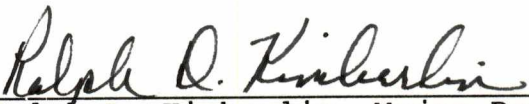


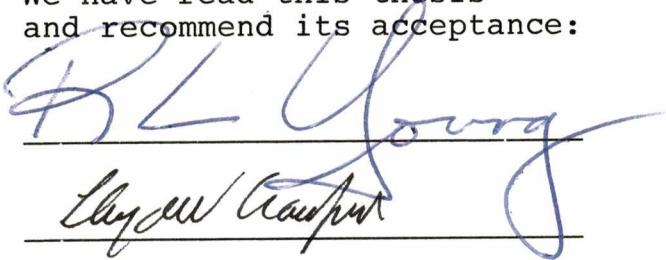
To the Graduate Council:

I am submitting herewith a thesis written by Lisa Jan Hughes entitled "An Analysis of Ethanol/Automotive Gasoline Blends for Use in General Aviation Aircraft." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.



Ralph D. Kimberlin, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:



The Graduate School

AN ANALYSIS OF ETHANOL/AUTOMOTIVE GASOLINE BLENDS
FOR USE IN GENERAL AVIATION AIRCRAFT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Lisa Jan Hughes

March 1985

Dedicated to Mother and Dad

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ABSTRACT

Considering the rising cost and diminished availability of 100-octane, low-lead (100 LL) aviation gasoline, owners of aircraft certified for 100 LL may be forced to find an alternative fuel in the near future. This study proposed a blend of 200-proof anhydrous ethanol (\$1.70 per gallon) and automotive gasoline (\$1.05 per gallon) as a replacement for aviation gasoline (\$1.75 per gallon). The research program included materials compatibility tests, Cooperative Fuel Research (CFR) engine tests, static thrust tests, and a flight test to determine the feasibility of such a blend as a fuel for an unmodified aircraft engine.

Throughout all tests, blends burned as well as aviation gasoline. Exhaust gas temperatures and cylinder head temperatures were hotter for the blends than for aviation gasoline. The static thrust tests indicated that a blend of 35% ethanol/65% automotive gasoline yielded the maximum thrust output. Fuel separation seemed to cause no engine problems. The materials tests revealed metals to be unaffected by contact with the blend fuel; the urethane elastomers showed signs of deterioration, but the nitrile elastomers seemed to perform satisfactorily. More research is needed in the area of materials compatibility. Fibrous growths were discovered in the blend and in the automotive gasoline samples.

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CHAPTER I

INTRODUCTION

For the past several years, owners of light general aviation aircraft have faced the problem of increased prices and reduced availability of aviation gasoline. The price of aviation gasoline has more than doubled in the last three years; some of the aviation gasolines are no longer distributed, making it difficult to properly fuel older aircraft. In the future, it is expected that all aviation gasoline will be phased out in favor of those fuels which are in greater demand. This is understandable, from the view of the petroleum refiners, since aviation gasoline constitutes 0.4% of the total gasoline produced in this country [1].¹ Even if aviation gasoline production is continued, the problems of diminishing a nonrenewable resource and of being dependent upon foreign oil imports are still present. Also to be considered is the pollution produced by burning aviation gasoline. The 100-octane, low-lead (100 LL) aviation gasoline contains up to 2.12 g/gal. of lead [2].

The problem of discontinued distribution of 80-octane aviation gasoline was successfully dealt with by

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

the Experimental Aircraft Association (EAA). Since 80-octane aviation gasoline was the certified fuel for the Cessna 150, the EAA obtained a Supplemental Type Certificate from the Federal Aviation Administration (FAA), which permits the use of unleaded automotive gasoline in a Cessna 150 [3]. Other aircraft engines have higher compression ratios and are certified to use only 100 LL aviation gasoline. The octane rating of automotive gasoline is insufficient for these engines. However, the octane number of automotive gasoline can be increased by adding 200-proof anhydrous ethanol [4].

There are several advantages in using an ethanol/automotive gasoline blend. Automotive gasoline is readily available and less expensive than aviation gasoline (\$1.05 per gallon versus \$1.75 per gallon, respectively). Ethanol costs \$1.70 per gallon, so a blend of automotive gasoline and ethanol is still less expensive than aviation gasoline. Also, since unleaded automotive gasoline contains less lead than 100 LL aviation gasoline (0.07 g/gal. [5] versus 2.12 g/gal. [2], respectively), two benefits can be realized. One advantage is that less lead fouling occurs in the engine; spark plugs and valves last longer [6,7]. A second benefit is that exhaust emissions are environmentally safer. Pollution characteristics can be further improved by the addition of ethanol which, compared to

automotive gasoline, reduces emissions of oxides of nitrogen, oxides of sulfur, carbon monoxide, smoke, unburned hydrocarbons, and Polynuclear Aromatics [8].

In addition to being cleaner and less expensive, an ethanol/automotive gasoline blend has other benefits. Ethanol is produced from many sources, mostly sugar and grain crops. Unlike petroleum fuel, these crops are renewable. Therefore, a natural resource is conserved and the dependence on foreign oil imports is decreased. The by-product obtained from manufacturing ethanol can be dried and used as a high protein food for animals and humans [9]. Farming the land and processing the crops could provide additional jobs and other economic benefits [10].

With these facts in mind, the objective of this investigation was to evaluate the feasibility of using a blend of ethanol and automotive gasoline to power the reciprocating engines of light general aviation aircraft. The analysis was, in part, achieved by implementing chemical, engine, ground, and flight tests. This study describes the program, experimental test results, and analysis.

CHAPTER II

BACKGROUND

To date, research done on ethanol/automotive gasoline blends in aircraft engines is either nonexistent or nonpublished. Because of the lack of testing on Gasohol,¹ Harry Zeisloft, EAA Aviation Foundation Technical Director, recommends that Cessna aircraft certified to operate on automotive gasoline use only straight unleaded regular gasoline. Although Gasohol has been used successfully in a number of EAA aircraft and functionally performed satisfactorily, Zeisloft recommends that materials compatibility and vapor lock characteristics are matters for further investigation [11]. The present investigator found no documentation on any other blend of ethanol/automotive gasoline with respect to utilization in aircraft engines.

The EAA has done extensive testing on the use of straight automotive gasoline in Cessna 150 aircraft and found it to be a superior fuel compared with aviation gasoline for 80-octane engines [11].

¹Gasohol is a trade name of the Nebraska Agricultural Products Industrial Utilization Committee and refers to a blend of 90% unleaded gasoline and 10% agriculturally derived, 200-proof anhydrous ethanol by volume [9].

Some testing using pure ethanol in aircraft engines has been done, but few publications have resulted. Although not documented, the Illinois Department of Transportation has conducted flight tests using 190-proof ethanol in a Cessna Skylane. The tests resulted in several aircraft modifications, three of which were: increasing the carburetor jet size, using a gasoline primer, and adding a fuel preheater. It is reported that not only have no major difficulties been encountered, but also the ethanol burned cooler and cleaner with less wear [12]. Other unpublished research has been done at Avco-Lycoming, but the reports are proprietary.

While published research on ethanol and ethanol blends for use in aircraft engines is scarce, many publications exist regarding their use in automobile engines. In 1941, Rogowski and Taylor [13] conducted a study and concluded that if the engine was optimized for the particular fuel tested by adjusting the spark and the fuel-to-air (F/A) ratio, then the addition of either 10 or 25% ethanol to automotive gasoline increased full-throttle power and part-throttle specific fuel consumption. The report also states that, "the optimum compression ratios for the multicylinder engine used . . . [were] seven for the 10% blend, eight for the 25% blend" The data presented tend to indicate that an increase in brake mean

effective pressure (BMEP) could be achieved by the addition of 25 to 50% ethanol. Also, the lowest brake specific fuel consumption (BSFC) occurred with the same blends. The optimum fuel blends which gave maximum BMEP or minimum BSFC for an engine with a compression ratio of 8.7:1 are approximately 40 to 50% ethanol, while for a compression ratio of 8.0:1 are approximately 30 to 40% ethanol.

Research on the use of ethanol/automotive gasoline blends in automobile internal combustion (IC) engines reveals several potential difficulties; three of these are vapor lock, materials compatibility, and phase separation.

Vapor lock occurs when the vapor pressure of a fuel is high enough that the fuel boils in the lines. Vapor lock will cause an engine to stop running. The probability of vapor lock increases with increasing temperature, decreasing ambient pressure, or increasing altitude. Vapor lock is also more likely to occur in fuel systems using fuel pumps than in systems using gravity feed, because the pump decreases the pressure below ambient conditions. The Reid vapor pressure (RVP) of automotive gasoline ranges from 9.0 psi (summer grade) to 14.5 psi (winter grade) [5]. Aviation gasoline vapor pressure varies between 5.5 and 7.0 psi [2]. Ethanol has an RVP of 2.5 psi [14]. The addition of ethanol to automotive gasoline has an unusual effect on the RVP of the fuel. As

ethanol is added, the RVP of the fuel increases. At approximately 10% ethanol, the RVP begins to decrease until, at 25% ethanol, the RVP of the blend is the same as the RVP of the gasoline. As the percentage increases beyond 25%, the RVP of the fuel decreases nonlinearly [9].

Although RVP indicates the likelihood of vapor lock, it is not a complete indicator. Any fuel will cause vapor lock if the operating conditions are severe enough [15]. In 1948, a test conducted in a Cessna 140 using a test fuel with an RVP far lower than 15 psi showed the limiting vapor pressure for incipient vapor lock on a 100°F day was 8.0 psi [7]. However, the EAA conducted tests under extreme conditions and observed no indications of vapor lock [16].² On the other hand, the EAA did experience vapor lock while using 100 LL aviation gasoline [6].

The compatibility of some materials used in IC engine fuel systems with ethanol blends may be cause for concern:

Ethanol will dissolve or adversely affect some of the nonmetallic constituents of fuel systems such as polyurethane, polyester bonded fiberglass laminate, and viton. . . . Ethanol can also cause moderate corrosion of metal parts, especially in conjunction with water. However, although laboratory tests of coupons of metals like zinc, iron, brass, copper, and

²A fuel was devised that had an RVP of 16 psi. The test consisted of a climb from sea level to a density altitude of 19,784 feet. The ambient temperature was 86°F.

lead showed significant corrosion rates, the controlled fleet tests that have been conducted with ethanol show no abnormal wear or rates of corrosion attributable to the fuel [4].

Another report summarizing results of the use of ethanol blends in fleet vehicles identified swelling or deterioration of ". . . rubber pump-plunger seals in carburetors, carburetor floats, accelerator-pump cups, and rubber gaskets. But these problems were not all directly traced to the use of gasohol" [16]. Nevertheless, problems with elastomers can be especially significant in the case of aircraft fuel systems, since elastomers are frequently used for fuel bladders.

Phase separation occurs because ethanol is hygroscopic; that is, it draws moisture out of the atmosphere. Water mixes with ethanol but not with gasoline. The ethanol/water mixture, being heavier, sinks to the bottom. For a 25% ethanol/automotive gasoline blend at 70°F, 1% water will cause separation [9]. Some sources state that an automobile or aircraft engine will not operate on an alcohol/water solution [9]. Some feel that it will run, but cannot be started [4]. Still others report smooth operation was obtained down to 80 proof [17].

The present study addresses the aforementioned potential difficulties of burning an ethanol/automotive gasoline blend in an unmodified aircraft engine. In the future, research should be conducted regarding the effect

of minor engine modifications (such as timing and carburetor adjustment) on performance. Other areas for investigation are cold starts and rapid acceleration.

CHAPTER III

TEST PROGRAM DESCRIPTION

The research described in this chapter was conducted with the expectation that it would result in the determination of an optimum alternative to 100 LL aviation gasoline, as well as to obtain new information concerning characteristics and properties of ethanol/automotive gasoline blends. Power output, performance, corrosion, and anti-knock characteristics were examined along with properties such as specific gravity. Fuel usage rate and necessary aircraft modifications were also considered in the determination of an alternate fuel. Knowledge of these factors will result in the best overall choice for an alternate fuel.

Selection and Mixing of Fuels

The automotive gasoline chosen was premium unleaded with no alcohol added. This fuel was chosen because of the desire to have the highest octane rating possible without the effects of alcohol. The alcohol obtained was 200-proof anhydrous ethanol. The ethanol was denatured with 4.5% unleaded gasoline.

The blends were mixed by volume percentage. Ethanol was first measured in a graduated cylinder and

poured into a second container. The gasoline was then measured in the graduated cylinder and poured into the container with the previously measured alcohol.

Based on the work done by Rogowski and Taylor [13], it was decided to use a higher percentage of ethanol than is used in Gasohol (10%). Blends of 15, 25, 35, and 45% volume were chosen as the test fuels.

Laboratory Test

Using a hydrometer, specific gravities of the fuels were measured. It was intended to determine properties of the test fuels such as RVP and heating values; unfortunately, laboratory equipment for the latter two tests was not available.

Materials Soak Test

The objective of this test was to find out what the long-term effects of the experimental fuels would be on a fuel system of a general aviation aircraft. The intent was to simulate as closely as possible the conditions to which the materials would be exposed while the experimental fuel was static in the system.¹ There are a number of materials used in aircraft fuel systems, and

¹In this study, the fuel system included the fuel tanks and lines up to the exhaust.

several of those more commonly used were chosen for this study. Aircraft often have elastomer bladders for fuel tanks (fuel cells). Four samples of fuel cell fabric were donated and identified as urethane A, urethane B, buna nitrile C, and nitrile D.² Urethane A and B are commonly used either inside or outside of fuel tanks. Buna nitrile C is always used outside, and nitrile D is used inside. Two kinds of stainless steel were tested. Also tested were aluminum 2024-0 tubing, 2024-T3 sheet, and 5052-H38 sheet. When aluminum is used for a fuel tank, it is coated with a substance commonly called slosh sealer.³ It was decided to coat a piece of 2024-T3 aluminum sheet with slosh sealer for testing. In all, 11 different materials were tested. The materials were cut into samples (1 to 2 inches square), photographed, and weighed.

Four fuels were chosen for testing: (1) 100% automotive gasoline,⁴ (2) 100% 100 LL aviation gasoline, (3) 100% ethanol, and (4) a blend of 25% ethanol/75%

²The letters A, B, C, and D have no significance except to differentiate among the four types of fuel cell fabric.

³Liquid sealer is poured into the tank, "sloshed," and emptied. As the sealer cures, it seals the small holes. However, the sealer always remains sticky.

⁴The automotive gasoline used was Exxon premium unleaded, 91 octane.

automotive gasoline. Four dozen pint-sized canning jars with lids were used for the soak test (one dozen for each type of fuel). A 3/32-inch-diameter hole was drilled in the lids for ventilation, simulating the conditions inside a fuel tank. The test was set up using one fuel-type at a time. The 12 jars were filled with 200 ml each of the particular fuel. Of the 11 kinds of material specimens to be tested, each one was cleaned, then submerged into one of the jars. The twelfth jar contained no specimen, as it was to be used for a baseline reference. The process was repeated for the remaining types of fuels until 11 different kinds of materials were being tested in four types of fuels. The lids were secured on the jars, and the jars were put in cardboard boxes. The boxes were placed inside a vented locker located outside, exposed to the weather. The samples remained undisturbed from May 17, 1984 until December 10, 1984, except for two inspections.

Upon removal from the jars, the specimens were laid out to dry. After drying, the samples were weighed and inspected with a 40-power microscope. Selected samples were photographed and subjected to an Energy Dispersion X-ray (EDX) scan.

Cooperative Fuel Research Engine Tests

This test was originally intended to investigate the anti-knock characteristics of the experimental fuels. The only Cooperative Fuel Research (CFR) engine found for the test was located at the U. S. Naval Academy in Annapolis, Maryland. However, upon arrival it was discovered that the engine was not equipped to conduct the desired tests.

The new purpose became to set up the engine to simulate as closely as possible the Lycoming IO-540K and the Continental O-470M engines. Although it was recognized that an aircraft engine is very different from a CFR engine, it was felt that relative information about the fuels would be revealed through the tests. On a more basic level, it was still possible and necessary to determine if the engine would operate and if knock would occur.

The University of Tennessee Space Institute Flight Research Department has two light general aviation aircraft suitable for flight testing. One is a 1981 Piper Saratoga equipped with a Lycoming IO-540K engine; the other is a 1957 Cessna 310 which has a Continental O-470M engine. Table 1 shows specifications of the two engines. These two engines were chosen for simulation in the event

Table 1. Aircraft Engine Specifications

Parameter	Lycoming IO-540K	Continental O-470M
Compression Ratio	8.7:1	8.0:1
Spark Timing	20° BTDC ^a	24° BTDC ^a
F/A	~0.078 ^b	~0.078 ^b

^aBefore top dead center.

^bA/F = 12.82.

that the test results would lead to future static thrust tests or flight tests.

The CFR engine (see Figures 1 through 8 for test setup and equipment) was prepared for the test by setting the spark timing (Figure 6) and compression ratio (Figure 7). The remaining parameters were set while burning aviation gasoline. It was determined that a carburetor jet size of 0.026 inch was required for best performance. The fuel-to-air ratio (F/A) was set by varying the level of the carburetor float (Figure 8). No readjustments were made throughout the testing.

The fuels chosen for testing were 100 LL aviation gasoline and 15, 25, and 35% ethanol mixed with automotive gasoline.⁵ After the engine was set up, the engine speed, which was read from the tachometer, was varied from 1,000 to 1,400 revolutions per minute (rpm) in increments of 100 for each fuel tested. At each tachometer setting, the following parameters were recorded: actual rpm, actual F/A, brake torque, exhaust emissions, fuel consumption rate, and ambient and exhaust gas temperatures.

⁵The automotive gasoline used was Phillips 66 premium unleaded, 93 octane.

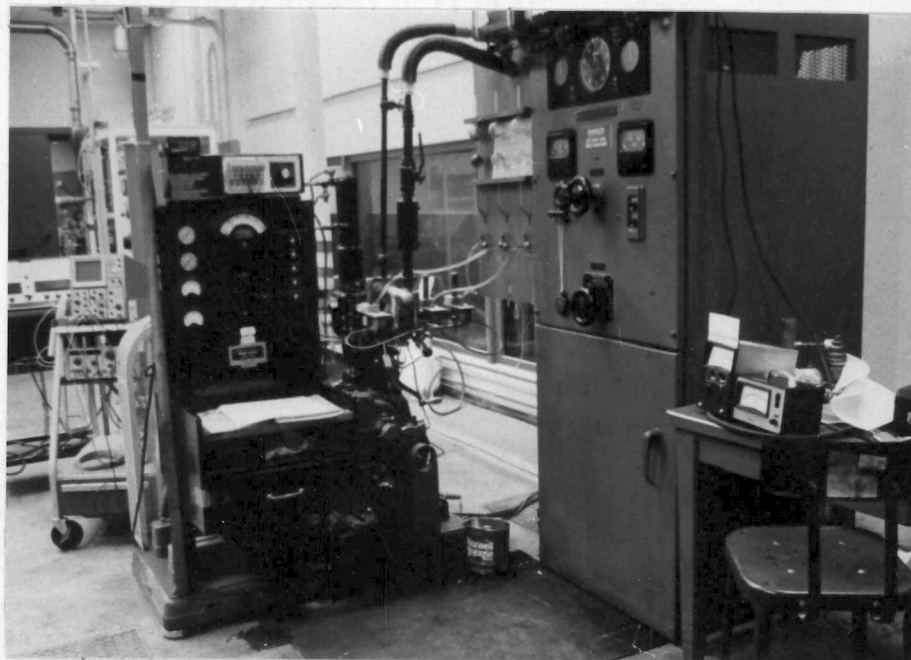


Figure 1. Cooperative Fuel Research Engine Test Setup.
Cooperative Fuel Research unit made by
Waukesha Motor Company, Wisconsin, 1951;
Serial No. 2152; engine Serial No. 852999.

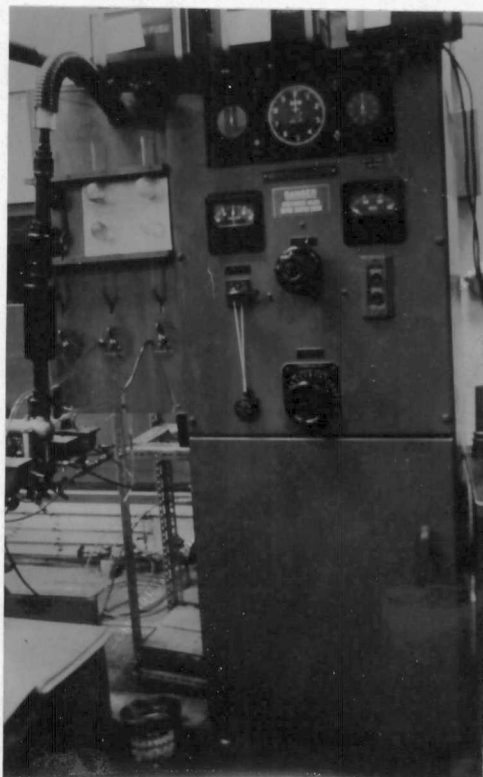


Figure 2. Cooperative Fuel Research Engine Control Panel.
Control panel manufactured by Westinghouse.

LANCASTER BOND

100% COTTON FIBRE

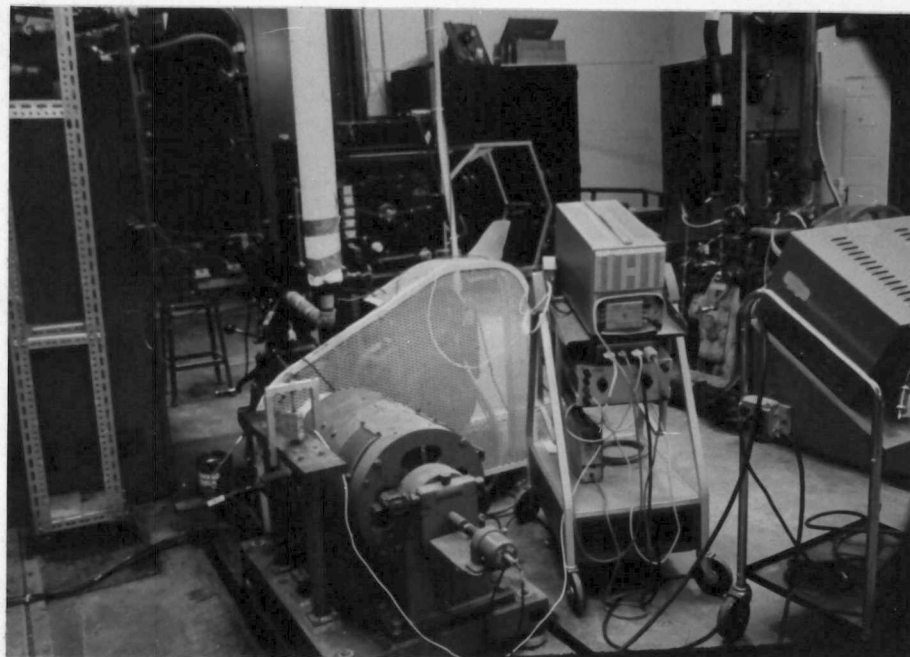


Figure 3. Cooperative Fuel Research Engine, Dynamometer, and Load Cell. Westinghouse Life Line dynamometer.

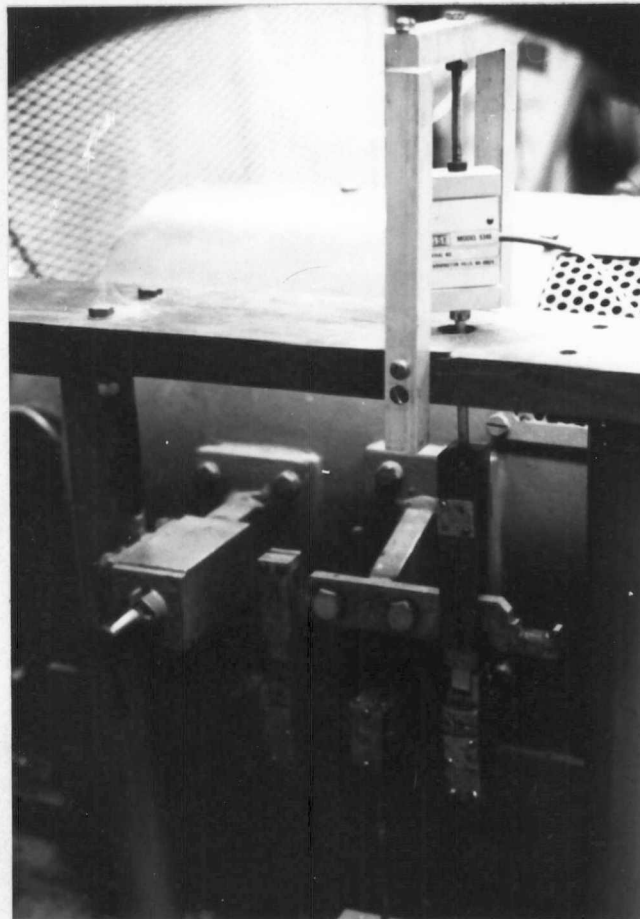


Figure 4. Load Cell.

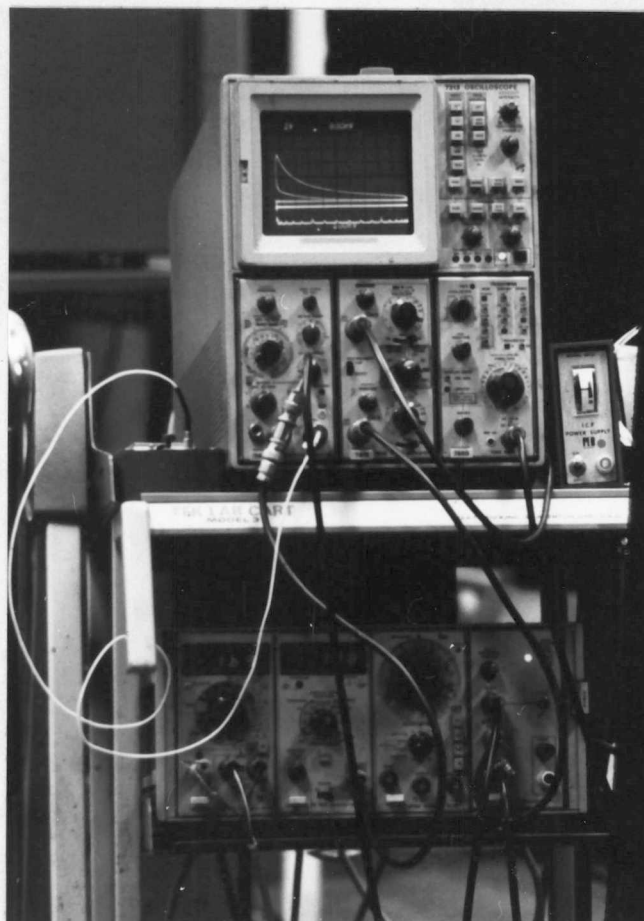


Figure 5. Oscilloscope and Power Module. Tektronix 7313 oscilloscope equipped with Tektronix C-5C oscilloscope camera Serial No. B038405; Tektronix TM504 power module Serial No. B016333. Pressure-versus-time and pressure-versus-volume diagrams came from the oscilloscope screen (upper half of photograph); load cell readout came from the power module (lower half of photograph).

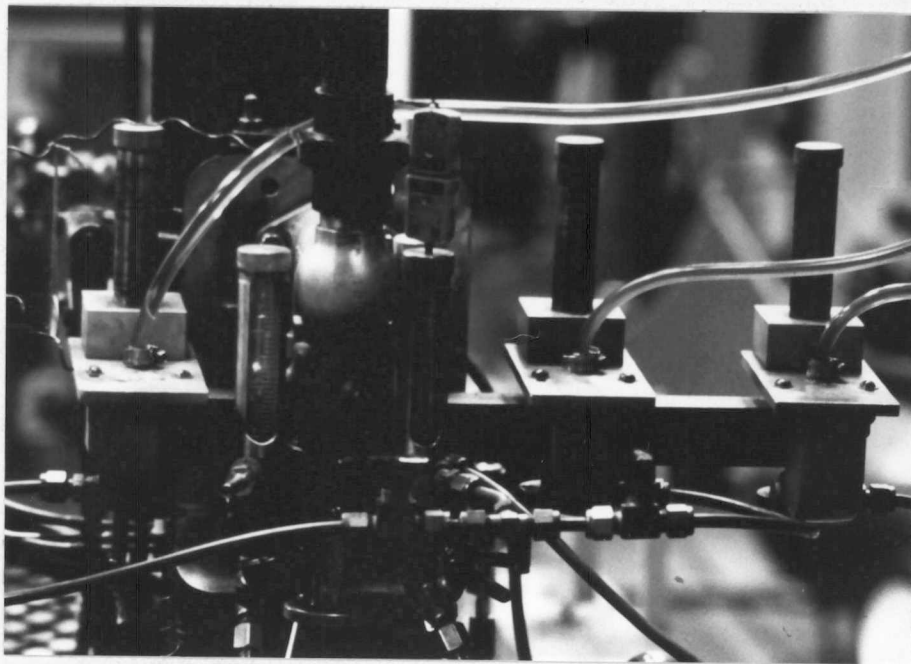


Figure 6. Carburetor Bowls.



Figure 7. Air Mass Flowmeter. Hastings mass flowmeter Model AHL-10P, Serial No. 67, 10 cfm total.



Figure 8. Exhaust Gas Detector. Beckman HC/CO tester, Model 590.

Static Thrust Tests

The objective of these tests was to measure the thrust of an unmodified aircraft engine while burning the different test fuels. The fuels chosen for testing were straight automotive gasoline and blends of 15, 25, 35, and 45% ethanol mixed with automotive gasoline. Also, 100 LL aviation gasoline was tested for baseline data. The Cessna 310 was used for the tests (see Figure 9 for test setup). The right wing and engine were strapped securely to a tie-down. Between the engine and the tie-down was a dynamometer (Figure 10) which measured pounds-force. The engine, dynamometer, and tie-down were kept in a straight line. The airplane was on a slight downhill grade to overcome friction in the tires.

The fuels were poured into the auxiliary tank. The airplane was started on aviation gasoline, warmed up, then switched over to the test fuel. The tests were conducted by keeping the mixture full-rich and using the throttle to vary manifold pressure from 14 to 26 inches of mercury in increments of 2 inches. At each manifold pressure setting, the following parameters were recorded: engine speed, thrust, cylinder head temperature (CHT), exhaust gas temperature (EGT), outside air temperature, and oil temperature.



Figure 9. Static Thrust Test Setup. Dynamometer and tie-down are located in lower left corner.



Figure 10. Dynamometer. Dillon dynamometer
Serial No. AP-7331, capacity
4,000 pounds.

Flight Test

The purpose of the flight test was to have a cursory look at the general performance of the engine with regard to knock, loss of power, and vapor lock. Based on results from the static thrust test, the fuel chosen for testing was the 35% ethanol blend. The blend was poured into the Cessna's auxiliary tank to be burned in the right engine. The take-off and climb to altitude were conducted using aviation gasoline. After climbing to a pressure altitude of 5,100 feet, level flight was established and cruise power was set. The engine temperatures were allowed to stabilize and were then recorded. While still burning aviation gasoline, a climb was conducted to 8,000 feet. Peak CHT and EGT were recorded to evaluate the possibility of engine overheat. During the descent back to 5,000 feet, the fuel being used was changed from aviation gasoline to the blend and the aforementioned procedure was repeated. The engine was switched to aviation gasoline again upon entering the flight pattern for landing.

Engine Inspection

The purpose of the last phase of testing was to determine what detrimental effects, if any, the experimental fuels had on the engine of the Cessna 310. All

cylinders of the right Continental 0-470M engine were removed and visually examined for abnormal wear or unusual deposits.

CHAPTER IV

TEST RESULTS AND ANALYSIS

Laboratory Test

The specific gravities of the test fuels as measured with a hydrometer are shown in Table 2.

Materials Soak Test

The materials soak test results (shown in Table 3) revealed the effects of the various fuels on fuel system components. Most of the metallic parts showed little change, while the elastomers were more affected. Several potential problems with growths, deterioration, and deposits were indicated.

A spherical, fibrous growth developed in at least two of the fuel samples. One of the growths appeared in the automotive gasoline sample containing a specimen of buna nitrile C. The other growth occurred in the 25% ethanol/75% automotive gasoline blend sample containing a piece of aluminum sheet coated with slosh sealer. Since the slosh sealer remained sticky, the growths stuck to it and made close examination possible. After viewing with a 40-power microscope (see Figures 11 and 12), it was determined that observation under an electron microscope and an EDX scan would reveal more about the nature of the

Table 2. Specific Gravities of Test Fuels

Fuel	Specific Gravity
100 LL Aviation Gasoline	0.717
100% Automotive Gasoline ^a	0.755
15% Ethanol ^b	
85% Automotive Gasoline	0.759
25% Ethanol	
75% Automotive Gasoline	0.765
35% Ethanol	
65% Automotive Gasoline	0.770
45% Ethanol	
55% Automotive Gasoline	0.776
100% Ethanol	0.788

^aThe automotive gasoline used was Phillips 66 premium unleaded, 93 octane.

^bPercentages are by volume before mixing.

Table 3. Results of Materials Soak Test

Material	Fuel	Percent Weight Change ^a	Observations
Urethane "A"	None ^b	-0.21	Black, flexible material, shiny on one side. Other side is covered with loose-woven fabric of clear strands, then covered with clear coating.
	Avgas ^c	-1.11	Unaffected.
	Blend	-1.65	Fuel sample separated. Material sample curled. Shiny finish gone. White streaks appear on same side. Microscope (40X) examination reveals streaks to be powdery. Gloss gone off of fiber side as well.
	Autogas ^d	-1.05	Microscope (40X) examination reveals clear fibers slightly discolored peach.
	Ethanol	-1.91	Microscope (40X) examination reveals shiny side lost gloss. Clear coating on back "fogged."

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Urethane "B"	None ^b	-0.38	Black, flexible material with clear fabric suspended inside. Fabric closer to one side than other. One side is semi-shiny; other side has fabric texture. Microscope (40X) examination reveals tiny open bubbles or pores on both sides, but many more on fabric side.
	Avgas ^c	+0.27	Material curled. Finish dulled on both sides. Microscope (40X) examination shows both sides have more pores.
	Blend	-1.85	Material brittle, tightly curled. Separated into three layers, fabric being middle layer. Both sides lost finish and puckered and shriveled. Microscope (40X) shows many more pores on semi-shiny side.
	Autogas ^d	-0.22	Material curled. Semi-shiny side is shinier, but fabric grain shows through more. Microscope (40X) shows more pores on shinier side. Fabric side appears unaffected.
	Ethanol	-1.86	Fuel sample was discolored pink. Material sample brittle, curled. Finish gone off both sides. Microscope (40X) shows many more pores on both sides.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Buna-Nitrile "C"	None ^b	-0.23	Black, soft, flexible material. Clear fabric in material is closer to one side than other. One side shows more fabric grain than other. Both sides coated with white, dusty powder.
	Avgas ^c	-5.34	Material has more white powder covering both surfaces. Otherwise unaffected.
	Blend	-5.40	Fuel sample separated, had brown tint. Material sample slightly stiffer. More white powder present.
	Autogas ^d	-4.20	Fuel samples discolored rusty-orange. Small fibrous spheres present in fuel. Material sample caked with white powder.
	Ethanol	-6.16	Slightly stiffer. More white powder on surface. Microscope (100X) examination reveals white circles growing on surface.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Nitrile "D"	None ^b	-0.33	Soft, black, flexible material. No fabric, but has fabric impression stamped on both sides.
	Avgas ^c	-13.58	Fuel discolored slightly greener. Material slightly less flexible.
	Blend	-10.71	Fuel sample slightly darker. Material slightly less flexible.
	Autogas ^d	-10.39	Material sample yellowed slightly.
	Ethanol	-16.16	Fuel sample discolored peach. Material sample yellowed. Less flexible.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Intake Manifold Hose	None ^b	-0.113	Thick hose of black elastomer outside, several layers of white fabric, and shiny black elastomer inside. Usually only inside is in contact with the fuel. Black rubs off. Not very flexible. Hose has been used.
	Avgas ^c	-5.14	Fuel discolored to dark olive-green. Hose brittle.
	Blend	-5.73	Fuel discolored black. Fuel separated. Inside elastomer had swollen more than outside elastomer and reversed the curvature of the hose.
	Autogas ^d	-3.22	Fuel discolored black. Microscope (40X) showed white, grainy deposits all over material sample. Hose is brittle.
	Ethanol	-6.58	Fuel discolored dark olive-green. Hose is brittle. With 40X microscope, white spheres found on surface of elastomers.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Stainless Steel Sheet	None ^b	+0.0014	Unaffected.
	Avgas ^c	-0.0027	Unaffected.
	Blend	-0.0047	Very slight rust around cut edges.
	Autogas ^d	+0.0035	Rust-colored deposits on cut edges.
	Ethanol	+0.0041	Rust-colored deposits on cut edges.
Stainless Steel Tubing	None ^b	+0.0062	Unaffected.
	Avgas ^c	-0.0085	Unaffected.
	Blend	+0.0013	Unaffected.
	Autogas ^d	-0.0038	Unaffected.
	Ethanol	+0.0029	Unaffected.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Aluminum 5052-H38 Sheet	None ^b	+0.0099	Unaffected.
	Avgas ^c	+0.0036	Microscope (40X) reveals small, white dots on one side of plate.
	Blend	+0.0217	Rusty-orange colored film on one side. Microscope (40X) shows tiny, white dots on other side of plate. Many rust-colored, grainy deposits on cut edge.
	Autogas ^d	+0.0264	Rusty-orange film on material. One rust-colored deposit on cut edge.
	Ethanol	+0.0101	Microscope (40X) reveals white, crystal-like deposits over surface.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Aluminum 2024-0 Tubing	None ^b	+0.0061	Coating not removed from outside.
	Avgas ^c	+0.0029	Unaffected.
	Blend	-0.0401	Specimen tinted rusty-orange. White and rust-colored deposits found on cut edges. Microscope (40X) revealed grainy texture to deposits.
	Autogas ^d	-0.0090	Orange tint to specimen.
	Ethanol	+0.0030	Rusty-orange deposit on cut edge.
Aluminum 2024-T3 Sheet	None ^b	+0.0109	Unaffected.
	Avgas ^c	+0.0212	Unaffected.
	Blend	+0.0164	Dark gray deposits on all surfaces. Microscope (40X) observation reveals rusty-orange, grainy deposits on cut edges.
	Autogas ^d	+0.0169	Rusty-orange colored film covering sample.
	Ethanol	+0.0108	Unaffected.

Table 3. (continued)

Material	Fuel	Percent Weight Change ^a	Observations
Aluminum 2024-T3 Sheet (coated with fuel tank slosh sealer)	None ^b	e	Slosh sealer gives light, pale-yellow tint to aluminum. Never completely dries; remains sticky.
	Avgas ^c	e	Unaffected.
	Blend	e	Fuel separated. Coating discolored slightly orange. Barely sticky. Several fibrous growths stuck to surface.
	Autogas ^d	e	Discolored dark, rust color. Very sticky.
	Ethanol	e	Color almost gone. Not sticky. Coating seems thinner.

^a (+) = gain; (-) = loss; samples weighed on the order of between one and five grams.

^b Sample kept dry during test for comparison.

^c Aviation gasoline.

^d Automotive gasoline.

^e No weight measurements made.

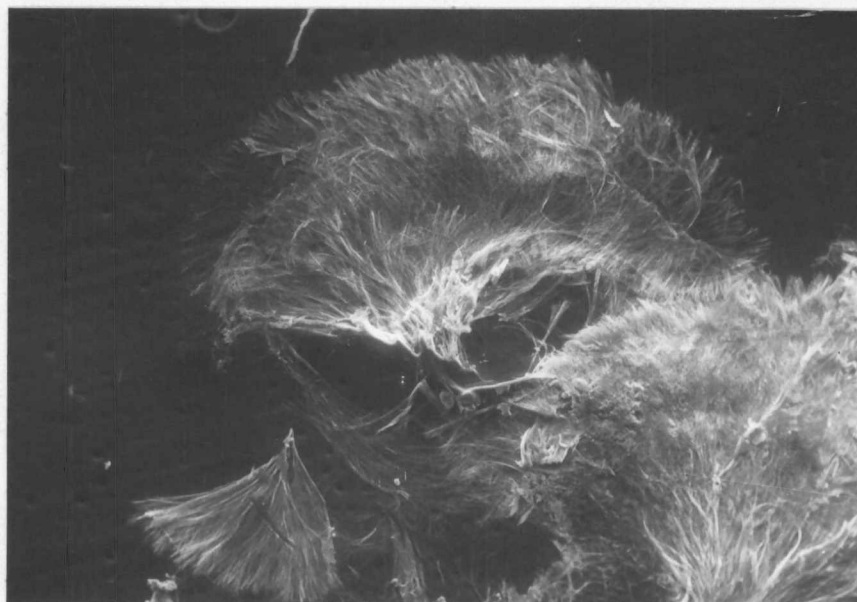


Figure 11. Growth Found on Aluminum 2024-T3 Sheet Coated with Slosch Sealer. Taken from 25% ethanol/75% automotive gasoline blend; 100X magnification.

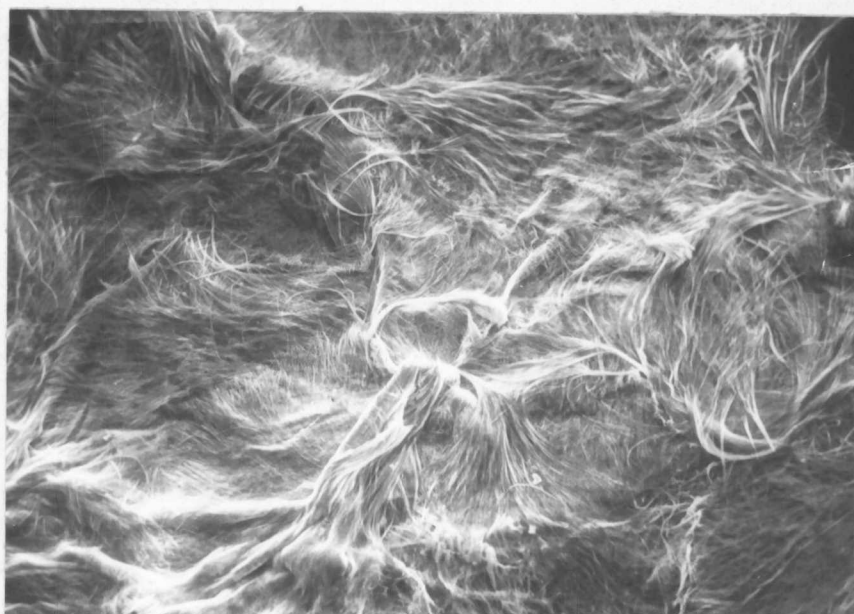


Figure 12. Growth Found in 25% Ethanol/75% Automotive Gasoline Blend. The fuel sample had contained a piece of aluminum 2024-T3 sheet coated with slosh sealer; 100X magnification.

growth. Unfortunately, due to the limitations of the equipment, no information was gained regarding the presence of elements with an atomic weight of 16 or less. Thus, the determination of whether the growth was organic or inorganic was not possible. The scan showed only that the growth contained molybdenum and zinc.

Another type of growth occurred in pure ethanol and resembled a circular crystal (Figure 13). An EDX scan showed the presence of silicon, chlorine, sulfur, zinc, and iron. This "crystal" was on buna nitrile C, and since elastomers are complex combinations of many elements, the possibility exists that the X-rays penetrated the crystal and were reflecting some of the constituents of buna nitrile. A scan of the unused material revealed chlorine, silicon, magnesium, and iron. Again, due to the limited capability of the equipment, conclusions as to whether the growth was organic were not possible.

Some of the elastomers suffered deterioration; the urethanes deteriorated more than the others. All of the elastomers lost weight in all fuels. As described in Table 3, the urethanes lost their finish or blistered. An aircraft having these types of fuel cells would do well to completely avoid any alcohol, blend or otherwise, from coming in contact with the tank. Fuel cell materials C and D seemed to test as well in the blend as in aviation



Figure 13. Growth Found on Buna Nitrile C. Taken from 100% ethanol; 100X magnification.

gasoline. More extensive testing needs to be done to determine the long-term effects. It may be that blends could be used for short periods of time without any adverse effects. It is believed that further tests would reveal a replacement fuel cell material. Several elastomers on the market today have already been tested for compatibility with alcohol and petroleum products. Polysulfide (Thiokol, for example), fluorocarbon (Viton), and polychloroprene (Neoprene), as well as some nitriles, have been shown to be resistant to the constituents in the fuel blends tested in this study [18,19].

Some of the aluminum parts acquired gray and rust-colored deposits on the cut edges. Two of the parts were subjected to an EDX scan. The scan on the 5052-H38 aluminum sheet taken from the blend showed the deposit (Figure 14) consisted of 51% zinc and 49% sulfur. The ethanol used in all the experiments was stored in 80-gallon galvanized steel drums. The zinc on the sample may have come from the zinc-galvanized coating. What the drums held before they were received and cleaned is not known. An EDX scan conducted on the 2024-0 aluminum tubing taken from pure ethanol (Figure 15) revealed zinc, sulfur, aluminum, and iron. Since the deposit occurred on the cut edge of the specimen, and since a steel cutter was used on

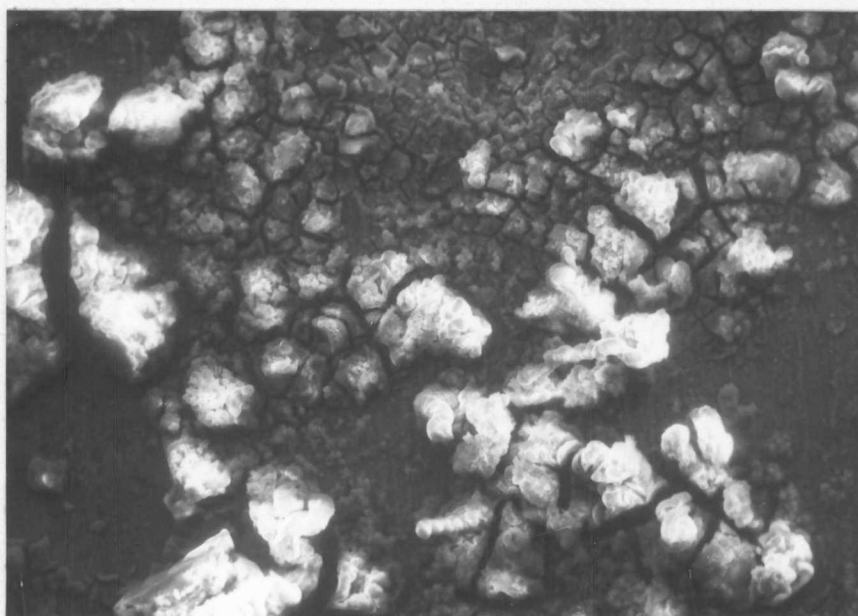


Figure 14. Deposits on Aluminum 5052-H38 Sheet. Taken from 25% ethanol/75% automotive gasoline blend; 100X magnification.

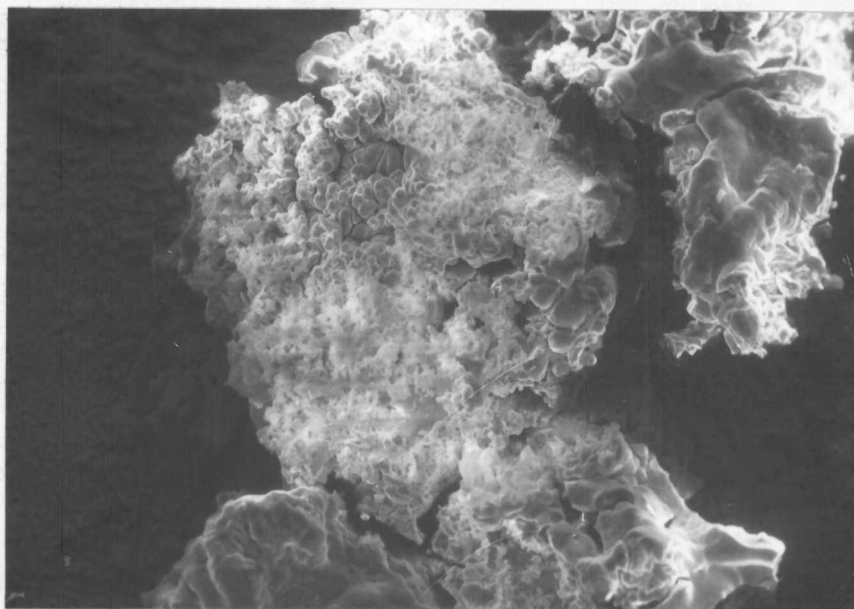


Figure 15. Deposits on Aluminum 2024-0 Tubing. Taken from 100% ethanol; 100X magnification.

the tubing, it is possible that the iron came from the cutter and was not cleaned off thoroughly before testing.

In general, the metals were not affected by the blend any more than by the aviation gasoline. However, the use of any type of alcohol in fuel cells made of urethane is not advised. Nitrile and buna nitrile materials need more extensive testing to determine long-term effects before conclusions can be drawn. However, they appeared to perform satisfactorily during the seven months of this test. The results of the test also showed that ethanol may thin the slosh sealer coating in an aluminum fuel tank.

Fuel Separation

During the course of the materials test, four out of twelve of the blend samples separated (see Table 3, page 32). Since separation has been a cause for concern for some researchers, it was felt that an additional test might yield more information about its importance.

The blend sample in the jar containing fuel cell A had about 10% of its volume separated out at the bottom in an ethanol/water mixture. The contents of the jar were poured into an open tank of a single-cylinder engine after

a warm-up on gasoline.¹ The fuel was not shaken or stirred and promptly separated out in the tank after pouring. The mixture burned with no noticeable difference from gasoline. The engine was stopped and restarted on the mixture without difficulty. The engine burned off the ethanol/water layer, then proceeded to burn the gasoline layer. Although it is not known how much water was in the ethanol/water part of the blend, there was no indication that the separated mixture would cause problems in an engine. In fact, it could be considered a safety feature that an ethanol/water blend does burn. Water in aviation gasoline does not burn.

Cooperative Fuel Research Engine Test

The data recorded during the CFR engine tests were reduced and are shown in Tables 4 through 11. Because of unforeseen difficulties, the reliability of some of the data is questionable, but trends can be seen.

There are several reasons why some of the test results were questioned. One problem was that the CFR engine had been modified. After learning what the engine's capabilities were, the test procedure was replanned. The

¹The engine used was a Continental Motors Corporation Model AU-3B, Serial No. 329, with a 2.4 continuous horsepower rating.

Table 4. Results of CFR Engine Test Using 100 LL Aviation Gasoline
(Compression Ratio: 8:1, Timing: 24° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	976	1,089	1,249	1,289	1,385
Actual F/A	0.0728	0.0729	0.0715	0.0754	0.0806
Brake Torque (ft-lb)	17.0	16.0	15.0	13.0	14.0
Fuel Consumption Rate (ml/min)	24.30	25.77	26.32	28.49	30.83
Temperatures					
Ambient Inlet (°F)	77	76	75	76	76
Intake Manifold (°F)	70	69	69	68	68
Exhaust (°F)	1,143	1,180	1,200	1,197	1,202
Exhaust Emissions					
Carbon Monoxide (%)	1.8	1.9	2.2	2.4	2.3
Hydrocarbons ^a (ppm)	9,500	11,800	13,500	10,700	9,500

^aUnburned hydrocarbons measured as hexane.

Table 5. Results of CFR Engine Test Using a Mixture of
15% Ethanol and 85% Automotive Gasoline
(Compression Ratio: 8:1, Timing: 24° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	985	1,048	1,177	1,285	1,402
Actual F/A	0.0716	0.0717	0.0755	0.0774	0.0702
Brake Torque (ft-lb)	23.0	16.0	16.0	13.0	10.0
Fuel Consumption Rate (ml/min)	22.59	23.61	25.87	27.59	26.66
Temperatures					
Ambient Inlet (°F)	78	79	80	80	72
Intake Manifold (°F)	76	74	72	70	67
Exhaust (°F)	1,195	1,210	No Data	1,234	1,288
Exhaust Emissions					
Carbon Monoxide (%)	0.75	1.0	1.3	1.6	1.0
Hydrocarbons ^a (ppm)	10,000	9,000	9,000	8,000	8,000

^aUnburned hydrocarbons measured as hexane.

Table 6. Results of CFR Engine Test Using a Mixture of
25% Ethanol and 75% Automotive Gasoline
(Compression Ratio: 8:1, Timing: 24° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	1,104	1,088	1,198	1,291	1,398
Actual F/A	0.0566	0.0684	0.0752	0.0752	0.0757
Brake Torque (ft-lb)	15.0	14.0	13.0	12.0	13.0
Fuel Consumption Rate (ml/min)	18.52	22.96	26.25	26.60	27.46
Temperatures					
Ambient Inlet (°F)	73	74	75	74	75
Intake Manifold (°F)	68	67	66	63	62
Exhaust (°F)	1,210	1,244	1,255	1,267	1,285
Exhaust Emissions					
Carbon Monoxide (%)	0.3	0.4	0.9	1.1	1.1
Hydrocarbons ^a (ppm)	4,000	6,000	6,000	5,500	4,500

^aUnburned hydrocarbons measured as hexane.

Table 7. Results of CFR Engine Test Using a Mixture of
35% Ethanol and 65% Automotive Gasoline
(Compression Ratio: 8:1, Timing: 24° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	987	1,092	1,196	1,297	1,382
Actual F/A	0.0697	0.0735	0.0756	0.0754	0.0781
Brake Torque (ft-lb)	14.8	14.0	13.0	12.0	12.0
Fuel Consumption Rate (ml/min)	21.96	23.84	25.39	26.48	28.15
Temperatures					
Ambient Inlet (°F)	74	75	75	75	76
Intake Manifold (°F)	61.5	62	60	58	58
Exhaust (°F)	1,200	1,258	1,278	1,290	1,305
Exhaust Emissions					
Carbon Monoxide (%)	0.1	0.2	0.4	0.5	0.7
Hydrocarbons ^a (ppm)	9,000	10,500	10,000	8,500	7,000

^aUnburned hydrocarbons measured as hexane.

Table 8. Results of CFR Engine Test Using 100 LL Aviation Gasoline
(Compression Ratio: 8.7:1, Timing: 20° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	990	1,085	1,188	1,285	1,392
Actual F/A	0.0702	0.0733	0.0753	0.0771	0.0775
Brake Torque (ft-lb)	16.3	15.0	13.5	12.5	11.6
Fuel Consumption Rate (ml/min)	23.75	25.59	27.35	28.69	29.98
Temperatures					
Ambient Inlet (°F)	79	78	79	79	79.5
Intake Manifold (°F)	71	71	72	70	68.5
Exhaust (°F)	1,161	1,167	1,175	1,188	1,210
Exhaust Emissions					
Carbon Monoxide (%)	1.4	1.7	1.9	2.2	2.2
Hydrocarbons ^a (ppm)	12,000	13,000	12,500	11,000	11,500

^aUnburned hydrocarbons measured as hexane.

Table 9. Results of CFR Engine Test Using a Mixture of
15% Ethanol and 85% Automotive Gasoline
(Compression Ratio: 8.7:1, Timing: 20° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	986	1,089	1,183	1,288	1,402
Actual F/A	0.0710	0.0735	0.0763	0.0781	0.0778
Brake Torque (ft-lb)	16.5	16.0	14.5	12.8	13.0
Fuel Consumption Rate (ml/min)	22.42	24.22	26.19	27.47	28.44
Temperatures					
Ambient Inlet (°F)	74	75	76	78	78
Intake Manifold (°F)	73	73	71	69	68
Exhaust (°F)	1,187	1,215	1,233	1,237	1,250
Exhaust Emissions					
Carbon Monoxide (%)	0.7	1.0	1.1	1.5	1.6
Hydrocarbons ^a (ppm)	12,500	14,500	11,000	11,000	9,700

^aUnburned hydrocarbons measured as hexane.

Table 10. Results of CFR Engine Test Using a Mixture of
25% Ethanol and 75% Automotive Gasoline
(Compression Ratio: 8.7:1, Timing: 20° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	996	1,092	1,200	1,290	1,398
Actual F/A	0.0704	0.0741	0.0893	0.0756	0.0753
Brake Torque (ft-lb)	16.0	15.0	14.0	12.6	12.0
Fuel Consumption Rate (ml/min)	22.35	24.52	30.76	26.74	27.35
Temperatures					
Ambient Inlet (°F)	74	74	74	74	74
Intake Manifold (°F)	68	67	65	63	62
Exhaust (°F)	1,206	1,230	1,242	1,266	1,290
Exhaust Emissions					
Carbon Monoxide (%)	0.3	0.7	1.0	1.0	1.0
Hydrocarbons ^a (ppm)	7,000	8,500	8,000	7,500	8,000

^aUnburned hydrocarbons measured as hexane.

Table 11. Results of CFR Engine Test Using a Mixture of
35% Ethanol and 65% Automotive Gasoline
(Compression Ratio: 8.7:1, Timing: 20° BTDC)

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5
Actual rpm	1,041	1,103	1,192	1,302	1,398
Actual F/A	0.0657	0.0667	0.0706	0.0729	0.0732
Brake Torque (ft-lb)	15.0	13.8	13.0	11.7	11.5
Fuel Consumption Rate (ml/min)	22.50	23.44	24.79	26.27	27.06
Temperatures					
Ambient Inlet (°F)	72	73	73	73	74
Intake Manifold (°F)	60	60	58	57	57
Exhaust (°F)	1,200	1,254	1,282	1,304	1,325
Exhaust Emissions					
Carbon Monoxide (%)	0.05	0.1	0.2	0.4	0.5
Hydrocarbons ^a (ppm)	6,000	7,000	6,500	6,000	6,500

^aUnburned hydrocarbons measured as hexane.

operator was unfamiliar with both the modified engine and the improvised test procedure. After the operator was comfortable with running the engine, certain difficulties still existed. The digital load cell that measured torque gave very unstable readings,² and the carburetor float level regulator required almost constant tending.

The scatter in the digital load cell readings rendered torque and horsepower calculations unusable. The displayed readings changed more frequently than once per second and covered a wide range of values, even though the engine gave no sign of rough or irregular running. The quantities recorded were thought to be a rough average of the numbers displayed over a period of about 10 seconds. It was realized afterwards that the resulting recorded data were poor.

The F/A varied from 0.0566 to 0.0806. It was, in fact, the intent to hold the F/A constant at 0.078. The fluctuation is believed to be due mostly to the carburetor float level regulator, which continuously vibrated away from the set position. The F/A has a bearing on power, fuel consumption, emissions, and engine and exhaust temperatures [9]. Although some of the data may be unreliable, the following paragraphs report the results.

²The load cell replaced a balance which normally gives very steady, accurate results.

The engine ran smoothly, giving no sign of knocking. The pressure-versus-volume and pressure-versus-time diagrams substantiate this (Figures 16 through 19), as knock would have shown up as sharp, spiked peaks. The four representative diagrams demonstrate that there is little difference between aviation gasoline at the lower compression ratio (best case) and the 35% blend at the higher compression ratio (worst case). It should be noted that the EGTs ran higher for the blends than for aviation gasoline.

In 97% of the runs, aviation gasoline had a higher rate of fuel consumption than any of the other fuels tested. This suggests that fuel economy would be improved by using an ethanol/automotive gasoline blend, provided power is constant or increasing.

Besides increased fuel economy, another benefit shown by the data was a reduction in the pollutants. As Tables 4 through 11, pages 50 through 57, indicate, carbon monoxide and unburned hydrocarbons (measured as hexane) decrease as the percentage of ethanol increases.

For both series of tests, brake torque versus engine speed was plotted (Figures 20 and 21). Figure 20 presents the data from the first series of tests. The points were scattered but became less scattered as the

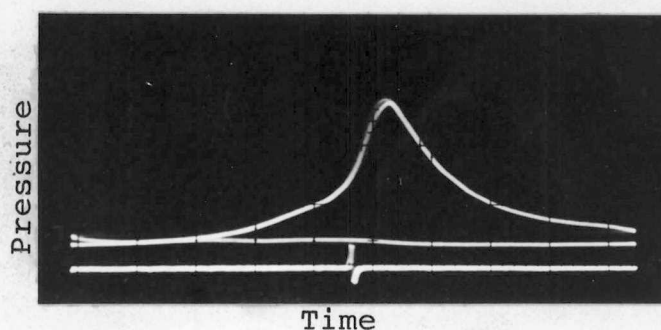


Figure 16. Photograph of Pressure versus Time Diagram Taken While Burning 35% Ethanol/65% Automotive Gasoline Blend. Compression ratio was set at 8.7:1; timing was set at 20° BTDC; engine speed was 1,400 rpm.

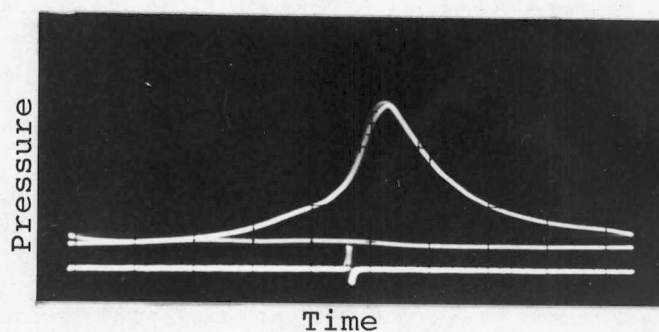


Figure 17. Photograph of Pressure versus Time Diagram Taken While Burning Aviation Gasoline. Compression ratio was set at 8.0:1; timing was set at 24° BTDC; engine speed was 1,400 rpm.

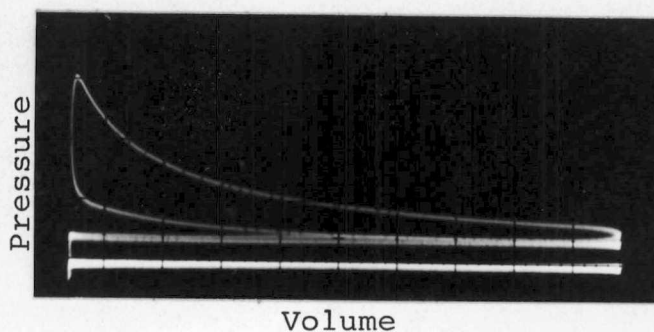


Figure 18. Photograph of Pressure versus Volume Diagram Taken While Burning 35% Ethanol/65% Automotive Gasoline Blend. Compression ratio was set at 8.7:1; timing was set at 20° BTDC; engine speed was 1,400 rpm.

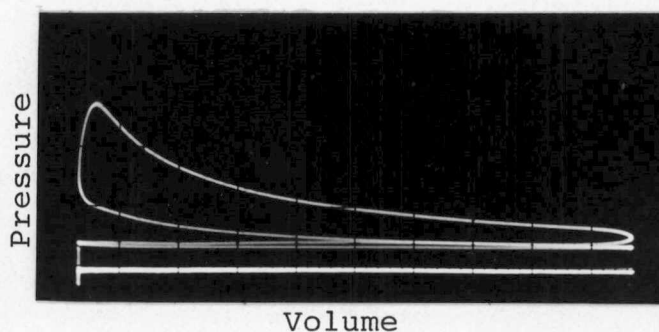


Figure 19. Photograph of Pressure versus Volume Diagram Taken While Burning Aviation Gasoline. Compression ratio was set at 8.0:1; timing was set at 24° BTDC; engine speed was 1,400 rpm.

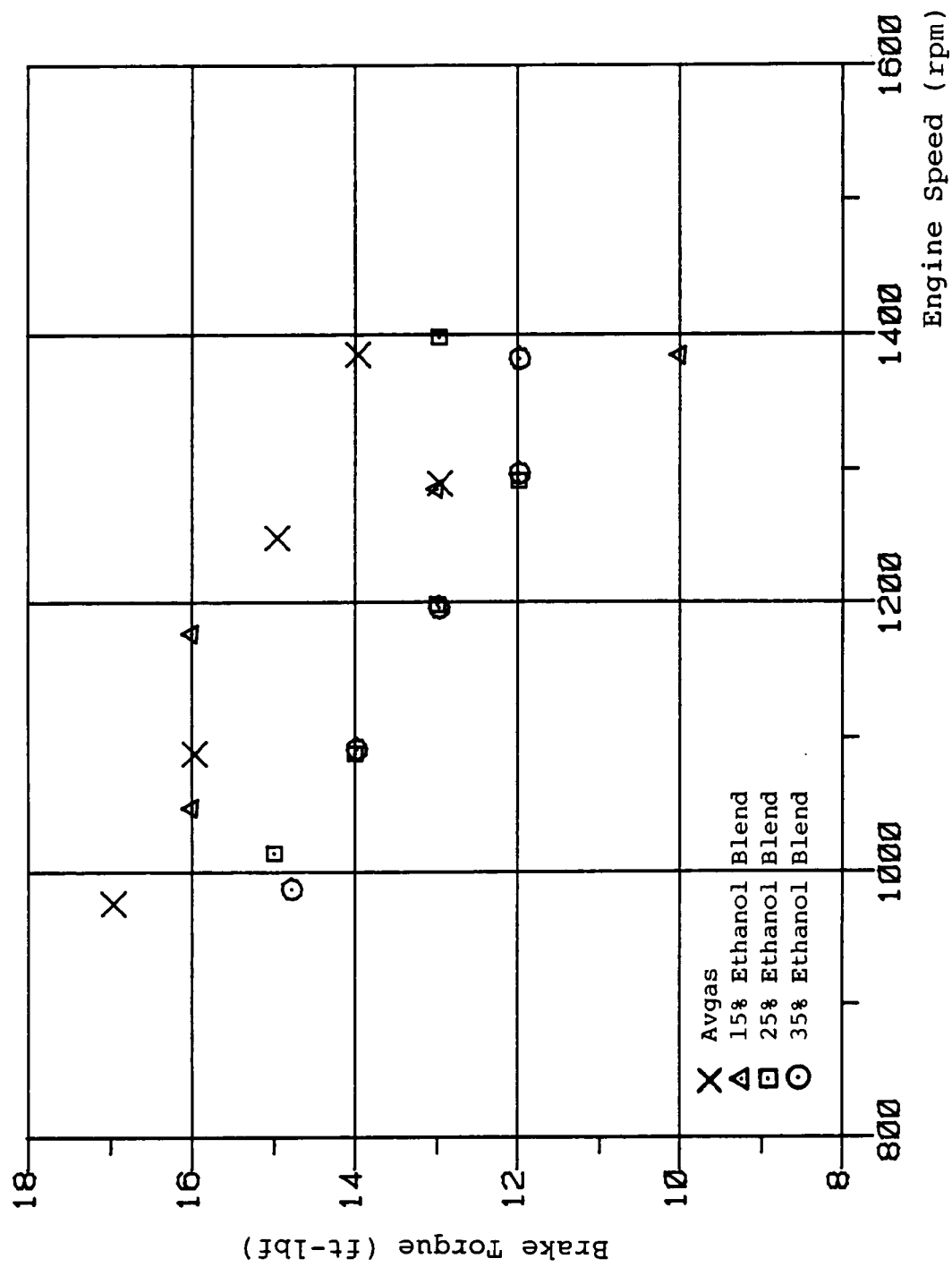


Figure 20. Brake Torque versus Engine Speed, Test Series 1.

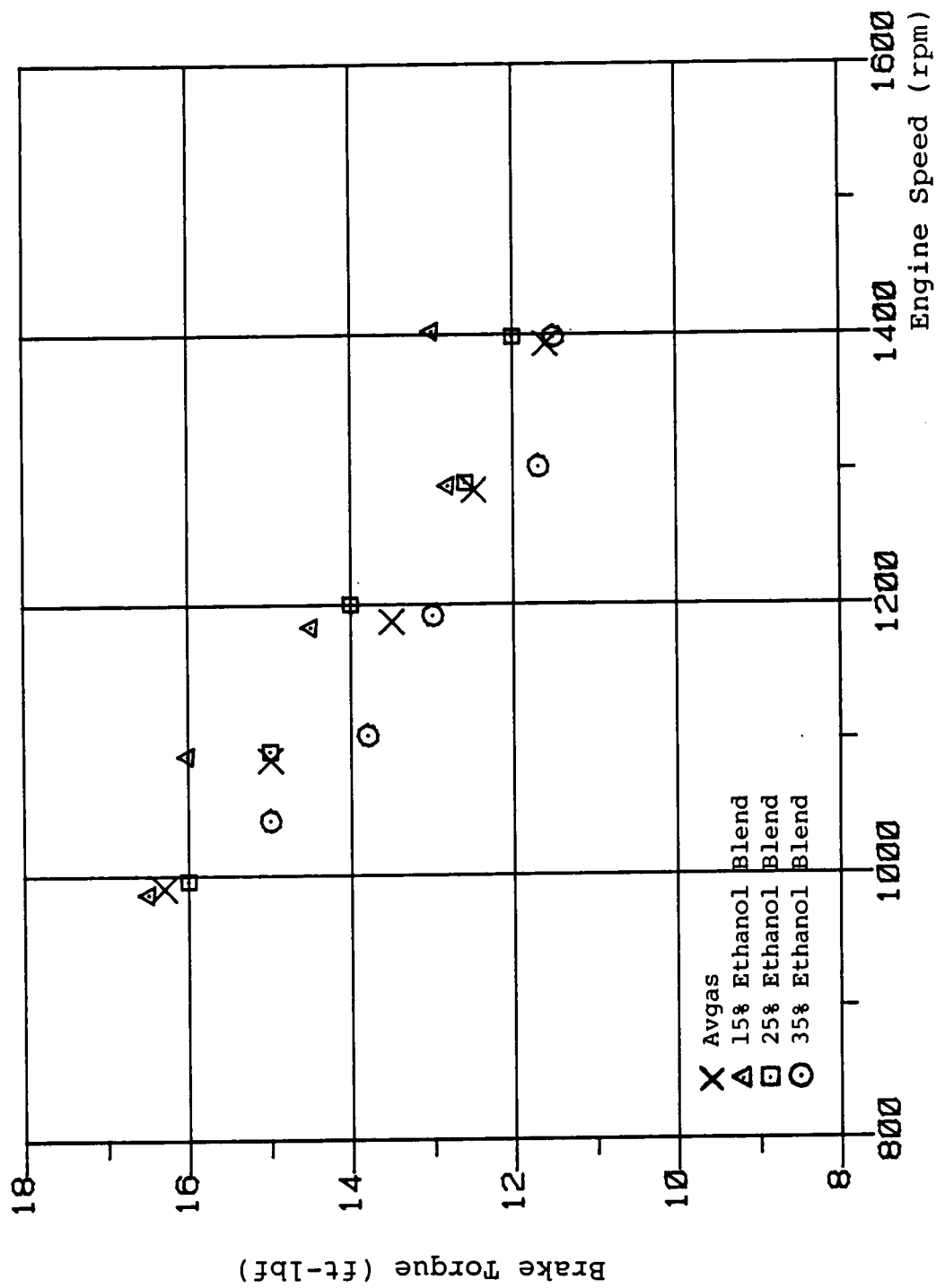


Figure 21. Brake Torque versus Engine Speed, Test Series 2.

test continued.³ It is believed that operator inexperience was the reason that the initial phase of the test proceeded roughly. The second series of tests went more smoothly (Figure 21), and a trend emerged. At four out of five of the tachometer settings, the 15% ethanol blend yielded the most torque, followed by the 25% blend, aviation gasoline, and the 35% blend.

It is not known to what extent the previously discussed trends are truly indicative of what occurs when alcohol blends are burned. Regardless of the problems encountered, the test did indicate that an unmodified aircraft engine could operate on the blends without knock. Since determining this was one of the test objectives, it is felt that conducting these tests was worthwhile. Although the reliability of some of the recorded data was questioned, the results indicate that, relative to aviation gasoline, blends yielded: increased fuel economy, decreased pollutants, and higher EGTs. With regard to torque output, the 15% blend was found to be optimum, followed by the 25% blend, aviation gasoline, and the 35% blend.

³The fuels were tested in the following order: aviation gasoline, 15, 25, and 35% ethanol.

Static Thrust Test

Results of the static thrust tests were reduced and plotted in terms of thrust versus engine speed and thrust versus manifold pressure (see Figures 22 through 26).

Figures 22 through 24 show that aviation gasoline yields the greatest thrust for a given engine speed through most of the range tested. This result is not surprising in light of the fact that the engine was designed and optimized to operate on aviation gasoline. However, the 35% blend curve falls almost on top of the aviation gasoline curve. The curves for 15, 25, and 45% blends, as well as the curve for automotive gasoline, are clustered together and are lower than the aviation gasoline and 35% blend curves.

The thrust-versus-manifold pressure curves are more indicative of actual thrust gains or losses than the curves of thrust versus engine speed.⁴ Figure 25 shows that the 35% blend actually yields more thrust than

⁴The manifold pressure reading is an indication of actual throttle setting. As thrust increases, so does manifold pressure. On the other hand, engine speed may not vary as thrust changes. If power is increased, and torque is also increased (by an amount dependent on the power increase), the result is constant rpm:

$$\frac{P}{T} \propto N ; \quad P = \text{power} ; \quad T = \text{torque} ; \quad N = \text{rpm}.$$

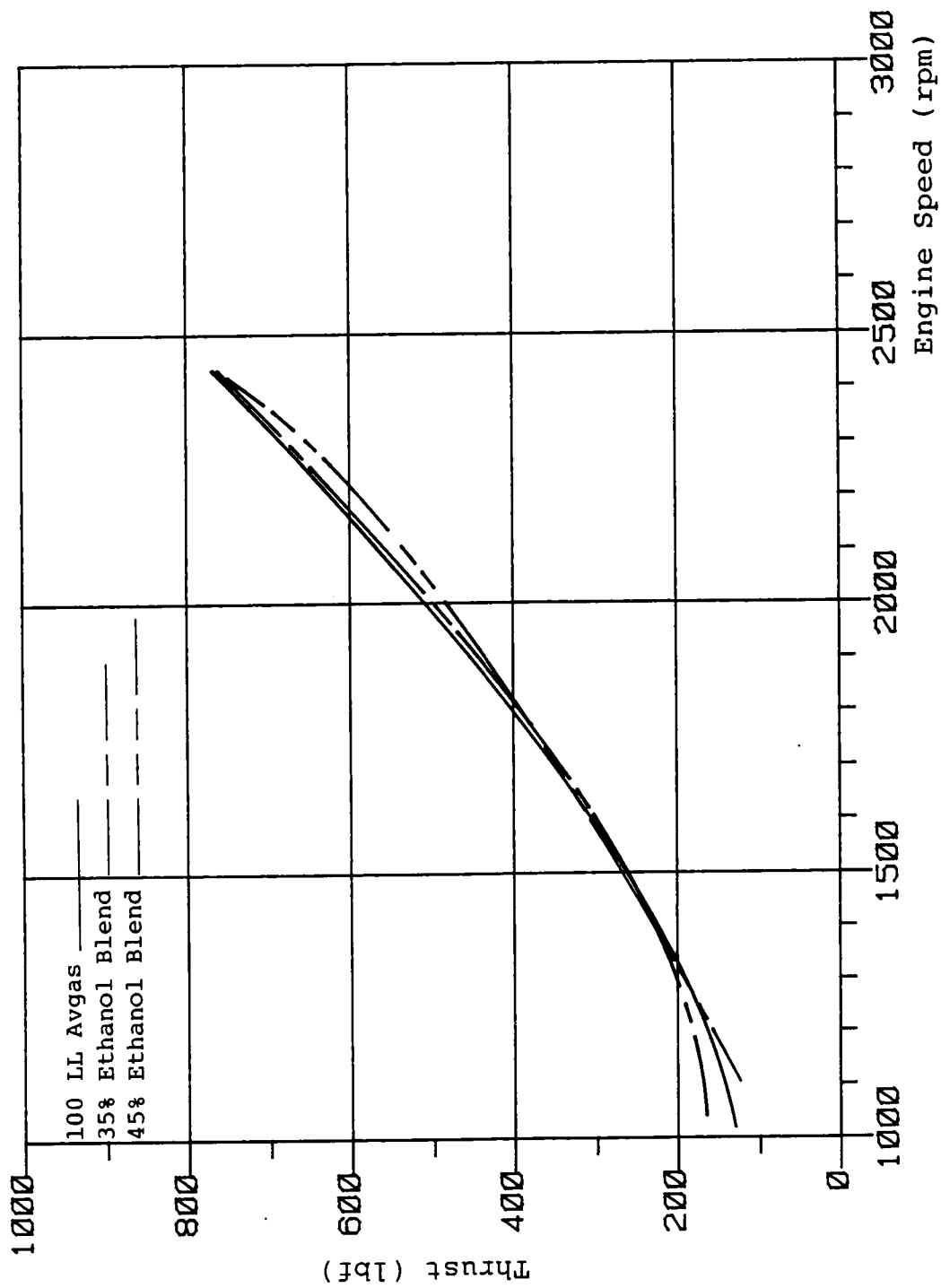


Figure 22. Thrust versus Engine Speed for 100 LL Aviation Gasoline, 35, and 45% Ethanol Blend.

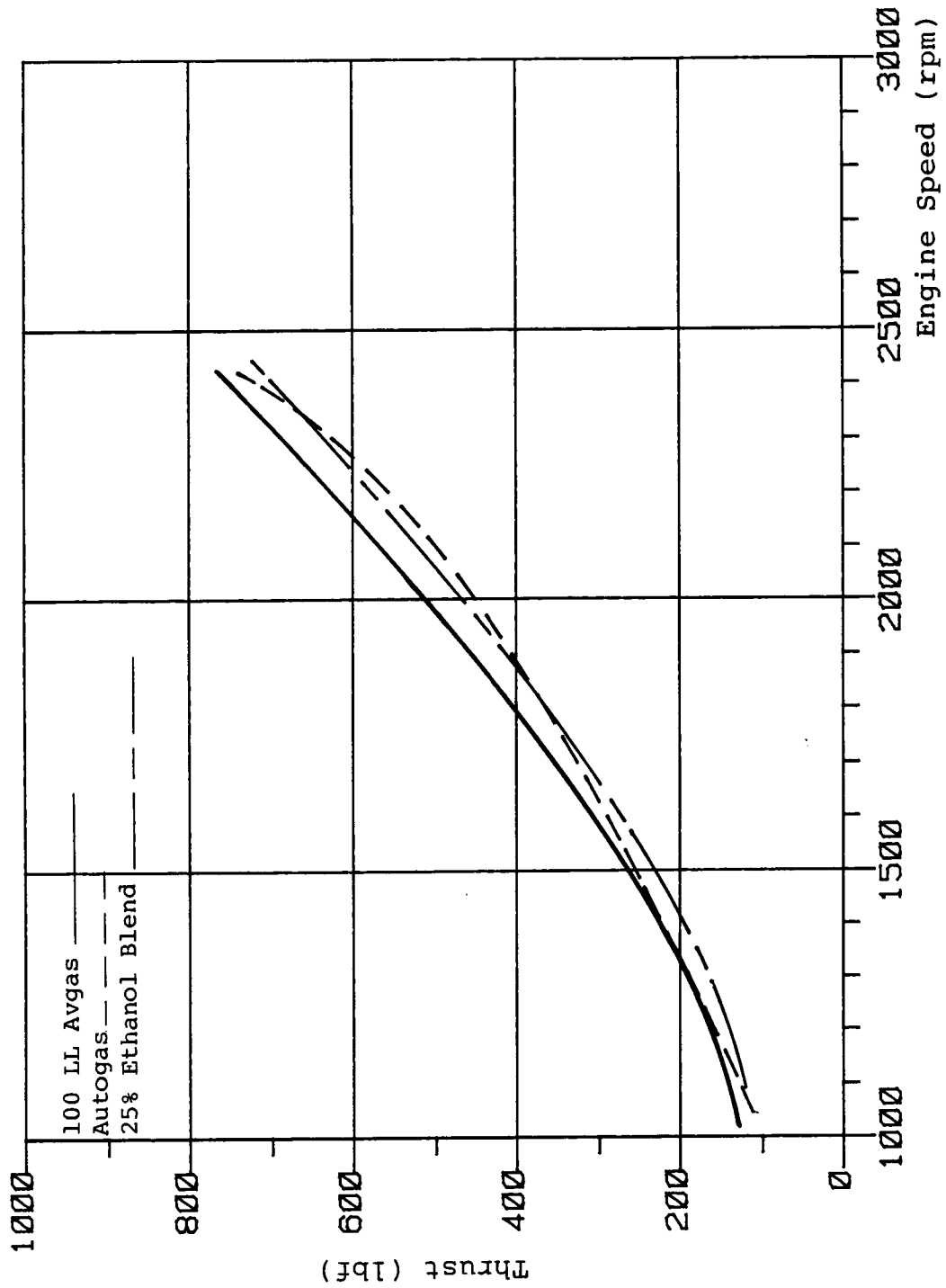


Figure 23. Thrust versus Engine Speed for 100 LL Aviation Gasoline, Automotive Gasoline, and 25% Ethanol Blend.

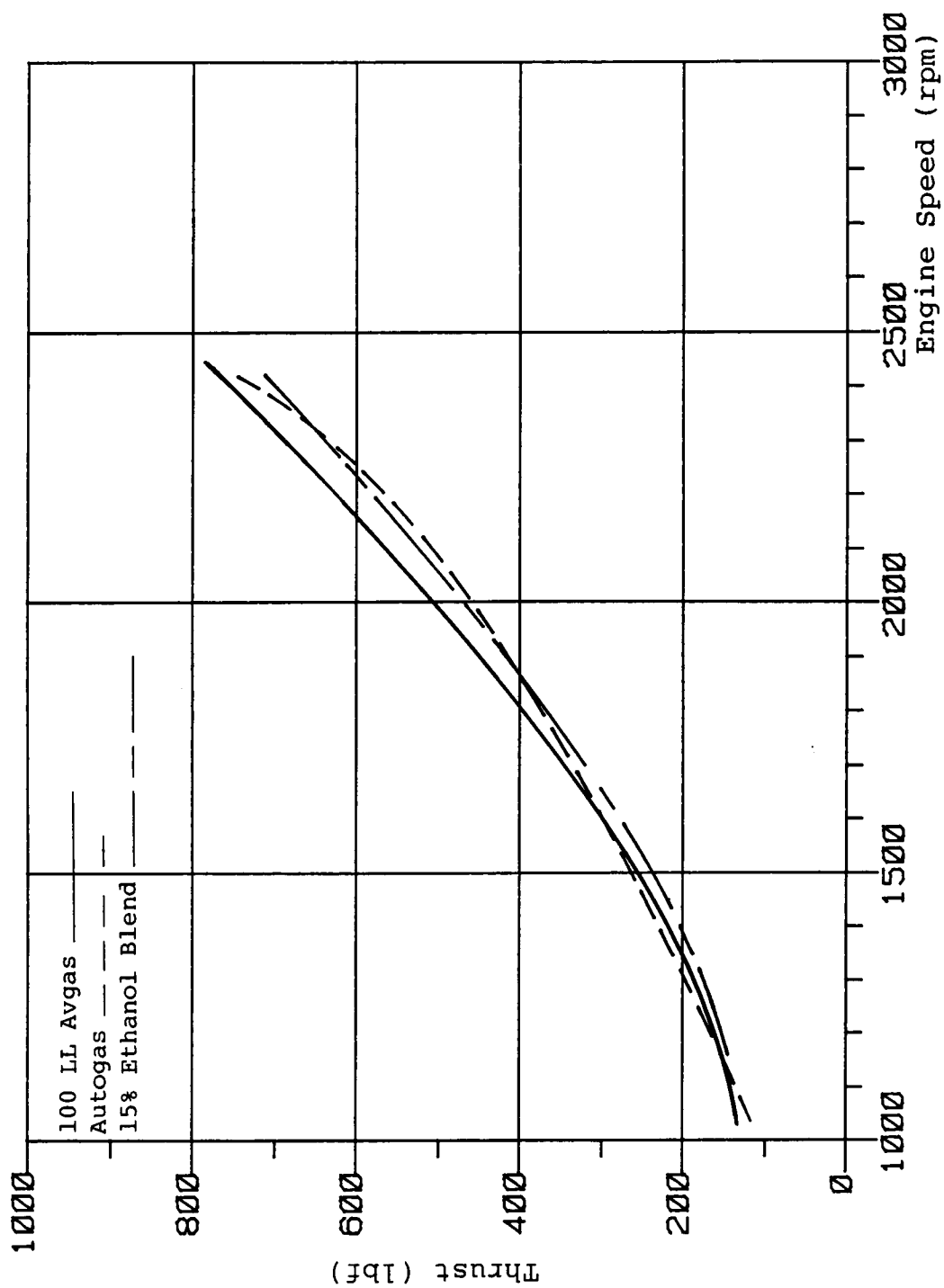


Figure 24. Thrust versus Engine Speed for 100 LL Aviation Gasoline, Automotive Gasoline, and 15% Ethanol Blend.

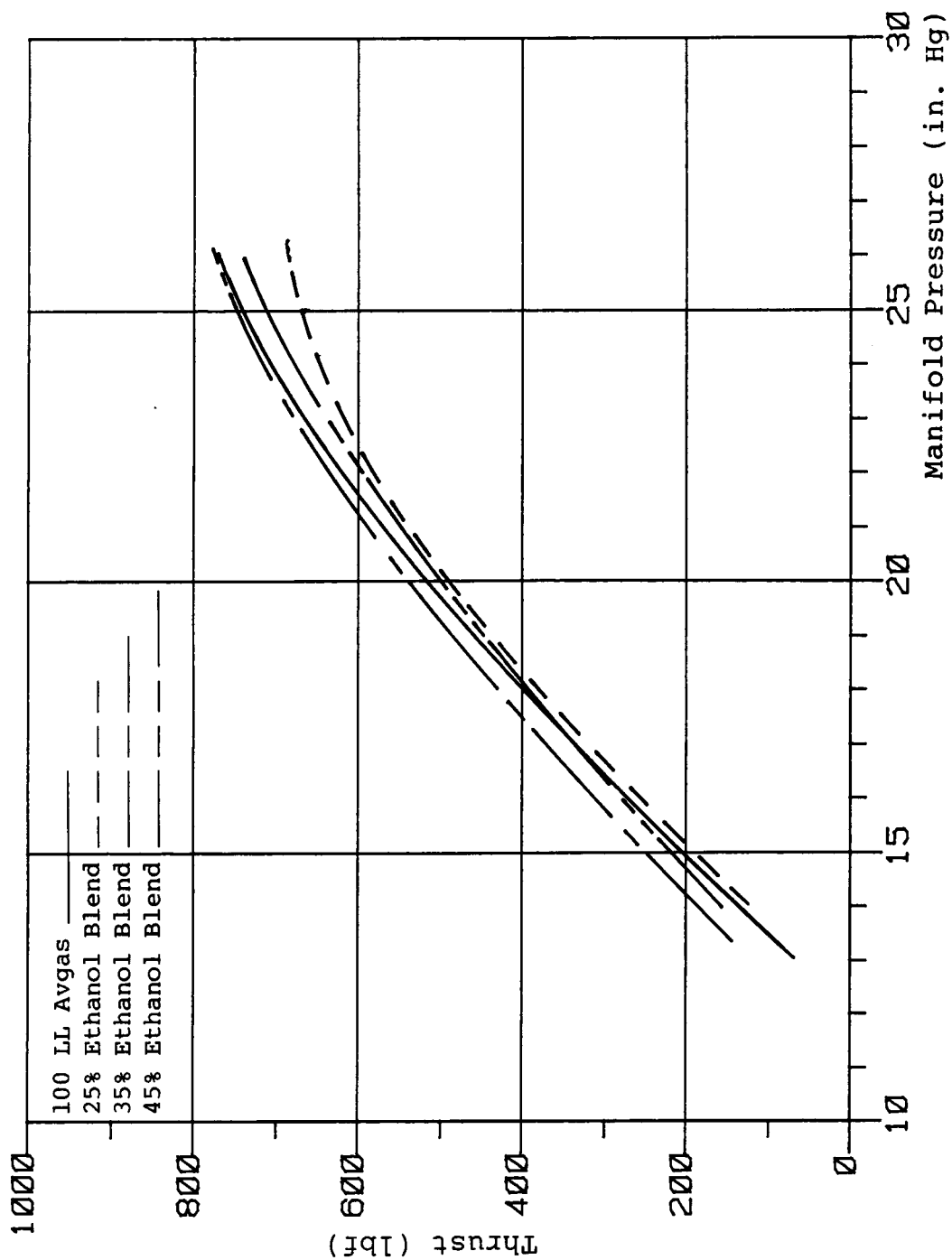


Figure 25. Thrust versus Manifold Pressure for 100 LL Aviation Gasoline, 25, 35, and 45% Ethanol Blend.

aviation gasoline at a given manifold pressure. Again, the curve for the 15, 25, and 45% blends, plus the curve for automotive gasoline, fall under the aviation gasoline and 35% curves (Figure 26).

During the tests, CHTs were monitored to identify the possibility of engine overheat. The peak temperatures are given in Table 12. All of the blends tended to burn hotter than aviation gasoline, with automotive gasoline being the hottest. It should be noted that aircraft engines are air-cooled. During static tests, normal cooling does not take place, causing engine temperatures to be higher than in actual flight.

It is evident that the addition of alcohol to automotive gasoline increases thrust output over pure automotive gasoline. Based on data from the static thrust tests, a blend of 35% ethanol/65% automotive gasoline is the optimum choice as an aviation gasoline replacement for an aircraft with an unmodified engine and cooling system similar to the Cessna 310. The 35% blend choice is within the estimates taken from the work of Rogowski and Taylor [13].

Flight Test

The data taken during the flight test are shown in Table 13. The aircraft was flown on the 35% blend for

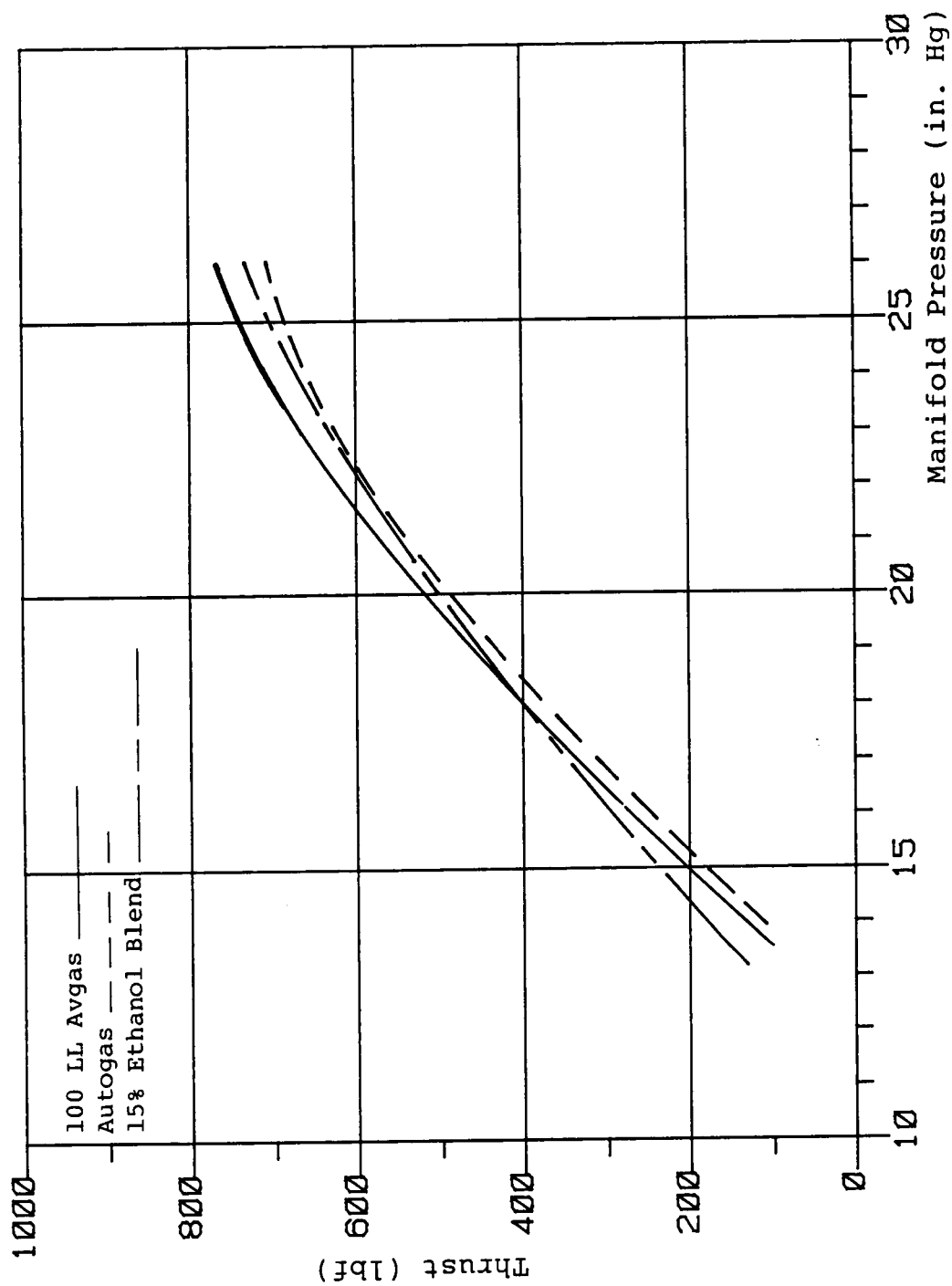


Figure 26. Thrust versus Manifold Pressure for 100 LL Aviation Gasoline, Automotive Gasoline, and 15% Ethanol Blend.

Table 12. Peak Cylinder Head Temperatures

Fuel	Temperature (°F)
100% Automotive Gasoline	460
25% Ethanol 75% Automotive Gasoline	460
35% Ethanol 65% Automotive Gasoline	460
45% Ethanol 55% Automotive Gasoline	445
15% Ethanol 85% Automotive Gasoline	410
100 LL Aviation Gasoline	390

Table 13. Results of Flight Test^a

Parameter	Data Point 1 ^b	Data Point 2	Data Point 3 ^b	Data Point 4
Fuel	Avgas ^c	Avgas ^c	35% Blend ^d	35% Blend ^d
Configuration	Cruise	Climb ^e	Cruise	Climb ^e
Manifold Pressure (in. Hg)	21.0	21.0	21.0	21.0
rpm	2,250	2,400	2,250	2,400
Pressure Altitude (ft)	5,100	8,000	5,200	8,000
Indicated Airspeed (mph)	175	110	175	110
Outside Air Temp. (°F)	51	48	52	48
Oil Temp. (°F)	140	145	142	148
Cylinder Head Temp. (°F)	315	340 ^f	335	375 ^f
Exhaust Gas Temp. (EGT) ^g (°F)	25	0	150	50

^aDate: 12/7/84; Time: 2:15 to 3:00 p.m.; Aircraft: Cessna 310, N11UT; Barometric Pressure: 29.022 in. Hg; Pilot: Ralph D. Kimberlin.

^bData Points 1 and 3 are stabilized conditions.

^cAviation gasoline.

^d35% ethanol/65% automotive gasoline blend.

^eClimbs are at full throttle.

^fPeak temperatures.

^gEGT gage indicates relative temperature between an unknown base temperature and EGT at data point.

approximately 25 minutes. There was no noticeable difference in the sound or performance of the engine after being switched over to the blend. The measurable differences that did occur were in the cylinder head and exhaust gas temperatures.

While burning the blend, the CHT ran 20 to 35°F higher and the EGT ran 50 to 125°F higher than on aviation gasoline. This was indicated previously in the CFR engine tests and static thrust tests. Flight test temperatures, however, were cooler than static thrust temperatures. Since aircraft engines are air-cooled, it was expected that static temperatures would be higher than flight temperatures. Whether the increased temperatures would be detrimental depends on the cooling system of the aircraft. Therefore, the effect of the hotter temperatures would have to be investigated by engine cooling tests for each aircraft model. In flight, it does not appear to pose a problem for the Cessna 310 used in this flight test.

Although no rough running, knock, or loss of power was encountered in this flight, the test was inconclusive with respect to vapor lock. The outside air temperature was only 48 to 52°F, which is not high enough to cause vapor lock, even for a fuel with a high RVP.

Engine Inspection

After the testing was completed, the six cylinders were removed from the right engine of the Cessna 310. The pistons and cylinders were visually examined. Compared to an engine that burns aviation gasoline, the Cessna 310 engine showed no signs of abnormal wear or unusual deposits.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Ethanol/automotive gasoline blends show promise for use in unmodified general aviation aircraft engines that are currently certified for 100 LL aviation gasoline. In the case that 100 LL becomes unavailable, it may be possible that a blend could be used as an aviation gasoline substitute. Further studies are needed to verify the safety of using blends with regards to materials compatibility, unidentified growths, engine cooling, and vapor lock.

Conclusions

1. Metals in the fuel system appear to be unaffected by the blends as compared to aviation gasoline. Some elastomers, particularly urethanes, are not suitable as fuel cell materials for blends containing ethanol. Sloss sealer effectiveness in an aluminum tank may be degraded.
2. Unidentified growths occurred in automotive gasoline and in a 25% ethanol/75% automotive gasoline blend.

3. Results from the Cooperative Fuel Research (CFR) engine tests, static thrust tests, and the flight test indicate that the tested ethanol blends burned at hotter temperatures than aviation gasoline. This may present problems for aircraft that are marginal with respect to cooling.
4. The CFR engine tests gave some indication that the volumetric fuel consumption rate was below that of aviation gasoline.
5. A 25-minute flight in a 1957 Cessna 310 was conducted up to a pressure altitude of 8,000 feet and an outside air temperature of 48 to 52°F. The 35% ethanol/65% automotive gasoline blend used during the test gave no indications of rough running, power loss, or vapor lock. The altitude and outside air temperature were too low to make the test conclusive with regard to vapor lock.
6. A superficial look at engine wear during this research program indicates that wear was not increased by using blends instead of aviation gasoline.
7. Fuel separation does not appear to present a serious problem as long as water content is

low. An internal combustion engine will operate on an ethanol/water mixture. This is a safety feature of the blends, considering that water in aviation gasoline does not burn.

8. Carbon monoxide and hexane emissions are reduced below aviation gasoline levels when using blends.
9. Based on data from the static thrust tests, a blend of 35% ethanol/65% automotive gasoline is the optimum choice as an aviation gasoline replacement for an aircraft with an engine and cooling system similar to a Cessna 310.

Recommendations

1. Further materials compatibility tests need to be conducted on aircraft fuel systems in order to determine the long-term effects on all material properties. Some elastomers such as polysulfide, fluorocarbon, polychloroprene, and nitriles might be acceptable replacements for fuel cell fabrics that are currently being used. The effectiveness of sloss sealer after contact with ethanol should be studied to determine if the use of sealer-coated aluminum tanks might also be satisfactory.

2. Studies on the growths occurring in automotive gasoline and ethanol/automotive gasoline blends should be conducted to determine what they are, what causes them, and how to control them.
3. Cooling tests must be conducted on any aircraft attempting certification on ethanol/automotive gasoline blends.
4. More studies are needed to verify that an improvement in fuel economy actually exists when using ethanol/automotive gasoline blends as opposed to aviation gasoline.
5. Vapor lock characteristics of the ethanol/automotive gasoline blends should be investigated following the standard FAA hot fuel test as outlined in the Federal Air Regulations, Part 23.961 [20].
6. Extensive engine-wear tests are needed to show long-term effects of blends on an aircraft engine.

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VITA

Lisa Jan Hughes, the daughter of Noah Hughes and Mary Pheribol Hutcheson Hughes, was born on March 4, 1958, and grew up in Crossville, Tennessee. She developed and pursued an interest in the sciences at an early age. She attended Crossville City School, Cumberland Elementary School, and Cumberland County High School. She held various part-time jobs while attending high school and graduated tenth in her class of 305. She attended Tennessee Technological University in Cookeville, Tennessee, receiving a Bachelor of Science degree in Engineering Science and Mechanics in 1982. In 1979, Ms. Hughes accepted a cooperative education position with the National Aeronautics and Space Administration (NASA) at George C. Marshall Space Flight Center in Huntsville, Alabama. In the fall of 1982, she entered The University of Tennessee Space Institute (UTSI) as a full-time student. As a Graduate Research Assistant, she worked half-time in the Flight Research Department, and continued her employment with NASA until July 1984. Ms. Hughes was awarded the Master of Science degree in Mechanical Engineering in March 1985. Upon graduation, she accepted a full-time position at UTSI as a research engineer.