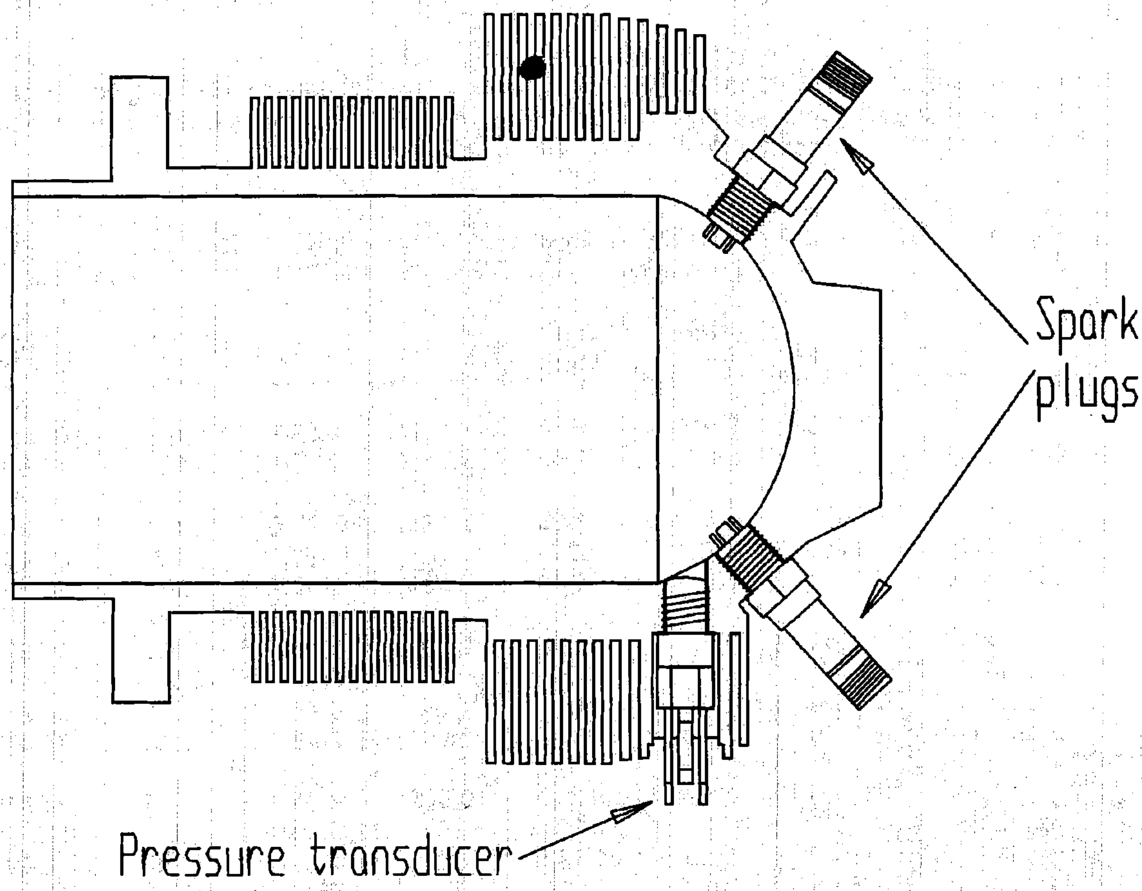


Figure 2.4.1. Typical Cylinder Cross Section Showing Approximate Transducer Location. Not to Scale.

A position crank angle encoder was attached to the tach drive via a rigid shaft. This meant that the encoder turned at the same speed as the cam shaft or half as fast as the crank shaft. Software displayed a pressure crank angle trace on the screen and allowed the user to save a number of engine cycles. The vibration pickups were connected to an oscilloscope which displayed the vibration amplitudes for all 720 degrees of crank angle rotation.

Figure 2.4.1 shows the pressure transducer to be located where the thermocouple that measures the cylinder head temperature is located. The temperature boss was drilled out and rethreaded for the pressure transducer.

For the engine knock mapping tests, rpm settings ranged from 2000 to 2700 in increments of 100 and the manifold pressure settings ranged from 530 mmHg (21 inHg) to full throttle in increments of 50 mmHg (2 inHg). The mixture settings ranged from full rich to 15 percent lean of full rich in increments of 5 percent. The procedures consisted of setting a manifold pressure and a rpm with the mixture set to full rich. The induction air temperature was regulated to 38 °C (100 °F) and the maximum cylinder head temperature was regulated to as close to 260 °C (500 °F) as possible. The engine was left at this setting until the cylinder head temperatures stabilized. If combustion was considered to be stable or nervous then the mixture was leaned by 5 percent to try and induce detonation. The cylinder head temperatures were again allowed to stabilize. If the engine was still not knocking then the mixture was leaned to a total of 10 percent. If the engine was still not knocking then the mixture was leaned to a total of 15 percent. If at any time the engine begins to knock then the mixture is returned to the full rich position and the next combination of rpm and manifold pressure are set. The procedures were repeated for each combination of manifold pressure and rpm.

After each point is set and after each mixture adjustment the cylinder head temperatures were allowed to stabilize. Engine knock was determined to occur by observing the pressure traces on the monitor and/or by the vibration patterns on the oscilloscope screen. The combustion was considered to be "nervous" when the pressure traces showed slight ringing on the tops of the curves and the vibration amplitude began to increase slightly. A knock cycle was considered to have occurred when the vibration amplitude was at least twice its normal size and the pressure curve showed ringing on its downslope. The severity of the knock was determined by the number of times the vibration amplitude flashed at least twice its normal height in one minute and by the severity of the ringing on the pressure curve.

Figures 2.4.2 through 2.4.5 show pressure traces of engine cycles with varying degrees of knock. The figures range from no knock to heavy detonation. When knock occurs the pressure traces show ringing

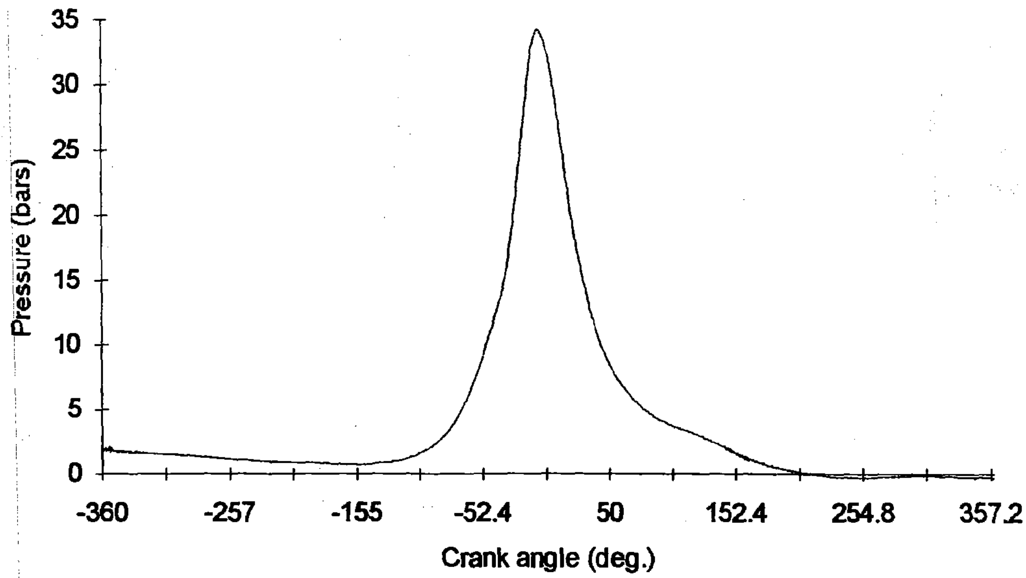


Figure 2.4.2. Pressure Trace Showing Normal Combustion.

on the downslope. The amplitude of the pressure spike increases as knock becomes more severe. Figure 2.4.5 shows the severe pressure increase that occurs in a cylinder that is experiencing heavy detonation. Along with the rapid pressure increase there is a rapid temperature increase which could result in significant damage to the engine.

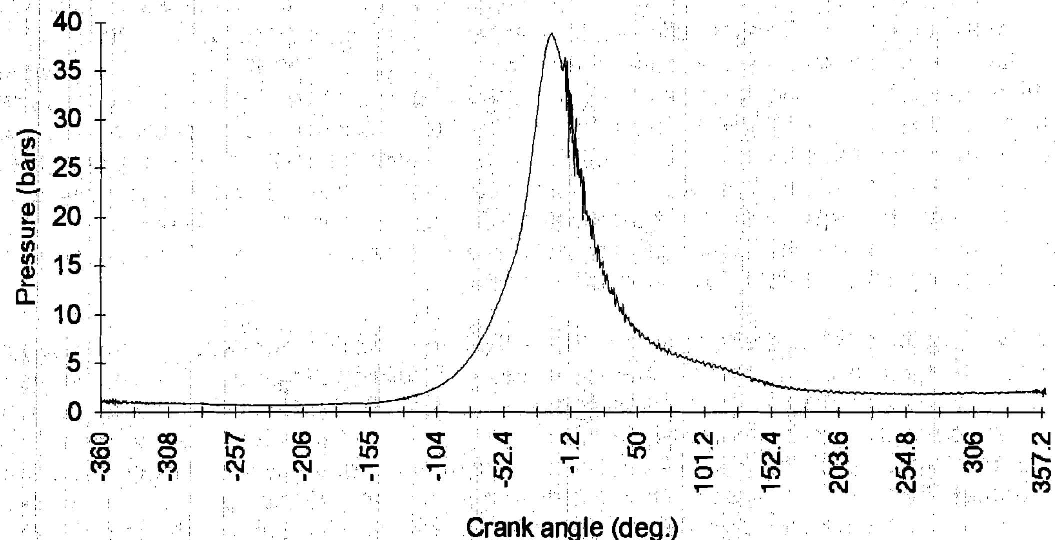


Figure 2.4.3. Pressure Trace Showing Incipient Detonation.

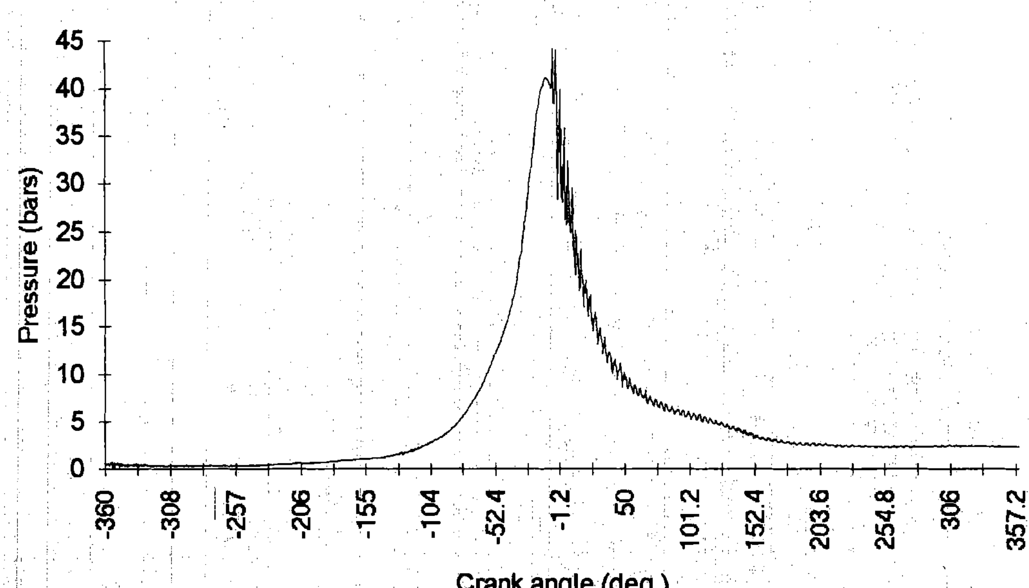


Figure 2.4.4. Pressure Trace Showing Detonation.

For the purpose of vibration analysis, knock was distinguished to have 3 different levels. Incipient detonation was considered to be between 5 and 9 flashes per minute or a 100 percent increase in vibration intensity. Detonation was considered to be 10 to 20 flashes per minute or a 200 to 300 percent increase in vibration intensity. Heavy detonation was considered to occur above 20 flashes per minute or at a 300 percent increase in vibration intensity. Figures 2.4.6 and 2.4.7 demonstrate these ratings. The knock frequency was found to be approximately 4.4 kHz, and the intake valve and exhaust valve frequencies were found to be 4.6 and 4.8 kHz, respectively.

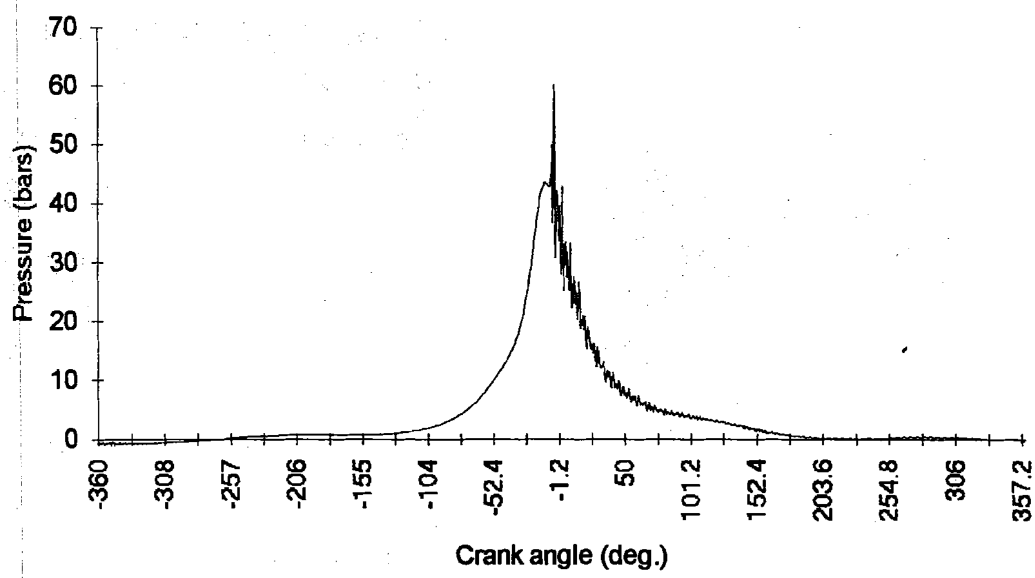


Figure 2.4.5. Pressure Trace Showing Heavy Detonation.

Figure 2.4.6 shows the vibration amplitude for combustion ranging from normal combustion to heavy detonation. The figure shows that incipient detonation has a vibration amplitude twice that for normal combustion; detonation has an amplitude that is between 2 and 3 times the normal amplitude; and heavy detonation has an amplitude that is above three times the normal amplitude. This is the level where significant damage can occur if the engine is left to operate at this threshold. The nervous condition as described in the pressure write-up is the same as an increase in vibration intensity which is greater than normal combustion but is not high enough to be considered to be incipient detonation or less than 5 flashes per minute are counted. The nervous condition is the case where the combustion is neither stable (normal combustion) nor is it completely unstable (detonation).

Figure 2.4.7 shows the typical oscilloscope screen display for the vibration sensing system. The figure shows the vibration noise generated by the closing of the intake and exhaust valves and the normal combustion and detonation vibration intensities.

The Lycoming IO320 engine that was used in the vapor lock tests was knock mapped to determine the three conditions most likely to develop knock. These three worst conditions were used for octane rating the engine and other detonation tests to conserve fuel. The three worst knock points for the IO320 engine were found to be at the 635 mmHg (25 inHg) manifold pressure, 2500 rpm; full throttle, 2500 rpm; and full throttle, 2700 rpm power settings. The worst point was found to be the full throttle, 2500 rpm power point. Above this point mixture enrichment is activated for an added margin of safety. This meant that the mixture had to be leaned out further at the higher rpm points to develop the same level of knock. This engine has been run on 100LL avgas and autogas containing various amounts of MTBE. Octane ratings were then performed on the IO320 engine using standard reference fuels (isooctane and N-heptane) with the help of experienced representatives from the Exxon Research and Engineering Company. The engine was found to be knock free on a 89 MON fuel.

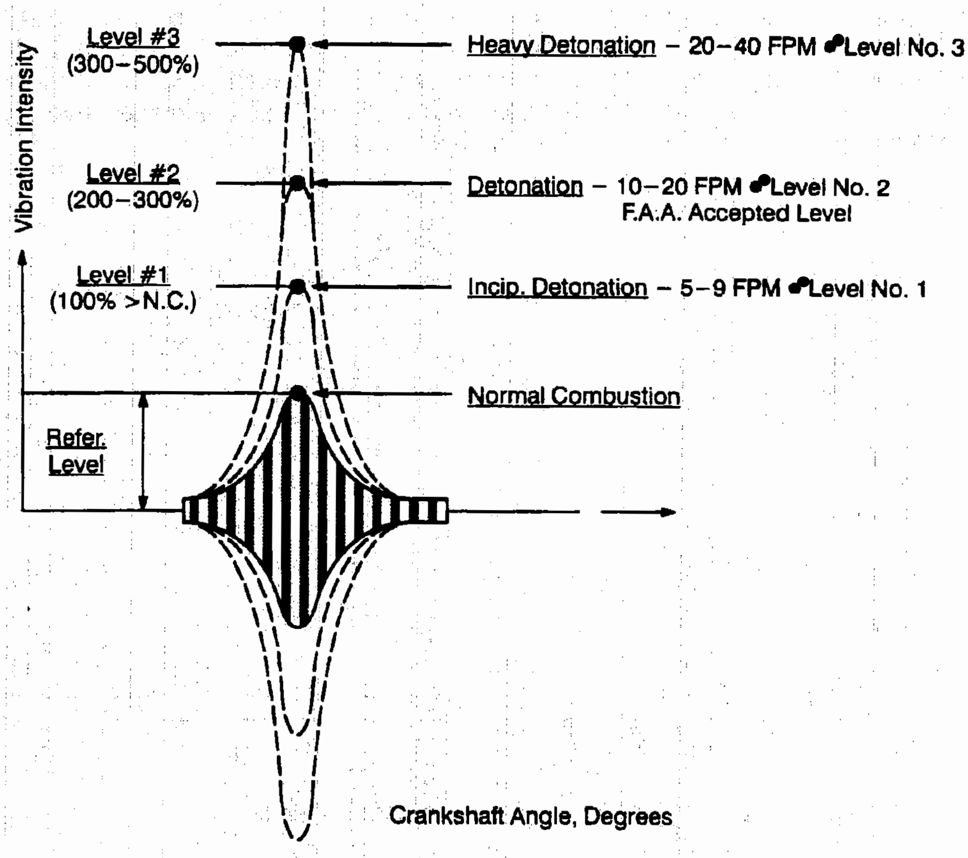


Figure 2.4.6. Detonation Intensity Rating Scale for the Vibration Isolation System. (reprinted with permission from SAE paper no. 931230 © 1993 Society of Automotive Engineers, Inc.)

Knock tests were also performed using a fuel with a MON of 86.9. The cylinder head temperatures were slowly increased from 200 °C (400 °F) by lowering the cooling air pressure until the onset of knock. It was found that by lowering the cylinder head temperatures by 33 °C the motor octane requirement decreased by two numbers.

The previously overhauled Lycoming IO320 engine was also octane rated. It was found that the overhauled engine was octane rated at 91 MON (free of knock). This engine was not run on any fuel containing tetraethyl lead (TEL), or MMT.

A timing check was performed on the old IO320 engine to determine why the knock free octane requirement for the old IO320 engine was lower than that of the overhauled IO320 engine. The timing of the old IO320 engine was found to be 15 degrees BTDC. It was adjusted to its proper value of 25 degrees BTDC. The old IO320 engine was then octane rated again. The new knock free octane requirement was found to be 93 MON. The ten degree timing adjustment resulted in an average power increase of two percent.

Six and one half meters (twenty feet) of a flexible metal, 75 mm (3 inch) diameter, exhaust duct and a muffler with a two-inch inlet were then connected to the old IO320 engine so that it could be audibly knock rated. Octane ratings were then performed again. The minimum MON (without knock) was found to be 95. The addition of the exhaust pipe and muffler resulted in a 5 percent average drop in power, increased operating temperatures, and subsequently an octane requirement increase of 2 motor octane numbers. The motor octane requirement increase between the overhauled and the old IO320 engines, with the proper timing and without the muffler, was found to be about 2 to 3 motor octane numbers.

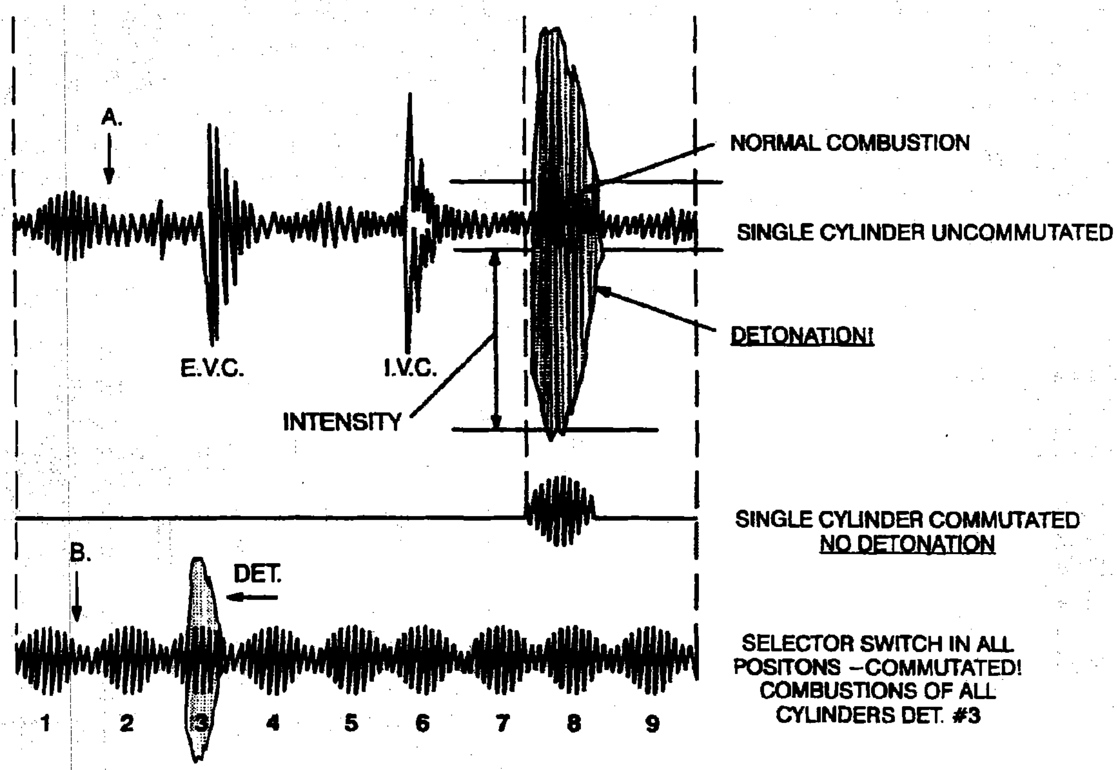


Figure 2.4.7. Illustration Showing Vibration Patterns With and Without Detonation. A. Single Cylinder Uncommutated. B. 9 Cylinders all Commutated. (reprinted with permission from SAE paper no. 931230 © 1993 Society of Automotive Engineers, Inc.)

Representatives from Exxon performed the audible octane ratings. This allowed a trained ear to be used to incorporate audible knock with the two knock sensing devices.

Detonation tests were performed with fuels containing oxygenates and fuels not containing oxygenates. The oxygenate did not appear to have any negative effect on knock behavior.

Care had to be taken when collecting data with the pressure trace software. The average data collection time with this software was roughly 2.5 seconds. Using the vibration system the flash counts are counted over a one-minute period, which for an engine speed of 2500 rpm results in the monitoring of 2500 cycles. In the case of incipient detonation or light knock (5-9 flashes per minute) it is very possible to miss the knock cycles that are counted using the vibration sensing system during a one-minute period. If none of the knocking pressure traces were caught then the statistical pressure data would not show any significant difference between the normal and the knocking pressure traces, making it difficult to quantify incipient detonation. To help rectify this situation the data was collected at the start of the one-minute flash count time period. This way it would be known whether or not a knocking pressure trace was recorded in the first three seconds.

A numerical threshold or test based on the cylinder pressure statistics was sought to allow for a quantification of knock severity. The statistics of the pressure data for the given number of cycles collected included: the mean, standard deviation, the maximum and the minimum of the maximum pressure, the maximum change of pressure with crank angle change, the crank angle location of the maximum pressure, and the crank angle location of the maximum rate of pressure change for all of the cycles.

Table 2.4.1 shows the pressure statistics for various power and manifold pressure settings. In theory, a cycle which knocked would have a higher peak pressure and rate of pressure change than a cycle with normal combustion, and they would occur sooner in the cycle. Also when comparing fifty cycles of knock data to fifty cycles of normal combustion at the same power setting, the knock data should have higher average values and on average they should have occurred sooner in the cycle. Also, the standard deviations of the maximum pressures and the maximum rates of pressure change should be higher for a knock cycle. The previously mentioned should have also increased as knock severity increased. However, it was found that since the knock was showing up on the downslope (expansion stroke of the

Table 2.4.1. Visual Knock Ratings and Pressure Statistics for Various Power and Manifold Pressure Settings.

Power (kW)	MAP (mmHg)	Visual knock rating	Flash count **	Pmean * (bars)	sd P • (bars)	Pmax • (bars)	dPmean * (bars/deg)	sd dP * (bars/deg)	dPmax * (bars/deg)
55.9	570	knock	18	23.1	3.7	31.9	0.5	0.2	1.0
56.7	571	knock	>10	24.9	3.2	34.1	0.6	0.2	1.4
57.4	572	light	5	24.6	2.8	32.0	0.6	0.2	1.2
57.4	573	light	4	24.3	3.1	31.8	0.5	0.2	1.1
58.9	573	nervous	0	25.7	2.9	30.9	0.6	0.2	1.1
59.7	574	knock	27	25.4	3.2	33.2	0.6	0.2	1.1
60.4	571	knock	23	27.6	3.0	37.4	0.7	0.2	1.1
71.6	636	knock	>10	30.2	4.0	47.6	0.8	0.2	1.4
71.6	637	nervous	0	30.2	2.9	35.7	0.8	0.2	1.3
72.3	642	nervous	0	30.0	3.0	38.7	0.8	0.2	1.4
73.1	644	nervous	0	30.2	3.0	37.5	0.8	0.2	1.6
73.8	633	knock	94	31.6	4.3	51.8	0.8	0.2	1.4
76.1	633	nervous	0	31.9	3.3	42.6	0.9	0.2	1.4
78.3	631	knock	55	31.2	3.5	42.9	0.8	0.2	1.4
88.0	680	knock	>10	33.3	3.8	42.0	0.9	0.3	1.8
88.0	681	knock	41	33.9	3.5	43.0	0.9	0.3	1.6
88.0	724	knock	>10	34.6	3.9	43.6	0.9	0.3	1.6
88.7	729	knock	>10	34.6	3.6	43.6	0.9	0.3	1.6
91.0	729	knock	22	37.1	3.6	45.5	1.1	0.3	1.8
91.7	724	light	1	37.3	4.0	46.2	1.1	0.3	1.8
93.2	722	nervous	0	37.5	4.1	45.4	1.1	0.3	1.7
94.0	725	knock	15	37.0	3.9	45.9	1.1	0.3	1.9
95.5	720	nervous	0	33.2	3.4	40.0	0.8	0.2	1.4
96.9	722	light	8	36.8	4.0	46.0	1.0	0.3	2.1
97.7	723	light	6	36.1	3.7	46.3	1.0	0.3	1.8
98.4	723	nervous	0	36.5	3.4	43.9	1.0	0.3	1.8
99.2	719	nervous	0	35.4	3.9	45.5	0.9	0.3	1.7
101.4	722	nervous	0	35.9	3.7	44.7	0.9	0.3	1.8

• based on 50 individual cycles of saved pressure data, ** based on a one-minute time period
Column 1 - uncorrected power; column 2 - measured manifold absolute pressure; column 3 - visual knock rating based on observation of pressure traces, oscilloscope flashes, and audible ratings; column 4 - number of flashes counted from oscilloscope screen using the vibration isolation equipment; column 5 - average of maximum pressures; column 6 - standard deviation of maximum pressures; column 7 - maximum pressure; column 8 - average of the maximum rates of pressure change; column 9 - standard deviation of maximum rate of pressure change; column 10 - maximum rate of pressure change.

combustion cycle) of the pressure curve, and not directly at TDC, that the locations of the maximum pressure and the maximum rate of pressure change are not good indicators of knock. These pressure statistics appear to show a trend when the knock cycles were caught in the two- to three-second data acquisition time. However, when the observer notes that knock is occurring and no knock cycles are caught, then the pressure statistics do not show a trend. This would explain why some of the data in the table shows a knocking cycle to have lower values than a cycle which was simply nervous at the same power setting.

An algorithm was established to aid in determining the knock characteristics of a given set of pressure data without requiring the viewing of each data set graphically. The algorithm uses the pressure versus crank angle data to calculate a numerical value which indicates the amount of ringing present in the pressure curve. For normal combustion cycles, the pressure curve should be smooth. For knocking cycles, the ringing was noticed to occur on the expansion stroke (downslope of the pressure curve) and to be more severe as the knock severity increased.

The algorithm finds the crank angle associated with the maximum pressure. From there, the program searches the data to find the location where the pressure slope is near zero. This point is equal to the peak or maximum pressure if no knock is present. Absolute values of the pressure differences between 250 consecutive pressure points before and after the peak are then calculated. The sum of these values before the peak and after the peak is then computed, and the difference between the sums is found. This method will later be referred to as the pressure difference method. Typically, for normal combustion this difference is negative, and for cycles which knocked, the difference is positive. For a limiting knock cycle, the difference is at least ten; for a light knock cycle, this difference is positive but less than ten, and for a simply nervous cycle the difference is negative.

Table 2.4.2 shows values generated from the pressure difference method for selected tests. This method appears to work very well. However, more statistical analysis of the pressure difference method is necessary in order to validate the method and establish confidence intervals. The pressure trace software will be modified with this algorithm to perform these numerical tests which will eliminate the need to collect and store large volumes of data.

Table 2.4.2. Examples of Knock Quantification Using the Pressure Difference Method.

Visual Knock Rating of Cycle	Pressure Difference Method
Normal combustion	-14.6
Normal combustion	-10.8
Normal combustion	-9.3
Normal combustion	-7.7
Nervous combustion	-3.5
Nervous combustion	-3.3
Nervous combustion	-2.7
Light knock	5.2
Light knock	5.4
Knock	10.8
Knock	11.4
Knock	23.9
Heavy knock	43.5
Heavy knock	65.5
Heavy knock	68.8

2.5 EMISSIONS.

A mobile emissions research facility (MERF) has been set up to study the level of emissions from piston aircraft engines running on automobile fuels containing additives of MTBE and MMT. The MERF contains five analyzers which measure NO_x (oxides of nitrogen), CO (carbon monoxide), CO_2 (carbon dioxide), THC (total hydrocarbons), and O_2 (oxygen).

The MERF will be connected to a Continental GTSIO520H engine which will be run on the eddy current dynamometer. The emissions testing sequence that will be used is the five-mode cycle, as defined by the EPA, which is shown in table 2.5.1.

Table 2.5.1. Proposed Emission Testing Sequence Defined by the US EPA.

Mode	Percent Power	Time (min.)
Idle/Taxi-out	------	12.0
Takeoff	100	0.3
Climb	75 - 100	5.0
Approach	40	6.0
Idle/Taxi-in	------	4.0

Data and discussion will be published at a later time.

2.6 MATERIAL COMPATIBILITY/FUEL STORAGE STABILITY.

The FAA has addressed the concern of compatibility of fuel additives with materials that exist in fuel systems. For example certain ethers have been known to cause appreciable swell in elastomers. Also addressed was the area of fuel storage stability.

A survey was taken of major suppliers of fuel system components for piston aircraft engines. A list of materials currently in use in fuel system components was compiled and can be seen in table 2.6.1.

Representative samples of various materials will be exposed to the fuels containing MTBE and ETBE in order to determine the effect of the ether additives on these materials. Measurements will be taken prior to exposure and after exposure to determine the amount of swell. Inspections will also be done to determine if the additives have any corrosive effects on the materials.

A tank containing the experimental unleaded fuel, that was used in the endurance testing, was exposed to the outdoor environment of the test facility. The fuel consisted of 70 percent aviation alkylate, 30 percent MTBE and 0.1 g MMT/gal. A similar tank containing an experimental ultra-low lead avgas was also placed outside. Two samples of common tank sealer and tank bladder materials were enclosed in the tanks. Both tanks were equipped with a sight gauge (there is concern that the MMT will settle out of the solution when it is exposed to ultraviolet radiation for an extended period of time).

A brown substance was observed in the sight gauge of the tank which held the fuel sample containing the MMT. Fuel bled from a valve at the bottom of the tank was clear. Pretest and post test samples taken from the tank showed that the MON decreased from 94.9 to 94. The MMT that was exposed to ultraviolet radiation appears to have come out of the solution whereas the MMT that was not exposed to ultraviolet radiation did not appear to come out of the solution. No indications of major problems regarding long term storage stability nor thermal stability have been found to date in either tank. No unusual corrosion or swell was found regarding the tank sealer and tank bladder materials in either tanks. Both samples were tested according to ASTM D4814 after six months of storage. With the exception of the drop in MON for the sample with the MMT, no significant changes in the fuel properties were noted.

The FAA Technical Center is in the process of evaluating a sample of fuel containing tertiary amyl methyl ether (TAME). This fuel will be evaluated at the Technical Center and at the Florida Institute of Technology (FIT) for storage and thermal stability studies. The Experimental Aircraft Association is supporting this effort by providing material samples and logistic support. This work is being conducted at FIT under a grant from the Technical Center.

Table 2.6.1. Listing of Commonly Found Fuel System Materials.

Elastomers	Metals
NBR	Aluminum Alloys
Buna N	Anodized
Nitrile	Chemically Filmed
Butadiene Acrylonitrile	Aluminum/Brass
	2024-T3 (etc.)
Neoprene	
	Stainless Steel
Fluorocarbon	321 Alloy
Viton	Passive Corrosion Resistant
	Precipitation Hardened - Corrosion Resistant
Fluorosilicon	
Polyethylene	Brass
Polyurethane	Rolled Steel
	Cadmium or Zinc Plated
Polyester	
	Other
Polyether	
	Acetal Resin
	Delrin
Tank Sealers	
	Nylon
Polysulfides	
Manganese Dioxide	Teflon (PTFE)
Dichromate	
	Tetrafluoroethylene
Polythioether	TFE

2.7 WATER CONTAMINATION.

The water separation tests were conducted in two steps. In the first sequence of tests, 100 ml graduated cylinders were filled with 10 ml of water and the balance with gasoline. The samples were vigorously shaken for 30 seconds and allowed to stand for 24 hours at 15 °C (50 °F). An observer noted the appearance of the fuel as the water settled and recorded the final water level. This simulated the high level of agitation that may occur during high speed refueling or during fuel transfer using impulse pumps.

The second level of tests simulated the conditions found in high pressure, high speed gear pumps. Fuel and water were added to an emulsifying apparatus at a ratio of 3 parts fuel to 1 part water. The sample was then emulsified for one minute, decanted and allowed to stand for 24 hours. An observer recorded the appearance of the fuel as the water settled. The Technical Center also conducted an investigation into the behavior of motor gasolines which contained ethers and surfactants, as might be found in reformulated automobile gasolines. These tests were conducted in response to reports that the use of surfactants in motor fuels could lead to the formation of a stable emulsion that would not burn in an aircraft engine.

The Technical Center tested a motor gasoline with surfactant, a motor gasoline with surfactant and 25 percent MTBE added, and a sample of 100LL aviation gasoline. The initial samples were inspected and all were bright and clear.

The first sequence in the water separation tests called for shaking samples of the fuel sealed in containers with water. The bulk water in the sample with MTBE settled within 30 seconds, but the sample remained slightly hazy. The water level did not change during the course of the test. At the end of 24 hours the sample was bright and clear, but there was a white film at the fuel/water interface.

The bulk of the water in the sample with only surfactant took approximately a minute to settle. The water level did not change as a consequence of being mixed with the gasoline. The fuel above the sample was bright and clear. There was a white substance at the fuel/water interface, which remained over the course of 24 hours.

The avgas sample was not tested at this time but previous experience indicated that the water would have settled out of the fuel within 30 seconds and the sample would have remained bright and clear.

The next sequence of tests called for passing a fuel/water sample through a homogenizing device. The sample of avgas was cloudy when taken from the apparatus. Portions of this sample remained cloudy for over 30 minutes with the upper levels becoming clear before the lower levels. The sample remained hazy for up to 2 hours afterward. The sample was bright and clear after 24 hours.

The sample with the surfactant remained cloudy for over 30 minutes with a gradual but uniform change in appearance. Within 24 hours the fuel was bright and clear, but again there was a thin white film at the fuel/water interface.

The sample with the MTBE remained cloudy for over 30 minutes with a gradual but uniform change in appearance. This sample took longer to clear than the sample with the surfactant only. Within 24 hours, the fuel was bright and clear with a thin white film at the fuel/water interface.

The Technical Center was unable to positively identify the substance found at the fuel/water interface. The most probable source of the white film at the fuel/water interface was a polymer used in preparing fire-safe fuels. The tests showed that the fuels which contained surfactant were more likely to suspend small droplets of water for longer periods of time than the current avgas, but they did not form stable emulsions (past experience indicates that motor fuels without surfactant were also more likely to suspend small droplets of water). The presence of MTBE did not appear to have an appreciable affect on the results. It should be kept in mind that these tests are more severe than the conditions that are likely to be encountered in flight.

2.8 FUEL BLENDS.

A number of fuel blends were prepared by the Pittsburgh Applied Research Center (PARC) in order to measure the effectiveness of both MTBE and ETBE as blending agents. PARC provided the full report in accordance with ASTM D-4814, but for the purpose of this report, the MON and the energy density of the blends will be considered. The results of selected tests are presented in table 2.8.1.

Based on the PARC data, the calculated octane blending value for MTBE was 102.4 MON when mixed with an aviation alkylate. This is greater than the octane rating of neet MTBE (98 MON). The calculated octane blending value for the ETBE was 102.2 MON.

Table 2.8.1. Laboratory Results on Various Blends.

MTBE wt. %	ETBE wt. %	Toluene wt. %	MMT (g/l)	Energy Density (kJ/kg)	Motor Octane Number
10				43,104	94.5
20				42,886	95.3
30				41,444	96.3
30			0.264	41,118	97.6
	10			43,181	94.7
	20			42,576	95.8
	30			42,211	96.3
	30		0.264	41,890	97.4
15	15			41,583	96.4
15	15		0.264	41,839	97.3
25		5		41,479	96.1
	25	5		41,695	95.9

From the perspective of octane blending value, both ethers prove to be excellent blending agents. While the ETBE does have a higher energy density than MTBE, the cost of ETBE at this time is prohibitive. It was noted that the sample with 30 percent ETBE did not pass the oxidation stability test, though it is uncertain at this time if this is a representative data point.

PARC looked into the use of toluene as an octane enhancer. Both samples that contained toluene had lower octane values than the samples with ether alone. The effectiveness of MMT was measured, and for blends of aviation alkylate and ethers, 0.1 g/gal. MMT yields an increase of approximately one octane number.

At the suggestion of Southwest Research Institute, 1-3-5 trimethyl benzene was tested by PARC. While the neet 1-3-5 trimethyl benzene is reported to have high MON, it did not prove effective in blends of aviation alkylate and ether.

2.9 FLIGHT TESTING.

The FAA has plans to utilize a twin engine aircraft to perform actual flight testing on a fuel which will be representative of the probable high octane unleaded aviation fuel. The FAA plans to conduct these tests during the summer of 1994.

3. CONCLUSIONS.

a. The use of MTBE in concentrations as high as 30 percent does not affect the volatility of the fuel.

b. The worse case scenario, for hot fuel testing with a gasoline that contains MTBE, is with the fuel in the tank heated to 43 °C and at takeoff power settings. This is identical to the current certification criteria.

c. The vapor-to-liquid ratio test is a better indicator of volatility than the Reid Vapor Pressure Test.

d. The use of MTBE increases the power output as much as 2 percent. This increase in power is roughly proportional to the concentration of MTBE.

e. The addition of MTBE to the test fuel reduces the energy content of the resulting blend. The increase in power does not offset the reduction in energy density. Fuel consumption could increase as much as 5 percent over existing gasolines.

f. The use of unleaded gasoline appears to affect valve seat wear. The wear observed was worse on older valve seat designs, and this implies that new material specifications will address this problem. The use of MMT may accelerate valve seat wear.

g. The use of MMT appears to result in engine deposits, which could result in ring sticking. This will cause high oil consumption and eventually power loss.

h. The use of vibration pickups is the current industry standard for detecting knock. The Technical Center was able to show that the use of pressure measurements results in the same knock ratings. The use of a trained octane rater resulted in similar knock ratings, when detonation occurred. The electronic systems were able to detect incipient knock before the trained octane rater.

i. The Technical Center developed a numerical technique for determining knock severity, when using pressure measurements. This makes the determination of knock severity more objective and it reduces the time required to train the operator to detect knock.

j. Reducing cylinder head temperatures by 33 °C resulted in a octane requirement reduction of approximately 2 points.

k. Retarding the spark timing reduced the octane requirement by approximately 4 points. This also reduced the power developed by approximately 2 percent.

l. Adding a muffler to the system increased the octane requirement by 2 to 3 points.

m. Knock was more severe at the 2500 rpm full throttle position for unleaded gasolines. Knock was more severe at takeoff power when using standard reference fuels. This implies that the aviation rich rating holds some significance for modern air-cooled aircraft engines.

n. A review of the literature and limited in-house testing did not reveal material compatibility problems for fuels with ether concentrations as high as 30 percent.

o. There is some concern that the use of surfactants in automobile gasoline would result in stable emulsions in aircraft fuel systems. The Technical Center was unable to generate a stable emulsion when mixing automobile gasolines with water.

p. Testing has not revealed significant fuel stability concerns for fuels that contain ethers.

q. MTBE has an octane blending value of 102.4 MON when mixed with aviation alkylates. ETBE has a similar octane blending value of 102.2 MON. MMT added approximately one MON when blended at a 0.1 g/gal concentration. Other compounds did not result in significant octane improvements.

The octane requirement testing was underway at the time this report was prepared, and the results to date are not conclusive, except to say that the octane requirement increase with unleaded gasolines may be on the order of 5 numbers. Emissions testing and flight tests will be conducted during Fiscal Year 1994.

4. REFERENCES.

Reference 1. Augusto M. Ferrara, Alternate Fuels for General Aviation Aircraft with Spark Ignition Engines, DOT/FAA/CT88/05, FAA Technical Center, Atlantic City International Airport, NJ 08405, June 1988

*U.S. GOVERNMENT PRINTING OFFICE: 1994-504-078-00010