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ENVIRONMENTAL TESTING OF A GAS TURBINE ENGINE UTILIZING EF4-101 EMULSIFIED JP-4 FUEL

By

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John Monarch

August 1968

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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CONTINENTAL AVIATION AND ENGINEERING CORPORATION

DETROIT, MICHIGAN

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This report was prepared by Continental Aviation and Engineering Corporation, Detroit, Michigan, under the terms of Contract DA 44-177-AMC-460(T). It consists of a study to determine the effects of environmental and endurance testing of emulsified JP-4 fuel in a gas turbine engine.

The results of this study indicate that engine operation, including starting and transient operation, with emulsified JP-4 fuel is essentially the same as that with liquid JP-4 fuel. Several areas in which further research is needed are brought out.

The information in this report will be utilized in the pursuance of further research in the area of fuel emulsions.

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ENVIRONMENTAL TESTING OF A GAS TURBINE ENGINE UTILIZING EF4-101 EMULSIFIED JP-4 FUEL

CONTINENTAL REPORT NO. 1098

by

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Prepared by

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Detroit, Michigan

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FORT EUSTIS, VIRGINIA

ABSTRACT

This report presents the results of laboratory, environmental, and endurance testing directed toward the determination of the effect of direct burning of emulsified JP-4 fuel in a gas turbine engine and the handling and pumping of emulsified JP-4 fuel.

Engine operation, including starting and transient operation, with EF4-101 emulsified fuel was essentially the same as that with liquid JP-4 fuel during all phases of testing. Engine testing was terminated when a "hot section" corrosion problem, caused by an excessive amount of sodium in the emulsified fuel, was encountered.

The use of emulsified fuel will require a new technology in the design of fuel filters, fuel pumps, fuel flow measuring devices, and fuel handling practices.

FOREWORD

This report, prepared by Continental Aviation and Engineering Corporation, discusses the results of tests conducted to determine the effect of the direct burning of an emulsified JP-4 fuel in a gas turbine engine under various environmental conditions and the handling and pumping characteristics of emulsified JP-4 fuel.

The program was sponsored by the U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, under Contract DA 44-177-AMC-460(T).

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INTRODUCTION

During the past several years, feasibility studies were conducted by various gas turbine engine manufacturers to determine if gas turbine engines could be successfully operated by direct burning of thickened fuels. During these studies, engines were run with both gelled and emulsified fuels, and engine operation was practically the same as when the engines were run with liquid fuels.

These preliminary tests further indicated that the emulsified fuels were reasonably compatible with existing engine fuel systems and that they could be used with a minimum number of changes to the existing fuel systems. However, actual engine testing was very limited; therefore, additional testing was initiated to investigate the effect of emulsified fuel on engine operation under various environmental conditions and for extended periods of operation.

In addition to engine testing, ways of measuring the rate of emulsified fuel flow were to be investigated, since the feasibility testing showed that the normally used flow measuring devices could not be used with emulsified fuel.

During this program, no attempts were made to evaluate the various emulsified fuels that were available, nor was any attempt made to determine the safety aspects of emulsified fuels.

All testing accomplished with emulsified fuel was done with the Air Logistics emulsified fuel and is referred to in this report as EF4-101. This fuel was used because it appeared to be the most developed and the most readily available emulsified fuel when the program was begun.

The emulsified JP-4 fuel used during this series of tests was an aqueous emulsion, generally referred to as a 98-percent emulsion of JP-4. It is an oil-in-water type emulsion. The external phase is a water type and is composed of water, emulsifying agents, and additives to modify the fuel as required.

The fuel has been subjected to ambient temperatures of from -65°F to +135°F and to simulated altitudes up to 15,000 feet. At -65°F, some breakdown of the emulsion occurred and approximately 5-percent liquid was present. The emulsion appeared to have about the same viscosity as it had at room temperature, and it poured as easily as it did at room temperature. At +135°F, approximately 10 percent of the emulsion reverted to a liquid.

During the temperature tests, it was observed that a long period of time was required to reach a stabilized temperature throughout the emulsion. During subsequent engine testing, a coil, made up of 100 feet of 1-inch-diameter copper tubing, had to be installed in the test cell fuel system in order to obtain the fuel temperatures required for the environmental testing within a reasonable period of time.

No visual changes in the emulsion were noted when it was subjected to simulated altitudes up to 15,000 feet.

Analysis of the emulsified fuel revealed that the fuel had a lower heating value of 18,002 Btu per pound of fuel. This compares with a lower heating value of 18,570 Btu per pound of fuel for the liquid JP-4 that was used in the manufacture of the emulsified fuel.

During the testing, approximately 26 hours of engine operation and 149 engine starts were completed using EF4-101 fuel. In some instances, the engines were idle for one week after being operated with EF4-101 fuel, and no problems were encountered during subsequent starts and operation.

The engine used for the testing discussed in this report was one engine of the Continental YT67-T-1 twin turboshaft powerplant. Its designation is the Continental Model 217-10B. An exterior view of the powerplant is shown in Figure 1, and a cross section of the engine showing the major engine components and the aerodynamic flowpath is shown in Figure 2.

The engine employs a straight-through aerodynamic flowpath. Air enters radially at the front of the engine and passes successively through a two-stage transonic axial compressor, a single-stage centrifugal compressor, radial and axial diffusers, an annular combustor, two stages of axial gas generator turbines, a transition duct, and a power turbine rotor. A diffusing tailpipe completes the aerodynamic flowpath. Shaft horsepower is transmitted back to the front of the engine by means of a concentric through-shaft.

Since the work discussed in this report deals with the direct burning of EF4-101 fuel, the engine fuel system, combustor chamber, and combustor air flowpaths, shown in Figure 3, will be described in more detail.

Fuel enters the engine through a fitting in the side of the combustor housing; then it passes through a tube into a stationary fuel manifold, from which it is injected into a rotating fuel distributor and then sprayed into the combustion chamber.

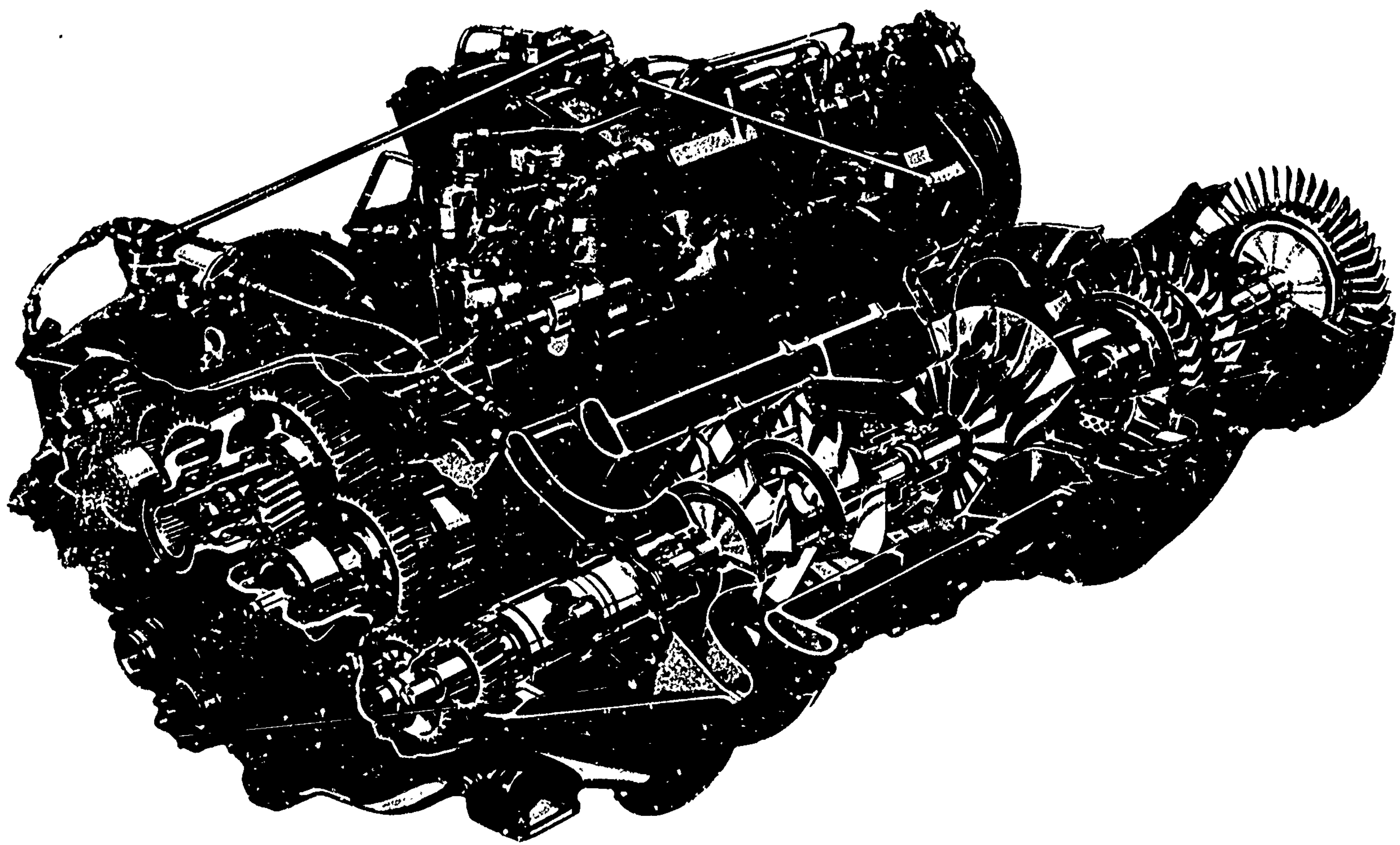

Figure 1. Continental YT67-T-1 Twin Turbine Powerplant.

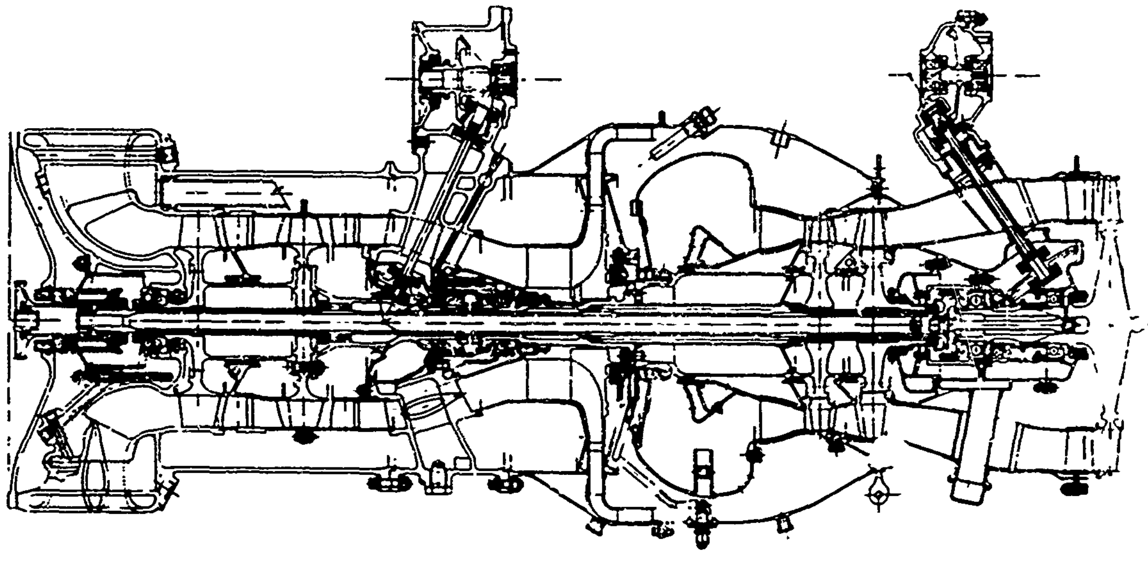

Figure 2. Continental Model 217-10B Cross Section.

The fuel manifold has eight equally spaced 0.026-inch-diameter holes on its periphery where it projects under the rotating fuel slinger. Because of the relatively large size of the fuel exit holes, the fuel can be injected out of the fuel manifold with low fuel pressure in the the fuel manifold. Upon entering the rotating slinger, the fuel is accelerated up to shaft speed before it is sprayed into the combustor through the nine equally spaced 0.090-inch-diameter holes on the outer diameter of the slinger. When the fuel is accelerated up to shaft speed, energy is imparted to the fuel, causing the fuel to break up into extremely fine particles as it enters the combustor.

Because of the fine atomization of the fuel, the combustor process is very smooth and stable.

The fuel injection arrangement makes the engine relatively insensitive to the type of fuel being used. The engine has been run with JP-4, JP-5, 115/145 octane aviation gasoline, No. 2 diesel oil, household furnace oil, Bunker C, and various thickened fuels with no appreciable change in engine operating characteristics.

Air entering the combustor housing is divided into three separate flowpaths; two provide primary air to the combustor and a third provides secondary cooling air, as shown in Figure 3. A portion of the primary air is delivered through the swirl vane, and a second portion passes over the outer combustor shell through the hollow vanes in the first-stage turbine inlet nozzle assembly and into the combustion zone through a series of holes and louvers in the inner combustor primary air admission plate. Secondary cooling air is supplied through a series of holes and secondary air tubes in the outer combustor shell to cool the combustor gases prior to entrance to the turbines.

The engine ignition system consists of an ignitor coil, a starting fuel solenoid, starting fuel nozzles, and ignitor plugs.

The starting fuel solenoid is incorporated as part of the fuel control; when energized, it diverts a portion of the metered fuel flow to the starting fuel nozzles. The starting fuel nozzles are simple nozzles and use a swirl chamber to obtain the starting fuel atomization and spray pattern required for ignition during engine starting. Air-gap ignitor plugs are used to ignite the starting fuel.

The Model 217-10B engine fuel system, shown in Figure 4, consists of a fuel pump, fuel filter, fuel control, and starting fuel system. The complete system has been designed to meet the qualification requirements of MIL-E-5009B.

The Model 217-10B fuel control system, shown schematically in Figure 5, provides the following functions:

1. Power turbine governing
2. Gas generator governing
3. Fuel scheduling during starts
4. Fuel scheduling during acceleration or load application
5. Fuel scheduling during deceleration or load rejection
6. Scheduling of the interstage bleed valve operation
7. Manual control

The control incorporates a condition lever which determines the setting of the gas generator governor; a second lever determines the setting of the power turbine governor, while a third is a two-position

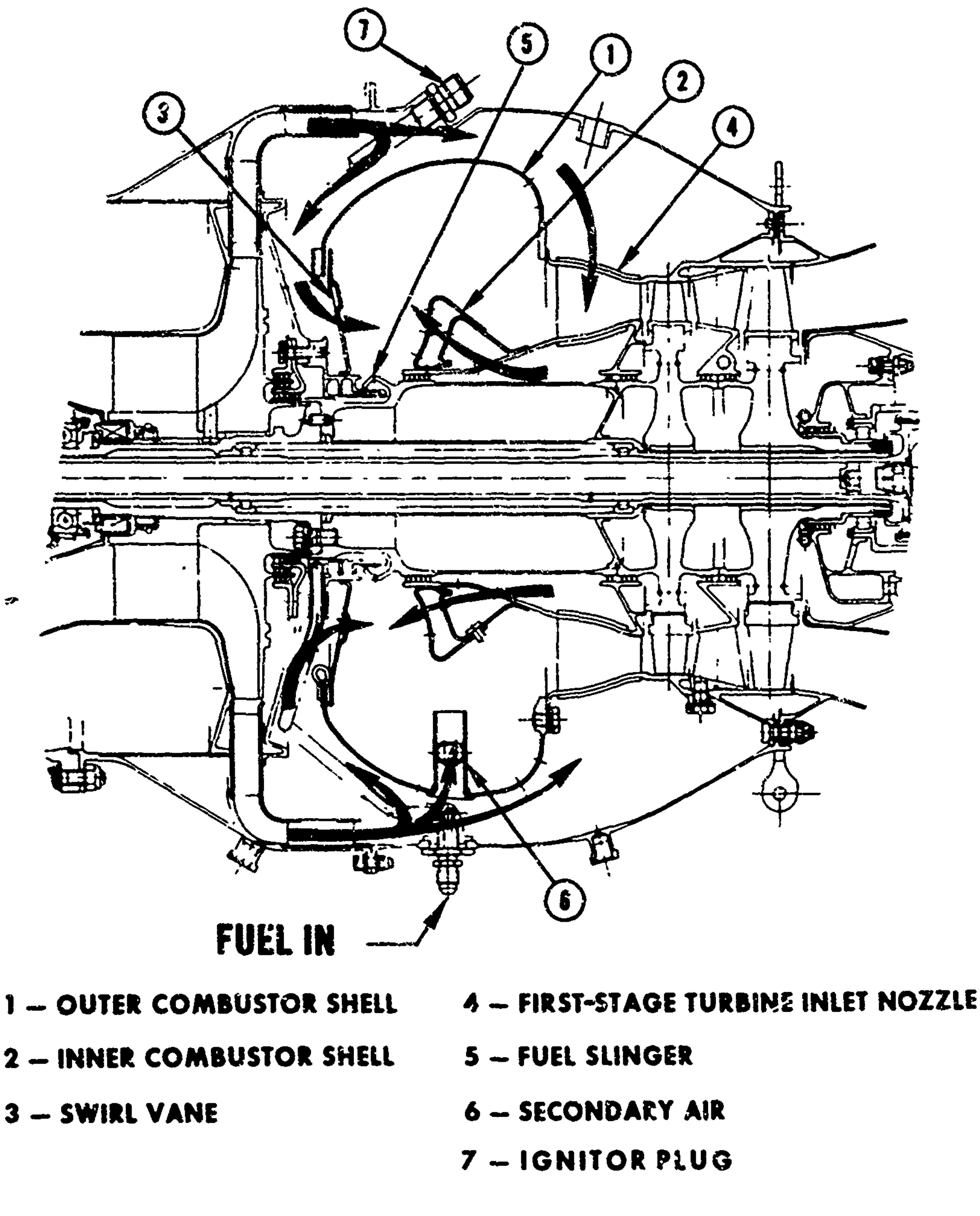

Figure 3. Model 217-10B Engine Annular Combustor Showing Airflow Path and Fuel Injection Arrangement.

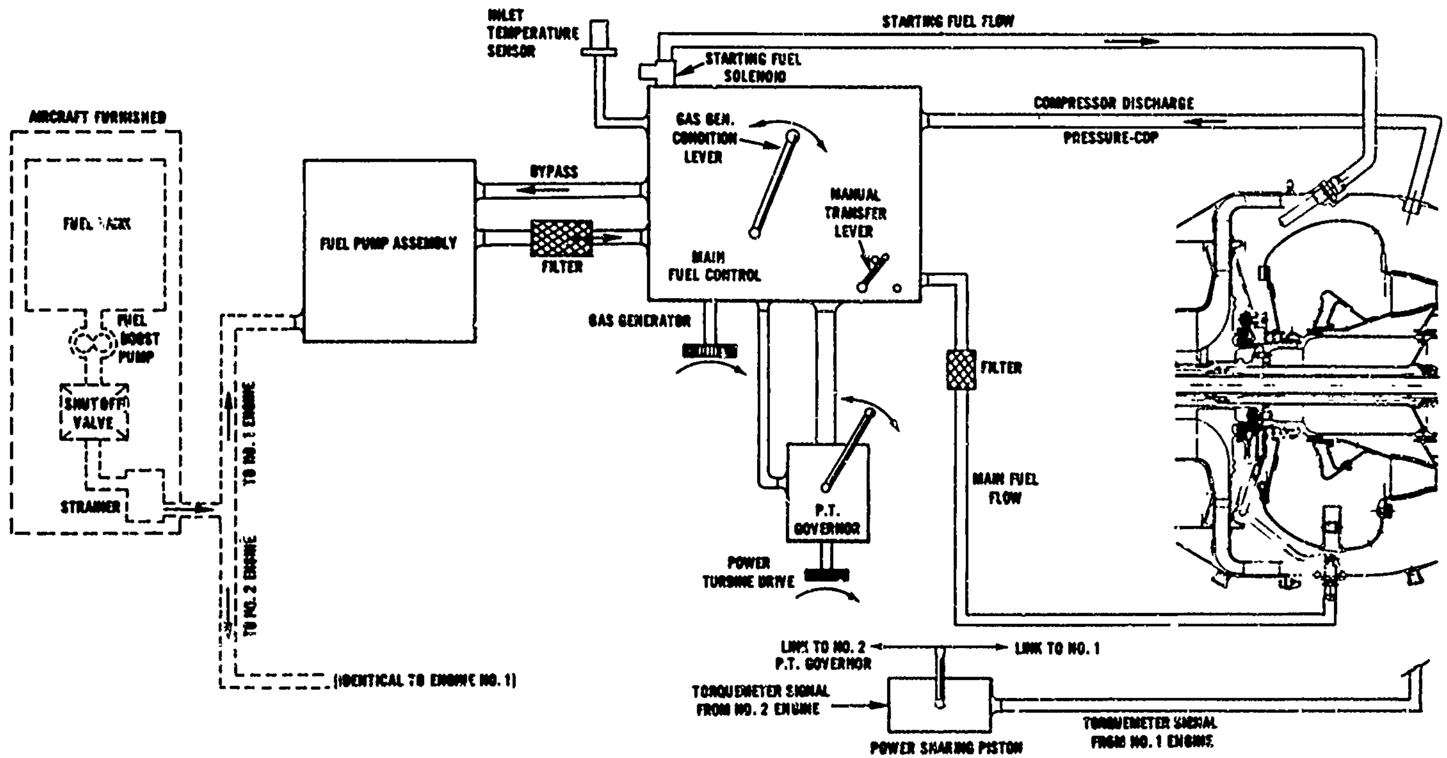

Figure 4. Continental Model 217-10B Fuel System.

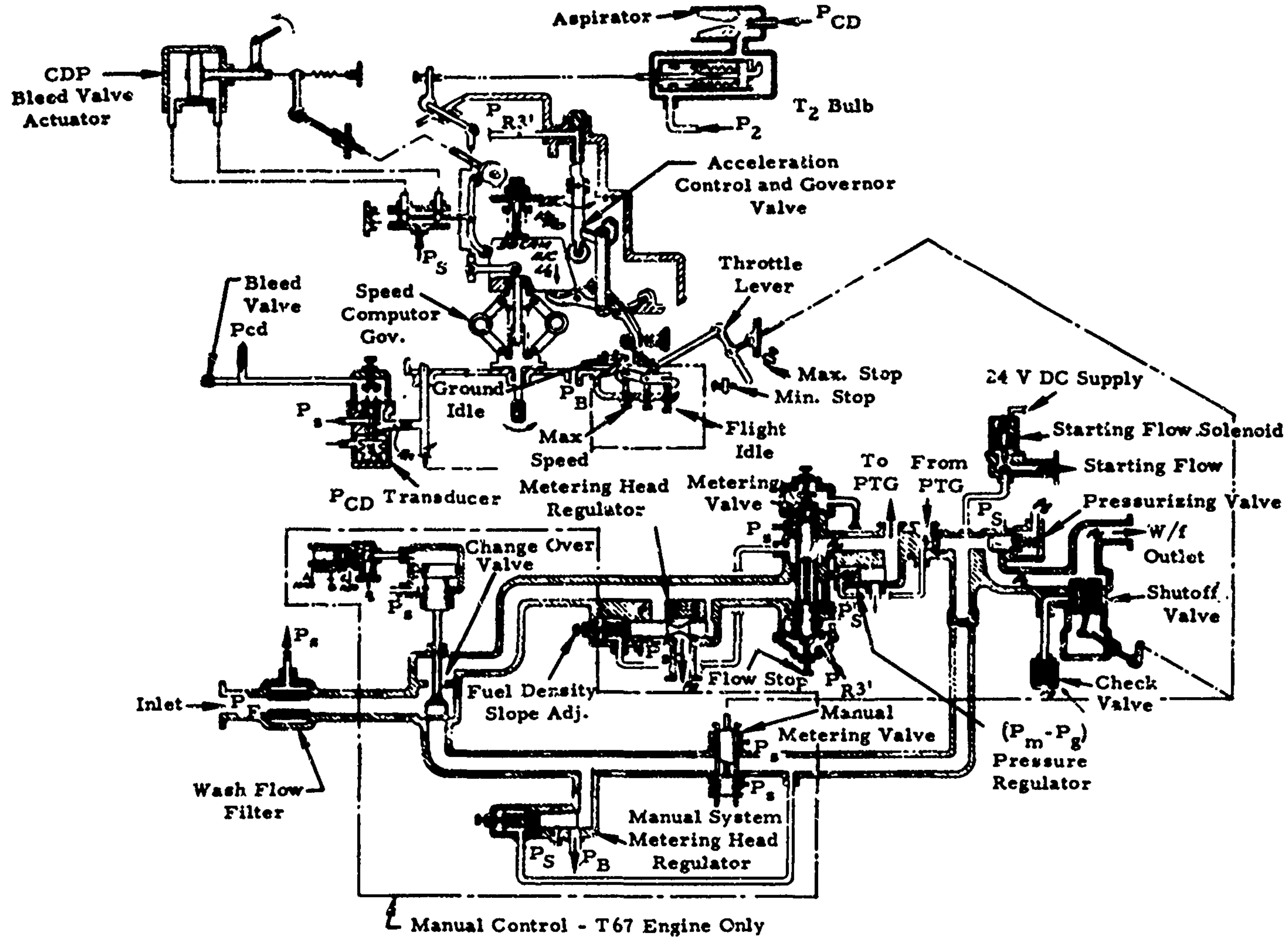

Figure 5. Fuel Control Schematic.

emergency transfer lever which determines whether the control system is on automatic or manual control. The control levers are located on the fuel control in positions that permit the helicopter manufacturer to use a simple direct linkage to the cockpit.

The fuel pump, which incorporates a centrifugal boost element, a fuel filter, and a main pressure element, is suitable for continuous operation with fuel which has been deliberately contaminated in accordance with the requirements of MIL-E-5007B. The fuel control incorporates a three-dimensional cam-type acceleration control for optimum transient performance; an automatic starter, to eliminate overtemperature starts; a direct fuel handling power turbine governor; a manual control system; and an interstage bleed valve actuator, which is automatically operated in both primary and manual system modes.

The scheduling variables utilized for the control of the engine are the gas generator speed, power turbine speed, compressor outlet pressure, compressor inlet temperature, and gas generator condition lever. Environmental capabilities include air temperatures of -65°F to +250°F around the control assembly, fuel temperatures of -65°F to +200°F, and ambient air pressure from 8 to 30 inches Hg. absolute.

Fuel flow during acceleration is scheduled as a function of compressor discharge pressure (PCD), gas generator speed (Ng), and compressor inlet temperature (T2). A three-dimensional (3-D) cam is positioned as a function of Ng and T2 and, in turn, modifies the PCD signal from the engine by varying one of a set of pneumatic orifices. The PCD signal, thus modified, then establishes the proper fuel flow for this inlet temperature and gas generator speed. By relatively simple contouring of the 3-D cam, complicated functions of fuel flow (Wf) versus PCD, Ng, and T2 can be metered, allowing optimum use of the available surge margin and therefore giving minimum acceleration time. The 3-D cam is also used to provide scheduling of the interstage bleed valve actuator which regulates compressor interstage bleed air to optimize acceleration and to prevent surge. This bleed valve is scheduled from open to closed over a speed change of about 7 percent Ng, providing optimum surge-skirting without objectionable discontinuities in power level.

The power turbine governor provides power turbine speed regulation through an independent power turbine governor drive directly coupled to the turbine. Thus, in the power regime, load changes from minimum to maximum are sensed by power turbine speed (Npt) changes over the 5-percent droop range of the governor.

As the load is changed from minimum to maximum, the Npt governor bypass regulator valve, sensing the underspeed condition, closes and the governor valve opens, transferring control to the Ng governor system. Since the Ng governor position is at maximum at all times in the power regime, the underspeed condition is sensed, the gas generator is accelerated along the acceleration schedule up to a maximum of 100 percent Ng, and this condition is maintained until the power turbine governor and bypass regulator again assume control of the fuel flow when Npt has come up to speed.

If the engine is operating at high power on the power turbine governor and the load is suddenly decreased, the power turbine governor senses the overspeed condition and reduces the fuel flow by opening the bypass valve and the gas generator is decelerated on minimum flow to the flight idle condition.

The test program was accomplished in three phases:

1. Laboratory Testing

2. Environmental Testing

3. Endurance Testing

LABORATORY TESTING

OBJECTIVES

The objectives of the laboratory testing were:

1. To determine if EF4-101 emulsified JP-4 fuel could be used in a T67-T-1 fuel control.

2. To determine a means of accurately measuring the rate of flow of EF4-101 emulsified JP-4 fuel.

3. To determine means of handling and pumping EF4-101 emulsified JP-4 fuel without causing it to break down into a liquid.

4. To determine the effect of environmental conditions on EF4-101 emulsified JP-4 fuel.

TEST PROCEDURE

Prior to actual engine operation, the complete engine fuel system was run on a flow bench to determine what adjustments or modifications would have to be made to the fuel control to obtain the same fuel flow schedule with EF4-101 emulsified JP-4 fuel as with liquid JP-4 fuel.

Since one of the objectives of the test program was to simulate a fuel system that could be used in a helicopter, the emulsified fuel to be used during the fuel control calibrations was stored in a standard Army helicopter auxiliary fuel tank. The fuel tank was the type used in the Army UH-1D helicopter during ferry missions, and it was equipped with a submerged 24-volt DC pump for supplying the fuel to the helicopter engine.

Before bench testing could be started, it was necessary to determine what kind of pump could be used for transferring the EF4-101 fuel from its shipping containers into the auxiliary fuel tank.

A portable, electric-motor-driven gear pump which is normally used in the fuel laboratory was tried, but it was observed that the EF4-101 fuel being discharged into the auxiliary fuel tank was 50-percent liquid and 50-percent emulsified fuel. It was felt that the shearing action of the high-speed gear pump was breaking down the emulsion. Therefore, the gear pump was removed and replaced with a centrifugal pump. However, when the vane pump was tried, the pump would not pick up the emulsified fuel from the shipping containers. This first attempt with the vane pump was made with the pump sitting approximately 2.0 feet below the level of the EF4-101 fuel and the pump intake line, which in this case was a No. 10 flexible hose, lifted up and inserted into the EF4-101 fuel.

For the next attempt, the centrifugal pump intake line was attached to a fitting on the lid of the shipping container, and the shipping container was laid on its side in a supporting cradle. The level of the EF4-101 fuel was approximately 3.0 feet above the pump, but now the pump intake lines were also below the level of the fuel and a positive head pressure was present at the inlet of the pump intake line. With this arrangement, pump operation was satisfactory and emulsified fuel could be transferred into the auxiliary tank without breaking down.

It was felt that this arrangement would be very cumbersome during subsequent engine testing; therefore, various gear-type pumps were tested, since the initial testing showed that the gear pumps were self-priming and could lift the EF4-101 out of the shipping containers without a positive head pressure.

It was subsequently found that slow-turning gear pumps could be used for transferring EF4-101 fuel from one container to another, but these pumps worked only as long as the full capacity of the pump could be used. All attempts to regulate the pump flow by bypass valves were unsuccessful, in that the fuel being bypassed was broken down by the shearing action of the bypass valve and resulted in liquid fuel being bypassed.

The complete Model 217-10B fuel control system was installed on the flow bench and calibrated to determine what modifications, if any, would be needed to make the Model 217-10B fuel system compatible with EF4-101 emulsified JP-4 fuel.

Both the liquid JP-4 fuel and the EF4-101 fuel used during the fuel control calibrations were stored in the auxiliary fuel tank and pumped to the engine-mounted fuel pump by means of the submerged fuel pump located in the bottom of the auxiliary fuel tank. Both the liquid JP-4 and the EF4-101 fuels were supplied to the engine from the auxiliary fuel tank in order to get comparative data of pressure drops in the system plumbing and the power required by the electric motor to drive the centrifugal pump. Figure 6 is a plot of pressure available at the inlet of the engine-mounted fuel pump versus observed engine speed. From this plot, it is evident that there is little change in supply pressure when using either liquid or emulsified JP-4 fuel over the flow range tested. Figure 6 also shows the amperage required by the electric motor to supply fuel to the

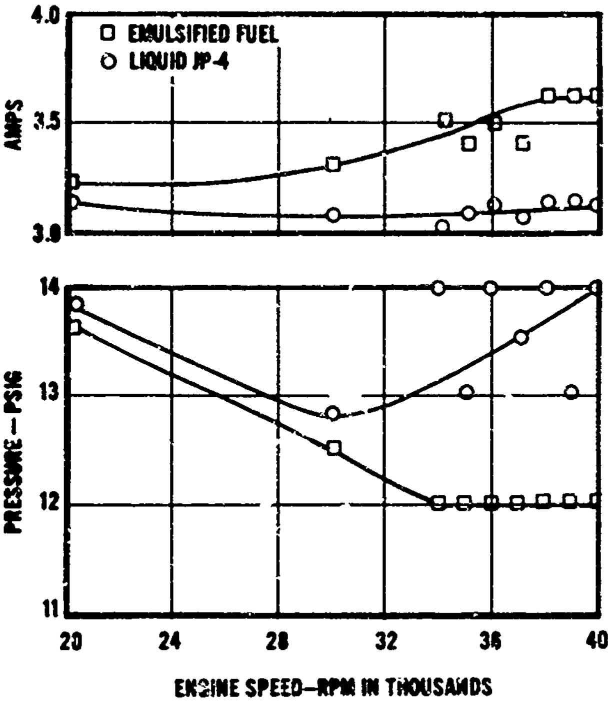

Figure 6. Fuel Pump Inlet Pressure and Fuel Pump Amperage Requirements for Liquid and Emulsified JP-4 Fuel.

inlet of the engine-mounted fuel pump. From Figure 6, it can be seen that approximately 0.4 AMP more is used when pumping the emulsion than when pumping liquid JP-4 fuel.

During the control calibrations with EF4-101 fuel, the engine-mounted pump inlet pressure was varied, and it was determined that it was necessary to have a positive pressure at the engine-mounted pump inlet in order to maintain stable fuel control operation. The engine-mounted fuel pump was not capable of supplying fuel to the fuel control when the auxiliary fuel tank mounted pump was shut off.

During the fuel control calibrations, it was found that the devices normally used for measuring fuel flows would not work with the EF4-101 fuel. The turbine-type flowmeters became unstable and the data read-out system indicated wide changes in fuel flows (100 to 300 pounds per hour), even though actual fuel flow was constant, after a short period of operation. Disassembly of the flowmeters showed that the turbine bearing journals, which are normally lubricated by the liquid being measured, were galled and worn due to a lack of lubrication while the EF4-101 fuel was being used.

Flowmeter A, which is essentially a hydraulic Wheatstone bridge, was tried and discarded when repeatable flows could not be obtained, even during steady-state operation.

Flowmeter B was then tried and found to give fairly consistent fuel flow readings, even during transient operation.

Flowmeter B is a flow measuring device which measures the strain imposed on a "finger-like" rod that projects into the flow stream. It has no rotating parts, and by means of a suitable calibration, the strain imposed on the rod can be correlated to mass flow.

The only limitation of Flowmeter B is that the consistency of the emulsion being measured must be known, and the flowmeter must be calibrated with the particular emulsion that is being used.

During all of the above-mentioned calibrations, the flow measuring device being examined was checked by simultaneously measuring the fuel flows by means of a dead-weight system.

Figure 7 shows the fuel control acceleration schedule calibrations for both the liquid JP-4 and the EF4-101 fuels, with no adjustments or modifications to the control. The scheduled fuel flow met the engine requirements with both fuels, and the fuel control was used without adjustments.

During the fuel control calibrations, various pressures were measured throughout the engine fuel system; it was found that for the flows being measured, the pressure drops were 2.0 to 3.0 psi higher for the EF4-101 than for the liquid JP-4. However, it should be remembered that these pressures were measured while the fuel was being handled and used under laboratory conditions. During subsequent engine testing, when larger quantities of fuel were being used, contaminated filters became a major problem.

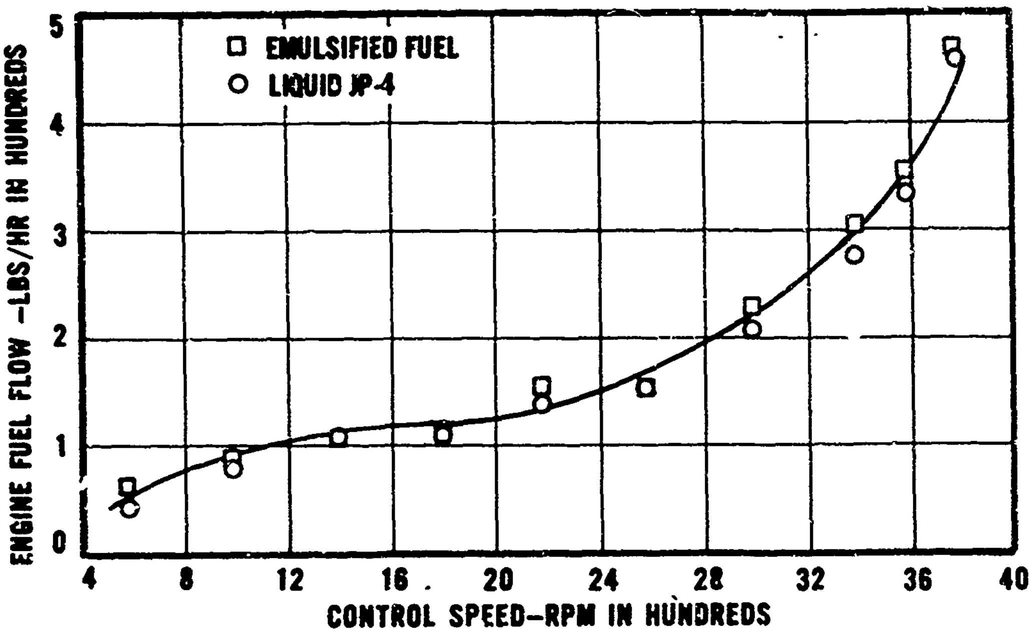

Figure 7. Calibration of Fuel Control Acceleration Schedule With Liquid and Emulsified JP-4.

CONCLUSIONS

1. Bench testing showed that liquid JP-4 and EF4-101 emulsified fuels can be used interchangeably in the Model 217-10B fuel control system without affecting the operation of the fuel control system.

2. Slow-turning gear pumps are the best for transferring EF4-101 fuel from one container to another; centrifugal pumps are the best for supplying fuel to the engine-mounted fuel pump.

3. Flowmeter B is the best for measuring EF4-101 fuel flows.

4. Over the flow range tested, the pressure drops in the fuel system are almost the same for liquid JP-4 and EF4-101 fuels.

ENVIRONMENTAL TESTING

OBJECTIVES

The objectives of the environmental testing were:

1. To evaluate engine operation from static sea level conditions up to simulated altitudes of 20,000 feet when using JP-4 and EF4-101 fuels.

2. To evaluate the engine starting characteristics in ambient temperatures from +135°F to -65°F when using JP-4 and EF4-101 fuels.

3. To evaluate the engine combustor "blow out" limits from static sea level conditions to simulated altitudes up to 20,000 feet and simulated forward speeds of 150 knots, with JP-4 and EF4-101 fuels.

DISCUSSION

The engine used for the environmental testing consisted of only the gas generator section of the Model 217-10B engine. A special exhaust duct was fabricated to replace the power turbine inlet nozzle, permitting operation of the engine as a straight turbojet engine to facilitate testing.

The engine was calibrated at static sea level conditions to check out the engine's mechanical integrity and at the same time to get a base line calibration for evaluations.

The static sea level testing consisted of calibrations and transient recordings of engine starts and accelerations using JP-4 and EF4-101 fuels. For this testing, the fuels were stored in the UH-1D helicopter auxiliary fuel tank.

No appreciable change in engine operation could be observed when operating on either JP-4 or EF4-101 fuels. The engine was sent to the Continental environmental test facility, Figure 8, where high and low ambient temperature starts, altitude starts, and altitude operation were checked out, using EF4-101 and JP-4 fuels. The engine is shown installed in the test cell in Figure 8.

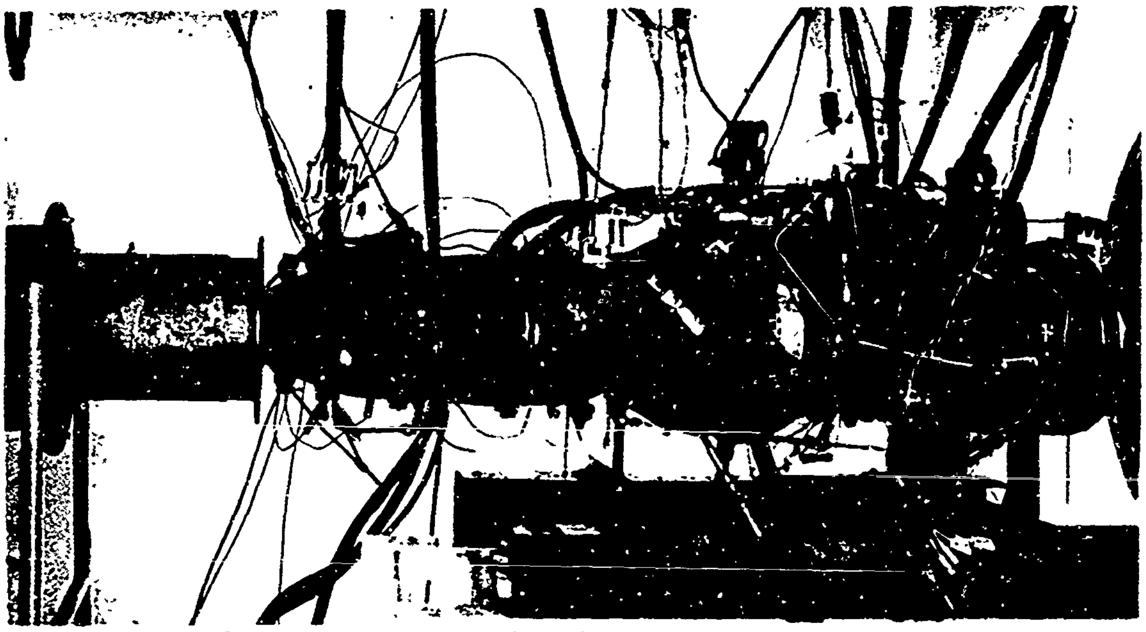

Figure 8. Continental Model 217-10B Engine Mounted in Test Cell.

No problems were encountered that could be attributed to the use of emulsified JP-4 fuel. The only problem encountered was that when the fuel was contained in the UH-1D helicopter auxiliary fuel tank, the fuel temperatures would not change with the changes in ambient temperature. For example, a 24-hour chamber soak at -65°F resulted in only a 1.0°F change in the temperature of the fuel in the tank. It was necessary to install a 100-foot coil of 1-inch-inner-diameter copper tubing between the fuel tank and the engine in order to have fuel within plus or minus 2 degrees of the ambient temperatures for the starting tests.

Successful starts were made at ambient temperatures of +130°F and -40°F and at simulated altitudes of 20,000 feet. A successful light-off and acceleration was made at -60°F with emulsified fuel, but the start was aborted when the engine went overtemperature at approximately 15,000 rpm gas generator speed.

Examination of the engine data showed that the overtemperature condition was caused by too much fuel entering the engine, due to improper scheduling by the fuel control.

No attempts were made to correct the fuel control deficiency, since the primary objective of the program (that is, to determine if emulsified fuel could be pumped and burned in an engine at low ambient temperature) had been achieved. In addition, a successful start was made at -40°F while using emulsified fuel.

RESULTS

The environmental tests showed that EF4-101 fuel could be used the same as JP-4 under various environmental conditions, and engine operation was similar with either fuel within the limits of the fuel control, fuel scheduling, and the engine operator's techniques.

Figure 9 is a plot of starts made at -40°F while using liquid and emulsified JP-4 fuels. As can be seen from Figure 9, the starts are very similar and any variations are caused by a change in the engine operator's technique.

Figures 10 and 11, which are plots of the engine starting envelope, show that successful starts were made from static sea level conditions up to simulated altitudes of 20, 000 feet and simulated forward speeds of 0.5 Mach number.

Figure 12 is a plot of starts made at an ambient temperature of +130°F. Here, again, the starts are identical except for the changes in operator techniques.

Figure 13 is a plot of the start attempt that was made at an ambient temperature of -60°F.

As can be seen in Figure 13, the start attempt was proceeding satisfactorily until after about 16 seconds the fuel flow continued to rise instead of leveling off; this excess fuel caused the engine to go overtemperature. It must be pointed out again that the excess fuel was the result of a deficient fuel control and not the result of using emulsified fuel. The plot is presented only to show that a successful light-off and acceleration was possible with emulsified fuel at an ambient temperature of -60°F, using an emulsified fuel with the standard control and ignition system.

Engine operation was checked out at simulated altitudes up to 20, 000 feet with both liquid and emulsified JP-4, and no change in engine operation could be observed. In general, however, engine operation was more stable with EF4-101 fuel, and the engine had less tendency to undershoot or overshoot when the engine conditions were changed.

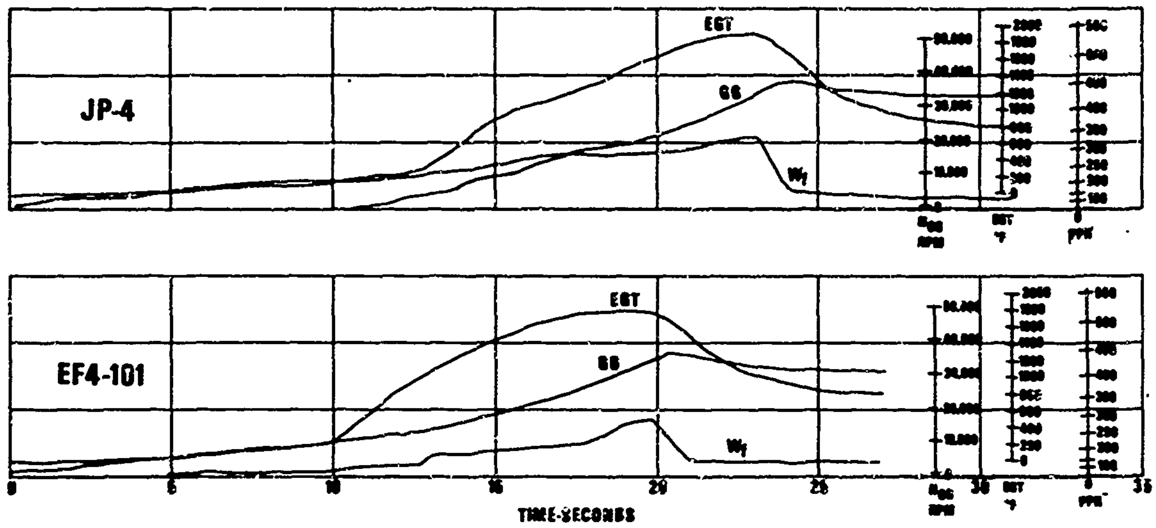

Figure 9. Transient Recording Plots of Starts Made With JP-4 and EF4-101 After a 10-Hour Cold Soak at -40°F.

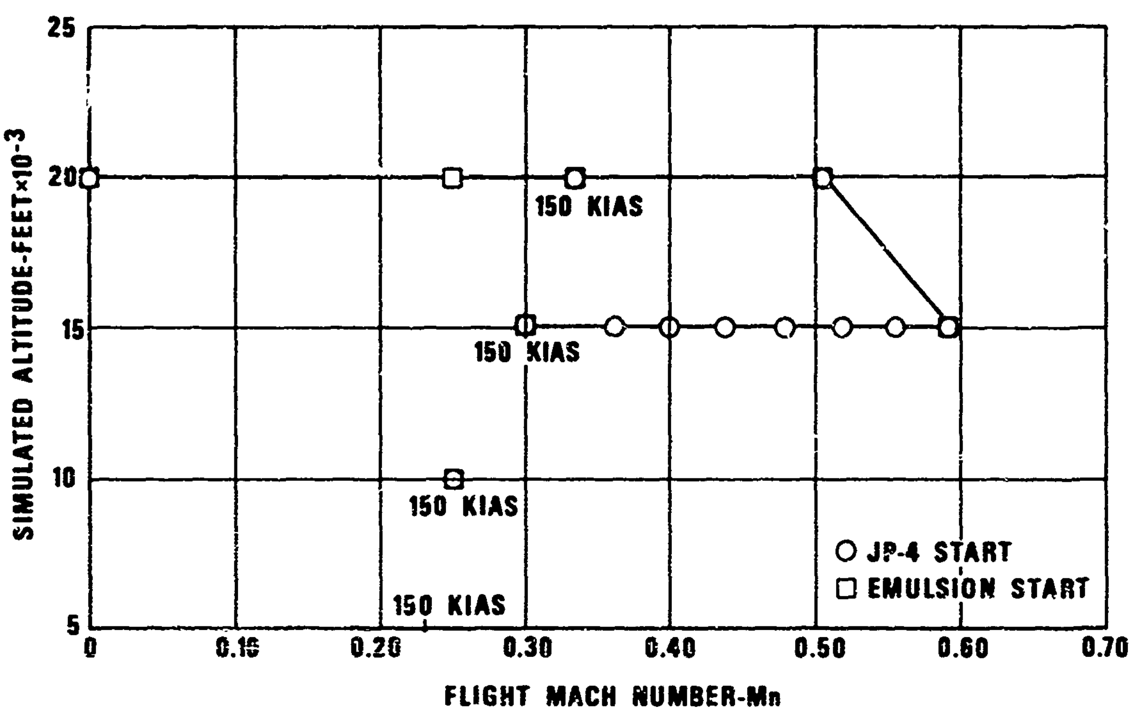

Figure 10. Altitude Performance Evaluation - Altitude Versus Mach Number.

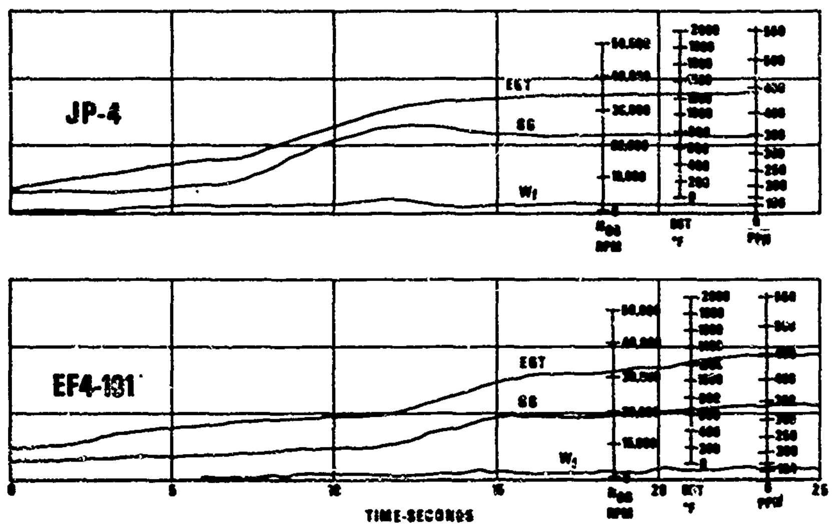

Figure 11. Transient Recording of Starts Made at 15,000 Feet and 0.5 Mach Number With JP-4 and EF4-101.

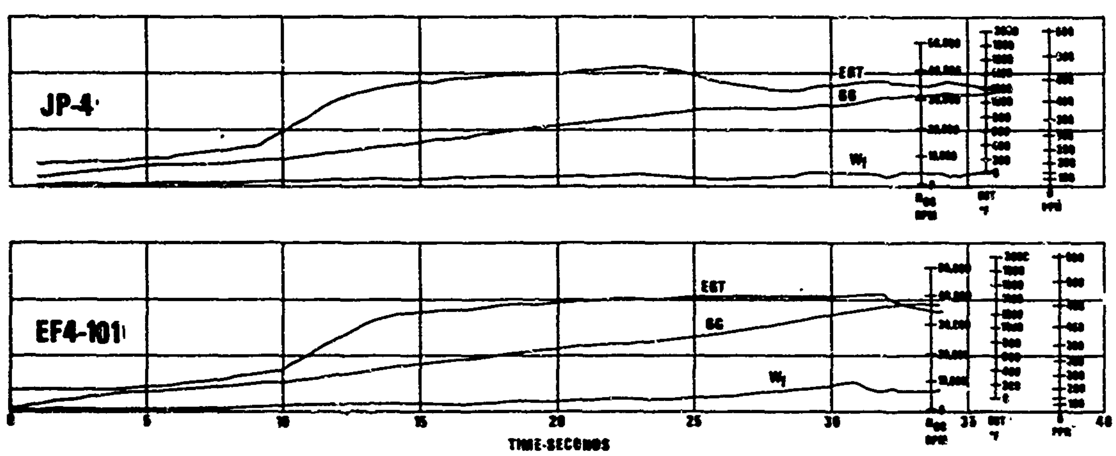

Figure 12. Transient Recording of Starts Made at +130°F With JP-4 and EF4-101.

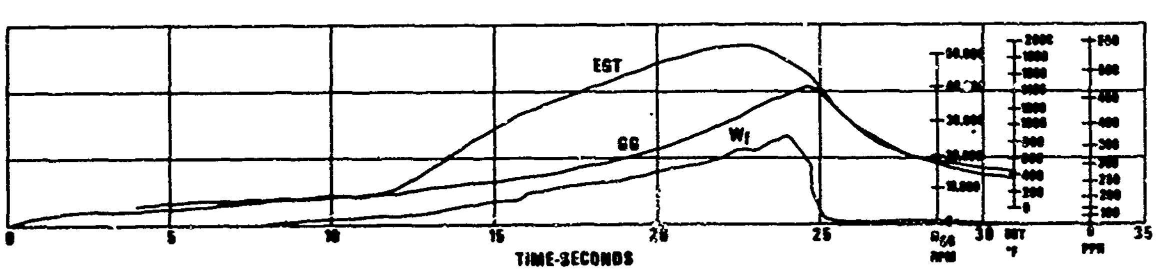

Figure 13. Transient Recording of Engine Start Using EF4-101 Fuel After Cold Soaking for 8 Hours at -60°F.

CONCLUSIONS

1. EF4-101 fuel can be used the same as JP-4 fuel for engine operation.

2. EF4-101 fuel cannot be used for cooling engine oil as is presently the practice in some engine fuel-oil oil coolers.

ENDURANCE TESTING

OBJECTIVE

The objective of the endurance testing was to determine if the Model 217-10B engine and its complete fuel system could be operated for a minimum of 30 hours without deleterious effects.

TEST PROCEDURE

The engine used for the endurance testing was identical to the engine used for the environmental testing except that the engine was assembled as a complete turboshaft engine.

Prior to being assembled, all the engine components were visually inspected. The major components, particularly the hot-section components and the fuel system components, were subjected to visual, dimensional, and fluorescent penetrant and/or magnetic particle inspection.

The engine fuel control system used on the engine was identical to the fuel control system normally used on the Model 217-10B engine when using liquid JP-4 fuel. No modification whatsoever was made to the fuel control system to facilitate using EF4-101 emulsified JP-4 fuel. In fact, the fuel control system used for the endurance test was the same one used for the environmental testing except for the addition of a power turbine governor for controlling power turbine speed. This system was used in order to have a fuel control system with a maximum amount of exposure to the EF4-101 emulsified fuel.

The fuel control was calibrated prior to being installed on the endurance engine. The calibration showed that an excessive amount of fuel was being passed through the control. Subsequent inspection showed that the excessive fuel flow was caused by a piece of dirt which was stuck on the minimum-flow fuel valve and prevented the valve from closing completely. This allowed an excessive amount of fuel to pass through the control at the cranking and light-off speeds and could have accounted for the high fuel flows encountered during the starting tests. The minimum flow valve was cleaned, and the fuel control was reassembled and recalibrated.

The engine was assembled and mounted on the left-hand side of a T67 combining gearbox. The engine was installed in Test Cell A3, and testing was started 3 November 1966.

Check runs were made to ascertain the engine's performance and operating characteristics. Several good starts were made, and then all further start attempts were aborted due to excessive power turbine inlet temperatures. The fuel control was removed from the engine and sent to the fuel laboratory, where subsequent examination showed that a small aluminum particle was stuck on the minimum-flow fuel valve and prevented the valve from closing. The control was cleaned, reassembled, recalibrated with liquid fuel, and reinstalled on the engine. Starts were then made with a maximum power turbine inlet temperature of 1200^{o}F.

While the fuel control problem was being investigated, the test cell fuel system was modified so that the fuel could be transferred back and forth between liquid JP-4 and EF4-101 emulsified fuel while the engine was running. This was done by using suitable electrically operated solenoid valves and check valves in each fuel supply line, then "teeing" the two fuel supply lines together just ahead of the engine-mounted pump, as shown in Figure 14. A sight glass was installed in the fuel system at the inlet of the engine-mounted fuel pump so that the condition of the fuel could be observed as it was entering the fuel pump.

During steady-state engine operation, approximately 3.0 to 5.0 seconds were required for the liquid JP-4 in the sight glass to be replaced with the EF4-101 fuel. There was no change in engine operation when switching from one fuel to another at any operating condition. Figure 15 is a typical composite transient recording trace taken while the fuel system was transferred from liquid JP-4 to EF4-101 fuel during steady-state engine operation at 32,750 rpm gas generator speed.

During all phases of engine operation, the EF4-101 fuel observed in the sight glass consisted of at least 95-percent emulsion whenever the EF4-101 fuel was being used. When the engine was operated at speeds above flight idle, solid emulsion was observed in the sight glass.

After being recalibrated with liquid fuel, the fuel control was reinstalled on the engine. The engine was checked out, and operation was satisfactory with both liquid JP-4 and EF4-101 fuels.

At one point while operating with EF4-101 fuel, engine operation became erratic and the engine stopped running. The erratic operation was caused by a loss of boost pressure at the inlet of the engine-mounted fuel pump. Subsequent checking showed that the ferry-tank-mounted fuel boost pump had failed due to EF4-101 fuel's leaking into the electric motor and causing it to short out and burn the motor windings. Figures 16 through 18 show the emulsion adhering to various components of the boost pump. The pump was replaced with another pump, and testing

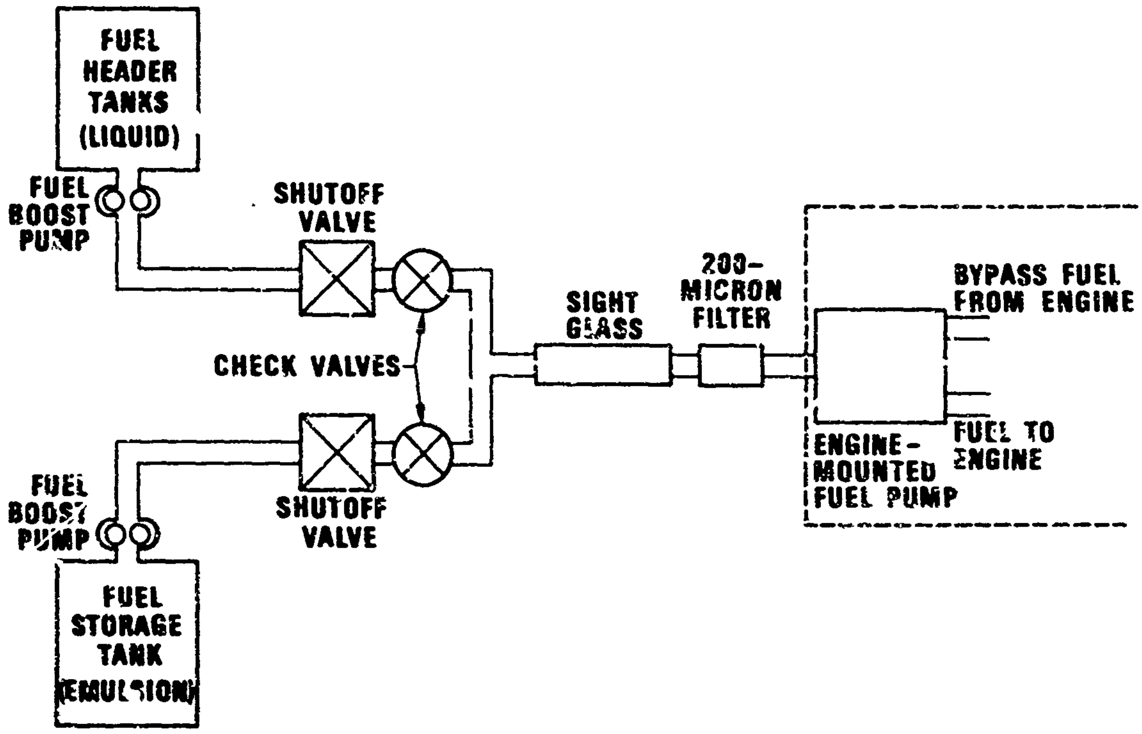

Figure 14. Schematic Showing Test Cell Setup Permitting Switching of Fuels During Engine Operation.

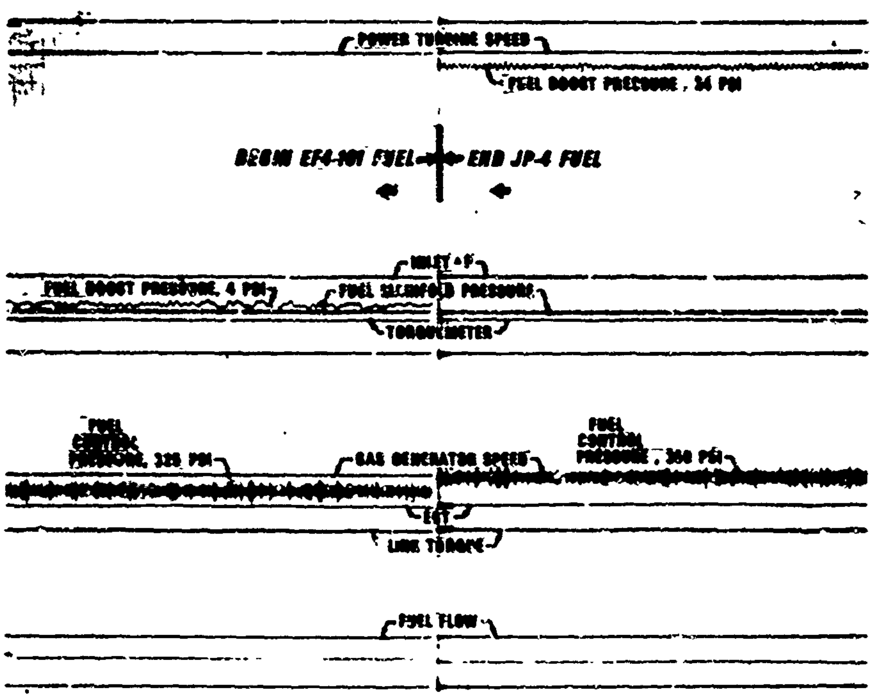

Figure 15. Transient Recording Showing Switch From JP-4 to EF4-101 Fuel.

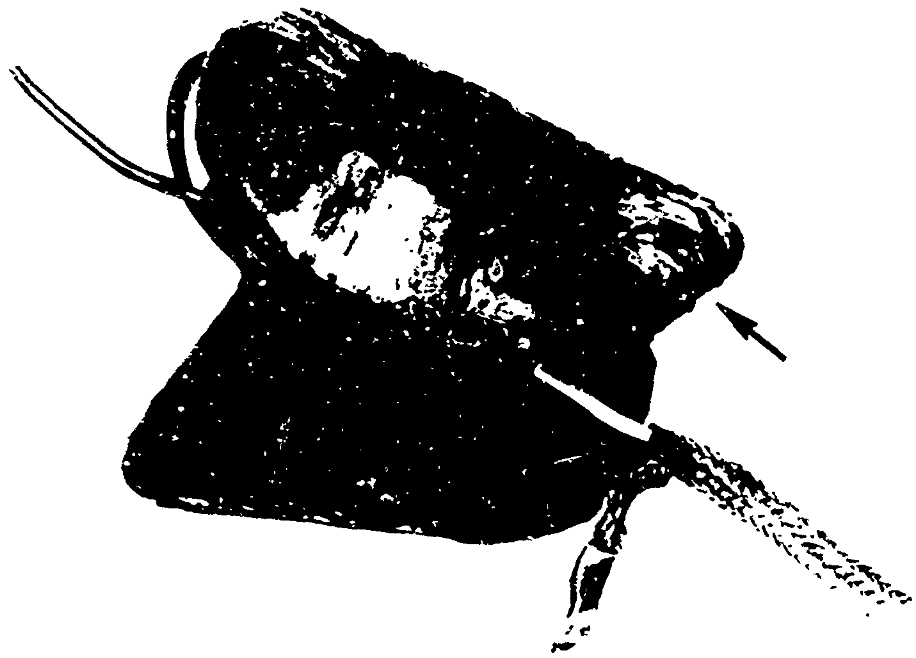

Figure 16. Emulsion Adhering to Boost Pump Component.

was continued.

The engine was calibrated on both liquid JP-4 and EF4-101 fuels, and transient recordings of steady-state operation, accelerations, decelerations, and starting characteristics were made. Following this, a 30-hour endurance test was started with the engine using only EF4-101 fuel.

After approximately 4 hours of endurance testing, engine operation became unstable during steady-state operation. Check runs were made but failed to show any reason for the unstable engine operation. The engine was then removed from the test cell and disassembled.

RESULTS

The testing that was completed was interrupted several times to determine the cause of erratic engine operation; it was found that it was caused either by the fuel control or by plugged fuel filters which restricted the fuel flow to the fuel control. Two fuel controls became inoperative when dirt caused the minimum-flow valve and the bypass valve to stick in the open position. The dirt reached the controls when larger micron

Figure 17. Emulsion Adhering to Boost Pump Components.

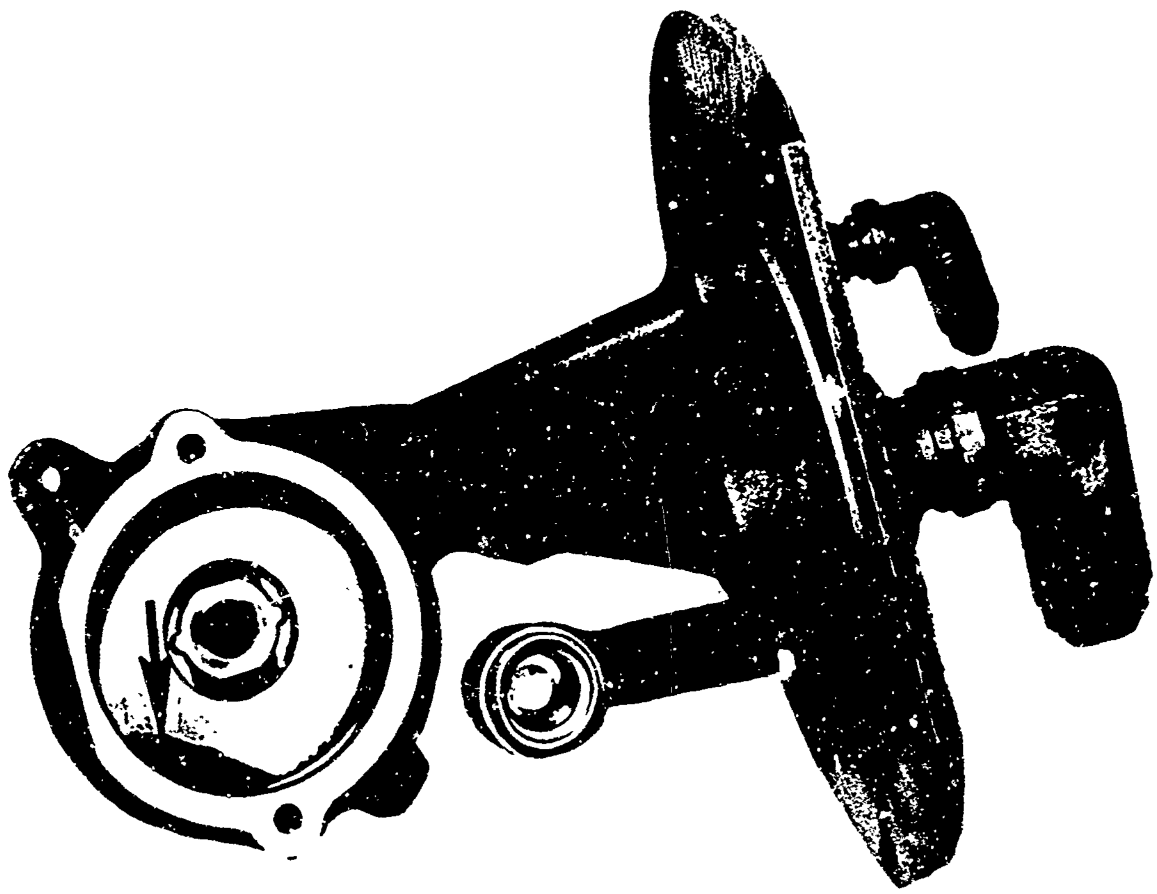

Figure 18. Emulsion Adhering to Boost Pump Component.

size filters were installed in the fuel system to keep the filters from being plugged by the dirt that was entrained in the fuel. Figures 19 through 22 show typical examples of the dirt that was encountered. The dirt consisted of common household lint, dust particles, small pieces of metal and rubber, and even chips of the plastic coating that lined the fuel shipping drums to prevent rusting.

The reason that the dirt and the plugged filters were experienced during this testing and not during either the laboratory testing or the

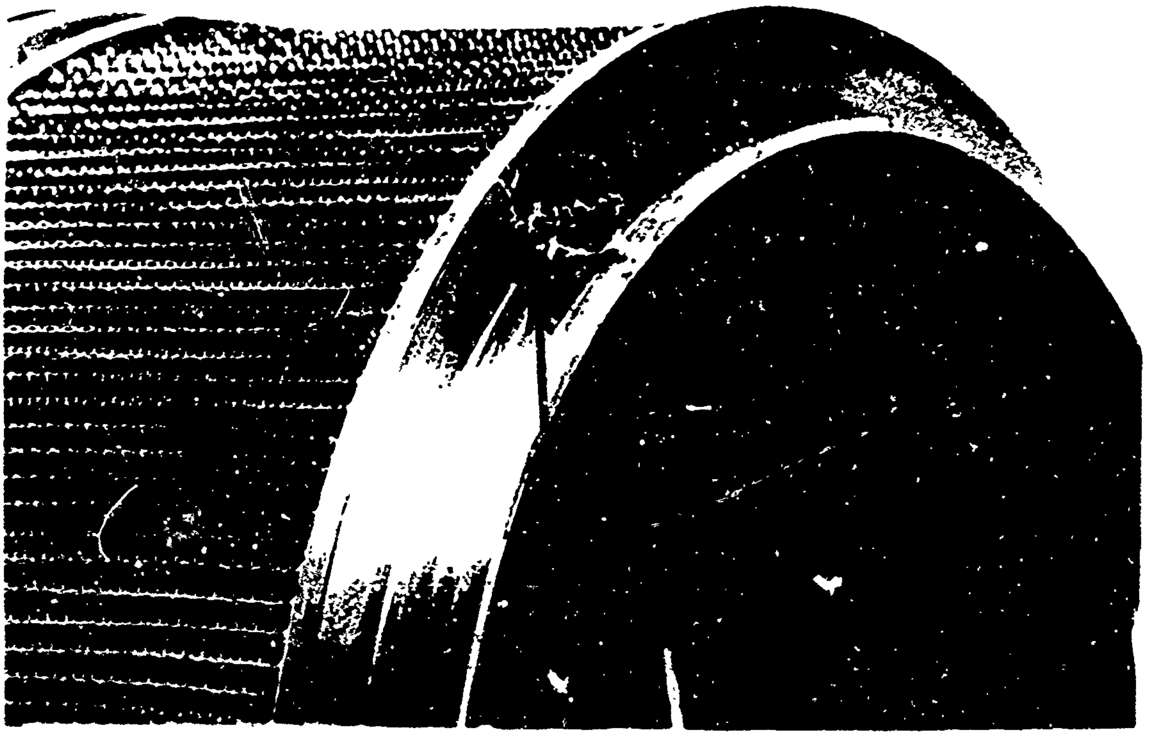

Figure 19. Dirt Particles Encountered in Fuel Pump Filter.

Figure 20. Dirt Particles Encountered in Fuel Pump Filter.

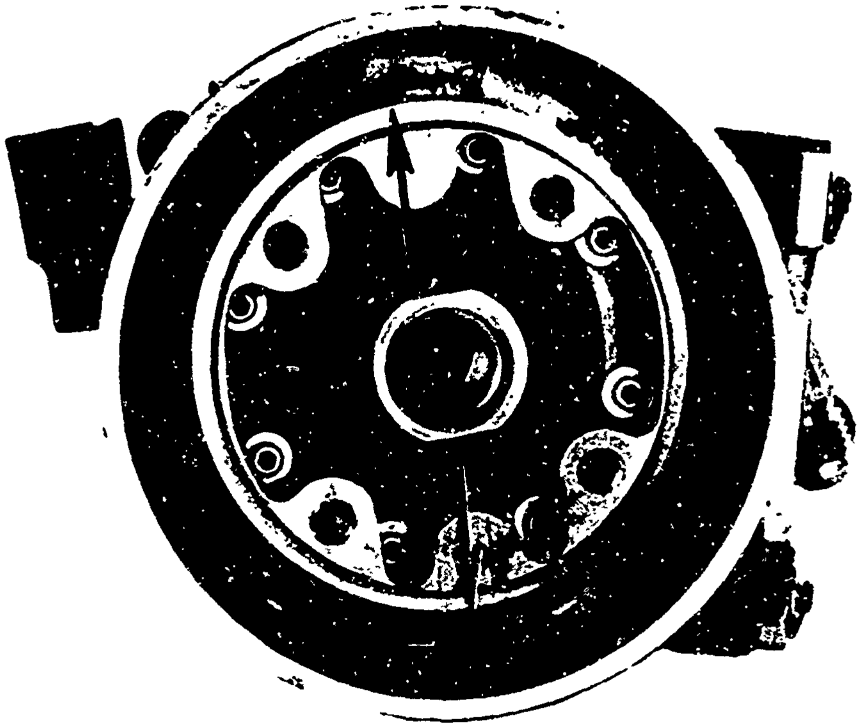

Figure 21. Dirt Particles Encountered in Fuel Pump Filter.

Figure 22. Dirt Particles Encountered in Fuel Pump Filter.

environmental testing is that during the latter two tests, only a small amount of fuel was used; also, in most instances, the fuel was stored, handled, and transferred indoors, and extreme care was used in handling the fuel. During the endurance testing, the UH-1D ferry tank was located in the test cell anteroom, where there was a constant traffic of people in and out of the cell; when the fuel was being transferred from the shipping drums to the ferry tank, the drum lid was removed and the fuel was exposed to the atmosphere.

Engine operation was the same with EF4-101 as with JP-4 fuel, as long as an uninterrupted supply of fuel was available to the engine.

The engine was calibrated while using first liquid and then emulsified JP-4 fuel. Figures 23 through 26 show the engine performance, including combustor efficiency, to be the same with the emulsified JP-4 fuel as with the liquid JP-4 fuel except for the increase in fuel flow and specific fuel consumption. The increase in emulsified JP-4 fuel flow is the direct result of the lower Btu content of the emulsified JP-4 fuel.

Figures 27 and 28 are plots of engine starting characteristics for both liquid and emulsified JP-4 fuels. Figure 27 shows a start using liquid JP-4 fuel. From Figure 27, it can be seen that the engine attained stabilized ground idle speed 15 seconds after ignition occurred, and the maximum power turbine inlet temperature (PTIT) during the start was 1390°F. Figure 28 shows a start using EF4-101 fuel; it can be seen that the engine attained stabilized ground idle speed 16.3 seconds after ignition, and the maximum PTIT during the start was 1340°F. The most significant difference between the two starts was that the time to ignite was approximately 4 seconds longer during the JP-4 start. Once ignition was achieved, the starts were the same within the normal limits of the fuel control scheduling.

Figures 29 and 30 show the transient operation characteristics of the engine for both liquid and emulsified JP-4 fuels. They also show transient operation from flight idle to maximum power. From these figures, it can be seen that the accelerations were identical with both fuels. In both instances, maximum power was reached in approximately 3.2 seconds, with a maximum power turbine inlet temperature of 1300°F. Engine deceleration was completed in 2 seconds, and fully stable operation was achieved in 4.5 seconds.

Visual inspection revealed a severe scaling of the "hot section" parts, particularly the gas generator turbine blade (Figures 31 through 34). Further inspection revealed that, in addition to the scaling, the turbine blade airfoil section contours were changed because of erosion of

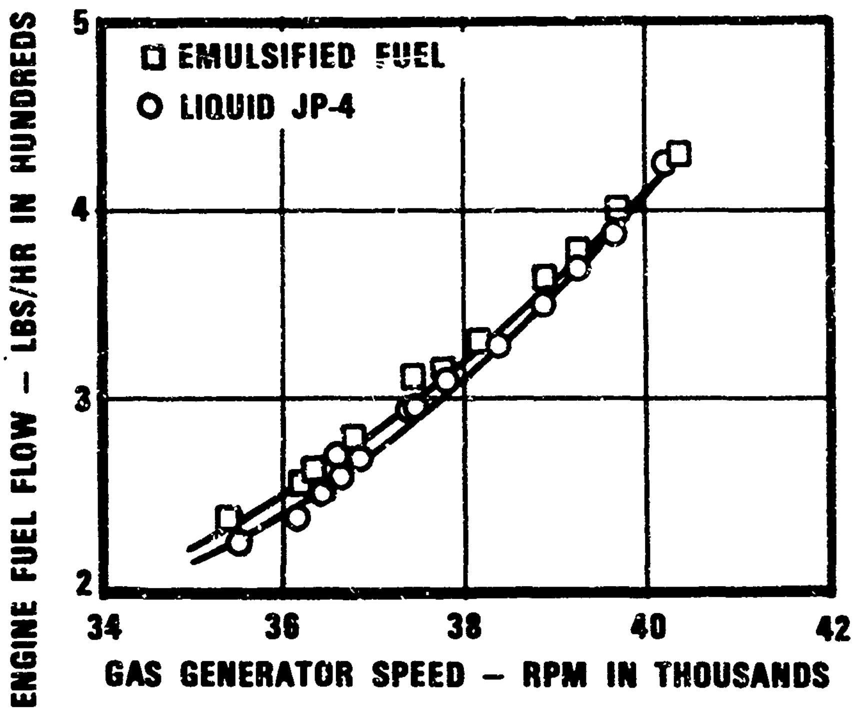

Figure 23. Engine Fuel Flow Versus Gas Generator Speed.

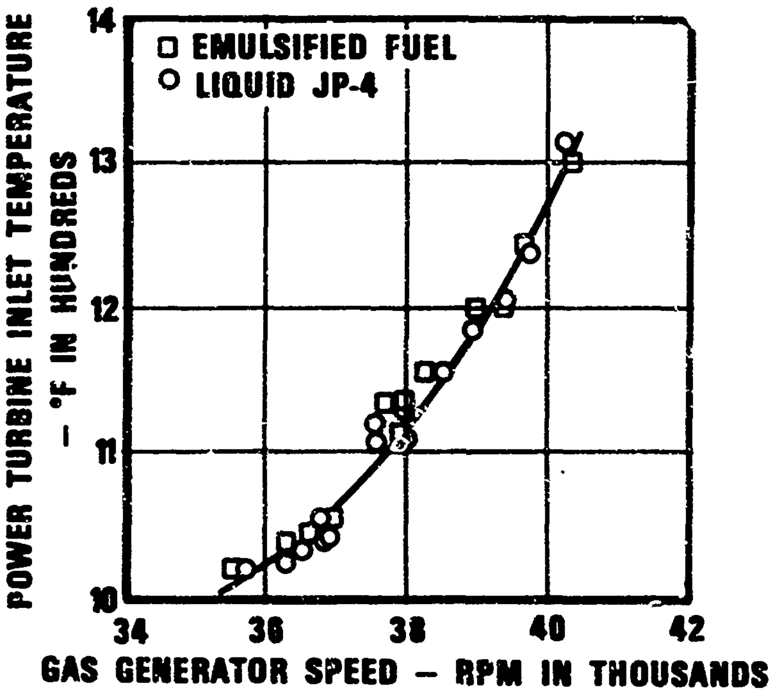

Figure 24. Power Turbine Inlet Temperature Versus Gas Generator Speed.

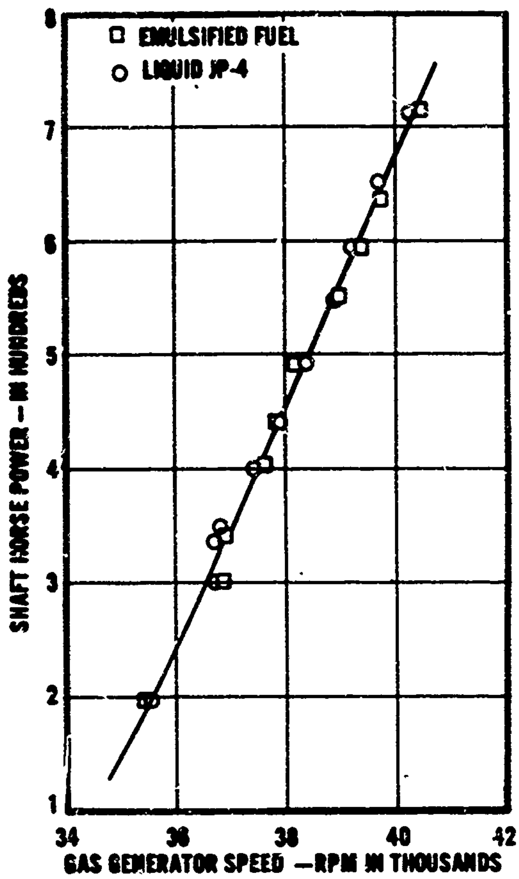

Figure 25. Engine Shaft Horsepower Versus Gas Generator Speed.

the blade material, particularly at the leading-edge section of the blade.

The change in turbine blade contour was sufficient to change the match of the engine and to cause unstable engine operation.

Subsequent investigations disclosed that the scaling was caused by a corrosion of the superalloy metals, generally described as sulfidation; this is a problem common to gas turbine engines. However, the magnitude of the corrosion which occurred during the testing (with emulsified fuel) is normally associated with 3000 to 4000 hours of normal engine operation and could have occurred only if the ingredients which cause sulfidation were present in copious amounts.

Chemical analysis of the fuel disclosed that sodium, which must be present to cause sulfidation, was present in the emulsified fuel in quantities of 30 parts of sodium per 1 million parts of fuel (30 PPM). This is considerably more than the amount that is intentionally introduced into engines when special sulfidation tests are being conducted to promote this type of corrosion.

The sodium found in the emulsified JP-4 fuel was not a required ingredient for producing the fuel. It was used only as a catalyst in the manufacture of the external phase of the emulsified fuel. Emulsified JP-4 fuels with minute traces (0.23 PPM) of sodium have been made, but as yet these fuels have not been tested in the T57 engine.

Disassembly of the fuel control showed that it was in satisfactory condition. As the fuel control was being disassembled, emulsified fuel was observed in the various pockets and cavities. Figures 35 through 37 show sections of the control with quantities of emulsion still adhering to the fuel control components. It was noted, however, that the emulsion

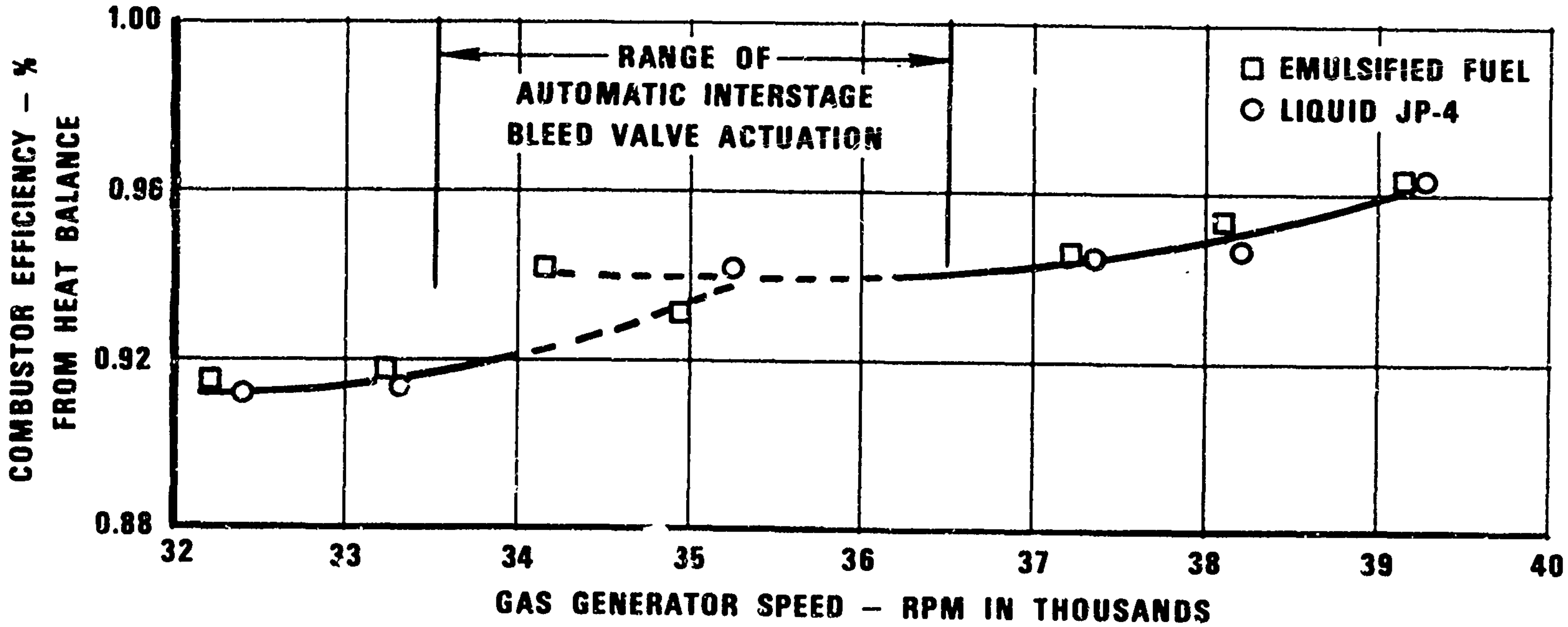

Figure 26. Evaluation of Combustor Efficiency Calibration With Liquid and Emulsified JP-4 Fuel.

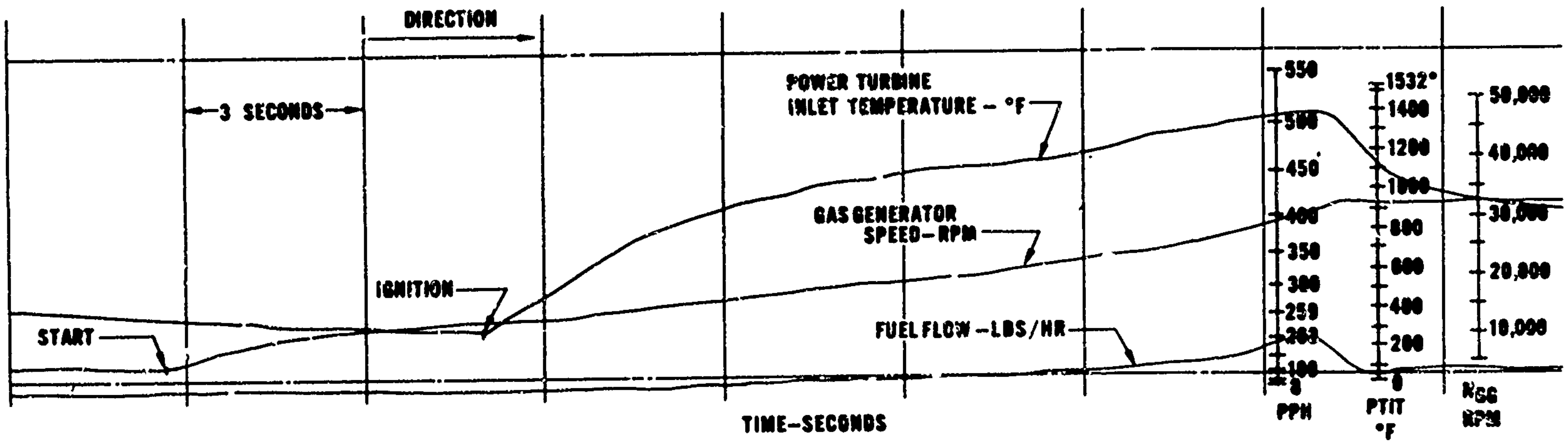

Figure 27. Transient Recording of Engine Start Using Liquid JP-4 Fuel.

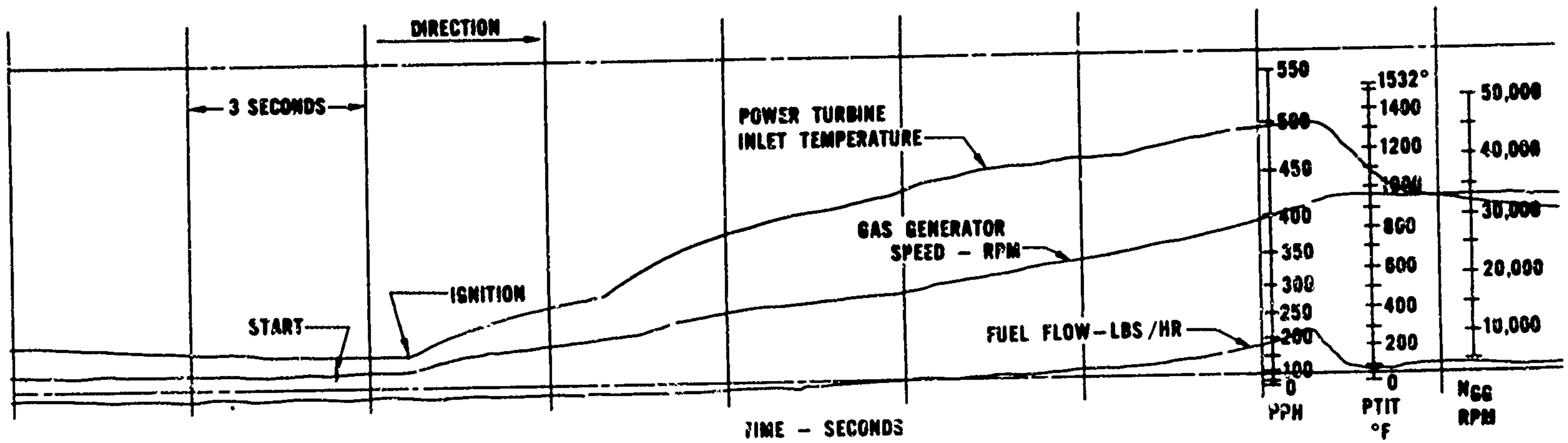

Figure 28. Transient Recording of Engine Start Using Emulsified JP-4 Fuel.

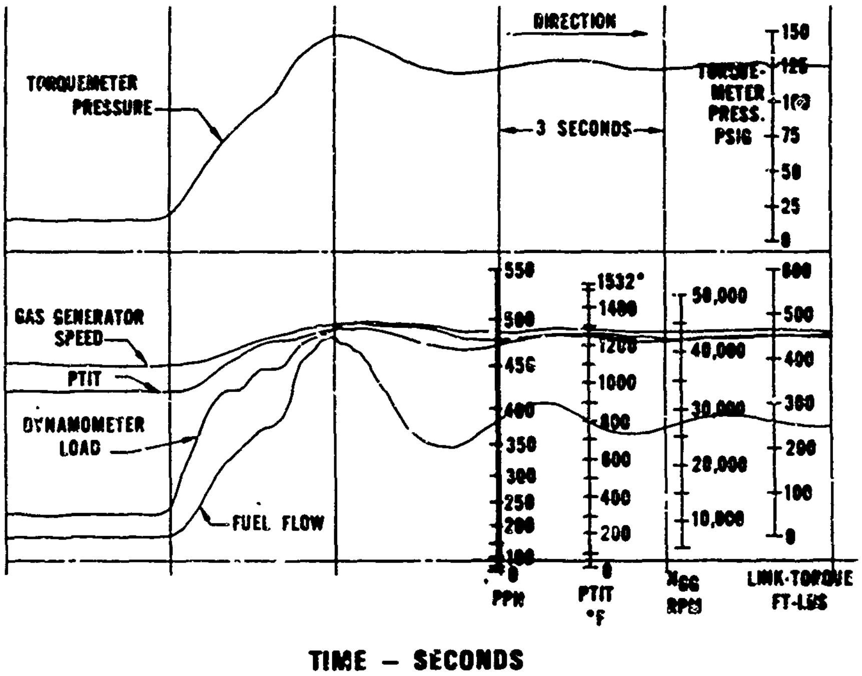

Figure 29. Power Transient Recording of Engine Acceleration From Flight Idle to Maximum Power Using Liquid JP-4 Fuel.

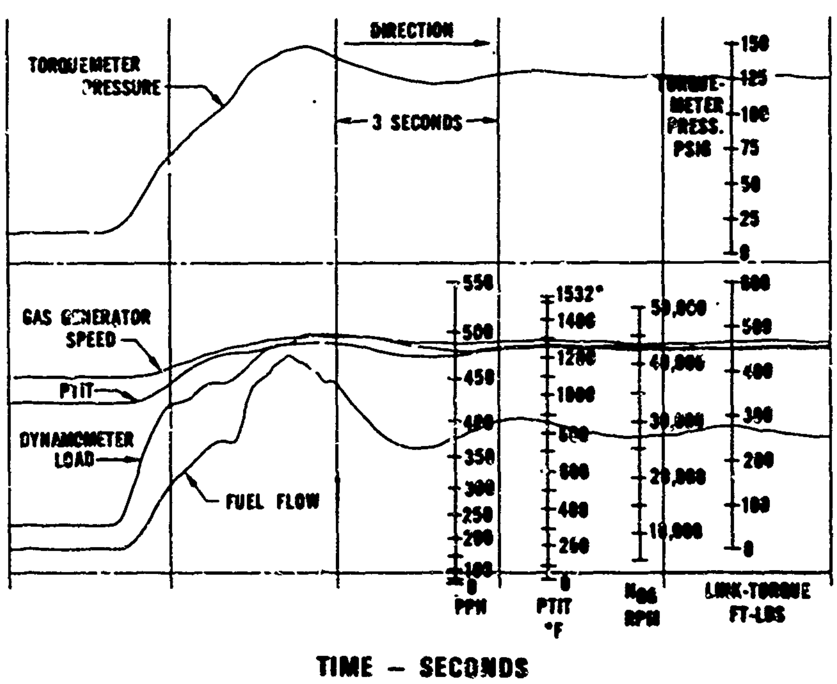

Figure 30. Power Transient Recording of Engine Acceleration From Flight Idle to Maximum Power Using Emulsified JP-4 Fuel.

Figure 31. Gas Generator Turbine Blades Showing Deposits After 11 Hours of Operation With Emulsified JP-4 Fuel.

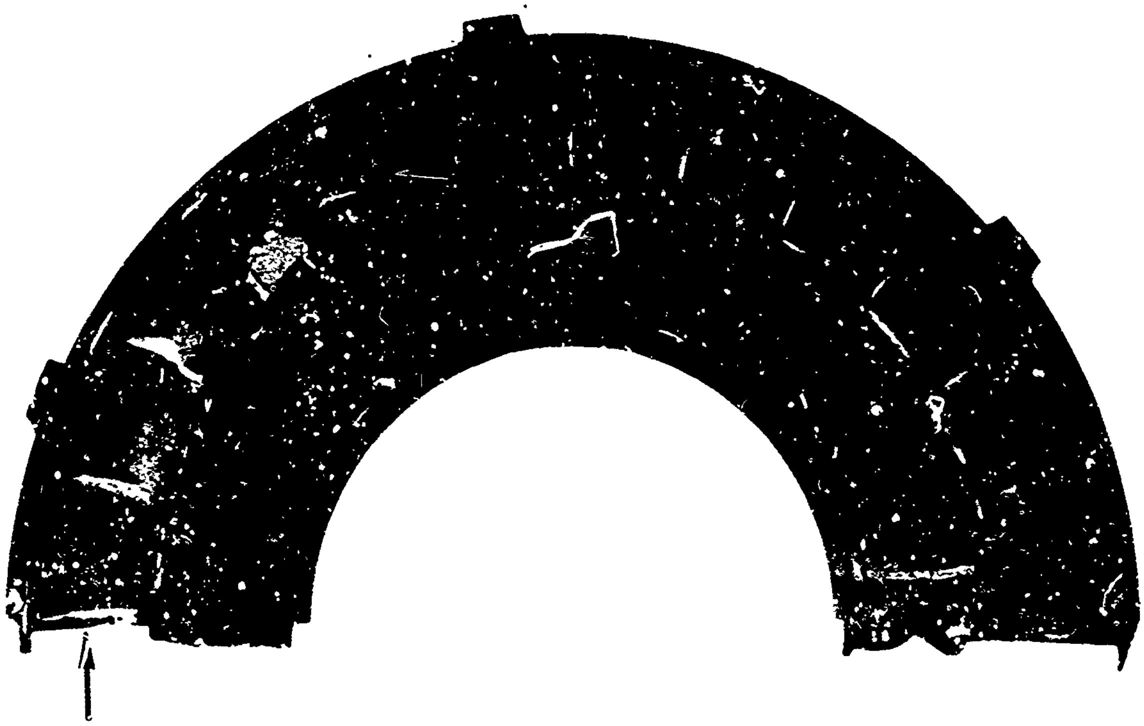

Figure 32. Nozzle Stator Showing Scaling (Arrows).

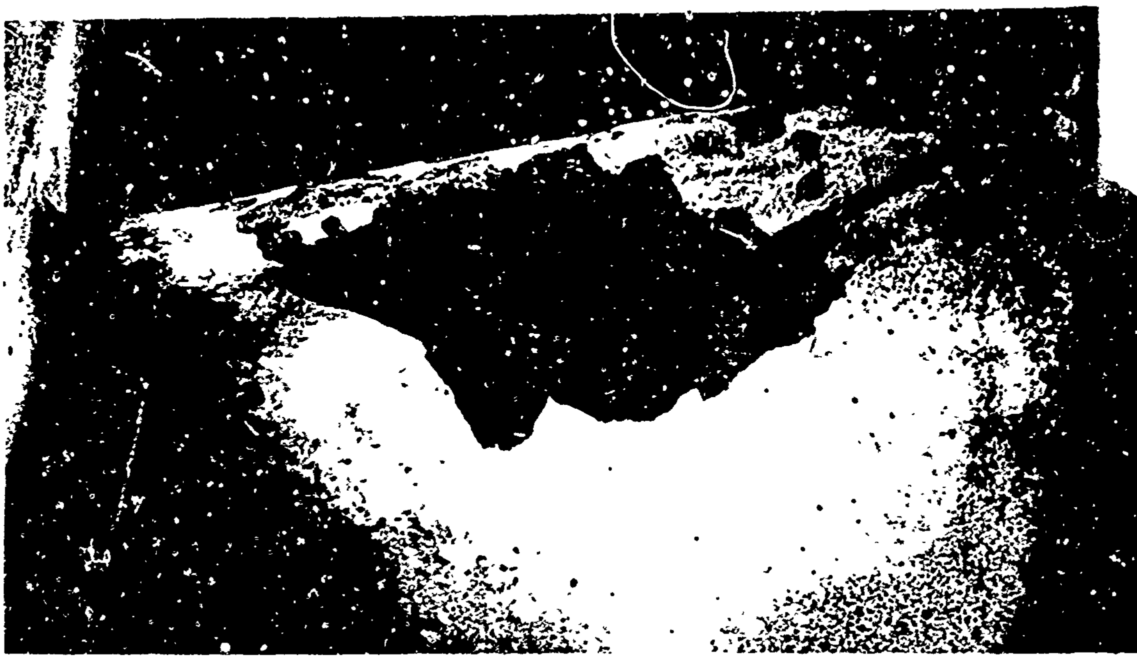

Figure 33. Scaling on Leading Edge of Stator Vane.

Figure 34. Turbine Blade After a 16-Hour Run on EF4-101 Fuel - Etched to Show Grain Size (Arrows Indicate Intergranular Cracks).

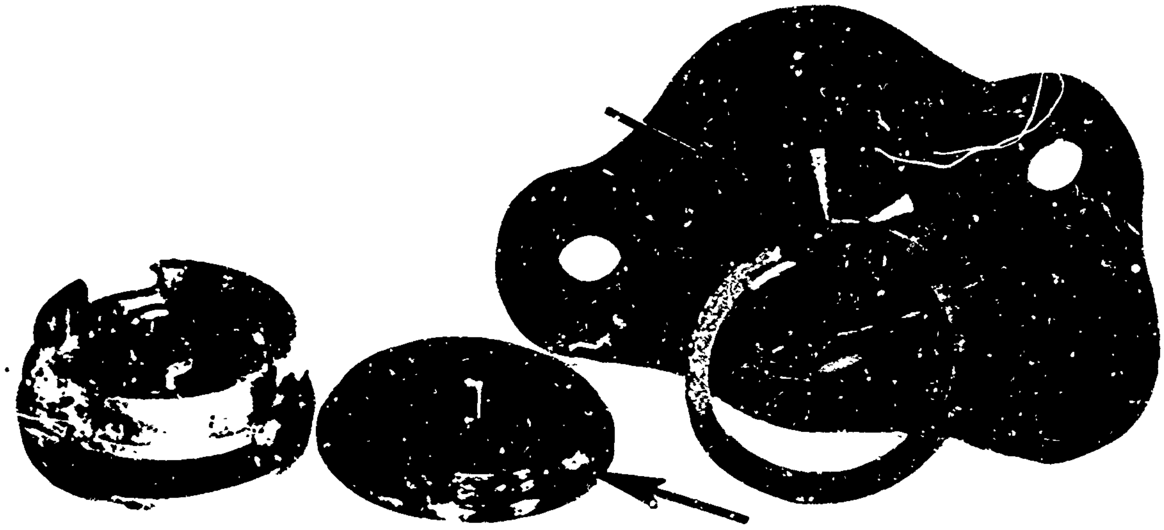

Figure 35. Fuel Control Minimum Makeup Valve Parts With Emulsion Deposits (Note White Power-Like Substance on Lower and Middle Pieces).

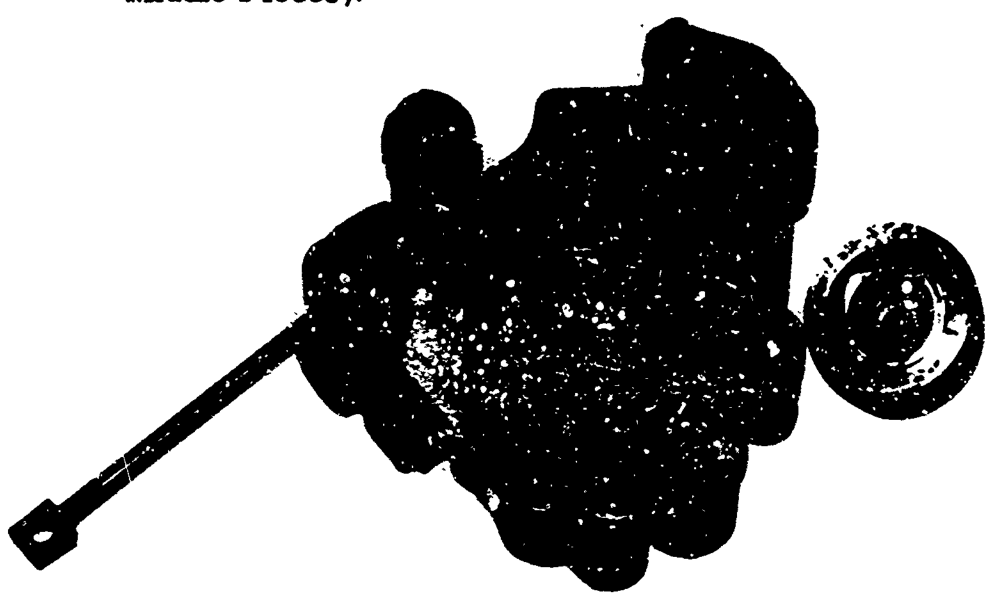

Figure 36. Fuel Control Feedback Diaphragm Retainer, Showing Light Fretting on Surface of Retainer (Note Quantity of Emulsion Trapped in Fuel Control Feedback Chamber).

that was found in the fuel control would eventually thicken into a jelly-like substance, more with the consistency of petroleum jelly, if it was left exposed to the air for any length of time. This jelly-like substance would then dry out completely into a white powdery substance.

Figure 37 shows the deterioration of the fuel control shutoff valve seal. This type of deterioration has been observed on valves from fuel controls which were used with only liquid fuels. Therefore, the deterioration cannot be specifically attributed to using emulsified fuels.

The engine-mounted fuel pump was also disassembled and inspected; it, too, was found to be in satisfactory condition. Except for the dirt that was found in the fuel pump filter, no detrimental conditions were found.

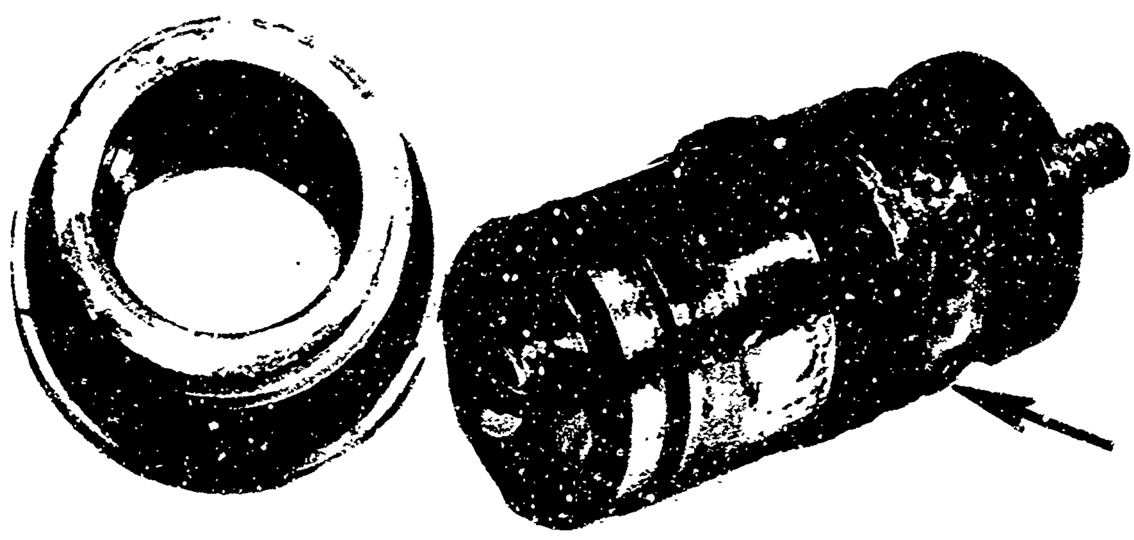

Figure 37. Fuel Control Shutoff Valve, Showing Deteriorated Rubber Valve Seat (Note Quantities of Emulsion Adhering to Piston).

CONCLUSIONS

1. Engine operation (steady-state, starting, and transient) is the same with EF4-101 fuel as with liquid JP-4 fuel, as long as an uninterrupted supply of fuel is available to the engine-mounted fuel pump.

2. Engine power output was the same with EF4-101 fuel as with liquid fuel.

3. Engine fuel consumption on the basis of heating value was the same with both EF4-101 and JP-4 and was increased 2 to 3 percent on a weight basis when using EF4-101 fuel.

4. Over the range tested, combustion efficiency was not affected by the use of EF4-101 fuel.

5. Use of thickened fuels will require a new technology in the design of fuel filters and in fuel handling practices.

6. Additional laboratory testing should be done with emulsified fuels to ensure that they are "safe" for use in turbine engines before additional engine testing is undertaken.

APPENDIX

INSTRUMENTATION AND DATA ACQUISITION

The testing described in this report was conducted at the Continental Aviation and Engineering Corporation facilities at Detroit, Michigan and Toledo, Ohio. The test cell facilities are described below.

I. LABORATORY TESTING

A. Continental Detroit Fuel Laboratory

Detroit Fluids Lab -

Fuel Back Pressure	0 to 600 psig	Greer No. 1 Duragauge S/N -10
Pump Outlet Pressure	0 to 600 psig	Greer No. 1 Duragauge S/N - 8
Fuel Control	0 to 7000 rpm	Crouse - binds tachometer and timer
CDP	0 to 300 psia	Greer No. 1 Heise gauge S/N H25948
PT-3	0 to 300 psia	Greer No. 1 Heise gauge S/N H10316
Flowmeter B ΔP	0 to 100 psia	Greer No. 1 Barton Instrument Co.
Fuel Boost Pressure	0 to 30 psi	Bancroft gauge

II. ENVIRONMENTAL TESTING

A. Continental Detroit Test Cell A10

Pressure before fuel pump	0 to 60 psia	Duragauge

Oil out of pump	0 to 100 psia	
Fuel boost pressure	0 to 60 psia	
Fuel pressure aft pump	0 to 600 psia	
Fuel pressure at Bell Tanks	0 to 60 psia	
Scavenge oil pressure	0 to 200 psia	Duragauge
Oil in pressure	30 Vac psia to 0 to 30 psia	Duragauge
Engine oil pressure	0 to 100 psia	Duragauge
CDP	0 to 200 "Hg	Heise gauge
RPM	0 to 70,000	Standard
W_f	150 to 850 PPH 800 to 4650 rpm	Fischer and Porter Rotometer Co. Instruments Rotometer
EGT	0 to 2000°F	Honeywell Brown
Thrust	0 to 5000 lb.	A. H. Emery Co. (Heise Bourdon Tube Co.)
EGT	0 to 2000°F	Honeywell Brown
Inlet air temperature	0 to 2000°F	
Fuel temperature	0 to 2000°F	
Inlet ΔP	0 to 100" No. 3 Fluid	Dynametrics Corp.
Vibration	Oscilloscope	Panoramic Sonic Analyzer MW Electron Inc.
Exhaust P_t	0 to 60 "Hg	Dynametrics Corp.

<u>Transducers</u> (for transient data)

Fuel pump pressure	0 to 500 psi	Statham
CDP	0 to 100 psi	Statham
Inlet P	0 to 5 psi	Statham

Fuel boost pressure	0 to 251 psi	Statham
Thrust	0 to 1000 psi	Statham
Fuel manifold pressure	0 to 500 psi	
Inlet air temperature	32 to 132°F	Iron Constantine T/C
EGT	32 to 1532°F	Chromel Alumel T/C
Speed	0 to 50,000 rpm	EPUT Generator
CDT	32 to 632°F	Chromel Alumel
Fuel flow	0 to 300 PPH	Flowmeter A (transducer limited)
P transducer	0 to 60" water	Schavitz (LVDT)

B. Altitude Tank No. 2

Engine speed -	Chronotach 0 to 70,000 rpm standard Electric Time Co., Springfield, Mass. Model MVT-4454
	RPM Counter, Computing digital indicator, Dynac Inc., Palo Alto, Calif. Model DY-2500
Vibration -	Vibration meter, Consolidated Electrodynamics Corp., Pasadena, Calif. Vibration Meter Type 1-117
	Vibration pick-up (front-vertical) Chandler Evans Company Monoronia, Calif. Type 4-125-0001
	Vibration pick-up (mid and rear vertical) Chandler Evans Company Type 4-123A (Detroit supplied)
Transient Recorder -	Minneapolis Honeywell Visicorder Heiland Instruments Model 906 Oscillograph S/N 9-6155

Compressor Discharge -	Absolute Pressure Gage (0 to 300 "Hg) Wallace and Tierman Belleville, N. J. Model FA 233 S/N DD 02232
Temperatures -	Brown Potentiometer Pyrometer Brown Instrument Co. (Division of Minneapolis-Honeywell) Philadelphia, Pa. IC Temperatures, Model No. 156X15P (0 to 2400°F) S/N 503226
Fuel Flow -	Rotometers (JP-4 only) Fischer and Porter Hatboro, Pa. S/N W4-1319/1 (0-130 pph) S/N W4-1319/2 (110 to 600 pph) S/N W6-1419/1 (400 to 2000 pph)
Airflow P -	0 to 50 H_2O Manometers (Fluid - Meriam Unity Oil, Meriam Instrument Co., Cleveland, Ohio) Sp. Gr. - 1.00 Spec. No. D-2969
Pressures -	
Inlet Ps and Pt	0 to 100 "Hg standard manometer
Exhaust Pt and Lip Static	0 to 100 "Hg standard manometer
Primer fuel pressure	0 to 150 psia CECO type 4-312-001 pressure transducer
Main engine fuel pressure	0 to 350 psia CECO type 40313A pressure transducer, Jas. P. Marsh Corporation, Chicago, Ill.
Oil in and oil out	Compound Gage 0 to 30 psig
Engine oil	0 to 200 psig
Fuel boost pressure	0 to 100 psig
Engine fuel pump	0 to 600 psig

III. ENDURANCE TESTING

A. Continental Detroit - Test Cell A3

Inlet P (2)	0 to 30" No. 3 Fluid	The Meriam Inst. Co.
Vibration	Oscilloscope	Panoramic Sonic Analyzer, MOD LP-1A A2M, S/N 3RT30
Vib. Meters	0 to 1.5 mils	Consolidated Electrodynamics Corp.
CDP	0 to 300 "Hg	A. H. Emery Co.
Power turbine rpm	0 to 130%	Standard
Torquemeter pressure	0 to 200 psia	Duragauge
Lb Ft. torque	0 to 2000 lb ft	Wallace and Tiernan
G.G. rpm	0 to 60,000 rpm	Standard
Fuel flow (JP-4)	18 to 750 pph	Cox Instruments FO-239 FO-240
EGT	0 to 2000°F	M. H. Brown S/N PC 37 S/N POO 54
Oil in temp	0 to 800°F	Min Honeywell Brown I.C., T/C S/N 5182
Fuel boost pressure	0 to 60 psia	Duragauge S/N G-0522
Fuel pressure	0 to 300 psia	Duragauge
Fuel inlet pressure	0 to 60 psia	Duragauge
Oil outlet pressure	0 to 60 psia	Duragauge
Oil in pressure	30 psia Vac., 0 to 30 psia	Duragauge S/N G-0539
Fuel flow (EF4-101)		Flowmeter B

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13. ABSTRACT

This report presents the results of laboratory, environmental, and endurance testing directed toward the determination of the effect of direct burning of emulsified JP-4 fuel in a gas turbine engine and the handling and pumping of emulsified JP-4 fuel.

Engine operation, including starting and transient operation, with EF4-101 emulsified fuel was essentially the same as that with liquid JP-4 fuel during all phases of testing. Engine testing was terminated when a "hot section" corrosion problem, generated by one of the additives in the emulsified fuel, was encountered.

The use of emulsified fuel will require a new technology in the design of fuel filters, fuel pumps, fuel flow measuring devices, and fuel handling practices.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
JP-4						
EF4-101						
Emulsified Fuel						
Environmental Testing						
Laboratory Tes ing						
Endurance Testing						
Twin Turboshaft Powerplant						
Compressor Discharge Pressure (PCD)						
Cas Generator Speed (Ng)						
Compressor Inlet Temperature (T2)						

END

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