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The Performance of Alternate Fuels in General Aviation Aircraft

FEDERAL AVIATION ADMINISTRATION
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July 1988

Final Report

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16. Abstract

This report describes the results of a study which measured the effects of pressure altitude on fuel weathering. In this study, samples of unleaded automobile gasoline were exposed to varying pressure altitudes, and the effects of this exposure on aircraft performance and volatility were measured. The composition of the fuel, aircraft configuration, and the initial temperature of the fuel when transferred to the tank were varied to determine the extent these variables affected the aircraft performance.

Experiments were conducted which demonstrated that the use of 110-degree Fahrenheit fuel during aircraft certification will provide the greatest margin of safety. In addition, the suitability of methyl-tertiary-butyl ether as an acceptable fuel for use in general aviation aircraft was demonstrated.

Several different oxygenated fuels (including gasolines containing alcohols) were aged in ground-based tests. The results are presented in this report.

17. Key Words

Autogas, Alcohol Fuels, Methyl-tertiary-butyl Ether (MTBE), Alternate Fuels, Aircraft, Material Compatibility, Vapor Lock, Engines, Aircraft, Flight Tests, Gasohol, Spark Ignition Engines

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LIST OF ABBREVIATIONS AND SYMBOLS

ASTM	American Society for Testing and Materials
Avgas	Aviation Gasoline
Autogas	Automobile Gasoline
B	Butane Rich Fuels
C-172	Cessna 172
CHT	Cylinder Head Temperature
CO	Carbon Monoxide
DOE	United States Department of Energy
DOT	United States Department of Transportation
EGT	Exhaust Gas Temperature
EPA	United States Environmental Protection Agency
^{o}F	Degree(s) Fahrenheit
FAA	Federal Aviation Administration
kg	Kilogram
kJ	Kilojoule
mL	Milliliter
MON	Motor Octane Number (dimensionless)
MSL	Height Above Mean Sea Level (feet)
MTBE	Methyl-Tertiary-Butyl Ether
N_2	Nitrogen
NIPER	National Institute for Petroleum and Energy Research
O_2	Molecular Oxygen
OAT	Outside Air Temperature - ^{o}F
P	Iso-Pentane Rich Fuels
psig	Pounds Force Per Square Inch, Gauge Pressure
RPM	Revolutions Per Minute

RON	Research Octane Number (dimensionless)
RVP	Reid Vapor Pressure - psig
sec	Seconds
TBA	Tertiary-Butyl Alcohol
TEL	Tetra-Ethyl-Lead
V_i	Volume Fraction of a Component
VPBI	Vapor Pressure Blending Indices
100LL	100 Octane Aviation Gasoline with a Low Lead Content
$>$	Greater Than

EXECUTIVE SUMMARY

Tests were conducted to determine the effects of pressure altitude, fuel temperature, fuel composition, and aircraft configuration on fuel weathering. In these tests, fresh fuel was heated in a sealed container, carried to the designated pressure altitude, then transferred to the aircraft wing tank. The aircraft was then operated on the test fuel, and changes in performance were noted. The results from this portion of the program indicated the butane rich fuels exhibited more severe vapor lock behavior (i.e., vapor lock occurred more often) than the pentane rich fuels. The pentane rich fuels weathered more slowly, however, and the problems with vapor lock persisted for a greater period of time. Samples of the test fuel were taken before heating and following the test flight. The volatility of these samples was measured using the Reid Vapor Pressure method. The changes in fuel volatility tended to follow the trend noted with aircraft performance, with the butane rich fuels weathering more rapidly than pentane rich fuels. Transferring hot fuel resulted in the immediate loss of the more volatile components; as a consequence, the 70-degree Fahrenheit (°F) fuel exhibited more severe vapor lock than the 90- or 110-degree Fahrenheit fuels. (It should be noted that transferring hot fuel will result in fewer cases of vapor lock than heating the test fuel in the aircraft tanks.) The aircraft configuration did not affect the above trends, though vapor lock would occur at different Reid Vapor Pressures depending on aircraft configuration.

Tests were also conducted to evaluate the certification procedures for gasoline in aircraft fuel systems. These tests showed the existing practice of (1) transferring cool fuel into the aircraft tank, (2) heating the fuel in the aircraft tank to 110°F, and (3) conducting a maximum performance takeoff and climb was the most severe condition for inducing vapor lock. Heating the fuel to 115°F substantially reduced the probability of the vapor lock occurring.

Fifty hours of flight time were accumulated using methyl-tertiary-butyl ether (MTBE) as the test fuel. During the course of this phase of the testing, paint incompatibility and a viton o-ring swelling were the only problems encountered. No valve seat recession or operational problems were encountered.

Several oxygenated fuels were weathered in ground tests. These tests were conducted with alcohol/gasoline and MTBE/gasoline blends. Both exhibited similar losses in volatility when weathered for 48 hours at 110°F.

INTRODUCTION

PURPOSE.

The Experimental Aircraft Association's request for a supplemental type certificate, allowing the use of automobile gasoline (autogas) in general aviation aircraft, resulted in a review of the procedures used to certify fuels for use in light aircraft (references 1 through 6). All of the results obtained as a consequence of these programs were based on ground tests. This caused some uncertainty as to the applicability of the procedures identified as the most severe for hot fuel certification (i.e., most likely to result in vapor lock).

The principal goal of this study was to identify the most severe conditions for vapor lock certification by using aircraft in realistic flight conditions. To achieve this goal, fuels with carefully controlled volatility were needed, so the FAA Technical Center requested the assistance of the Department of Energy (DOE). With DOE's cooperation, this program was conducted at the National Institute for Petroleum and Energy Research (NIPER), Bartlesville, Oklahoma.

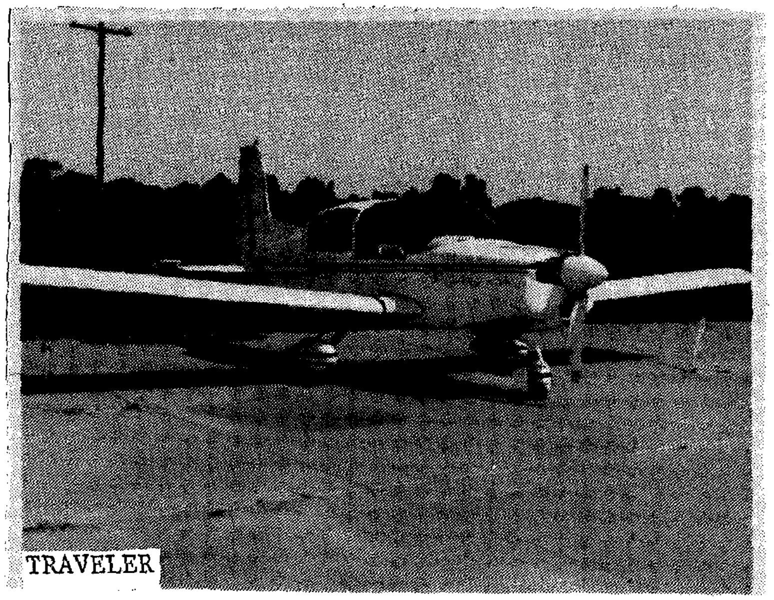
Additional tasks were designed to investigate the effect of fuel composition and pressure altitude on vapor lock and fuel weathering behavior.

BACKGROUND.

Three types of aircraft were used for this study with the intent of investigating the various fuel system configurations; a Cessna Model 172 (C-172), a Beechcraft Musketeer, and an American Aviation Corporation Traveler. The C-172 is a 4-place aircraft with a gravity feed fuel system and a carbureted engine. The Musketeer is a 4-place aircraft with a suction feed system and a fuel injected engine. The Traveler is a 4-place aircraft with a suction feed fuel system and a carbureted engine. A side view of these aircraft is contained in figure 1. The engine in the C-172 was originally certified to operate on aviation gasoline (avgas) with a minimum aviation lean octane rating of 80. The engines in the Musketeer and the Traveler were originally certified to operate on avgas with a minimum aviation lean octane rating of 91.

SIGNIFICANCE OF THE ASTM TESTS. The American Society for Testing and Materials (ASTM) publishes the standards for tests that are routinely used to ensure the material or product being manufactured meets given qualities. The particular standards that are of concern to this program are described below. For a more detailed description of the individual tests, refer to the individual standards listed along with the test description.

The Reid Vapor Pressure (RVP), ASTM D-232, is a measurement of the volatility of a fuel. In the RVP test, the pressure generated by a sample of fuel in a sealed container is measured at 100°F. Fuels with a high RVP have a high volatility and vice versa. High volatility aids cold starting but aggravates the formation of vapor in the fuel system, possible leading to vapor lock.



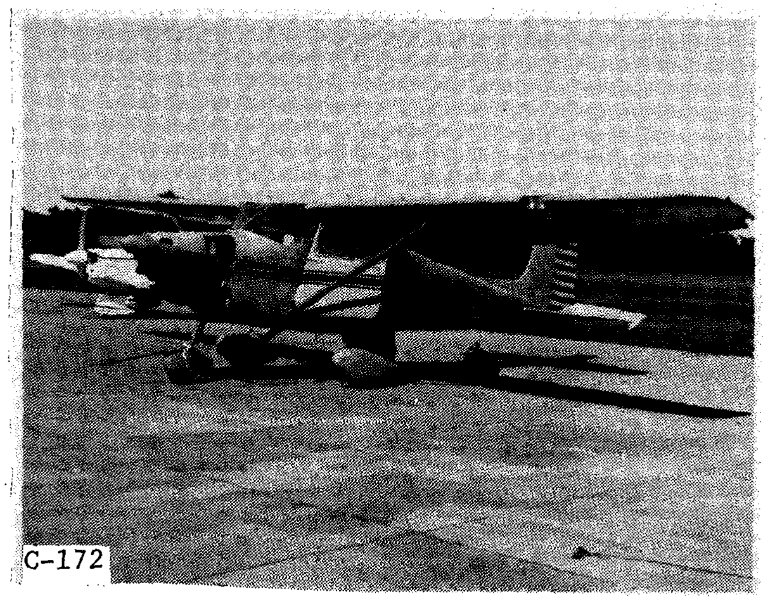


FIGURE 1. SIDE VIEW OF THE TEST AIRCRAFT

The distillation curve, as determined by ASTM D-86, is a rough measure of the components contained in the fuel. In this test, the quantity of fuel collected in the distillation apparatus is plotted against the temperature of the gases above the liquid being distilled. A large concentration of low boiling point constituents indicates a fuel with a high volatility and vice versa.

The motor octane number (MON) is a measure of the tendency for a fuel to detonate in a special test engine under heavy load conditions. Likewise, the aviation lean octane number is a measure of the tendency for fuel to detonate at the high power settings used in aircraft, and it is possible to convert the MON into the aviation lean octane number. The description of the test and the conversion tables between these octane ratings are contained in ASTM D-2700.

The tendency to detonate under light duty cycles in a special test engine is described in ASTM D-2699, the procedure for the research octane number (RON).

THE NATURE OF ALCOHOLS. The principal alcohols considered as alternative fuels for general aviation aircraft are methanol and ethanol. Methanol is commonly referred to as wood alcohol, whereas ethanol is referred to as grain alcohol. Currently, methanol is primarily manufactured from either the destructive distillation of coal or by catalytically treating natural gas.

Methanol is being considered as either a direct replacement for avgas or as an extender to be blended with gasoline. Methanol has two factors in its favor: it has a relatively high octane rating (the MON is 91), and it is inexpensive when purchased on a volume basis. In order to use methanol as a direct replacement fuel, the fuel system will need to be modified to allow for greater fuel consumption since neat methanol (neat fuels are those without any additives) has 52 percent of the energy density of gasoline, and provisions for cold starts must be provided. The energy density is calculated on a mass basis. For example, methanol has 22,670 kJ/kg (kiloJoules per kilogram), and 100LL (100 octane avgas with a low lead content) has 43,100 kJ/kg. To use methanol as an extender for gasoline, a cosolvent must be added to keep the methanol in solution. Methanol will come out of solution in the presence of bulk water, and it will absorb water from the air possibly to the point of phase separation. Methanol will react with most of the materials found in the current fleet of general aviation aircraft. For example, many of the rubbers currently used will either swell, crack, or become porous in the presence of methanol, and methanol will corrode many of the metals found in existing fuel systems. The presence of water will aggravate any corrosion problems encountered. Materials and procedures have been developed which allow for the safe use of methanol, but they will need to be adapted to aircraft usage.

Ethanol is being considered primarily as an extender for the gasoline supply, because it would be difficult to produce enough ethanol to directly replace gasoline. As with methanol, ethanol will absorb water from the air, possibly to the point of phase separation, and it will come out of solution in the presence of bulk water. Ethanol will react with some of the rubbers found in the existing fleet of aircraft and corrosion may be a problem if phase separation occurs. Ethanol does have a relatively high octane rating (the MON is 89), and its energy density is approximately 69 percent of the energy density of gasoline.

Tertiary-butyl alcohol (TBA) and isopropyl alcohol are the principal alcohols used as cosolvents for methanol. As with the other higher order alcohols (more than three carbon atoms), the sensitivity to water is less than with either ethanol or methanol, and the solubility in gasoline increases. A rule of thumb is the greater the number of carbon atoms, the less severe the water, solubility, and material compatibility problems become. The energy density of TBA is approximately 83 percent of the energy density of gasoline.

THE NATURE OF METHYL-TERTIARY-BUTYL ETHER. Methyl-tertiary-butyl ether (MTBE) is a high octane blending agent used to improve the octane ratings of unleaded autogas. It is manufactured from methanol and butanes, both of which are readily available from domestic resources. It does not have the water sensitivity problems associated with the alcohols that are used as blending agents with gasolines, and it is compatible with most of the materials used in the current fleet of general aviation aircraft (reference 7). The energy density is 84 percent of the energy content of 100LL avgas, and this makes its cost competitive with methanol on an energy basis. In general, MTBE behaves as a gasoline with moderate volatility, but for the most part it is not used as a neat fuel. The octane qualities of MTBE are attractive from the standpoint of its use as a gasoline substitute. The MON is 98+, and the RON measured for NIPER was 116, very close to the value published as the blending octane number. The MTBE as delivered from the supplier is essentially a single component (over 98.5 percent), and it has a boiling point of 130°F. As a consequence, MTBE would exhibit minimal deterioration of octane quality due to the loss of high volatility components (unlike many gasolines). Given the attractive properties of the substance, MTBE was selected as a potential alternative fuel for general aviation aircraft with spark ignition engines and was evaluated in the Musketeer.

TEST APPARATUS

FUEL PREPARATION EQUIPMENT.

The fuel storage and blending facilities at NIPER were used for preparation of the test fuels prior to the altitude profile, and takeoff and climb experiments. The fuel blending components consisted of a base gasoline, normal butane, and iso-pentane. The latter two are commonly used in gasolines for volatility enhancement, i.e., increasing fuel vapor pressure. The components were obtained from local suppliers and kept sealed in the refrigerated storage area at less than 50°F prior to blending and utilization. The base fuel was a Sun Oil super premium unleaded gasoline certified by the refinery to meet ASTM D-439 specification. The averaged octane value--(RON+MON)/2--was 91. The butane and iso-pentane were commercial grade substances obtained from Phillips Petroleum Company.

Test fuels were blended to specific vapor pressures in a 50°F room to minimize losses of the highly volatile additives during the process. Component measurements were done on a weight basis into 55-gallon drums utilizing manual transfer pumps in conjunction with a large calibrated floor balance. Finalized fuels were transferred to 15-gallon stainless steel tanks and sealed for use in the aircraft flight tests. These containers were pressure tested and verified adequate to the United States Department of Transportation (DOT) rating of

120 pounds per square inch (psi). The tanks were provided with thermocouples to allow in-cabin fuel temperature monitoring.

For heating the test fuels to specified temperatures, an electrically heated, thermostatically controlled, circulating water bath system was fabricated. This bath was large enough to hold two tanks and was capable of elevating fuel temperatures in the sealed tanks to 115°F in less than 6 hours.

AIRCRAFT INSTRUMENTATION.

The aircraft were modified to provide for fuel transfer capabilities and data collection during the altitude profile portion of this study. The general location of the instrument rack, the tank drains, the sediment bowls, and the fuel transfer equipment is presented in appendix A.

The fuel transfer system consisted of an insulated fuel tank (15 gallons), a low pressure nitrogen container, and the tubing and valves necessary to transfer the fuel to the wing tank.

The nitrogen tank was equipped with a pressure gauge, a pressure regulator, and another pressure gauge on the output of the regulator. The insulated tank was equipped with a thermocouple and a quick connect for attaching the nitrogen tank.

The line running from the insulated fuel tank to the wing tank had quick connect fittings isolated by two ball valves. The transfer line ran from the insulated fuel tank to the bottom of the wing tank. This kept fuel agitation to a minimum. In addition to the above, the fuel caps were modified to allow for additional venting during the fueling operation, and a thermocouple was installed in the wing tank. A schematic of the system is shown in figure 2.

The aircraft carried an instrumentation rack that contained an oxygen (O_2) and carbon monoxide (CO) analyzer, a thermocouple conditioner, and a strip chart recorder. The temperatures that were measured using this system included the fuel temperature in the insulated tank, the fuel temperature in the wing tank, the cylinder head temperature (CHT), and the exhaust gas temperature (EGT). A J-tube and an EGT probe were secured to the exhaust stack. The Cessna installation, shown in figure 3, was typical (the J-tube is marked with a solid arrow and the EGT probe is marked with an open arrow). The exhaust gas sample line and thermocouple line were routed through the engine compartment, through the fire wall, then into the instrument rack. The sample gas was then vented overboard. The instrument rack contained a selector valve that would direct cabin air into the O_2 and CO analyzer for calibration purposes.

The O_2 and CO analyzer operated on 12-volt dc as did the thermocouple conditioner and the strip chart recorder. Power to the instruments was provided from the aircraft electrical system. A battery backup was also provided.

The outside air temperature (OAT), altitude, airspeed, engine speed, oil temperature, oil pressure, and fuel pressure data were manually recorded from the existing aircraft instrumentation. An audio recorder was carried aboard the aircraft to record any pertinent pilot observations. Radio communications were maintained with a ground observer who also recorded the observations relayed to him.

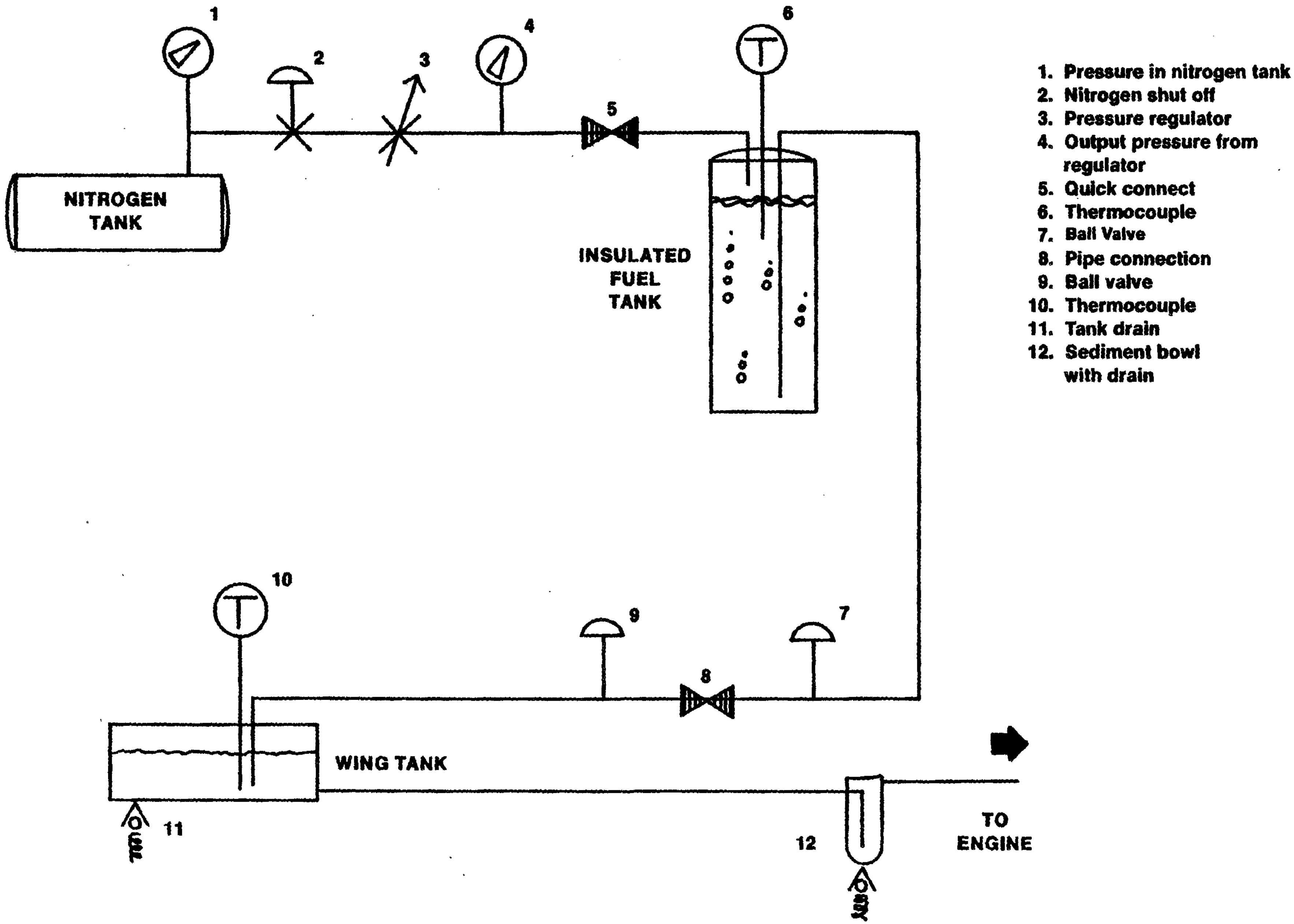


FIGURE 2. SCHEMATIC OF THE FUEL TRANSFER SYSTEM

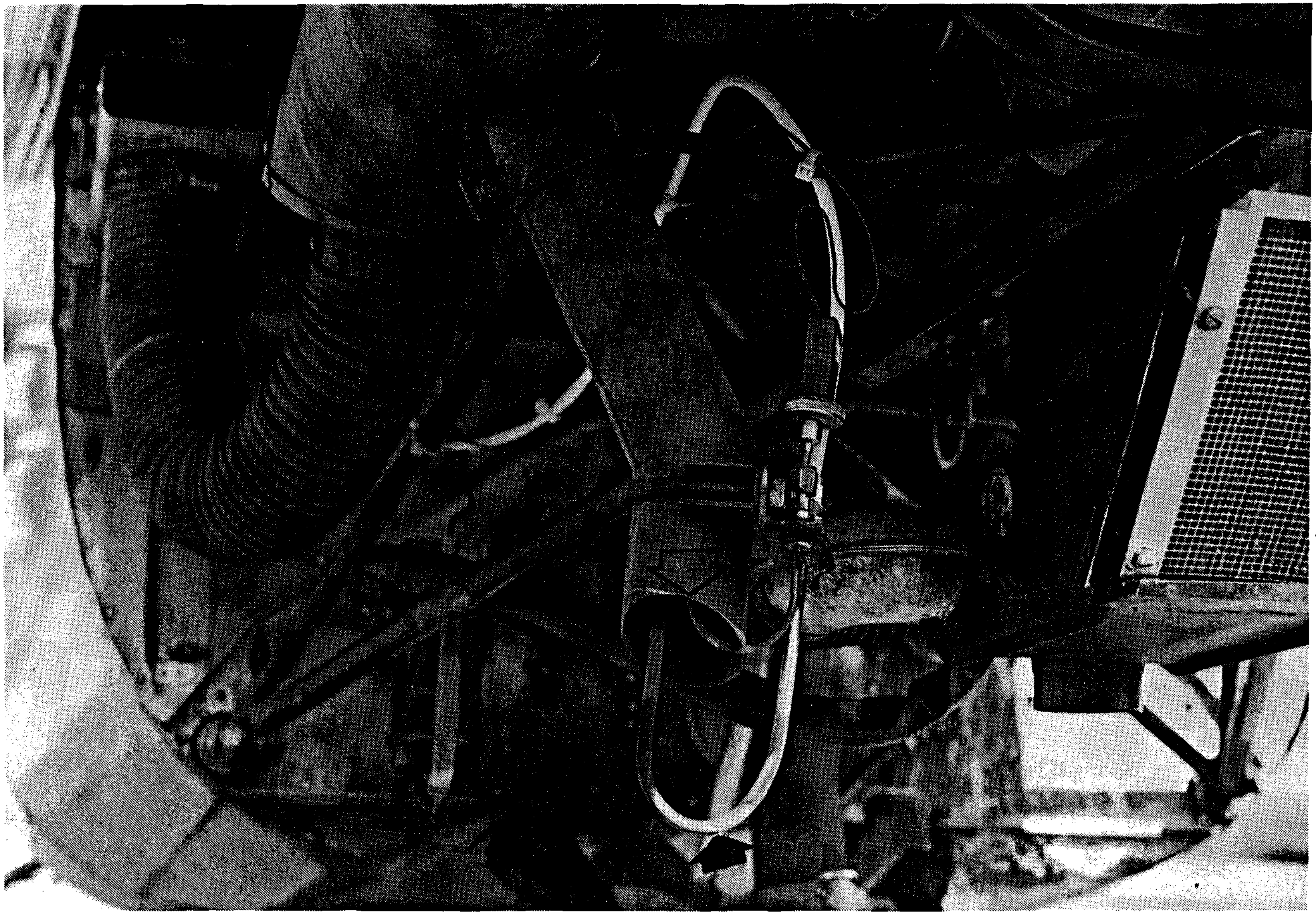


FIGURE 3. EGT AND J-TUBE INSTALLATION IN THE CESSNA 172

The insulated fuel tank and the related fuel transfer hardware were removed from the aircraft for the takeoff and climb and the MTBE evaluation flights. The wing tank thermocouple was moved from the Musketeer's starboard wing to the port wing for these flights.

For the takeoff and climb tests, the test fuel was transferred from an insulated fuel tank to wing tanks using a hand-operated vane pump. The vane pump was also used to transfer the MTBE from the 55-gallon drums to the wing tank during the MTBE evaluations.

The fuel was heated in the wing during the takeoff and climb tests using a forced hot air setup. A commercially available kerosene space heater was used with a section of 12-inch-diameter air-conditioning duct directing the air to the wing bottom. Insulated blankets were draped over the wing to keep the wind from carrying the hot air away from the wing bottom. The temperature of the hot air from the space heater was in excess of 250°F. By varying the positioning of the space heater about 10 inches from the inlet of the duct, ambient air would mix with the hot air: the temperature was maintained between 160 and 165°F when heating the fuel in the Traveler, and it was kept between 180 and 185°F when heating the fuel in the Musketeer. A schematic of the heater setup is shown in figure 4.

Fuel samples were taken from the wing tank drains using a piece of tubing to direct the stream into the bottom of a chilled, 1-liter container. The sample jars were filled to the 750 milliliter (mL) level then sealed. The sample was placed in an ice bath for transportation to the fuels lab.

FUEL WEATHERING APPARATUS.

The volatility of the oxygenate/gasoline blends was determined for both the initial condition and after weathering. For the oxygenated fuel tests, four blending components were utilized: a commercial regular unleaded gasoline, MTBE, neat ethanol, and neat methanol.

Prior to weathering, the test fuels were blended by weight into 55-gallon drums at the NIPER fuel facility mentioned earlier and stored at 50°F. For these tests, two steel fuel tanks were used with shapes representative of those found in light aircraft. These tanks were rectangular shaped with low height and large bottom surfaces. Total tank volumes were 13 gallons. Each tank was vented through a fill port with an area less than 2 percent of the tank top area.

For test fuel temperature control and maintenance, a closed loop, circulating water bath--similar to the system described above--was used. The 80-gallon system had a temperature control range of from ambient to 120°F $\pm$3°F and was large enough to hold both tanks. Straps maintained the test fuel tanks in the bath at a level about 2 inches from tank top surface. Approximately 6 hours were required for a fuel temperature increase from 50 to 110°F. Thermocouples were placed approximately 1 inch above the bottom surface to monitor fuel temperature.

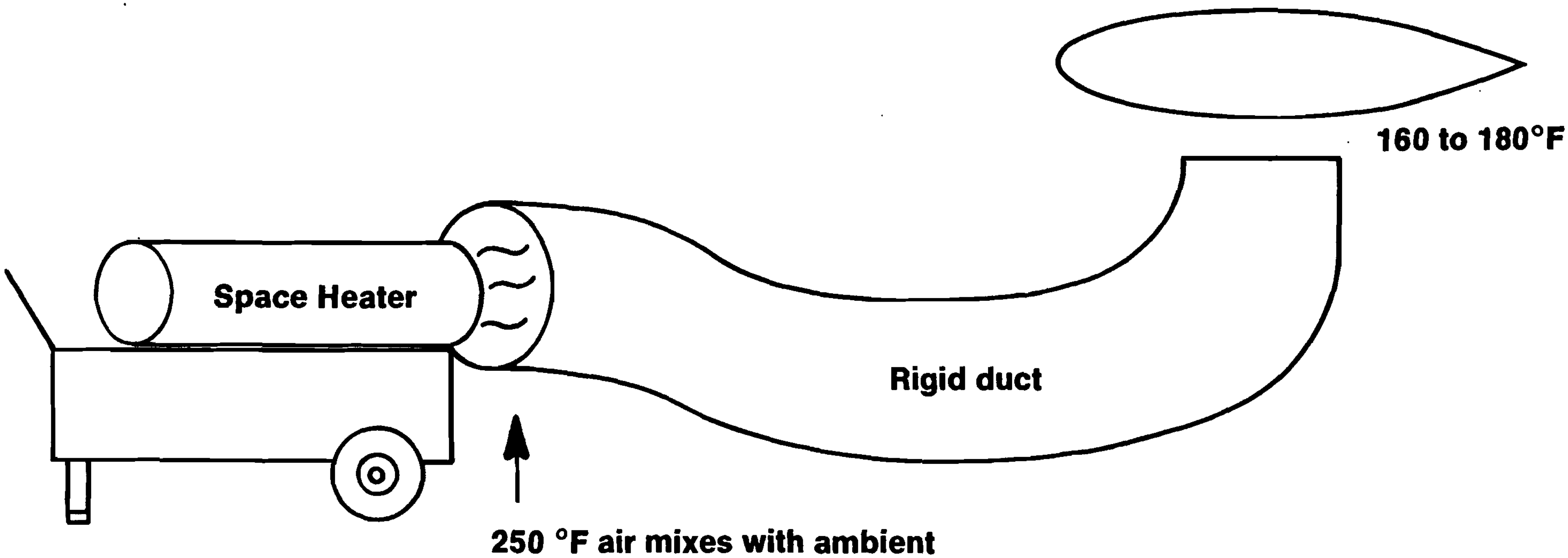


FIGURE 4. WING TANK HEATER SCHEMATIC

TEST PROCEDURES

FUEL PREPARATION.

Six test fuels with enhanced volatility were blended for the flight tests. The fuels were prepared utilizing the base gasoline (RVP = 9.3 psig), and the vapor pressures were altered by adding mixtures of normal butane and iso-pentane. Distillation information, according to ASTM D-86, was obtained for the base premium unleaded gasoline. These results are presented in table 1. The average (RON+MON/2) octane value of 91 was increased to 94 by addition of tetraethyl lead (TEL). This was done to ensure meeting the minimum octane requirements of all the aircraft engines.

The fuel matrix consisted of the following:

1. a 13 psi RVP fuel with a ratio of 3:1 iso-pentane to butane
2. a 15 psi RVP fuel with a ratio of 3:1 iso-pentane to butane
3. a 17 psi RVP fuel with a ratio of 3:1 iso-pentane to butane
4. a 13 psi RVP fuel with a ratio of 3:1 butane to iso-pentane
5. a 15 psi RVP fuel with a ratio of 3:1 butane to iso-pentane
6. a 17 psi RVP fuel with a ratio of 3:1 butane to iso-pentane

The amount of butane and iso-pentane, which was added to the base fuel to obtain the values listed in the above matrix, was calculated from the results of a chromatographic analysis of the base fuel and a model developed by the Chevron Research Company. This model makes use of vapor pressure blending indices (VPBI) that have been compiled for each of the various components. The blend RVP is essentially equal to the following:

$$RVP_{blend} = \sum_{i=1}^{n} V_i (VPBI)_i$$

where

V_i = the volume component fraction, and
$(VPBI)_i$ = the component vapor pressure blending index.

The six fuels were volume blended and stored at 50°F. Post blending samples were taken from each fuel to ensure the proper target fuel RVP was obtained prior to testing.

TABLE 1. DISTILLATION DATA - BASE FUEL

Specific Gravity		0.724
Distillation, ASTM D-86, °F:		
	Initial Boiling Point (IBP)	92
	5 pct evaporated	114
	10 pct evaporated	128
	20 pct evaporated	156
	30 pct evaporated	185
	40 pct evaporated	208
	50 pct evaporated	228
	60 pct evaporated	238
	70 pct evaporated	274
	80 pct evaporated	301
	90 pct evaporated	348
	95 pct evaporated	397
	END POINT	412

FLIGHT TESTS.

The O_2 and CO analyzer was calibrated prior to every flight test. The calibration was typically conducted during the taxi/ground idle phase of the flight test. The procedure is outlined below.

1. Drain the water trap and visually inspect the particulate filter.

2. Powerup the analyzer and set the air flow rate if necessary. At the same time, turn on the chart recorder. Allow the analyzer to warm until the display readings stabilize.

3. Depress the calibration button and adjust the full-scale reading on the CO display and set the zero on the O_2 display.

4. Release the calibration and turn the intake selector valve so that the analyzer draws in cabin air. Set the span on the O_2 display to indicate 21 percent and set the CO reading to zero. Return the intake selector valve to allow exhaust gases to be drawn into the analyzer.

5. Repeat steps 3 and 4 as necessary.

6. Set the scales on the strip chart to the desired setting. Adjust the zero and span for each trace as steps 3 and 4 are repeated.

7. Select the desired chart speed and set the recorder on standby.

ALTITUDE PROFILES. These tests were conducted to identify the effects of fuel composition and exposure to altitude on fuel weathering. The effects of weathering on aircraft performance were measured over a range of control variables.

Prior to starting this series of flight tests, a full insulated fuel tank was carried to altitude to get an estimate of the temperature drop as the fuel was carried to altitude. This difference was later used to determine the temperature the fuel would be heated to in order to obtain the desired target temperature.

Cool test fuel was transferred from the barrel into the insulated fuel tanks by pressurizing the barrel. The quantity of fuel (minimum of 12 gallons) in the insulated container was determined by weight. The insulated fuel tank was then sealed and transported to the hot water bath. After removing the insulation, the container was placed in the hot water bath and the temperature of the fuel was monitored until it reached the target temperature plus the expected temperature drop. The insulation was replaced and the sealed, insulated fuel tank was transported to the test aircraft.

After the tank was placed in the aircraft and secured, the transfer line was hooked up and the nitrogen tank attached. The pressure in the nitrogen tank would be checked to ensure enough nitrogen was available to complete the fuel transfer. The thermocouple in the insulated fuel tank was plugged in and the temperature checked.

Prior to staring the aircraft, the wing tank drain was checked to ensure no fuel remained in the starboard tank and the fuel level in the port tank was checked. The aircraft preflight was completed as the observer prepared the run sheets (see appendix B). The aircraft was then started and taxied to the runway as the instruments were calibrated. The operation of all the thermocouples were checked at this time. The recommended engine runup and magneto checks were conducted, followed by the takeoff. Takeoff and climb were conducted using 100LL avgas.

Fuel transfer was timed to begin so that the fuel transfer would be completed just after reaching a pressure altitude of 12,500 feet. Typically, this meant starting at a pressure altitude of 12,000 feet and completing the transfer 2 minutes after reaching 12,500 feet. The typical transfer took 12 minutes. The specific steps followed were:

1. Open the nitrogen shutoff valve and set the pressure regulator to between 7 and 10 pounds-per-square-inch gauge (psig) pressure.

2. Open the valve that connects the nitrogen to the insulated fuel tank.

3. Open the valve on the fuel transfer line that is closest to the insulated fuel tank first, then open the valve that is closest to the wing tank.

4. Monitor the pressure indicator on the pressure regulator. When the regulator can no longer maintain the air pressure going into the insulated fuel tank, all the fuel has been transferred.

5. Shut the valves in the reverse order listed above then reduce the pressure output from the pressure regulator.

After reaching 12,500 feet, the power setting was set to full throttle (maximum power) and the instrumentation was monitored until conditions stabilized. The run sheet for the 12,500-foot pressure altitude was filled out, then the tank containing the test fuel was selected. Readings were taken at the intervals indicated on the run sheets until the engine vapor locked, as indicated by the loss of power, or until 10 minutes passed.

At the end of the data point, the tank containing the 100LL avgas was selected and descent was initiated to the 10,000-foot pressure altitude. The procedure described in the above paragraph was repeated at 10,000 feet; then a descent was initiated to 7,500 feet. After completing the data point at 7,500 feet, a fourth data point was taken at the 5,000-foot pressure altitude.

Upon landing, a sample was taken from the starboard wing tank drain, and the tank was drained of all the remaining test fuel in preparation for the next test.

TAKEOFF AND CLIMB TESTS. These tests were conducted to confirm the test results obtained during ground based testing. In summary, the ground based tests indicated that the most severe test for vapor lock, when using autogas, included a takeoff and climb sequence using a winter grade autogas that was heated in the wing tank to 110°F (reference 4). The ambient temperature at the surface was 85°F or higher for these tests.

Fifteen gallons of cool test fuel was transferred to an insulated fuel tank. The tank was sealed and the test fuel was transported to the aircraft. The aircraft tank drain was checked to ensure the wing tank was empty, then the test fuel was transferred to the aircraft wing tank using a hand-operated vane pump. The port wing tank was used when testing autogas in the Musketeer, and the starboard wing tank was used when testing the Traveler. The other wing tank was filled with 100LL avgas to be used as the recovery fuel, should vapor lock occur.

Immediately following the transfer, a fuel sample was taken, and the wing tank heater setup was positioned and turned on. The temperature of the fuel in the wing tank was monitored until it reached the desired temperature. As the test fuel was heated, the aircraft preflight was conducted and the run sheets were prepared by the test observer. After the fuel reached the target temperature, a second fuel sample was taken.

The tank selector was set to the tank containing the test fuel; then the sediment bowl was drained until no trace of avgas was noted. In both aircraft this purged the fuel lines to just prior to the engine driven pump. The engine was then started in as short a period of time as practical. As the aircraft was taxied to the runup area, the instrumentation was calibrated and the run sheets were updated. The recommended ground and magneto checks were conducted, and the engine instruments were checked to ensure the engine oil temperature was above 100°F and the cylinder head temperature was above 250°F.

The takeoff and climb were conducted per the procedures contained in the pilot's operating handbook for the best rate of climb, with the exception that the electrically operated boost pump was left off. This made the test more severe than with the boost pump on, and it provided another safety margin should vapor lock occur.

The test was terminated when either vapor lock occurred or the aircraft reached a pressure altitude of 12,500 feet. If vapor lock occurred, the tank containing the avgas was selected and the boost pump was turned on. Upon landing, a sample of the test fuel was taken.

MTBE EVALUATION. The MTBE evaluation consisted of two phases; an initial takeoff and climb test, to ensure the aircraft could be operated safely with varying fuel temperatures, and a simulated cross country phase, which was used to accumulate the bulk of the operating time. These tests were conducted in the Musketeer since it possessed the most complex fuel system of the three aircraft, and with the greater number of parts, it would probably have experienced material compatibility problems sooner than the other test aircraft.

Prior to running the engine on MTBE, the engine was given a top overhaul and the clearances in the valve train were measured. The engine was broken-in with 100LL avgas until the oil consumption stabilized. The compression was then checked, and the valve train clearances were measured again. The aircraft was operated solely on MTBE after this time.

The takeoff and climb evaluations with MTBE were conducted in a fashion similar to takeoff and climb tests conducted with autogas. As before, 100LL avgas was carried in the starboard tank of the Musketeer as a recovery fuel, should fuel related problems occur. The boost pump of the Musketeer was left on until a pressure altitude of 5,000 feet was reached, since the use of the boost pump resulted in richer operations which would partially offset the lower energy density of the fuel.

The cross country phase consisted of the following flight regimes:

1. An engine start, taxi, magneto, and systems check.

2. After reaching normal operating temperatures, a takeoff and climb-to-altitude per the operating procedures contained in the pilot's operating handbook.

3. Upon reaching an altitude greater than 3,000 feet above mean sea level (MSL), the power was set between 60 and 75 percent of maximum rated power, and the fuel to air ratio leaned according to the procedures given in the pilot's operating handbook for best economy. This altitude was maintained for a minimum of 1 hour.

4. Reduce the power and descend to landing.

5 Taxi, ground systems check, and shutdown.

This procedure was repeated until a total of 50 hours operating time on MTBE was accumulated. At the 25- and 50-hour intervals, the valve train clearances were measured. At the conclusion of the test, the engine was torn down and inspected for any unusual wear patterns or corrosion.

FUEL WEATHERING.

This part of the test program at NIPER was initiated to provide information on the weathering of oxygenated fuel blends and the subsequent effects on fuel volatility. Four blends were chosen for investigation. These were on a volume basis as follows:

1. 10 percent methanol, 90 pct regular unleaded gasoline
2. 10 percent ethanol, 90 pct regular unleaded gasoline
3. 10 percent MTBE, 90 pct regular unleaded gasoline
4. 15 percent MTBE, 85 pct regular unleaded gasoline

The selection rationale was not based on current Environmental Protection Agency (EPA) waivers for alcohol blends, but rather, for the first three fuels, to keep total oxygenate constant. The 15 percent MTBE blend selection was made for comparison to the methanol fuel, since they are approximately equal on a total fuel oxygen basis. No cosolvents were used in these fuels.

The test procedure consisted of the following:

1. Fuels were stored at 50°F, and an initial (fresh fuel) sample was taken for RVP measurements.

2. Tanks were filled with 50°F fuel to the 12-gallon (95 percent) level.

3. The tank vent holes were vented to the atmosphere.

4. Fuel tanks were placed in the heated water bath, and fuel was brought to 110°F. This temperature was maintained throughout the test period to ±3°F.

5. Samples were taken within 1 hour of attaining the desired temperature. That is referenced as time = 0.

6. Additional samples were taken at 24 and 48 hours following fuel temperature equilibration.

Vapor pressures were measured for all samples taken. A Herzog semi-automatic RVP apparatus was used for these measurements.

RESULTS

FLIGHT TESTS.

The test fuels used during the altitude profiles and the takeoff and climb tests were unleaded premium gasolines with modified RVP's. In addition, 1 gram per gallon of tetraethyl lead (TEL) was added to the fuel when testing with the Traveler and the Musketeer since the MON of the test fuels without the TEL was lower than the minimum required octane for the engines in these aircraft.

The original test plan called for testing fuels with a vapor pressure ranging from 9 to 17 psig pressure. After observing the amount of fuel venting that occurred when transferring the 15 psig test fuel in the Traveler, the test pilot determined tests with the 17 psig test fuel would be unsafe and those tests were not conducted.

<u>ALTITUDE PROFILES</u>. The data from the altitude profiles were converted to attribute data. This means applying a "1" for yes and a "0" for no in response to specific questions. By averaging the responses, one can determine the fraction of the events that met the criteria established in the question. If there was no answer to a specific question, the entry was left blank and the data point was not included in the averages. For example, when testing with the C-172, there was no fuel pressure reading so the data presented on fuel pressure does not include any C-172 data.

Table 2 lists the data from the altitude profiles. The first column gives the RVP of the test fuel, and the second indicates if the test fuel was either butane rich (B) or iso-pentane rich (P). The target tank temperature is listed in the third column followed by the aircraft code. The pressure altitude is listed next followed by the OAT. Column 7 answers whether the EGT rose more than 25°F, and column 8 indicates if the engine speed dropped more than 50 revolutions per minute (RPM). These two questions were designed to filter out small changes that are normally observed in the presence of turbulence or as a consequence of small differences in the energy density of the fuels. If a performance loss was noted, the magnitude of that loss and the time of the greatest loss were recorded in columns 9 and 10. It should be noted that it typically took 30 to 40 seconds to purge the avgas out of the lines and for the engine to actually operate on the test fuel. Any changes in the measured amount of CO, O_2, or in the fuel pressure are noted in columns 11 through 13. The total duration of aircraft operation on the test fuel is noted in column 14, and the post-test RVP is given in column 15. Appropriate comments are listed at the end of each line.

During the course of the testing, water condensation was a greater problem than anticipated. This often resulted in water collecting in the CO and O_2 analyzer, rendering the readings meaningless. A backup filter/water separator was added approximately half way through the testing to address this problem. A second problem encountered with the instrumentation was radio interference with the strip chart recorder. This interference would feed back through the recorder and affect the readings indicated on the analyzer. Disconnecting the recorder resulted in normal operations. The exact cause of this problem was never identified, and the recorder was disconnected for much of the test program. When the readings were in question, no attribute data were entered in the appropriate column.

The test fuels were evaluated at three target temperatures: 70, 90, and 110°F. To obtain these temperatures at altitude, the 70°F fuel was loaded into the aircraft at between 60 and 70°F and it would heat to the target temperature as the aircraft climbed. The 90°F fuel was loaded at approximately 90°F, and the 110°F fuel was heated to 115°F prior to the test. The ambient air temperature at the surface ranged from 77 to 103°F for these tests.

TABLE 2. SUMMARY OF THE ALTITUDE PROFILE TEST DATA

INIT RVP (psig)	FUEL CODE	FUEL TEMP (°F)	A/C ID	PRESSURE ALTITUDE (ft MSL)	OAT (°F)	EGT RISE >25	POWER LOSS >50	POWER LOSS (RPM)	MAX DROP (sec)	--DELTA-- CO	O2	F/P	TOTAL TIME (sec)	POST RVP (psig)	COMMENTS:
15	B	90	C	12500	36	1	1	100	180	1	0		732		POWER LOSS SHORT TRANSIENT
15	B	90	C	10000	48	0	0			0	0		705		
15	B	90	C	7500	54	0	0			0	1		708		
15	B	90	C	5000	68	0	0			0	0		691		
15	B	110	C	12500	36	1	1	150	180		1		758		GRADUAL IMPROVMENT AFTER 3 MIN
15	B	110	C	10000	46	1	1	70	240		1		711		GRADUAL IMPROVMENT AFTER 3 MIN
15	B	110	C	7500	57	1	1	70	60		1		715		POWER LOSS SHORT TRANSIENT
15	B	110	C	5000	68	1	0				1		887		
15	P	70	C	12500	37	0	0			1	0		702	12.5	
15	P	70	C	10000	42	0	1	100	180	1	1		699	12.5	EGT MAY HAVE BEEN PAST PEAK ON AVGAS
15	P	70	C	7500	50	0	0			1	1		590	12.5	
15	P	70	C	5000	57	0	0			1	1		624	12.5	
15	P	90	C	12500	34	0	0			1	0		701		
15	P	90	C	10000	46	0	0			0	0		693		
15	P	90	C	7500	54	1	0			1	1		698		
15	P	90	C	5000	57	1	0			1	1		703		
15	P	110	C	12500	36	0	0			0	0		654		
15	P	110	C	10000	45	0	0				0		704		POWER IMPROVED!
15	P	110	C	7500	54	0	0				0		660		
15	P	110	C	5000	59	0	0						669		
15	B	70	C	12500	34	0	1	100	90	1	1		715		POWER LOSS SHORT TRANSIENT
15	B	70	C	10000	45	0	0			1	1		724		
15	B	70	C	7500	54	1	0			0	1		715		
15	B	70	C	5000	61	0	0			0	0		694		
13	P	110	T	12500	45	1	0				0	0	649		
13	P	110	T	10000	56	1	1	80	180		0	1	664		STEADY EGT DROP, SLIGHT F/P DROP
13	P	110	T	7500	68	0	0				0	1	681		SLIGHT F/P DROP
13	P	110	T	5000	75	0	0				0	0	711		
15	P	90	T	12500	44	0	0				0	1	687	10.3	SLIGHT F/P DROP
15	P	90	T	10000	51	0	0				0	1	662	10.3	INITIAL 1.5 PSI F/P DROP, THEN STEADY
15	P	90	T	7500	60	0	0				0	1	679	10.3	
15	P	90	T	5000	73	0	0				0	1	687	10.3	
15	P	110	T	12500	44	1	0				0	1	493	10	
15	P	110	T	10000	50	0	1	70	20		0	0	480	10	
15	P	110	T	7500	60	0	0				0	1	487	10	
15	P	110	T	5000	74	1	0				0	1	540	10	
15	P	70	T	12000	40	0	1		40		0	1	143	12.1	BOOST ON AFTER APPROX. 40 SEC.
15	P	70	T	10000	49	0	0				0	1	496	12.1	
15	P	70	T	7500	59	0	0				0	1	483	12.1	
15	P	70	T	5000	71	1	0				0	1	488	12.1	
15	B	70	T	12500	44	0	1	150	360	1	1	1	342	10.7	ENGINE ALMOST QUIT AT 230 SEC.
15	B	70	T	10000	49	1	1	80	240	1	1	1	639	10.7	
15	B	70	T	7500	59	0	0				1	1	669	10.7	INITIAL 0.5 PSI F/P DROP, THEN STEADY
15	B	70	T	5000	70	0	1	100	240		0	1	668	10.7	INITIAL 0.5 PSI F/P DROP, THEN STEADY
13	P	90	T	12500	43	0	0				0	1	664	11.8	
13	P	90	T	10000	57	1	0				0	1	660	11.8	
13	P	90	T	7500	67	0	1	200	240		0	0	640	11.8	
13	P	90	T	5000		0	1	150	120		0	1	616	11.8	

TABLE 2. SUMMARY OF THE ALTITUDE PROFILE TEST DATA (Continued)

INIT RVP (psig)	FUEL CODE	FUEL TEMP (°F)	A/C ID	PRESSURE ALTITUDE (ft MSL)	OAT (°F)	EGT RISE >25	POWER LOSS >50	POWER LOSS (RPM)	MAX DROP (sec)	—DELTA— CO	O2	F/P	TOTAL TIME (sec)	POST RVP (psig)	COMMENTS:
13	P	70	T	12500	42	0	0				0	1	663	9	
13	P	70	T	10000	54	0	1	100	120		0	1	664	9	
13	P	70	T	7500	66	0	0				0	1	676	9	
13	P	70	T	5000	75	0	0				0	1	684	9	
13	B	70	T	12500	38	1	1	100	240	1	0	1	659	8.3	
13	B	70	T	10000	49	0	1	100	60	0	0	1	667	8.3	
13	B	70	T	7500	59	0	0				0	0	666	8.3	
13	B	70	T	5000	68	0	0				0	0	645	8.3	
15	B	90	T	12500	34	0	1	100	90	1	1	0	666		
15	B	90	T	10000	42	0	1	100	40	1	0	1	660		
15	B	90	T	7500	46	0	1	100	60		0	1	671		
15	B	90	T	5000	55	1	0					0	665		
15	B	110	T	12500	35	0	1	100	600	0	0	1	756	9.3	SLIGHT DETERIORATION AT END OF RUN
15	B	110	T	10000	44	0	1	70	150		0	1	685	9.3	
15	B	110	T	7500	47	1	0				1	1	691	9.3	
15	B	110	T	5000	55	0	1	100	180		1	0	684	9.3	
13	B	70	M	12500	43	1	1			1	1	1	102		LOST POWER, AIRSPEED, AND F/P
13	B	70	M	10000	47	1	1	100	240		1	1	600		
13	B	70	M	7500	56	1	1	200	600	1	1	1	630		
13	B	70	M	5000	63	1	1	400	210	1	1	1	414		
13	B	90	M	12500	44	1	1	450	180	1	1	1	444	10.9	ENGINE QUIT WHILE SWITCHING TO AVGAS
13	B	90	M	10000	51	1	1	50	180	1	1	1	628	10.9	POWER ACTUALLY INCREASED
13	B	90	M	7500	59	1	0			1	1	1	654	10.9	
13	B	90	M	5000	68	1	0					1	840	10.9	DESCEND ON TEST FUEL
13	B	110	M	12500	39	1	1	100	540			1	641	12.7	
13	B	110	M	10000	52	0	0					1	666	12.7	
13	B	110	M	7500	63	1	0					1	653	12.7	
13	B	110	M	5000	69	1	0					1	660	12.7	
13	P	70	M	12500	40	1	1	500	120		1	1	228	11.9	IMMEDIATE RECOVERY WITH BOOST PUMP
13	P	70	M	10000	53	1	1	380	660		1	1	680	11.9	GRADUAL DECREASE IN RPM AND F/P
13	P	70	M	7500	63	1	1	160	600			1	670	11.9	GRADUAL DECREASE IN RPM AND F/P
13	P	70	M	5000	72	1	1	150	480			1	727	11.9	GRADUAL DECREASE IN RPM AND F/P
13	P	90	M	12500	40	1	1	350	180		1	1	330	11.2	
13	P	90	M	10000	53	1	1	130	600		1	1	645	11.2	
13	P	90	M	7500	60	1	0				0	1	662	11.2	
13	P	90	M	5000	74	1	1	250	960		1	1	1045	11.2	GRADUAL PERFORMANCE DECAY
13	P	110	M	12500	42	1	1	550	120		1	1	602	11.8	BOOST ON AFTER 120 SEC., STILL MISFIRING
13	P	110	M	10000	53	1	0				1	1	678	11.8	PERFORMANCE GOOD DESPITE EGT CHANGE
13	P	110	M	7500	60	1	0				1	1	603	11.8	
13	P	110	M	5000	76	1	1	150	360		1	1	609	11.8	SOUNDS FUNNY...MISFIRE?
15	B	90	M	12500	43	1	1	?	40		1	1	212	13.3	ONLY RUNS WITH BOOST PUMP ON!
15	B	90	M	10000	52	1	1	400	300		1	1	448	13.3	BACKFIRE; BOOST ON AFTER 360 SEC
15	B	90	M	7500	60	1	1	220	600		1	1	631	13.3	GRADUAL PERFORMANCE DECAY
15	B	90	M	5000	74	1	1	350	600		1	1	623	13.3	SLOW PERFORMANCE DECAY, BUT ENGINE SMOOTH
15	B	70	M	12500	41	1	1		40			1	185	14.2	ONLY RUNS WITH BOOST ON AFTER 40 SEC.
15	B	70	M	10000	51	1	1		40			1	68	14.2	ONLY RUNS WITH BOOST ON AFTER 40 SEC.
15	B	70	M	7500	60	1	1	450	360		1	1	519	14.2	PERFORMANCE DECAY, BOOST AFTER 420 SEC.
15	B	70	M	5000	73	1	1	600	90		1	1	169	14.2	STEADY DECAY, BOOST ON AFTER 120 SEC.

TABLE 2. SUMMARY OF THE ALTITUDE PROFILE TEST DATA (Continued)

INIT RVP (psig)	FUEL CODE	FUEL TEMP (OF)	A/C ID	PRESSURE ALTITUDE (ft MSL)	OAT (OF)	EGT RISE >25	POWER LOSS >50	POWER LOSS (RPM)	MAX DROP (sec)	--DELTA-- CO	O2	F/P	TOTAL TIME (sec)	POST RVP (psig)	COMMENTS:
15	P	70	M	12500	46	1	1		40		1	1	62		BACKFIRE, BOOST ON AFTER 50 SEC.
15	P	70	M	10000	53	1	1		35		1	1	86		BACKFIRE, BOOST ON AFTER 40 SEC.
15	P	70	M	7500	61	1	1		45		1	1	78		BACKFIRE, BOOST ON AFTER 55 SEC.
15	P	70	M	5000	74	1	1		40		1	1	85		BACKFIRE, BOOST ON AFTER 45 SEC.
15	B	110	M	12300	46	1	1	990	35		1	1	115	12.8	RECOVER WITH BOOST AFTER 60 SEC.
15	B	110	M	10000	52	1	1	600	240		1	1	248	12.8	RECOVERY WITH BOOST AFTER 210 SEC.
15	B	110	M	7500	59	1	1	125	600		0	1	614	12.8	SLOW PERFORMANCE DECAY, RECOVER W/O BOOST
15	B	110	M	5000	74	1	1	100	240		0	1	621	12.8	SLIGHT PERFORMANCE DECAY,RECOVER W/O BOOST
15	P	110	M	12500	40	1	1				1	1	151	14.4	BACKFIRE, BOOST ON AFTER 87 SEC.
15	P	110	M	10000	49	1	1	300	150		1	1	312	14.4	BACKFIRE, BOOST ON AFTER 240 SEC.
15	P	110	M	7500	58	1	1	200	600		1	1	763	14.4	GRADUAL PERFORMANCE DECAY
15	P	110	M	5000	68	1	1	120	600		1	1	726	14.4	ENGINE SLIGHTLY ROUGH AT END OF RUN

notes: A/C denotes aircraft
B indicates butane rich fuel
C indicates C-172
F/P denotes fuel pressure
M indicates Musketeer
P indicates pentane rich fuel
T indicates Traveler
W/O indicates without
> indicates greater than
1 equals yes
0 equlas no

Table 3 lists the power loss as a function of RVP. The total number of events are listed. An event is a test fuel, in a specific aircraft, at a target temperature and at a pressure altitude. The fraction power loss column was calculated from the power loss greater than 50 RPM column (table 2). The fraction EGT column lists the fraction of the events where the EGT changed more than 25°F. Finally, the average time to the greatest drop in engine speed is listed. This value was calculated from only those events where power loss was experienced.

TABLE 3. POWER LOSS AS A FUNCTION OF RVP

RVP (psig)	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE	AVERAGE TIME TO POWER LOSS (seconds)
		All Aircraft in Database		
13	40	0.55	0.68	333
15	68	0.54	0.50	212
		C-172 Data Removed from Database		
13	40	0.55	0.68	333
15	44	0.70	0.59	224

The first analysis indicated the tendency to vapor lock was inversely proportional to the RVP, which was contrary to the expected behavior. A review of the test data revealed the C-172 data were biasing the test results. The C-172 was initially tested with the 15 psig test fuels, and since vapor lock with these fuels did not result in an engine stoppage, it was never tested with the 13 psig fuels. The large number of data points without vapor lock in the 15 psig range biased the results. The analysis was repeated without the C-172 data, and the results were as expected.

When testing with the 13 psig test fuels, there were several cases where the EGT changed indicating a change in the fuel-to-air ratio, but no power loss was detected. Indeed, there were several events where the power that was generated actually increased slightly. When testing with the 15 psig fuel, there were many cases where the loss of power was so abrupt that the EGT probes did not respond to the changes in fuel-to-air ratio. As expected, the average time to vapor lock was shorter for the 15 psig test fuels than the 13 psig test fuels.

Table 4 lists the same data as table 3, but as a function of fuel composition. As before, the data are listed with and without the C-172 included in the analysis. Under the fuel category column, the results for all the butane fuels are listed as well as the 13 and 15 psig butane fuels; likewise, the results for all the iso-pentane fuels are listed followed by the 13 psig and 15 psig iso-pentane rich fuels.

TABLE 4. POWER LOSS AS A FUNCTION OF FUEL COMPOSITION

FUEL CATEGORY	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE	AVERAGE TIME TO POWER LOSS (seconds)
		All Aircraft in Database		
Butane	52	0.67	0.63	240
13 psig	16	0.56	0.75	281
15 psig	36	0.72	0.58	227
Iso-pentane	56	0.43	0.50	282
13 psig	24	0.54	0.63	365
15 psig	32	0.34	0.41	175
		C-172 Data Removed from Database		
Butane	40	0.75	0.68	255
13 psig	16	0.56	0.75	281
15 psig	24	0.88	0.63	245
Iso-pentane	44	0.52	0.59	287
13 psig	24	0.54	0.63	365
15 psig	20	0.50	0.55	174

The fraction of events which experienced power loss and EGT changes was greater when testing with the butane rich fuels than when testing with the iso-pentane rich fuels. Likewise, the average time to vapor lock was shorter when using the butane rich fuels. Both of these trends indicate a butane rich fuel with the same RVP as an iso-pentane rich fuel will vapor lock sooner than the iso-pentane rich fuel. As expected, the butane rich 15 psig test fuels exhibited a greater tendency to vapor lock than did the 13 psig butane rich fuels. The trends noted when comparing the 13 and 15 psig iso-pentane rich fuels are contradictory, however. The fraction of power loss and the fraction of EGT changes indicate the 13 psig fuel is more likely to vapor lock than the 15 psig fuel. The average time to vapor lock indicates the 15 psig fuel is more likely to vapor lock than the 13 psig test fuel. A satisfactory explanation for this anomaly has not been developed.

Table 5 lists the effects of altitude on the indicators of vapor lock (power loss, EGT, and average time to power loss). As before, the results are listed with and without the C-172 included in the database.

TABLE 5. THE EFFECTS OF PRESSURE ALTITUDE ON POWER LOSS

PRESSURE ALTITUDE (feet MSL)	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE	AVERAGE TIME TO POWER LOSS (seconds)
		All Aircraft in Database		
5,000	27	0.44	0.59	343
7,500	27	0.37	0.56	377
10,000	27	0.67	0.52	204
12,500	27	0.70	0.59	181
		C-172 Data Removed from Database		
5,000	21	0.57	0.67	343
7,500	21	0.43	0.57	412
10,000	21	0.76	0.62	203
12,500	21	0.76	0.67	188

There is a definite trend indicating that the incidence of vapor lock decreases with altitude. This is apparently a function of time; as the fuel ages, the tendency to vapor lock decreases. This trend slows or is reversed at the 5,000-foot level. This may be due to the increasing fuel flow rate as the maximum power developed increased with decreasing pressure altitude.

By listing the effects of altitude for the type of fuel blend, one can decide if the composition determines the rate at which the fuel ages. Table 6 lists the results according to pressure altitude and fuel composition. The results show the butane rich fuels rapidly weather, with the incidence of vapor lock decreasing from 100 percent at 12,500 feet to approximately 50 percent at 5,000 feet. The iso-pentane rich fuels do not show a consistent trend in weathering with the exception of time to maximum power loss. This implies the iso-pentane rich fuels weather slowly in comparison to the butane rich fuels. There does not appear to be a significant difference between the butane rich fuels and the iso-pentane rich fuels after weathering during the approximately 30 minutes it takes to descend to 5,000 feet.

TABLE 6. THE EFFECTS OF PRESSURE ALTITUDE AND FUEL COMPOSITION ON POWER LOSS

PRESSURE ALTITUDE (feet MSL)	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE	AVERAGE TIME TO POWER LOSS (seconds)
Butane Rich Fuels, All Aircraft in Database				
5,000	13	0.46	0.62	260
7,500	13	0.46	0.69	380
10,000	13	0.77	0.54	173
12,500	13	1.00	0.69	215
Iso-pentane Rich Fuels, All Aircraft in Database				
5,000	14	0.43	0.57	427
7,500	14	0.29	0.43	371
10,000	14	0.57	0.50	243
12,500	14	0.43	0.50	100
Butane Rich Fuels, C-172 Removed From Database				
5,000	10	0.60	0.70	260
7,500	10	0.50	0.70	444
10,000	10	0.90	0.60	166
12,500	10	1.00	0.70	236
Iso-pentane Rich Fuels, C-172 Removed from Database				
5,000	11	0.55	0.64	427
7,500	11	0.36	0.45	371
10,000	11	0.64	0.64	252
12,500	11	0.55	0.64	100

The effect of temperature on the tendency to vapor lock is shown in table 7. As before, the results are presented with and without the C-172 in the database. There is not a significant difference in the standings between the 90 and 110°F data, either with or without the C-172 included in the database. The 70°F condition clearly results in more incidents of vapor lock, and vapor lock occurs sooner than with the hotter fuels. The controlling factor appears to be the rapid weathering that occurs when the hot fuel is transferred. As noted earlier, the test pilot was concerned with the volume of vapor and liquid that was venting while transferring the 110°F fuel in the Traveler.

TABLE 7. THE EFFECT OF TEMPERATURE ON POWER LOSS

TRANSFER TEMPERATURE (°F)	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE	AVERAGE TIME TO POWER LOSS (seconds)
		All Aircraft in the Database		
70	40	0.63	0.50	215
90	32	0.47	0.53	291
110	36	0.53	0.67	283
		C-172 Removed From the Database		
70	32	0.72	0.59	223
90	24	0.58	0.58	299
110	28	0.57	0.71	308

Table 8 shows the results comparing the aircraft design on the tendency to vapor lock. In general, the simpler the aircraft fuel system is the less likely the tendency to vapor lock. This agrees with the results observed in reference 4. When reviewing the data, keep in mind the C-172 was operated solely on 15 psig fuels, whereas the others were operated on both 13 and 15 psig fuels. This would tend to bias the C-172 standing. Also keep in mind the C-172 never experienced an engine stoppage during this series of tests.

TABLE 8. THE EFFECTS OF AIRCRAFT CONFIGURATION ON POWER LOSS

AIRCRAFT/CONFIGURATION	NUMBER OF EVENTS	FRACTION POWER LOSS	FRACTION EGT CHANGE
C-172 Gravity Feed	25	0.24	0.36
Traveler/Suction Feed	40	0.43	0.25
Musketeer/Suction Feed, Fuel Injection	44	0.82	0.97

TAKEOFF AND CLIMB TESTS. The Traveler and the Musketeer were used to conduct the takeoff and climb tests. As indicated earlier, the purpose of these tests was to confirm the conditions used in the hot weather certification tests as the most likely to result in vapor lock.

The conditions at the start of each of the takeoff and climb tests are listed in table 9. The aircraft model, RVP, fuel temperature in the tank at engine start and at takeoff, ambient air temperature, and field pressure altitude are listed. The tests are listed in the order of occurrence.

TABLE 9. TEST CONDITIONS FOR THE TAKEOFF AND CLIMB TESTS

AIRCRAFT	RVP (psig)	TANK TEMPERATURE (°F) START/TAKEOFF	AMBIENT TEMPERATURE (°F)	PRESSURE ALTITUDE (feet MSL)
Traveler	15	73 / 79	86	350
Traveler	15	110 / 104	91	370
Traveler	15	110 / 107	97	430
Traveler	15+	90 / ---	92	450
Musketeer	13	70 / ---	91	630
Musketeer	9.3	70 / 80	89	680
Musketeer	9.3	90 / 90	79	770
Musketeer	9.3	110/ 106	82	820
Musketeer	11	70 / 74	85	850
Musketeer	11	90 / 88	84	850
Musketeer	11	110 / ---	84	840
Musketeer	11	115 / 102	85	860

Based on the results from the altitude profile tests, which indicated the Traveler could operate on 15 psig autogas under certain conditions, a 15 psig test fuel was prepared. This fuel, and all the fuels used for the takeoff and climb tests, was prepared to have a 3:1 butane to iso-pentane ratio. The only exception was the base fuel, which was used in the Musketeer, and that had a ratio of 1:1. The other test fuels used in the Musketeer had RVP's of 11 and 13 psig.

The test fuel for all three 15 psig tests with the Traveler was blended into a 55-gallon drum then transferred to an insulated tank for transportation to the aircraft. In addition, the fuel was stored and handled between 65 and 70°F instead of below 50°F as a consequence of limited space in the cold storage facility. Initially, it was thought the results would still be useful despite these conditions as long as all the samples were handled in the same manner.

The 70°F target temperature was exceeded by 3° when the engine was started for the first test with the Traveler. The fuel reached a temperature of 79°F by the time the engine warmed enough to conduct the takeoff. With the exception of a slight fluctuation in the fuel pressure between 5,000 and 6,000 feet, the aircraft performed normally. The fuel temperature was 71°F and the OAT was 56 to 57°F between these altitudes. The test was terminated at 12,500 feet.

The next test was conducted with the test fuel at 110°F at engine start. The ground runup did not result in the normal engine speed, but the engine seemed to be performing satisfactorily so the takeoff was begun. The boost pump was inadvertently left on during the takeoff and climb up to 2,000 feet. Immediately after turning the boost pump off, the fuel pressure dropped and performance decayed slightly. The test was continued to 11,750 feet, where fuel exhaustion terminated the test. As the aircraft climbed, the fuel pressure increased until it stabilized at 3.5 psig. The 110°F test was repeated with another sample of the same fuel blend. This time the engine quit when the aircraft reached approximately 630 feet (200 feet above ground level). The boost pump resulted in immediate recovery, and the test continued to 2,000 feet. Whenever the boost pump was turned off as the aircraft climbed to 2,000 feet, the engine performance decayed. The combination of these two tests indicates the Traveler could not handle the 110°F test fuel at the fuel flows required for takeoff. As the fuel aged, and as the fuel flow rate decreased during the first 110°F test with the Traveler, the performance improved. It should be noted that during the second 110°F test, the ground observers heard the engine misfiring as the engine runup and takeoff were conducted. The test pilot and the observer did not notice this from in the aircraft.

There was insufficient fuel remaining to conduct the 90°F test with the Traveler, so a second blend of fuel was prepared. This fuel was blended using the same ratios as the original test fuel, but it was handled differently. In this case, the fuel was blended directly into the insulated tank and kept below 50°F until it was in the wing tank. The aircraft would not operate on this test fuel at 90°F. Unfortunately, the pretest RVP sample was lost, so there is no record of the initial RVP. The post test RVP was 14.6 psig as compared to between 11 and 13 for the 70 and 110°F tests. This indicates the initial RVP must have been above 15 psig and was probably closer to 16 or 17 psig. As a consequence, it is uncertain as to whether the fuel temperature or the RVP difference was the cause of the aircraft's inability to even idle on the test fuel. Lease requirements prevented a repeat sequence with this aircraft.

The takeoff and climb sequence was conducted with the Musketeer, and the fuel handling procedures were more tightly controlled. The fuel was stored and transferred between containers at 50°F or below, and the same pumps were used at the same stages in the test cycle. The engine would not operate on the 13 psig test fuel, so the base fuel was used for the next sequence. The aircraft operated normally using this test fuel at both the 70 and 90°F initial tank temperatures. There was a slight fuel pressure fluctuation at 500 feet above ground level (1,350-foot pressure altitude) with the 110°F fuel. The 70°F, 11 psig, test fuel resulted in a number of anomalies. There was a slight lag in throttle response; and the fuel pressure decayed as the aircraft climbed, then gradually recovered. The lowest pressure was observed 15 minutes into the flight at a pressure altitude of 8,000 feet. The 90°F, 11 psig, test fuel also resulted in reduced fuel pressure. In addition, the EGT was significantly higher than normal, and at a pressure altitude of 3,900 feet, the EGT appeared to pass through peak and decline. The engine performance decayed slightly at this time and the O_2 indications climbed slightly, indicating the engine was running lean of stoichiometric. Above 4,500 feet, the fuel pressure gradually recovered and the engine performance improved. The aircraft would not operate on the 110°F, 11 psig, test fuel. The sample of test fuel from the 110°F test was heated to 115°F. The total time from first pouring the 50°F test fuel into the tank and starting the 115°F flight was just under an hour. The 115°F test fuel operated normally during the taxi and runup, but it resulted in engine stoppage at 200 feet above ground level (1,060-foot pressure altitude). Unlike the Traveler, the boost pump did not immediately improve engine performance and it was necessary to switch to the tank containing avgas.

The preceding sequence showed the use of 110°F autogas provides the most severe test for vapor lock. Heating the fuel to 115°F improved the fuel's performance though it was still marginal. The experience with the Traveler showed the importance of heating the test fuel in the aircraft. Even handling 70°F fuel resulted in sufficient weathering to significantly alter the test results. As an example of the type of weathering that can be experienced, it was noted that the fuel drained from the sediment bowl following heating would boil vigorously as it exited the sediment bowl drain.

MTBE EVALUATION. Following the break-in period, the engine timing was retarded by 5 degrees, as indicated during ground based tests (reference 6), to compensate for the leaner operations that were expected with MTBE. The aircraft was started on MTBE but would not idle without the boost pump on. The boost pump in the Musketeer fuel system results in richer operations than normal, so its use probably resulted in more normal fuel-to-air ratios. The taxi and ground runup were normal, with the exception that the boost pump was on, so at 13:33 central standard time, on September 17, 1987, a takeoff and climb test was conducted using 70°F MTBE as the test fuel. The ambient conditions at the time of the test were 89°F and a pressure altitude of 640 feet. The boost pump was left on until the pressure altitude was 5,000 feet, at which time it was turned off. The EGT immediately climbed 100°F, but the fuel-to-air ratio remained on the rich side of stoichiometric. At approximately 9,000 feet, the engine began to run roughly. A magneto check conducted at 9,400 feet indicated the left magneto had failed, so the flight was terminated.

Throughout the flight, the CHT's were 25 to 50°F higher than normal. This appeared to be tied to a temperature inversion which kept the OAT above 60°F even at 8,200 feet. Above 9,000 feet, the CHT's were significantly (70 to 100°F) higher than normal. The failed magneto in conjunction with the temperature inversion explains these high cylinder head temperatures.

Given the difficulty recovering from vapor lock with this aircraft, and the results from the ground based testing (reference 6) which indicated the worst case occurred with MTBE heated to its boiling point, the takeoff and climb tests with the 90 and 110°F MTBE were not conducted. Instead, the simulated cruise profile tests were started and 50 hours of operations on MTBE accumulated.

During the 50-hour accumulation tests, no significant operational problems were noted due to utilization of MTBE. As expected with the reasonably low vapor pressure of MTBE, there were no volatility or aging problems attributable to the fuel. Fuel consumption appeared to be comparable to gasoline on an energy basis. The cruise altitude varied between 6,000 and 12,000 feet during these tests. Climb rates to 10,000 feet were comparable to those attained with avgas. Temperature of the MTBE in the fuel tank for the start of flights ranged from 70 to 90°F. Engine temperatures were somewhat elevated during this accumulation series. In particular, exhaust gas temperature increased approximately 50°F during climbs to cruise altitude. Engine operation appeared to be somewhat on the lean side of stoichiometric to about the 5,000-foot region. The air fuel ratio was in a more normal, i.e., slightly rich, regime at higher altitudes. No evidence of preignition appeared either during the flights or during post test engine teardown and examination.

Table 10 presents the data obtained from valve recession measurements during the 50-hour accumulation period. Cumulative differences in valve clearances from the initial or rebuilt conditions are shown. As can be seen, clearance changes for both intake and exhaust are minimal, essentially within the measurement reliability. Although the time period of the accumulated operation with MTBE is somewhat limited, experiences with automotive spark ignition engines designed for use with leaded fuel have shown that if recession of the exhaust valves is going to be a problem, indications will be present within the first 30 hours. With an engine typical of current light aircraft designs, no evidence was found pointing to problems of valve recession with use of this fuel.

TABLE 10. VALVE SEAT RECESSION MEASUREMENTS

	Accumulated Hours	
	25	50
Recession, inches/1000		
Intake		
1	0.5	1.5
2	2.0	1.5
3	1.0	2.0
4	3.0	4.0
Exhaust		
1	1.0	2.0
2	0.0	0.0
3	1.0	1.0
4	0.0	1.5

Tables 11 and 12 show results of engine wear measurements for the 50-hour accumulation. In table 11, differences in micrometer gauge readings for the period are essentially zero for all cases. Likewise, piston ring wear data in table 12 show only minimal changes in the ring dimensions. The information from figure 5 depicts individual cylinder bore wear. These differences were measured at opposite points on a cylinder circumference and at various cylinder heights: 1 inch from the top, 4 inches from the bottom, and 2 inches from the bottom. Little, if any, measurable wear was found. All of the data were well within the normal wear value range for the engine operating period.

TABLE 11. CHANGES IN VALVE STEM-TO-GUIDE CLEARANCE (IN/1000)

CYLINDER NUMBER	INTAKE	EXHAUST
1	0	0
2	1	0
3	0	0
4	1	0

TABLE 12. CHANGES IN PISTON RING DIMENSIONS (IN/1000)

	RING WIDTH	RING THICKNESS
Cylinder Number 1		
Compression Ring 1	0	0
Compression Ring 2	0	0
Scraper Ring	2	0
Oil Ring	1	0
Cylinder Number 2		
Compression Ring 1	2	0
Compression Ring 2	1	0
Scraper Ring	1	0
Oil Ring	1	0
Cylinder Number 3		
Compression Ring 1	1	0
Compression Ring 2	1	0
Scraper Ring	1	1
Oil Ring	2	0
Cylinder Number 4		
Compression Ring 1	1	0
Compression Ring 2	0	0
Scraper Ring	1	0
Oil Ring	2	0

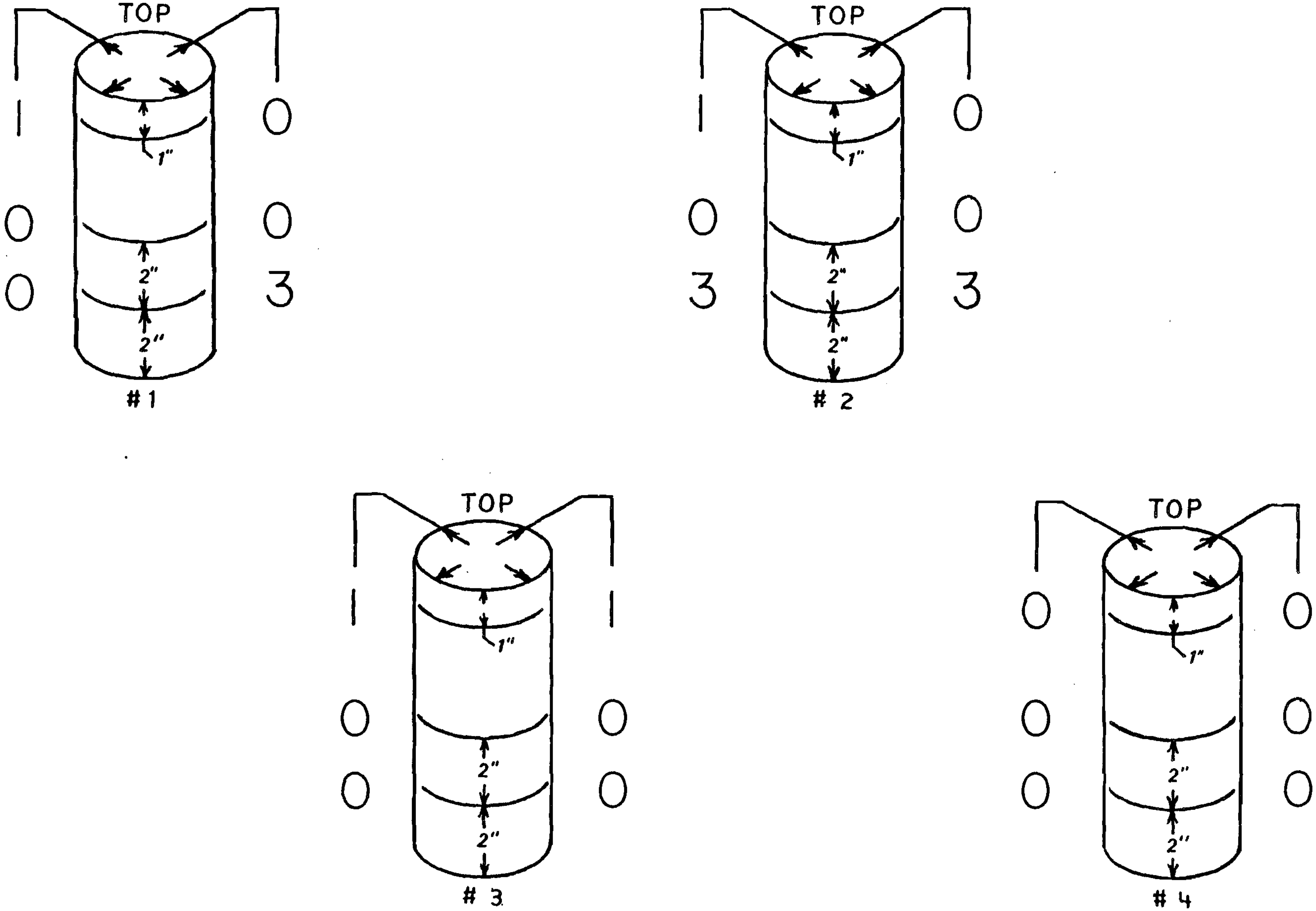


FIGURE 5. CHANGES IN CYLINDER BORE DIMENSIONS (In/1000)

Several observations concerning the use of MTBE were made during the course of testing with MTBE. The odor of MTBE is unpleasant and prolonged breathing of its vapor resulted in a headache. The exhaust had a distinctive odor that was bittersweet. No analysis of the exhaust was conducted to determine the constituents of the exhaust gases. MTBE removed some of the paint in the hand-operated pump, and particles were found in the sediment bowl towards the end of the tests. In addition, MTBE removed some of the paint on the wing surface where it ran along the adhesive in the metal tape used for fairing the thermocouple leads. It should be noted that the paint on the aircraft was the original paint from the manufacturer. An o-ring in the fuel filler cap swelled over a period of time, gradually making operation of the filler cap difficult.

FUEL WEATHERING.

Table 13 shows a tabular history of the fuel vapor pressure changes of the oxygenate/gasoline blends due to weathering at 110°F. The heat soak time required for 110°F fuel temperature equilibration was less than 6 hours for all fuels. The base gasoline RVP was 9.0 psi. As a group, initial vapor pressures had an approximate range of 12 to 13.5 psi or 3 to 4.5 psi higher than the base gasoline value. Such increases over base fuel values are typical for alcohol fuel blends. The 48-hour weathered fuel vapor pressures were consistently in the area of 11 psi, indicating losses ranging from about 1 to 2.5 psi for the period. With the exception of the somewhat higher methanol fuel initial RVP, the weathering histories for all fuels were highly similar. Indeed, both the blending RVP's and volatility changes for the two MTBE fuels were very close. In general, most of the vapor pressures decrease occurred between the zero and 24-hour times, with the methanol showing a similar loss (about 1 psi) during the temperature equilibration period.

TABLE 13. VAPOR PRESSURE VERSUS TIME

FUEL	REID VAPOR PRESSURE (psi) TIME (hrs)			
	INITIAL	0	24	48
Ethanol, 10 percent	12.3	12.3	11.3	11.2
Methanol, 10 percent	13.5	12.5	11.4	11.3
MTBE, 10 percent	12.3	12.0	11.4	11.0
MTBE, 15 percent	11.8	11.8	11.1	11.0

CONCLUSIONS

1. Storing autogas at or below 50°F will minimize the amount of unintentional weathering and increase the probability of vapor lock occurring.

2. The autogas used for hot weather certification tests should be heated in the aircraft tanks to obtain the most severe conditions possible. A fuel temperature of 110°F results in the most severe test for vapor lock when using autogas to conduct a hot fuel certification test. Heating autogas above 110°F decreases the chance of experiencing vapor lock.

3. Overall, the butane rich fuels experience more vapor lock than the iso-pentane rich fuels.

4. Weathering a fuel reduces the chance of encountering vapor lock. After 30 minutes, there is no significant difference between the butane rich fuels and the iso-pentane rich fuels. Since it takes approximately 30 minutes to heat the fuel in the aircraft wing tank, either butane rich or iso-pentane rich fuels may be used for hot fuel certification.

5. The fuel flow rate affects the chance of vapor lock occurring: the higher the fuel flow rate, the greater the tendency to vapor lock.

6. Vapor lock results in lean fuel-to-air ratios eventually exceeding the lean misfire limit.

7. The more complex an aircraft fuel system is, the greater the tendency to vapor lock. This is probably a consequence of the fuel's increased exposure to heat and turbulence, both of which aggravate vapor lock behavior.

8. Abrupt power loss due to vapor lock can occur without prior indication on the existing aircraft instrumentation.

9. Methyl-teriary-butyl ether (MTBE) has the potential for use in existing aircraft. There were some material compatibility problems in the aircraft used in this study, however. Some compensation for the difference in the energy density of MTBE will need to be made.

10. Lead added to MTBE for valve recession control appears unnecessary. Engine wear with this fuel is no worse than with avgas.

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6. Ferrara, Augusto M., Alternate Fuels for General Aviation Aircraft With Spark Ignition Engines, Federal Aviation Administration Technical Center, Atlantic City International Airport, New Jersey 08405, Report No. DOT/FAA/CT-88/5, To Be Published.

7. Pecci, Giancarlo, and Telemaco Floris, Ether Ups Antiknock of Gasoline, Hydrocarbon Processing, Snamporogetti S.p.A., San Donato Milanese, Italy, December 1977.

APPENDIX A

TEST AIRCRAFT FUEL SYSTEM MODIFICATIONS

AMERICAN AVIATION CORPORATION TRAVELER.

The fuel transfer tube and thermocouple line were routed through an access panel in the floor of the Traveler. The fuel transfer tube was then attached to the fuel line which ran from the wing tank to the tank selector valve. The thermocouple line ran along the gear attachment fitting, exiting through the gear fairing, then into the wing tank drain. As before, the fuel cap was modified with a J-tube to provide additional fuel venting. The opening of the J-tube was oriented into the direction of flight. Figure A-1 shows the Traveler installation schematically.

BEECHCRAFT MUSKETEER.

The fuel transfer line in the Musketeer ran from the insulated tank, through an access panel in the floor, along the wing spar, exiting the cabin through the wing root fairing. It ran along the wing bottom parallel to the wing spar until abeam of the fuel cap. At this point, the fuel transfer line turned forward, over the leading edge, then through the fuel cap. The transfer line extended through the fuel cap to within 3/8 inch of the tank bottom. The wing tank thermocouple line was secured to the fuel transfer line and extended into the fuel tank through the fuel cap. As with the fuel transfer line, the thermocouple was placed within 3/8 inch of the tank bottom. Lines ran along the wing exterior and were faired with aluminum tape. This installation is shown in figure A-2.

CESSNA MODEL 172 (C-172).

The fuel transfer line the C-172 ran from the insulated tank, through the upper starboard air vent, along the wing root, then into the wing tank drain. The thermocouple line was secured to the fuel transfer line, then inserted approximately 3/8 inch into the wing tank through the tank drain. A J-tube was adapted to the fuel cap to allow for additional tank venting. The opening of the J-tube was oriented into the direction of flight. The locations of these modifications are shown in figure A-3.

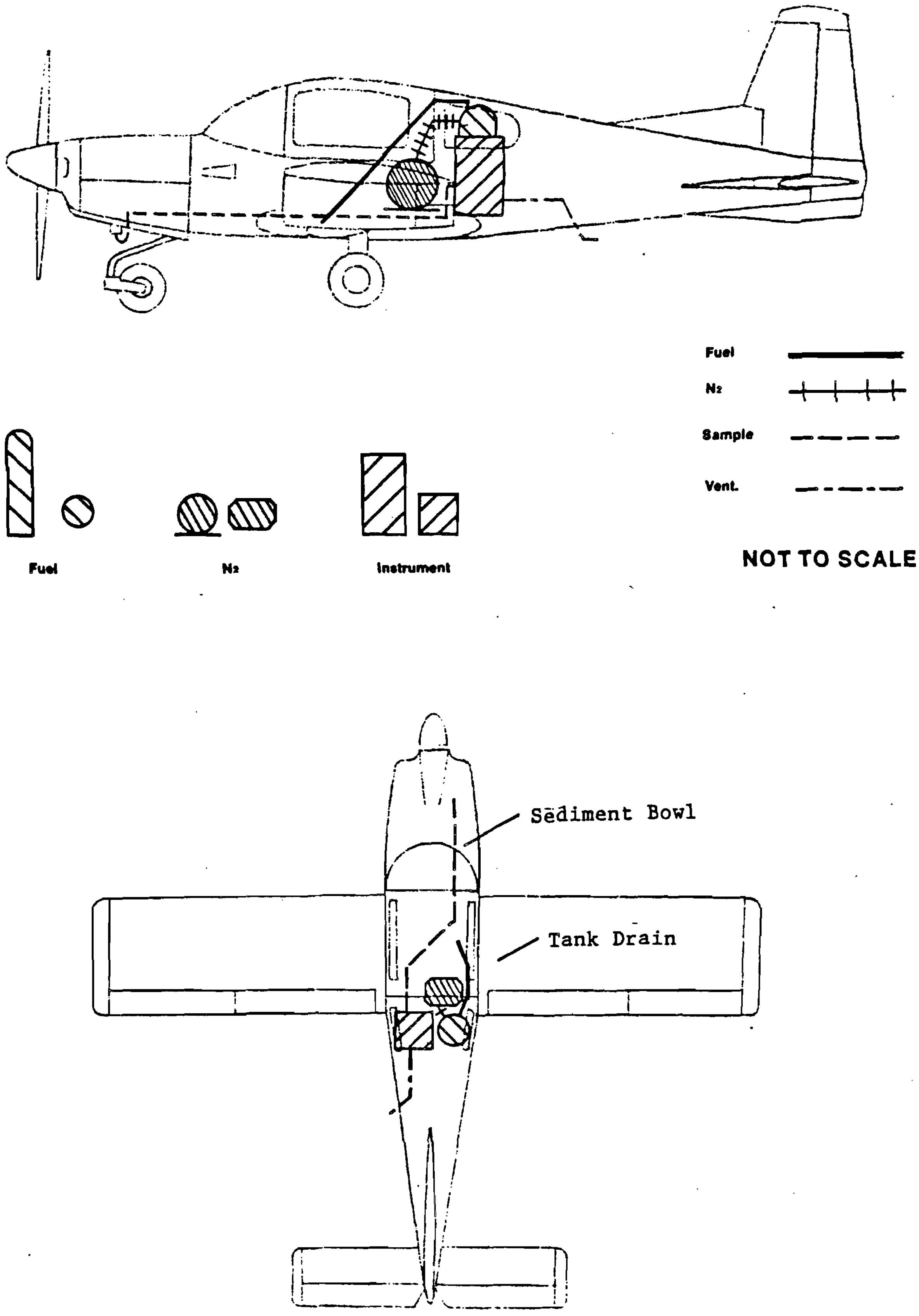

FIGURE A1. TEST EQUIPMENT INSTALLATION IN THE AMERICAN AVIATION TRAVELER

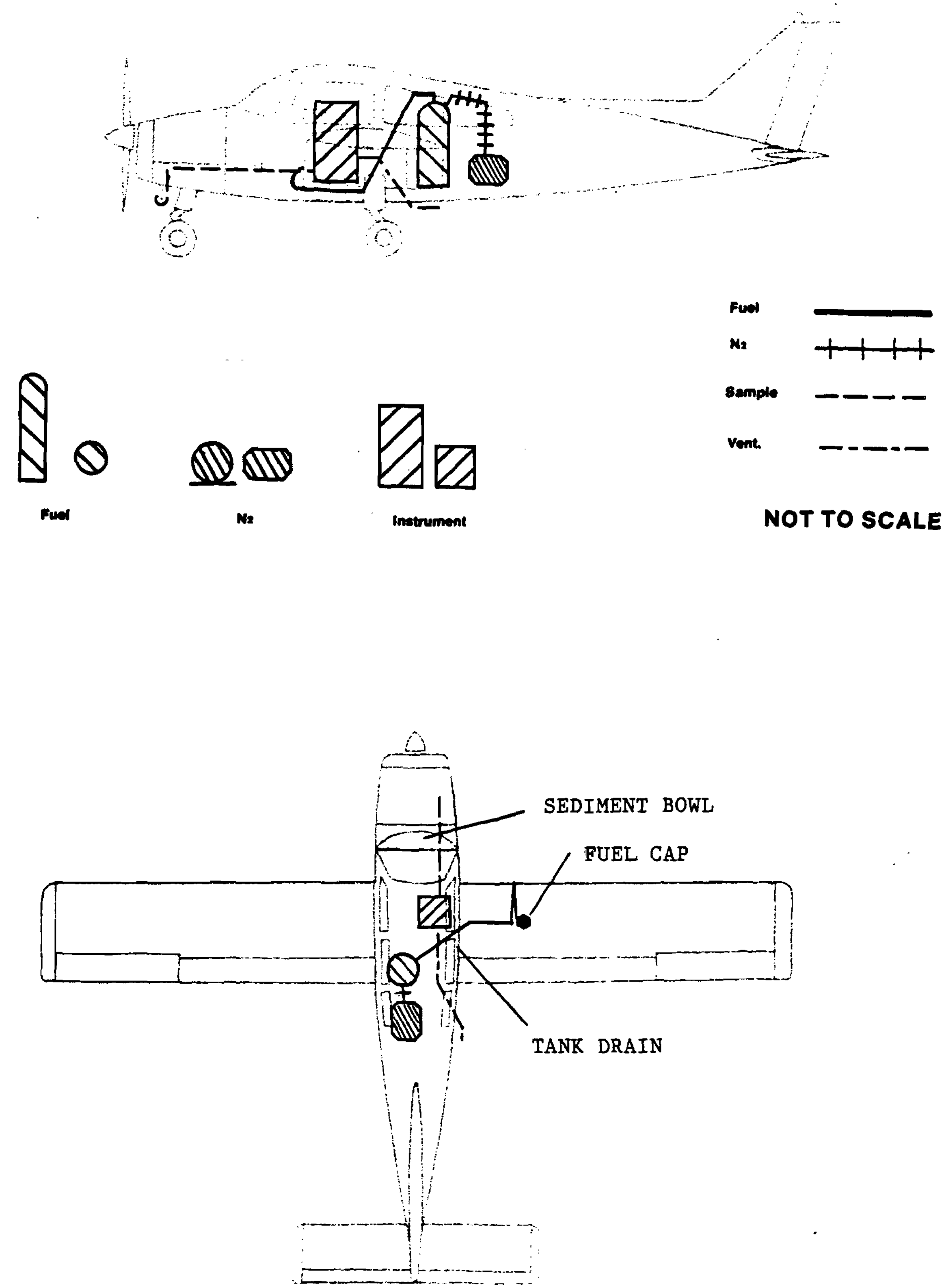

FIGURE A2. TEST EQUIPMENT INSTALLATION IN THE BEECHCRAFT MUSKETEER

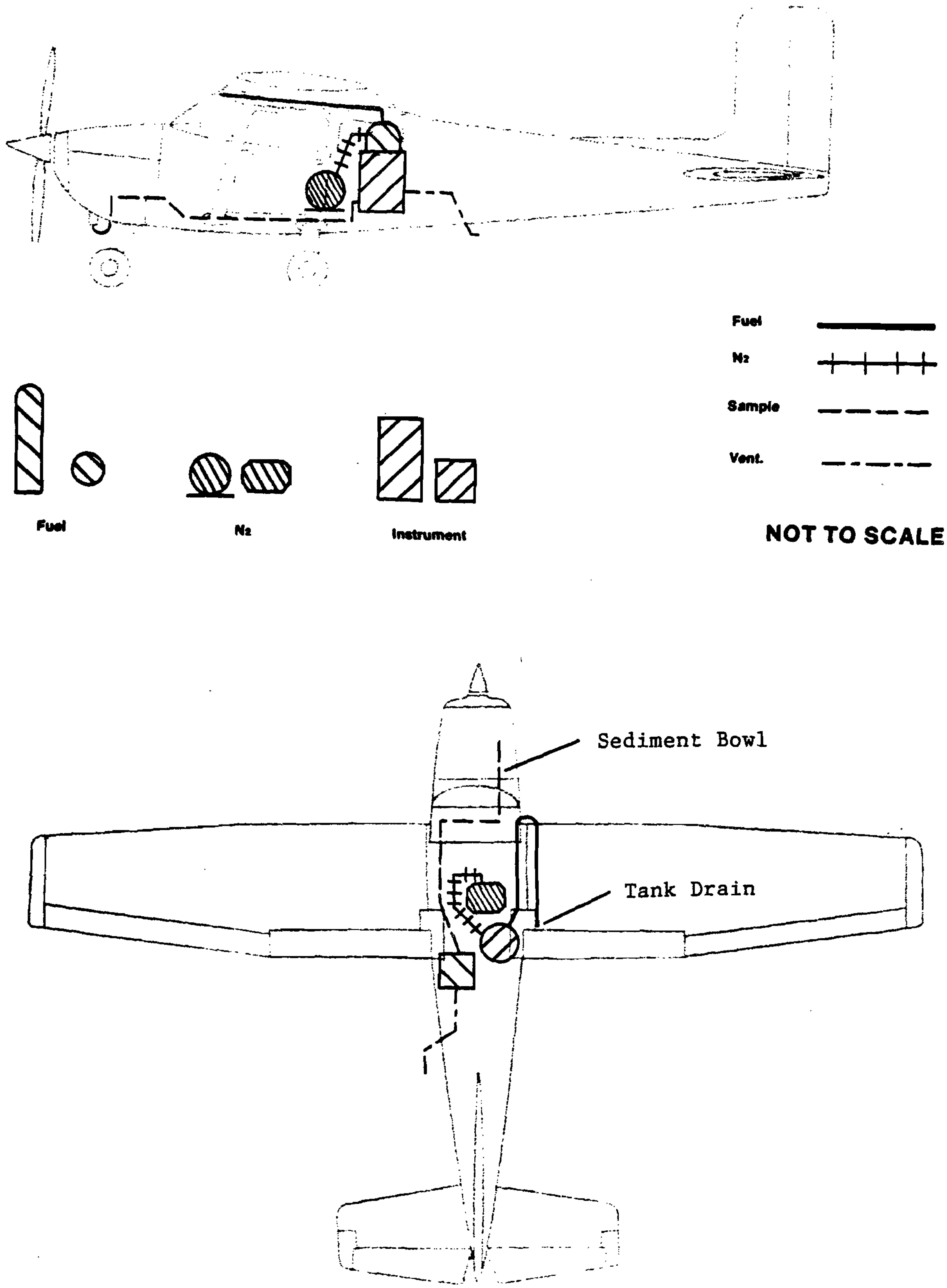

FIGURE A3. TEST EQUIPMENT INSTALLATION IN THE CESSNA 172

APPENDIX B

SAMPLE RUN SHEETS

TEST ______ ______ ______ ______ ______ DATE ____/____/____

RVP | Butane or Pentane | Temp (°F) | Aircraft | Run #

Start: Tach ____________________ Hobbs ____________________

Field P.A. ______________ ft O.A.T. __________________ °F

Altimeter Setting (field pressure) ________________________ in Hg

Chock Time Out: _____:_____

Takeoff Time: _____:_____

Wing (#1) _________ °F EGT (#2) _________ °F

CHT (#3) _________ °F Tank (#4) _________ °F

Fuel Transfer: Initial Tank Temperature _________ °F

Start Altitude _________ ft Time _____:_____

Stop Altitude _________ ft Time _____:_____

12500 (or max altitude) _____:_____ (Avgas readings)

Wing (#1) _________ °F EGT (#2) _________ °F

CHT (#3) _________ °F Tank (#4) _________ °F

Chart Setting:

Channel A, O_2 (Blue) ______________ mV

Channel B, CO (Red) ______________ mV

Chock Time In: _____:_____

Stop: Tach ____________________ Hobbs ____________________

Field P.A. ______________ ft O.A.T. __________________ °F

Altimeter Setting (field pressure) ________________________ in Hg

Observer: ___________________________________

COMMENTS:

Test ____________ Date ____________

Aircraft ____________ Fuel ____________ Altitude ________ ft

Time at Altitude ____:____ O.A.T. ____________ Test Fuel Schedule ____:____

Time			1 Wing	2 EGT	3 CHT	4 Tank	5 CO%	6 O_2%	7 RPM	8 MPH	9 F. P.	10 NOTES:	11	12	13
	0	1											CHART ON	!!!!!!!!!	!!!!
	20	2													
	40	3													
1	60	4													
	90	5													
2	120	6													
	150	7													
3	180	8													
4	240	9													
5	300	10													
6	360	11													
7	420	12													
8	480	13													
9	540	14													
10	600	15													
		16													
		17													
		18													
		19													
		20													
		21													
		22	Total Time on Test Fuel ____________										CHART OFF	!!!!!!!!!	!!!!
		23													
		24													
		25													
		26													
		27	A -- Avgas												
		28	F.P. -- Fuel Pressure (psi)												
		29	T -- Test Fuel												
		30	X -- Expletive												
		31	All temps °F												

APPENDIX C

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