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During the past year feasibility studies were conducted 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 existing fuel systems. Actual engine testing was, however, 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, 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 relative safety aspects of emulsified fuels.

All testing accomplished with emulsified fuel during this series of tests was done with one specific emulsified fuel. This fuel was used because it appeared to be the most developed and most readily available emulsified fuel when the program was started.

The emulsified JP-4 fuel used during

ABSTRACT

This paper 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.

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

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, the emulsifying agents and additives to modify the fuel as required.

The fuel has been subjected to ambient temperatures of -65°F to 135°F and simulated altitudes up to 15,000 feet. At -65°F some breakdown of the emulsion occurred and approximately 5.0 percent liquid was present. The emulsion appeared to have about the same viscosity as it had at room temperatures and it poured as easily as it did at room temperatures. At +135°F approximately 10.0 percent of the emulsion reverted back 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 1.0 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 it 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.

The engine used for the testing discussed in this paper was one engine of the Continental Model YT67-T-1 twin turboshaft powerplant.

An exterior view of the engine is shown in Figure 1, and a cross-section of the engine is shown in Figure 2. The flow path and major engine components are described in the following paragraph.

The engine employs a straight-through aerodynamic flow path. Air enters through a radial inlet, Figure 2, 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 flow path. Shaft horsepower is transmitted back to the front of the engine by means of a concentric through-shaft.

FUEL SYSTEM DESCRIPTION

The engine fuel system consists of a fuel pump, fuel filter, fuel control, power turbine governor, and starting fuel system.

The fuel control is manufactured by the Holley Carburetor Company and is typical of the hydro-mechanical fuel controls currently being used on gas turbine engines.

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 position.

IGNITION AND COMBUSTOR SYSTEMS

The engine fuel system, combustor chamber and combustor air flow paths are shown in Figure 3.

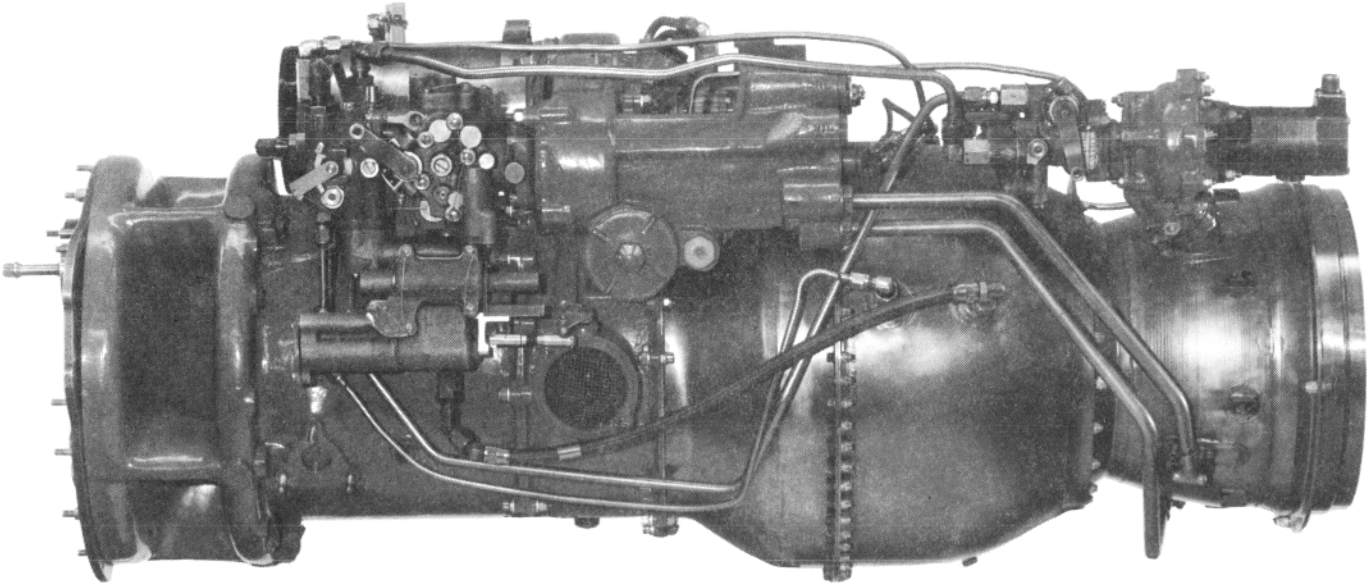


Fig. 1. Continental 217-10B Turboshaft Engine. Left Side View.

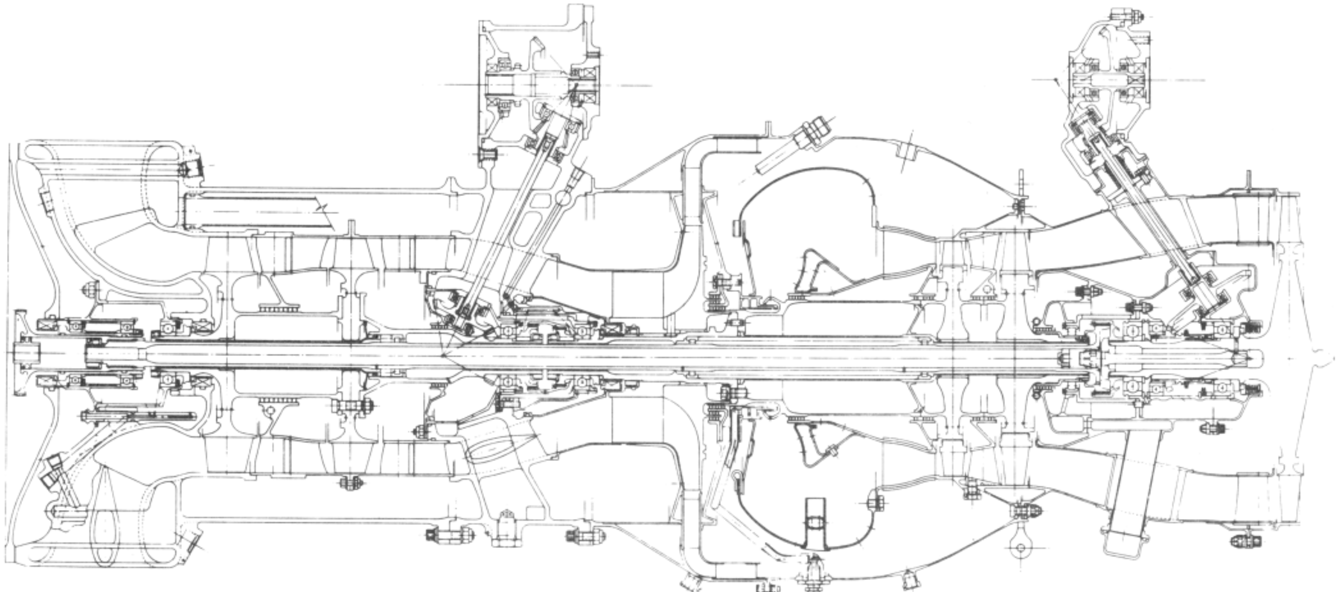
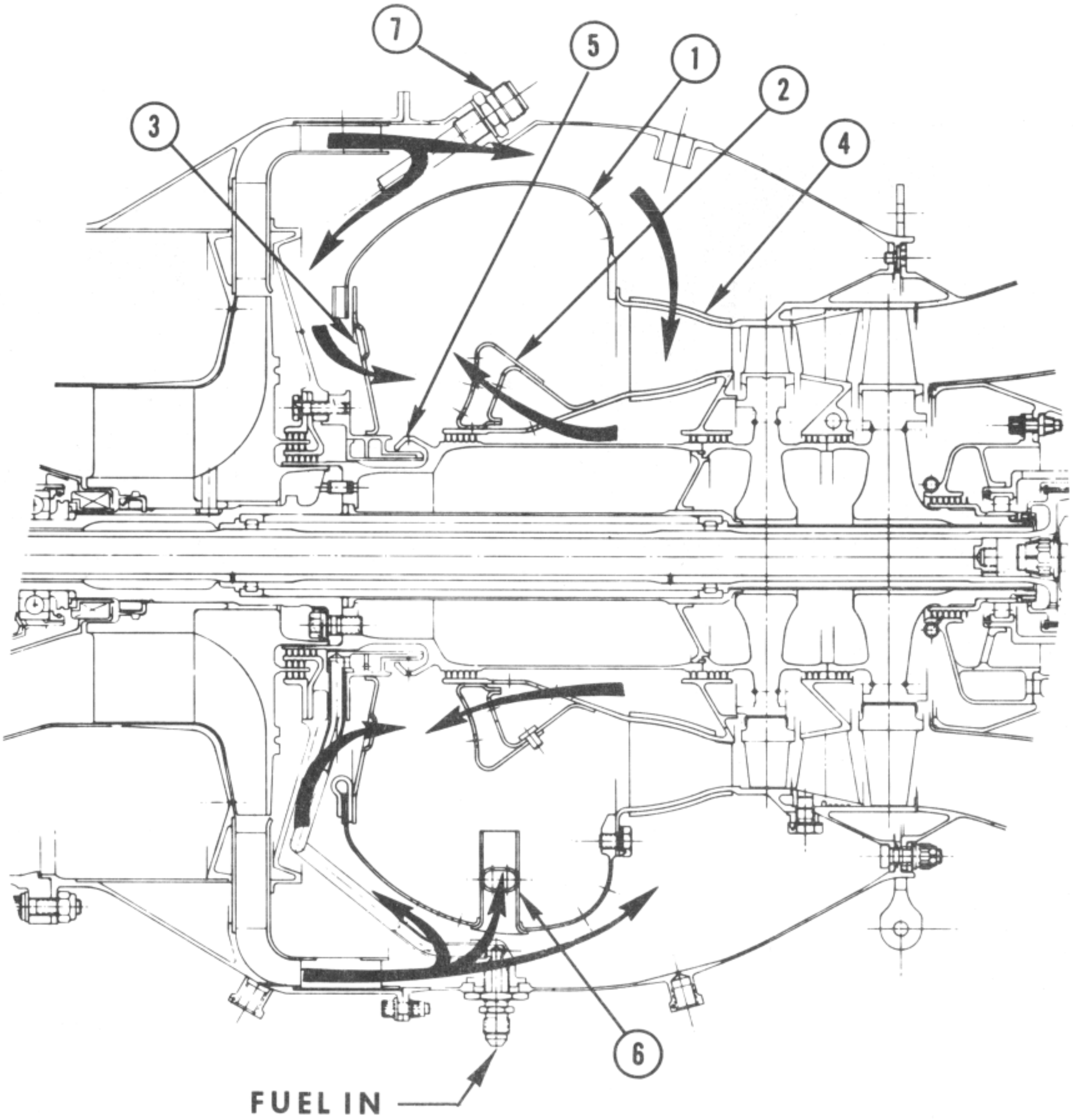


Fig. 2. Continental Model 217-10B Cross Section.



1 — OUTER COMBUSTOR SHELL

2 — INNER COMBUSTOR SHELL

3 — SWIRL VANE

4 — FIRST STAGE TURBINE INLET NOZZLE

5 — FUEL SLINGER

6 — SECONDARY AIR

7 — IGNITOR PLUG

Fig. 3. 217-10B Engine Annular Combustor Showing Airflow Paths and Fuel Injection Arrangement.

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, and no appreciable change in engine operating characteristics observed.

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

The starting fuel solenoid is incorporated as a part of the fuel control, and 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. Conventional ignitor plugs are used to ignite the starting fuel.

During all the starts conducted during this series of tests the standard ignition system was used for both the liquid and emulsified JP-4 fuels and no problems were encountered during any of the starts.

During the test program 149 starts and approximately 26 hours of engine operation were completed while using emulsified fuel - of these, 129 starts and 14.28 hours of engine testing were accomplished during environmental testing and 20 starts and 11.76 hours of testing were accomplished during static sea level operation.

The test program was accomplished in three phases:

1. Bench testing of the fuel control.
2. Engine testing under various environmental conditions.
3. Endurance testing.

1. Bench Testing - 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 accomplished in the fuel control to obtain the same fuel flow schedule with emulsified JP-4 as with liquid JP-4.

During the fuel control calibrations, various fuel flow measuring devices were investigated, but to date, only the Ramapo fuel flow meter was capable of accurate, repeatable flow measurements when emulsified fuel was being used.

The Ramapo fuel meter 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 in the use of the Ramapo is that the consistency of the emulsion being measured must be known and the Ramapo must be calibrated with the particular emulsion that is being used.

During the control calibrations with emulsified fuel, the fuel flow was measured with the Ramapo, and by means of a dead weight system.

Figure 4 shows the fuel control acceleration schedule calibrations for both the liquid and emulsified JP-4 fuels with no adjustments or modifications to the control. The scheduled fuel flow met the engine requirements with both fuels and

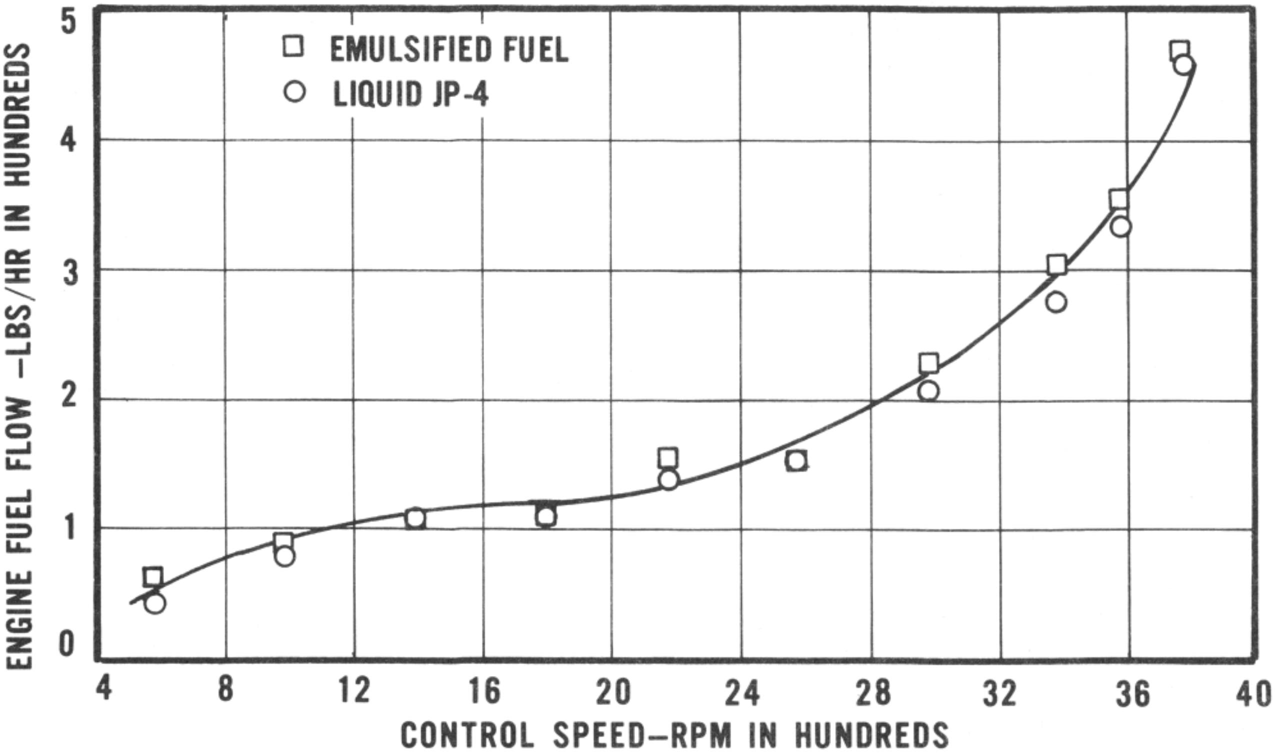


Fig. 4. Calibration of Fuel Control Acceleration Schedule With Liquid and Emulsified JP-4.

the fuel control was used throughout the program without adjustments.

During the laboratory testing the fuel used for the fuel control calibrations was contained in a standard Army helicopter auxiliary fuel tank. Both the liquid JP-4 and the emulsified fuel were pumped out of the fuel tank to the engine pump by means of the 24 volt D.C. submerged boost pump that was supplied with the auxiliary fuel tank.

The emulsified fuel was pumped out of the shipping containers (50 gallon drums) into the auxiliary fuel tank by means of a portable electric motor driven pump that was modified to reduce the pump speed.

With this fuel transfer pump arrangement, emulsified fuel flows of 5.0 to 7.0 GPM were possible without causing the emulsified fuel to break down. In fact, in most instances, transferring the fuel from the shipping containers to the fuel tank generally caused a slight thickening of the emulsified fuel.

During the course of the test program different types of pumps were tried and it was found that slow turning gear pumps were the best for transferring fuel from one container to another provided that the full capacity of the pump could be used. All attempts to regulate the pump flow by by-pass valves were unsuccessful in that the fuel being by-passed was broken down by the shearing action of the by-pass valve and resulted in some liquid fuel being by-passed.

A centrifugal pump was found to be the best pump for supplying fuel to the engine because it could be used without a by-pass. However, it was found that the centrifugal pumps worked satisfactorily with the emulsified fuel only as long as a positive head pressure was maintained at the centrifugal pump inlet.

It was also noted that with the centrifugal pumps some breakdown of the emulsified fuel occurred at low fuel flows. At moderate to high (100 to 450 pounds per hour) fuel flows no breakdown of the emulsified fuel was observed.

2. Environmental Testing - The engine used for this environmental testing consisted of the gas generator section of the YT-67-T-1 turboshaft engine. This was done to facilitate the environmental testing. The engine was calibrated at the Detroit facility to obtain base-line performance.

The static sea level testing consisted of calibrations and transient recordings of engine starts and accelerations using liquid JP-4 and emulsified JP-4 fuel. For this testing the fuel was stored in the previously mentioned auxiliary fuel tank.

Both the liquid JP-4 and the emulsion were supplied to the engine from this 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 5 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 tested.

Figure 5 also shows the amperage required by the electric motor to supply fuel to the inlet of the engine mounted fuel pump. From Figure 5 it can be seen that approximately 0.4 AMP more is used when pumping the emulsion than when pumping liquid JP-4 fuel.

This nominal increase in power required and reduced pressure available may require slightly larger boost pumps in aircraft fuel systems.

During the sea level testing starts, including false starts, accelerations and decelerations were made using both liquid and emulsified JP-4 fuels. No significant change in engine operation could be noted when using the emulsified fuel.

The engine was then installed in the environmental chamber where high and low temperature starts, simulated altitude starts and simulated altitude operation were checked out using both liquid and emulsified JP-4 fuels.

No problems whatsoever were encountered that could be attributed to using emulsified JP-4 fuel. Successful starts were made throughout the ambient temperature range of +130°F to -40°F and to simulated altitudes of 15,000 feet. A successful light-off and acceleration was made at -60°F with emulsified fuel, but the start was aborted when the engine exceeded the normal starting temperature limits at approximately 15,000 RPM gas generator speed.

Examination of the engine transient data showed that the over-temperature condition was caused by too much fuel entering the engine because of improper scheduling by the fuel control. Further engine testing showed that the same condition existed when a start attempt was made at -55°F while using liquid JP-4 fuel.

The starts that were made at the various ambient conditions were very similar, either with the emulsified or liquid JP-4 fuel and only varied within the range of normal fuel control fuel scheduling.

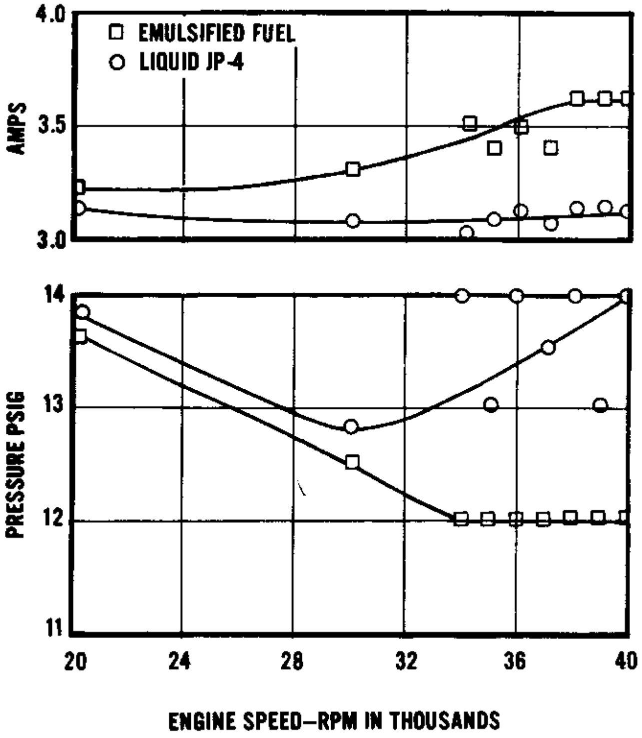


Fig. 5. Fuel Pump Inlet Pressure and Fuel Pump Amperage Requirements for Liquid and Emulsified JP-4 Fuel.

Engine operation was conducted over a range of altitudes up to 15,000 feet and 0.5 Mach Number with both liquid and emulsified JP-4 fuels and no significant change in engine operation could be observed. It was noted however, that engine operation tended to be more stable with emulsified fuel, and the engine had less tendency to undershoot or overshoot when the engine conditions were changed. This tendency is probably due to the non-Newtonian characteristics of the fuel and may be very desirable in certain applications.

3. Endurance Testing - 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.

The fuel control system used on the engine was identical to the fuel control system that is normally used on this engine when using liquid JP-4 fuel. No modifications whatsoever were made to the fuel control system. In fact, the fuel control system used for the endurance test was the same one used for the environmental testing. It was used without being disassembled and was used in order to have a control system with a maximum amount of exposure to emulsified fuel.

The fuel control was calibrated prior to being installed in 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 fuel valve and prevented the minimum fuel valve from closing completely. This stuck valve could also have accounted for the high fuel flows encountered during the starting tests. The fuel control was recalibrated and installed on the endurance engine. No further dirt problems were encountered with the fuel control.

During this portion of the testing, the liquid JP-4 fuel was supplied by the standard test cell system and the emulsified JP-4 fuel was contained in the Army helicopter auxiliary fuel tank and pumped to the engine by means of the submerged 24 volt D.C. fuel pump.

The test cell fuel system was modified so that the fuel could be transferred back and forth between liquid JP-4 and emulsified JP-4 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 fuel pump.

A sight glass was installed in the test cell 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 engine mounted fuel pump.

During all phases of engine operation the emulsified fuel observed in the sight glass consisted of at least 95 percent emulsion whenever the emulsified fuel was being used. When the engine was operated above flight idle conditions solid emulsion was observed in the sight glass. When the fuel system was transferred from liquid JP-4 to emulsified JP-4 fuel, approximately 3.0 to 5.0 seconds were required for the liquid JP-4 to be replaced with emulsified fuel. There was no change in engine operation when switching from one fuel to another at any engine operating condition.

The engine was calibrated while using first liquid and then emulsified JP-4 fuel. Figures 6 through 9 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.

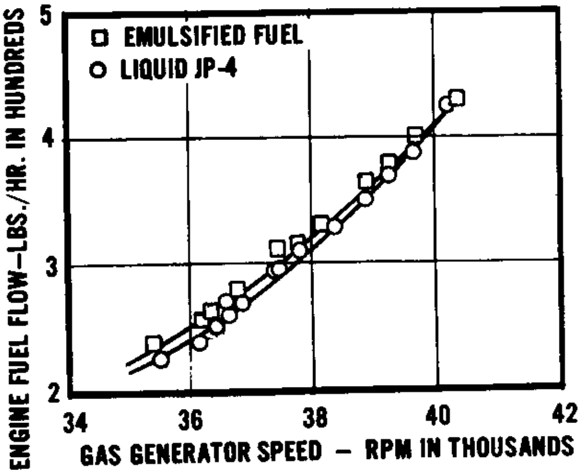


Fig. 6. Engine Fuel Flow Versus Gas Generator Speed.

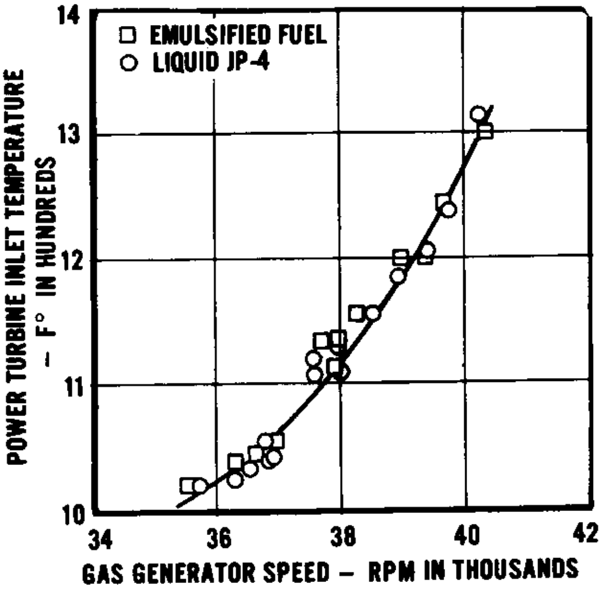


Fig. 7. Power Turbine Inlet Temperature Versus Gas Generator Speed.

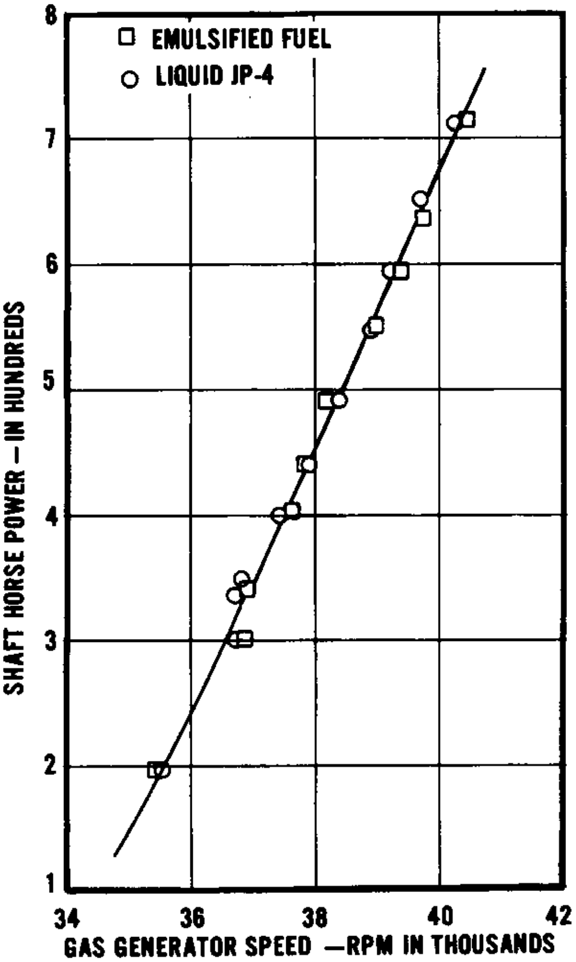


Fig. 8. Engine Shaft Horsepower Versus Gas Generator Speed.

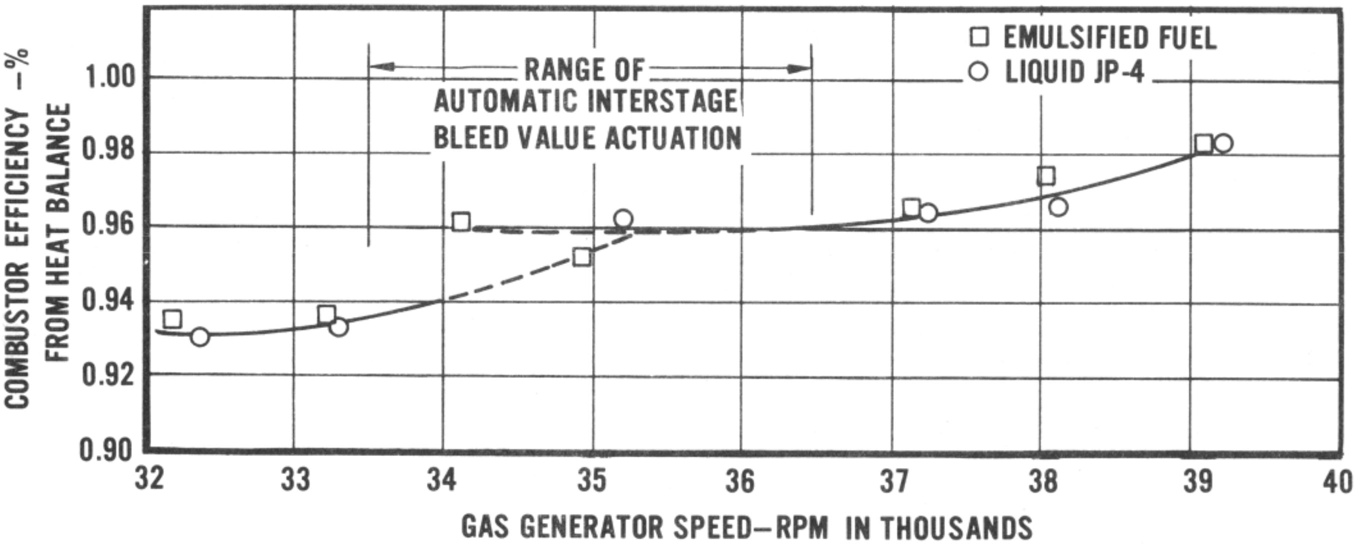


Fig. 9. Evaluation of Combustor Efficiency Calibration With Liquid and Emulsified JP-4 Fuel.

Figures 10 and 11 are plots of engine starting characteristics for both liquid and emulsified JP-4 fuels. Figure 10 shows a start using liquid JP-4 fuel. From Fig. 10 it can be seen that the engine attained stabilized ground idle speed 15.0 seconds after ignition occurred and the maximum Power Turbine Inlet Temperature (PTIT) during the start was 1390°F. Figure 11 shows a start using emulsified JP-4 fuel, and it can be seen that the engine attained stabilized ground idle speed 16.3 seconds after ignition occurred and the maximum PTIT during the start was 1340°F. The most significant difference between the two starts was that the time to ignition was approximately 4.0 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 12 through 13 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 2.0 seconds and fully stable operation was achieved in 4.5 seconds.

Following the calibrations and transient recordings a 30-hour endurance was started with the engine using only emulsified JP-4 fuels.

After approximately 4.0 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 removed from the test cell and disassembled.

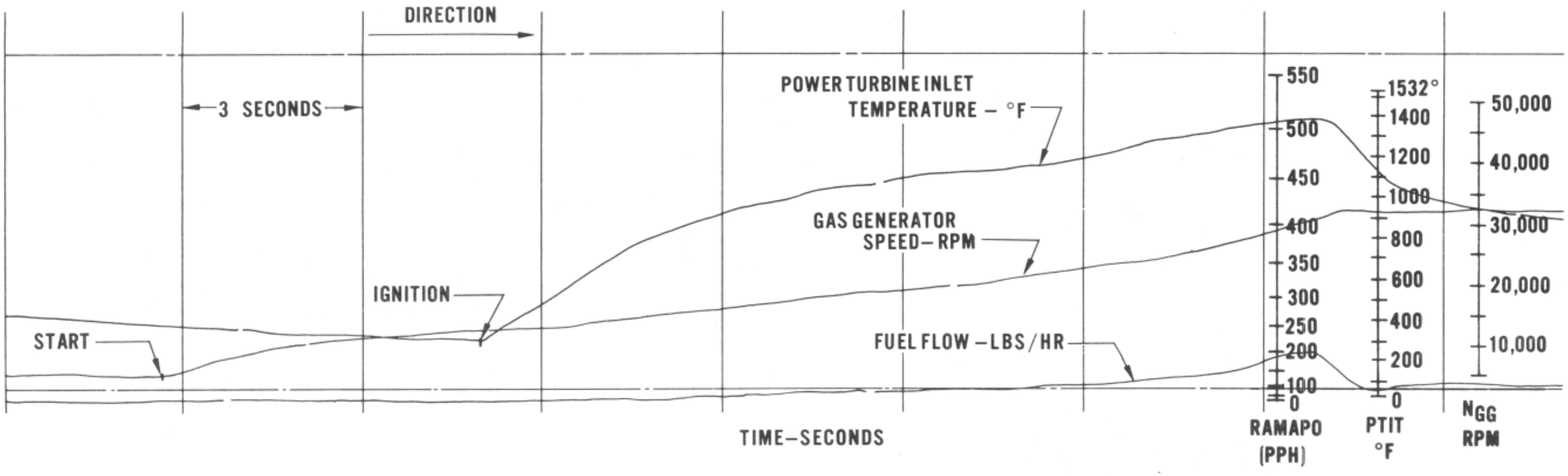


Fig. 10. Transient Recording of Engine Start Using Liquid JP-4 Fuel.

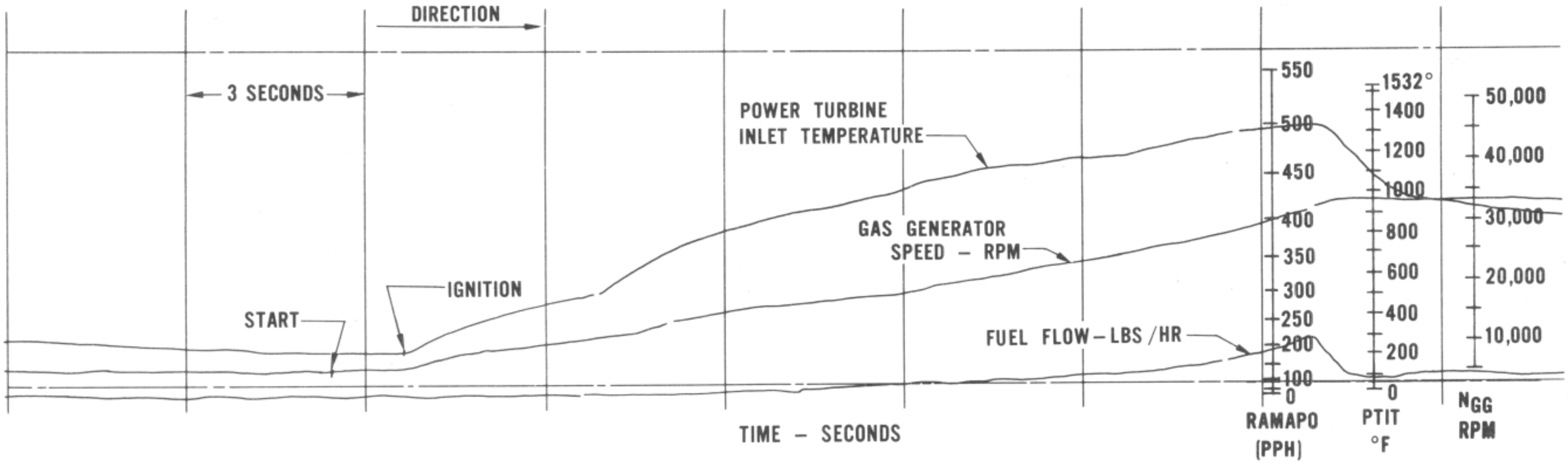


Fig. 11. Transient Recording of Engine Start Using Emulsified JP-4 Fuel.

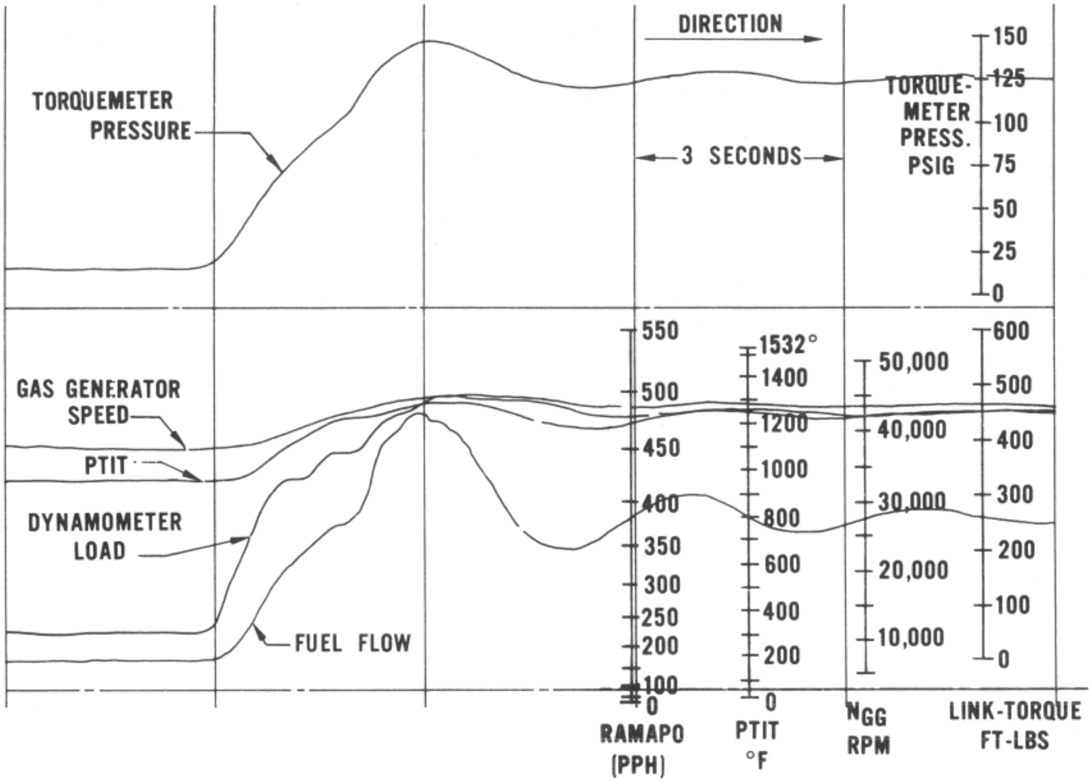


Fig. 12. Power Transient Recording of Engine Acceleration From Flight Idle To Maximum Power Using Liquid JP-4 Fuel.

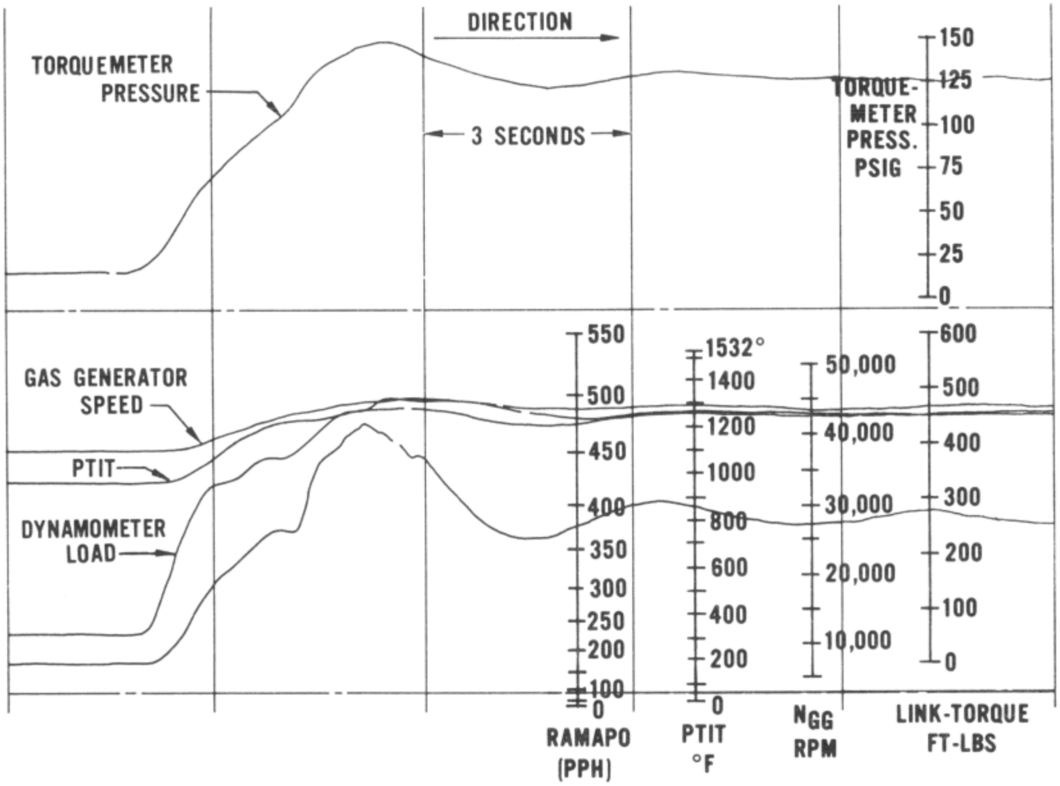


Fig. 13. Power Transient Recording Of Engine Acceleration From Flight Idle To Maximum Power Using Emulsified JP-4 Fuel.

Visual inspection revealed a severe scaling of the "hot section" parts, particularly the gas generator turbine blades, Fig. 14.

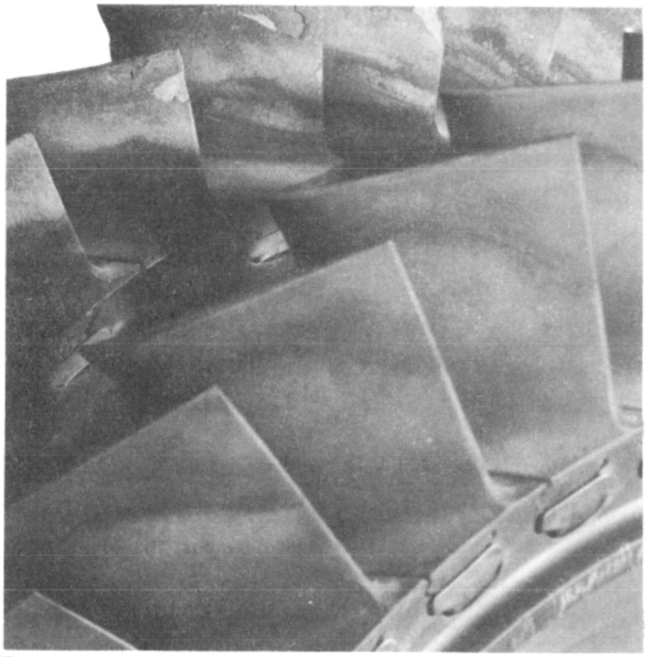


Fig. 14. Gas Generator Turbine Blades Showing Deposits After 11.0 Hours Of Operation With Emulsified JP-4 Fuel.

Further inspection revealed that, in addition to the scaling, the turbine blade airfoil section contours were changed because of erosion of 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 caused unstable engine operation.

Subsequent investigations disclosed that the scaling was caused by a corrosion of the supper-alloy metals, this is generally described as sulfidation and is a current problem with 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 only have occurred if the ingredients which cause sulfidation were present in copious amounts.

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 15 and 16 show sections of the control with quantities of emulsion still adhering to the fuel control components. It was noted, however, that the emulsion 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.

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 million parts of fuel (30 PPM). This is considerably more sodium 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 an engine.

Figure 17 shows the deterioration of the fuel control shut-off 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.

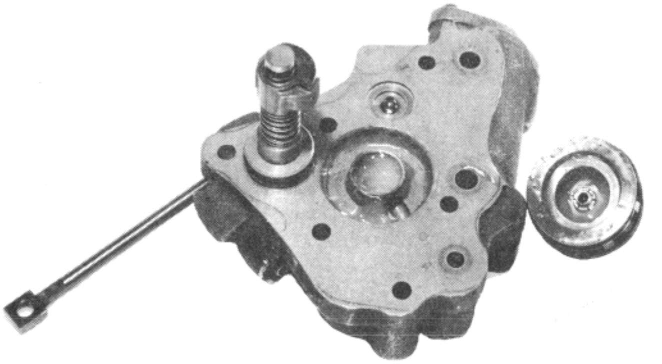


Fig. 15. Fuel Control Feedback Diaphragm Retainer Showing Light Fretting On Surface of Retainer. Also Note Quantity Of Emulsion Trapped In Fuel Control Feedback Chamber.

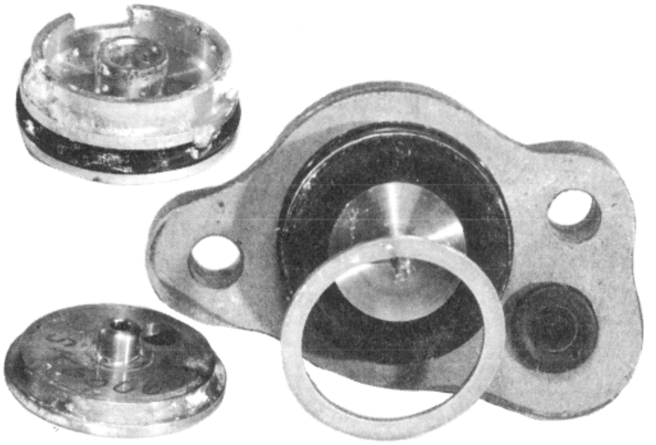


Fig. 16. Fuel Control Minimum Flow Make-UP Valve Parts With Emulsion Deposits. Note White Powder-Like Substance On Lower and Middle Pieces.

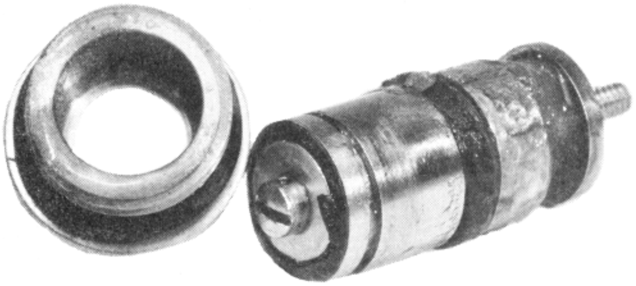


Fig. 17. Fuel Control Shut-Off Valve Showing Deteriorated Rubber Valve Seat. Note Quantities Of Emulsion Adhering To Piston.

The engine mounted fuel pump was also disassembled and inspected and 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.

To summarize, it can be said that:

1. Engine operation (steady state, starting and transient) prior to encountering the "hot corrosion" problem was unaffected by using emulsified fuel.
2. Engine power output was the same with emulsified fuel as with liquid fuel.
3. Engine fuel consumption on the basis of heating value was the same with both fuels and was increased 2 to 3 percent on a weight basis, when using emulsified fuel.
4. Over the range tested, combustion efficiency was not affected by the use of emulsified fuel.
5. Present technology fuel control systems can handle the emulsified fuel.
6. Use of thickened fuels will require a new technology in the design of fuel filters, fuel pumps, fuel flow measuring devices and handling practices.
7. The very encouraging results of this program indicate that emulsified fuels can be brought to a point of operational use if sufficient development effort is continued.
