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485 Lexington Avenue, New York, N. Y. 10017

Initial Experience with Emulsified Fuels at AVCO Lycoming

George Opdyke, Jr.
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BACKGROUND

Programs directed toward reducing the fire hazard in aircraft accidents have shown that the use of an emulsified fuel offers a promising approach. In an emulsified state, a hydrocarbon fuel is a very thick liquid with a significantly lower evaporation rate than normal liquid fuel. If ignited, it burns at a slow rate, and also flows relatively slowly, thus doubly reducing the rate of spread of a fire. Since a significant percentage of aircraft accident fatalities occur as a result of fire rather than the crash itself, a fuel in the aircraft tank which is difficult to ignite and burn will help to minimize the fatality rate. Of course, an emulsified fuel must at the same time be capable of flowing from the aircraft fuel tank to the engine, of being pumped and metered in the fuel control, and then adequately burned in the engine's combustor so that the aircraft and engine will continue to perform in a safe and reliable manner. Tests during the past year at Avco Lycoming have indicated that jet fuel, in this mayonnaise-like form, can be handled and burned in our gas turbine engines. There are, however, a number of development type problems that require a solution prior to operational usage of these fuels.

An emulsion is a heterogeneous system, consisting of one immiscible liquid finely dispersed into another in the form of colloidal size droplets, usually not round. The immiscible liquid that is separated into droplets is called the internal or disperse phase. In the tests at Avco Lycoming the disperse phase was always JP-4 fuel, usually in a volume concentration of approximately 97%. The liquid forming the matrix surrounding the droplets is called the external, or continuous phase. This phase contains an emulsifying agent and other chemicals which make it possible for this small quantity of continuous phase to coat the entire particle surface of the disperse phase. This results in the JP-4 being effectively isolated from its normal environment and the continuous phase being almost exclusively in contact with the tanks, lines, and other apparatus through which the emulsion passes. These parts, which were originally designed for liquid fuel, are now in contact with the continuous phase, and the effect of this change of fluid on these parts must be determined.

TEST EMULSIONS

The emulsions tested during the past year were:

1. Emulsion A had a 2.8% aqueous external phase containing a corrosion inhibitor and a biocidal agent for the suppression of bacterial and algae growth. It was delivered in uncoated mild steel drums, and was used over a period of several months.

2. Emulsion L contained a 3% nonaqueous continuous phase, and had a yield strength of approximately 1900 dynes/cm^2. It was delivered in steel drums coated internally with polypropylene and was also used over a period of several months.

ABSTRACT

This paper discusses the major effects observed in feasibility testing of three emulsified fuels in several gas turbine combustors, fuel controls, and fuel system component parts, and in three Avco Lycoming gas turbine engine models. Engine operation was essentially unaffected at power levels normally used for low altitude flight, but combustion was inhibited at starting and at altitude conditions. The fuel controls performed reasonably well, but showed that modifications will be required for reliable long term operation.

3. Emulsion T was made at Avco Lycoming under the direction of the manufacturer. This emulsion contained an aqueous external phase and was made with both 95% and 97% proportions of JP-4, using two emulsifying agents. The 97% formulation had a yield strength of 1300 dynes/cm^2. A fuel emulsifying and pumping console was procured from the emulsion manufacturer to serve as special laboratory equipment for the preparation of 50 gal batches of emulsion. A schematic of this console is shown in Fig. 1. A Roper gear pump was used to recycle the emulsifying agent to which JP-4 was slowly added at the pump inlet until the proper proportions were obtained in the reservoir tank. At this point, the emulsion yield strength was such that it could be readily formed into a "snowball." The emulsion was pumped from the reservoir tank for engine or component testing with an air powered piston pump with a follower plate resting on top of the fuel in the tank to insure that air did not channel into the submerged pump inlet. The piston pump used during the tests with emulsion A and T contained some mild steel parts which rusted and contaminated the emulsion pumped into the engine fuel control.

TEST PROGRAM SUMMARY

The test program conducted with emulsified fuel during 1966 consisted of four major areas of investigation.

1. Bench tests of the T53 and T55 engine fuel controls. The former is manufactured by Chandler-Evans and the latter by Hamilton Standard. They are both hydromechanical controls.

2. Bench tests of other fuel systems components, including filters, valves, a fuel-oil heat exchanger, flow dividers, and fuel injectors.

3. Laboratory tests of atomizing combustors at simulated altitude conditions. These included small can combustors as well as a full size annular engine combustor.

4. Sea level steady state performance and transient tests on T53 engine models with both atomizing and vaporizing combustors and on a T55 engine with an atomizing combustor.

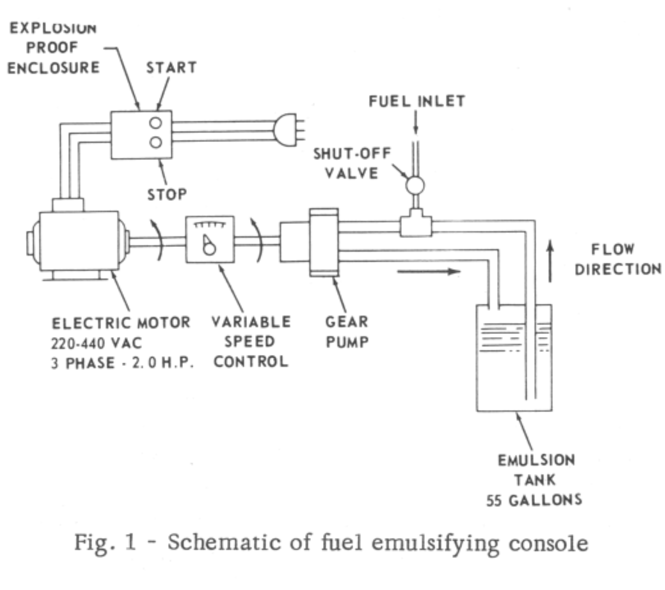

Fig. 1 - Schematic of fuel emulsifying console

FUEL CONTROL BENCH TESTS

Operating mockups of the T53 and T55 fuel systems were simulated on the laboratory flow bench, and a schematic of each system is given in Fig. 2. Fuel control calibrations were made with both MIL-F-7024 Type II calibrating fluid and emulsified fuel at ambient temperature, with flow rates measured by turbine elements for the liquid and a Flo-Tron mass flow meter and/or a time-weight measurement for the emulsions. The T53 control was calibrated on all three 97% emulsions and the T55 control was calibrated on emulsions L and T. In every case, the fuel control scheduled the same flow rates with emulsion as those obtained using calibrating fluid (Figs. 3 and 4).

When appreciable dirt, rust, and scale was contained in the emulsion, as was the case during some of the testing with emulsion T, neither control could generate the correct flow schedule. The contamination caused wear of the metering valves and pump elements which effectively destroyed the control's capability to meter any fuel properly. Since it is characteristic of any emulsion that all dirt contained in it never settles out, the design of any fuel metering valve or operational element which is in contact with emulsified fuel must be resistant to all the contamination contained in the emulsion at that point.

There was little indication of control instability when using the emulsion L in the fuel controls. Transient response

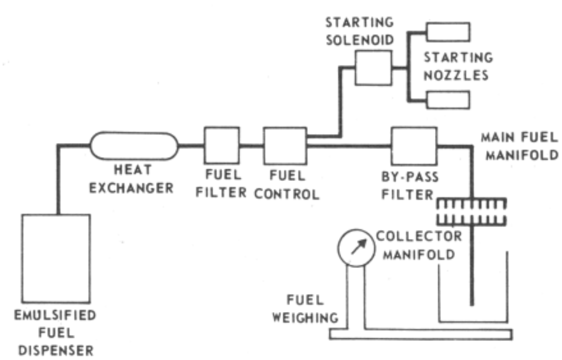

Fig. 2A - Schematic of T53 engine fuel system

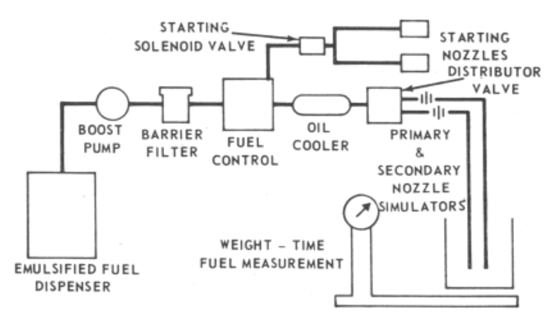

Fig. 2B - Schematic of T55 engine fuel system tests were run in the T53 fuel control with both calibrating fluid and emulsion L by simulating a step change in the metering valve position while recording the pressure drop across this valve as a function of time. The transient response was identical with both fuels. Likewise in the T55 fuel control, tests to determine the frequency response of the power turbine (N_{II}) servo loop showed that there was no major difference between emulsion T and calibrating fluid at frequencies up to 3 cycles per second. Above 3 cps there was a slight shift in both phase and gain apparently resulting from air contained in the sheared emulsion acting as a spring in the servo loop. The gas producer (N_I) servo performed the same on both fuels during simulated accelerations from 50 to 90% speed.

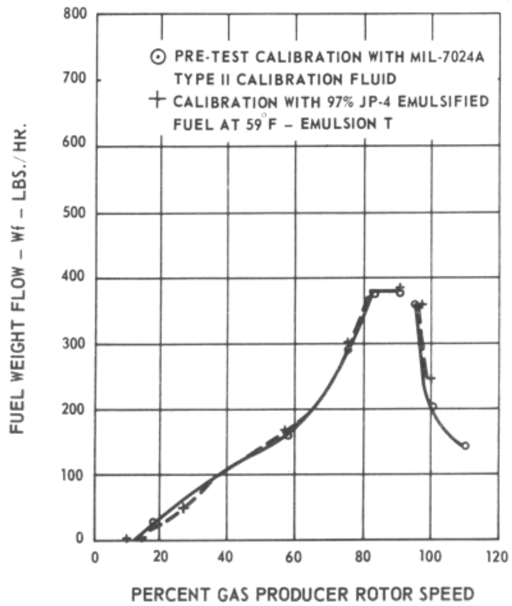

Fig. 3 - T53 fuel control calibration

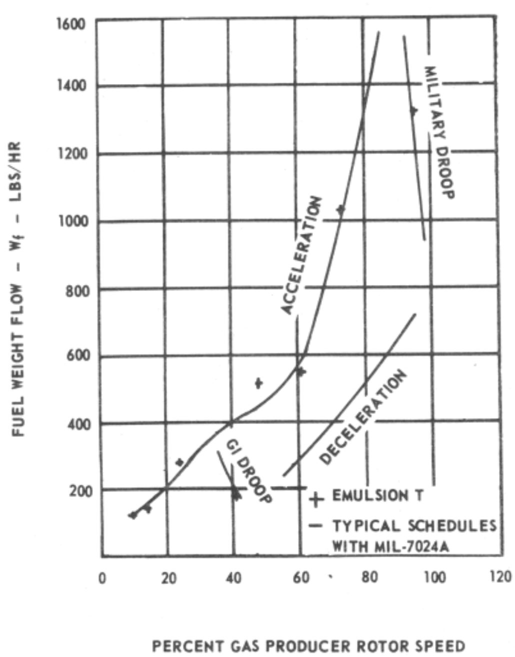

Fig. 4 - T55 fuel control calibration

Leather cup seals are used extensively in the T53 control and they have proved to be satisfactory with all types of liquid fuels. Endurance tests were run with both emulsions T and L. The seals showed no evidence of wear after 125 hr of cycling with emulsion L, but, with emulsion T complete wear failure occurred in less than 100 hr of cycling.

During T55 fuel control tests with emulsion L, samples of fuel were taken at three points in the fuel system to determine the degree of emulsion breakdown. At the discharge of the supply pump there was no change in the emulsion; after passing through a 40 micron barrier filter, the emulsion contained about 6% free fuel; and at the fuel control gear pump discharge it was broken down to about 90% free fuel. In another test, holding a fixed fuel flow, an increase of gear pump speed increased emulsion breakdown to 96%. With a single pass of emulsion through the pump (that is, no bypass of fuel back to the pump inlet) the breakdown was much less, indicating that repetitive shearing by the gear pump and bypass of a partially broken down emulsion back to the pump inlet is a very effective method of de-emulsification. The satisfactory control behavior described above is to a high degree attributable to this de-emulsification. Tests on spool valves, where the valve passages were artificially filled with the original emulsion without going through the gear pump, show a considerable dead band with emulsion L where none occurred with calibrating fluid. Fig. 5 shows the pressure drop across this valve during a valve movement of ± 0.003 in.

Corrosion tests were conducted on both T53 and T55 controls. No reaction of any type occurred with emulsion L, but the corrosion caused by emulsion T was extremely bad. (See the photo of the T53 fuel control in Fig. 6). Emulsion T rusted linkages of 400 series stainless steel, even when flash chrome plated, and pitted the anodized aluminum control housings. This emulsion also caused sticking of the servo amplifier valves in the T53 control because of increased friction between the valve stems and the 0-ring seals resulting from corrosion.

It appears that emulsified fuel with characteristics similar to those of emulsion L is compatible with these two hydromechanical controls at standard ambient temperatures, and probably also at higher than ambient temperatures. Operation at lower temperatures, when an emulsion might not break down as easily, is still to be investigated.

OTHER FUEL SYSTEM COMPONENTS

FUEL FILTER - Relieving filters with 10 micron paper cartridges are used at the inlets of both engines' fuel system. This filter's relief valve opened when any emulsified fuel was used and permitted contaminants to be carried into the fuel control. When a 40 micron wire filter was substituted, the relief valve stayed closed because the pressure drop across that filter element was only 2 psi.

The fuel filter located after the fuel control in the T53 fuel system has a filter element with 0.005 in. (127μ) openings. It was tested as part of the T53 fuel system test with emulsion T. There was no increased pressure drop or clogging of this filter caused by this emulsion.

HEAT EXCHANGER - A fuel/oil tubular heat exchanger is used on the T55 engine and is located downstream of the fuel control, with the fuel flowing through the small tubes. The pressure drop across this oil cooler was significantly higher with emulsion T (after passing through the fuel control) than with calibrating fluid, as shown on Fig. 7. The heat rejection rate was not measured, but since the heat transfer coefficient of an emulsion is reported to be less than that of liquid fuel, some reduction of the heat rejection rate is to be expected, which could be a problem at some engine operating conditions.

FLOW DIVIDER - Both T53 and T55 engines with atomizing combustors use dual orifice fuel injector nozzles. A single flow divider valve downstream of the fuel control is used to schedule fuel flow to the primary and secondary injector orifices. Tests with the T53 flow divider showed excessive hysteresis and incorrect flow scheduling with emulsion L which required that orifices in the flow divider be increased in diameter in order to make it operate satisfactorily.

FUEL INJECTOR NOZZLE - This last item in the engine's fuel system contributes to the breakdown of emulsified fuel. In order to vaporize and burn the fuel properly the droplet size in the nozzle spray must be small over a wide range of fuel flow, and this droplet size tends to increase when emulsified fuel is used.

In order to gain some insight into the problem of spraying emulsified fuel, a variety of fuel nozzles were bench tested. They included commercial oil burner nozzles, aircraft type pressure atomizing nozzles, and air assist nozzles. These

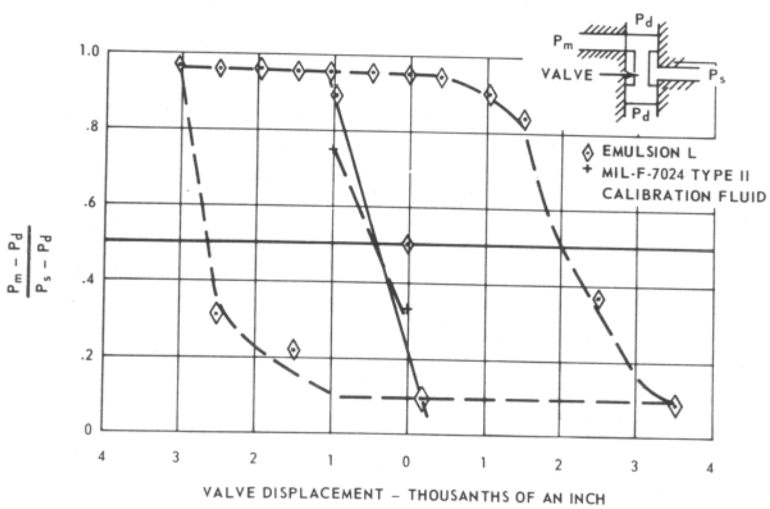

Fig. 5 - T55 spool valve hysteresis with solid emulsion L

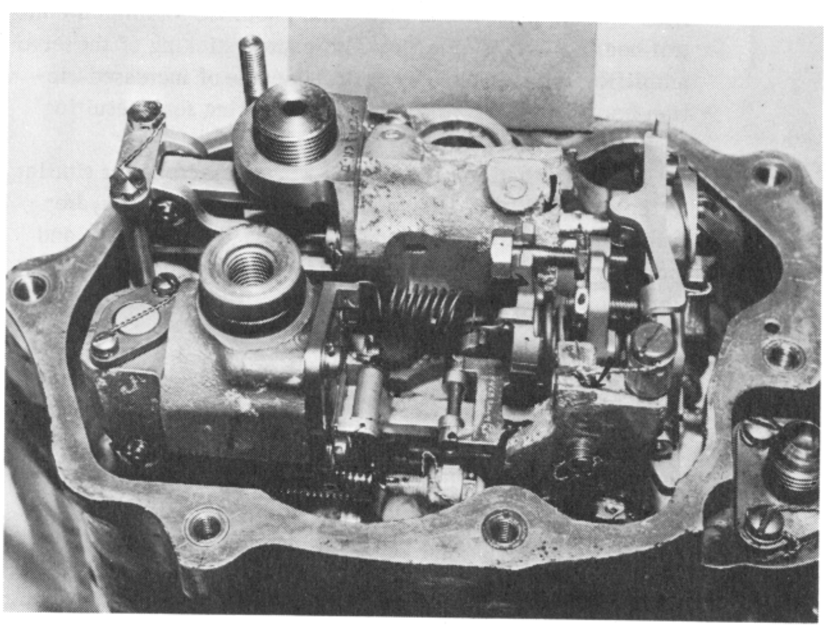

Fig. 6 - Photograph of T53 fuel control computer assembly after operation with emulsion T.

covered a range of sizes from 1/2 gal/hr to 24 gal/hr. Some of the nozzles were also used in burning tests. Although it was evident from the fuel control tests that emulsified fuel is significantly broken down before reaching the fuel injectors, the injector bench tests were performed with solid emulsion to show trends and obtain reasonably consistent results. All test were run at room temperature.

Breakdown tests were run with all emulsions using a T53 ignition nozzle with a flow number* of about 0.1 (1 gal/hr). These showed that the stiffer emulsions -- emulsion T in the 5% formulation and emulsion L with 1900 dyne/cm^2 yield strength -- were broken down significantly less than the looser emulsions -- emulsion T with 1300 dyne/cm^2 yield strength and emulsion A. The breakdown with emulsion T in the 3% formulation was about 90% and with emulsion L about 60%. There was less than 10% variation in breakdown as flow rate was varied as long as the spray was fully formed.

An emulsified fuel requires a higher nozzle pressure drop than does liquid JP-4 in order to obtain a fully formed spray. At low nozzle pressure drops the emulsion does not break clean from the nozzle orifice but instead wets the face of the nozzle tip. This indicates that an increase in coke deposition on the nozzle face could be expected during extended engine operation.

The fuel pressure drop did not significantly affect the emulsion breakdown with the air assist nozzles, but breakdown was greatly influenced by the air assist pressure drop. This is to be expected since the greatest proportion of the energy for atomization comes from the velocity of this air. Even with a relatively large amount of air assist the breakdown of emulsion L was under 60%, less than the breakdown obtained with most of the pressure atomizers tested. However, air assist injectors are of particular interest in spraying emulsified fuel, because they can swallow contamination much more readily than can a pressure atomizing injector of equivalent fuel rate. During the course of this bench test program the small amount of dirt contained in these emulsions collected on the injector screens and increased the pressure drop across these screens causing some spray fluctuations, particularly with the small flow number nozzles.

The flow-pressure drop relationship of all fuel nozzles tested was significantly affected by emulsion. First the yield strength of the emulsion requires some pressure drop across the nozzle before any flow will occur. Secondly, at low flow rates, a slight variation in injector pressure drop has a large effect on flow, and emulsion flows out of the injector almost like toothpaste. Then a transition zone follows in which the spray begins. Once the spray cone is well established, the flow-pressure drop relationship is nearly the same as with Newtonian fluids. Fig. 8 shows these relationships for five pressure atomizing simplex nozzles as determined with emulsion L.

When operating fuel injectors with partially broken down emulsion, the spray also tended to sputter and pulsate somewhat when large particles of emulsion passed through the nozzles.

A more detailed study is required to understand the operation of fuel injectors on emulsified fuel better and to determine which injector design factors will maximize emulsion breakdown, since these injectors provide the final opportunity for de-emulsification.

COMBUSTOR LABORATORY BURNING TESTS

Since emulsions burn so poorly compared with liquid jet fuels, a series of exploratory combustor burning tests were

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*Flow Number = Gallons per hour/Nozzle pressure drop 1/2.

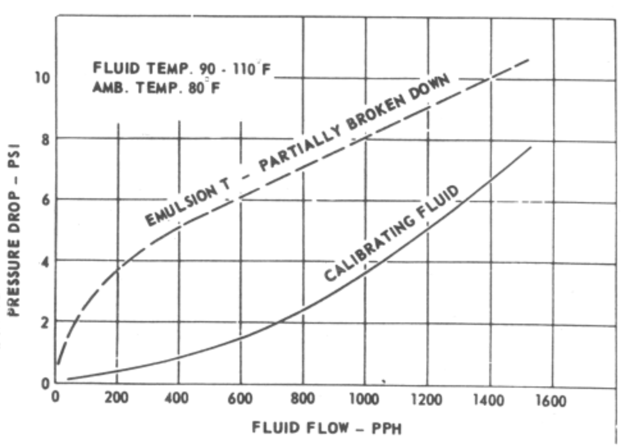

Fig. 7 - T55 oil cooler pressure drop -- fuel flow characteristic

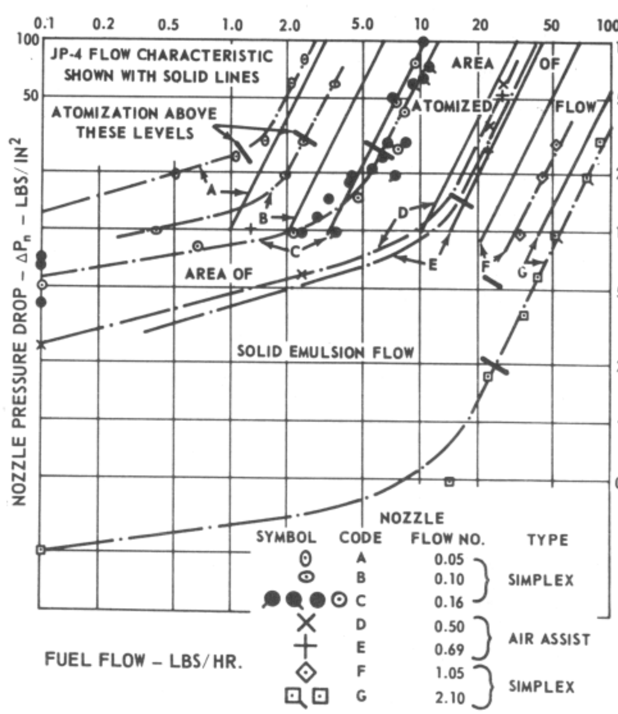

Fig. 8 - Pressure drop-fuel flow characteristic of atomizing injector nozzles

run to determine the magnitude of combustor efficiency loss to be expected when an emulsion is used as a fuel. As was expected, combustion is inhibited to the greatest degree when the fuel injector spray contains a large proportion of solid emulsion.

Three combustors were used: a 2-1/2 in. diameter can combustor, a 5-1/2 in. diameter can, and a production style T53 annular atomizing combustor. Emulsion L was tested in the 2-1/2 in. can while emulsions A and T were used in the other combustors. All tests were run at near ambient pressure; the 5-1/2 in. can and the T53 combustor at ambient temperature and the 2-1/2 in. can at 500 F inlet temperature. The test condition for the T53 combustor would be roughly equivalent to maximum power of the engine at 40,000 ft.

The fuel rate was measured with a linear mass flow meter manufactured by Flo-Tron. This flow meter is based on a hydraulic Wheatstone bridge principle reportedly insensitive to fluid density and viscosity, with readout signals from pressure transducers. Calibration tests showed that the meter gave the same readings with emulsion T as with liquid fuels, but in the combustor tests and in the engine tests intermittent minor electronic difficulties created some uncertainty in the fuel rate indications. Improvements are needed in emulsion flow rate measurement.

In the 5-1/2 in. diameter can, no ignition or combustion was possible with emulsion T in the 5% formulation, but the 3% emulsion T and emulsion A burned reasonably well, with only a 10-15% loss in efficiency. The flame length increased substantially. For a given flame length, about 60% more JP-4 could be burned than emulsion. The lean stability limit was also worsened. Fig. 9 shows the test results.

The flame length of emulsion L in the 2-1/2 in. can also increased in about the same proportion as in the 5-1/2 in. can. The stability range was very much reduced and combustor efficiency dropped about 20%. (See Fig. 10 for the test results.)

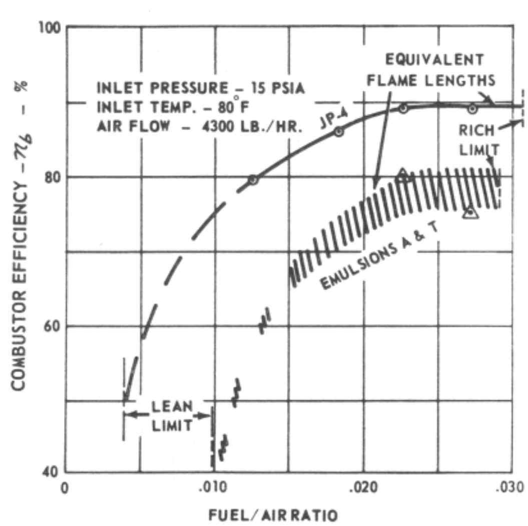

Fig. 9 - 5-1/2 in. can combustor performance - Emulsions A and T

In the T53 atomizing combustor, the flame length again increased significantly compared to JP-4. The combustor efficiency was reduced by 10-15% (Fig. 11).

In all these tests, the emulsion was supplied to the combustor as nearly unseparated as experimentally possible so that the breakdown of the emulsion in the fuel injector spray was between 70 and 95%. The strongly reduced vaporization rate of the emulsion contained in these sprays is probably the major reason for the increase in flame length and for some of the efficiency loss, but in addition there is probably also a reduction in the specific reaction rate in the

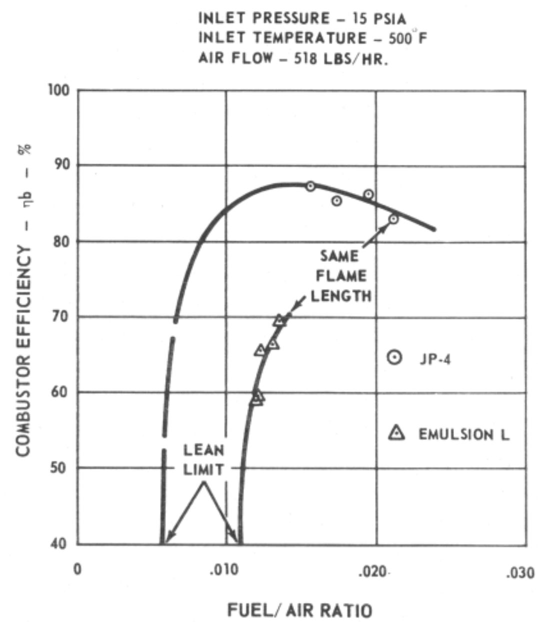

Fig. 10 - 2-1/2 in. can combustor performance - Emulsion L

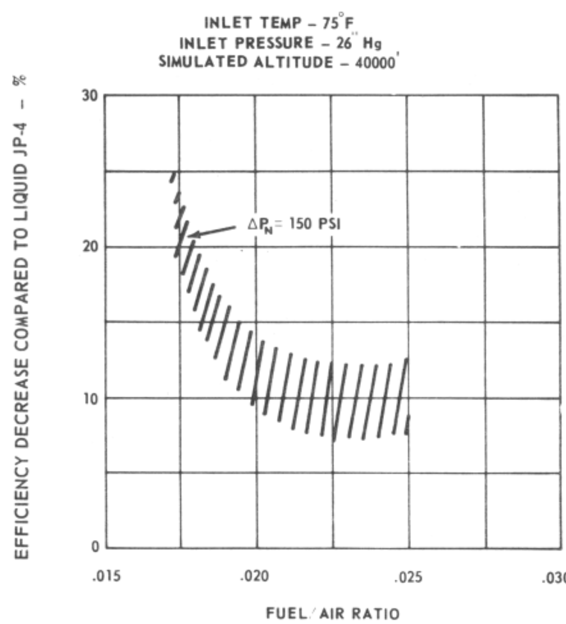

Fig. 11 - Effect of emulsion T on T53 atomizing combustor efficiency

primary zone which permits an increased proportion of the reactants to reach and be quenched in the diluent zone. Since it is likely that under some engine operating conditions a small amount of solid emulsion will reach the combustion zone, additional combustion tests are needed to determine the relationship between emulsion breakdown and combustor performance. Once this is better understood, com bustor modifications should be evaluated to minimize any combustor efficiency loss when switching from JP-4 to emulsion.

ENGINE TESTING

Three different engine models were tested with emulsified fuel. First, a T53 engine with the atomizing combustor previously evaluated in the Combustor Laboratory was tested with emulsions A and T. This same engine model was also outfitted with a production style vaporizing combustor for a 6 hr calibration with emulsion T. The third engine, a T55 model with an atomizing combustor, was also calibrated with emulsion T in a test which inadvertently illustrated the corrosive effects of this emulsified fuel. At high power, all engines operated as well with emulsions as with JP-4, but some loss in performance occurred at idle speeds or in starting.

The calibrations on the atomizing T53 engine were short: first a start on JP-4, then a fuel switchover at 75% normal rated power to emulsion T, followed by a three point calibration and shutdown. The engine was restarted on emulsion T and switched to emulsion A at 75% power for another three point calibration. There were no measurable changes in engine performance noted in this test. The comparative fuel rate and power speed curves are given in Figs. 12 and 13. It is significant that during the entire test of this engine the temperature of the fuel in the fuel injection manifold was always in excess of 160 F, a temperature sufficiently high to cause considerable thermal breakdown of these emulsions. This breakdown, plus that which occurred in the engine's fuel system and in the atomizing nozzles, probably insured that very little solid emulsion was injected into the combustor. If this was the case, these test results are readily understandable.

The fuel system of the vaporizing T53 engine was the same as the atomizing engine except that the former's fuel manifold does not absorb as much heat from the engine and there are no pressure atomizing fuel injectors, except for small ones used only during the starting cycle. The emulsion was, therefore, less broken down when it was injected into the combustion chamber. In spite of this, the engine performance was essentially the same on emulsion and JP-4 above 75% normal rated power, when the fuel rate was corrected for the 4% lower heating value of the emulsion. Likewise, jam acceleration time from flight idle to take-off power increased by 11%, exactly as predictable from the reduced heating value of the emulsion. At speeds below the 75% power point, the emulsion fuel rate became increasingly higher than the JP-4 value until near ground idle where engine speed could not be sustained. Starts were not possible with emulsion except for immediate restarts after a shutdown from above 30% normal rated power. The fuel rate-engine speed comparison is shown in Fig. 14. No other engine performance parameter was altered, indicating that only combustor efficiency was affected.

Some amount of fuel system development will be required before this vaporizing style combustor could satisfactorily

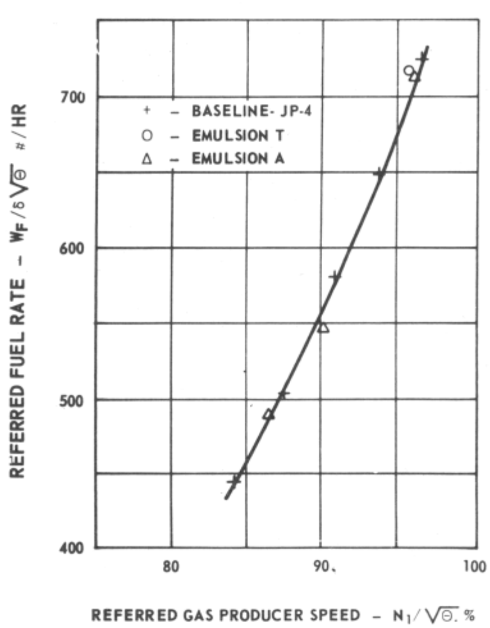

Fig. 12 - T53 engine-atmozing combustor - Fuel rate comparison, Emulsion A and T versus JP-4

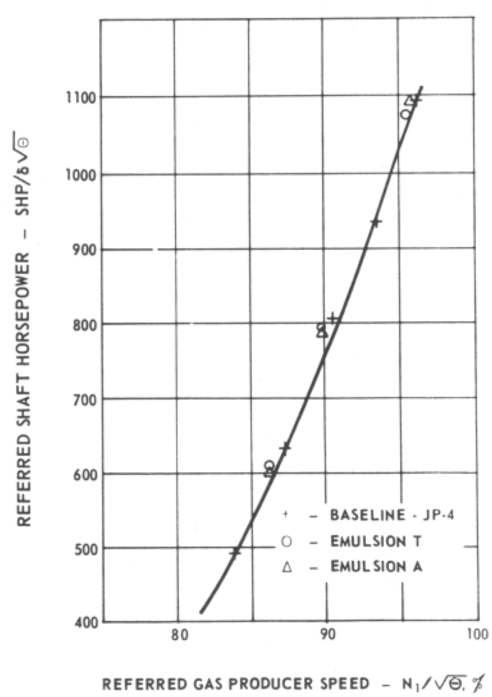

Fig. 13 - T53 engine atomizing combustor - Shaft horsepower comparison

use emulsified fuel. This would probably take the form of additional mechanical de-emulsification in the fuel system, possibly by simply adding atomizing nozzles to inject fuel into the vaporizing tubes.

The T55 atomizing engine performed similarly to the T53 atomizer, but this test was plagued with experimental difficulties. The Flo-Tron flow meter was erratic, the fuel control regulated poorly because of wear and corrosion in the valves caused by the emulsion, and the test was terminated prematurely by a failure of the fuel pump shaft, which was unrelated to the use of emulsion. The performance of the engine was difficult to assess because the fuel control instability prevented the obtaining of sufficient stabilized steady state data. The limited data available indicate that all engine operating parameters were essentially unaffected by emulsified fuel. Above approximately 30% normal rated power, the emulsion caused no increase in engine fuel rate, when corrected for heating value loss. The fuel rate-speed comparison curve is shown in Fig. 15.

Post test inspections of the turbine sections of the engines showed no evidence of damage from emulsified fuel. In the T53 vaporizing combustor there were slight coke deposits inside the vaporizing tubes and some coke on the combustor liner, probably caused by solid emulsion depositing on it during attempts to run at ground idle. The fuel system components were corroded and, in the T55 engine, the fuel injector nozzle screens were blocked with rust and dirt, decreasing their flow rate appreciably.

These engine tests show that at high pressure and temperature levels, conditions favorable for combustion, the use of emulsified fuel does not affect engine operation. The extent of this unaffected region depends to a large extent on how well the components of the fuel system break down the emulsion into free fuel.

EVALUATION OF TEST RESULTS

The tests on emulsified fuels conducted during the past calendar year at Avco Lycoming have involved all component parts of our gas turbine engines which are affected by fuel. These tests have been exploratory in nature, intended to give an indication of the major effects of using emulsified fuels and to indicate areas of immediate or potential problems. To this degree, the conclusions drawn are somewhat preliminary.

The overwhelming impression from these tests is that all tested items performed better than expected with emulsified fuels: there were no major problems of a fundamental nature. From the standpoint of starting, it appears that engines with an atomizing fuel injection system are better suited to emulsified fuel use than vaporizing combustors.

Combustion of emulsified fuel is inhibited except at conditions very favorable for combustion. A large degree of emulsion breakdown prior to injection of the fuel into the combustor will minimize this effect. Pressure atomizing nozzles, with areas of high shear in their swirl chambers, appear to do a fair job of de-emulsification except in the low flow region. There are indications that injector design can be tailored to increase emulsion breakdown and fuel nozzle specialists should study this possibility in depth. Once the emulsion is burned, there is no evidence of any emulsion residue which causes any trouble in the combustor or turbine section of the engine.

The fuel controls and associated fuel system hardware

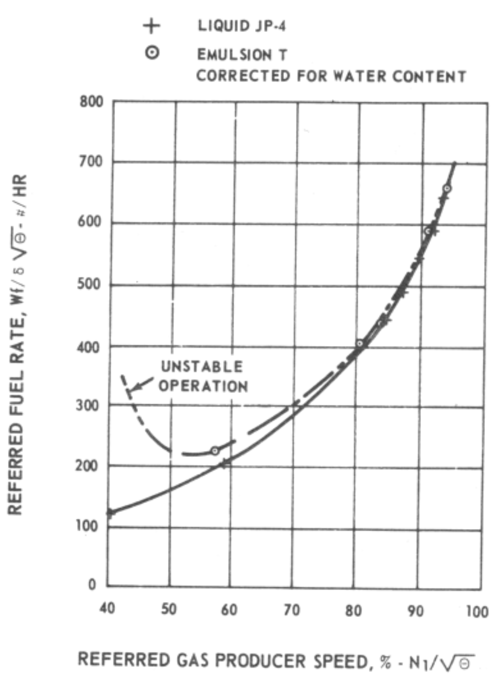

Fig. 14 - T53 engine - vaporizing combustor - Fuel rate comparison, Emulsion T and JP-4

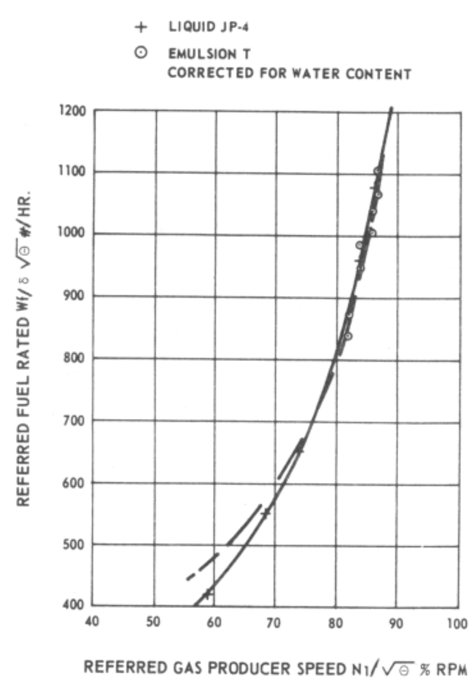

Fig. 15 - T55 engine - atomizing combustor - Fuel rate comparison, Emulsion T and JP-4

tend to be sensitive to the characteristics of the emulsion used. The intolerable corrosion caused by emulsion T can be eliminated by proper emulsion formulation, and emulsion L appears to be satisfactory in this respect.

All emulsions will obviously have different flow characteristics than the Newtonian fluids normally used for fuels. In those areas of the fuel control and fuel system where the operation is sensitive to Reynolds number or requires the transmission of small pressure forces, some degree of redesign will be required for proper operation. The 1900 dyne/cm^2 yield stress required to move emulsion L may be higher than required for reasonable aircraft safety, and any reduction would be beneficial. If future tests, for example those at very low ambient temperatures, should indicate an intolerable change of fuel control operating characteristics, then a fuel control with a computer section separate from the fuel pump and operating on a different fluid -- say engine oil -- may be a possible method of solution.

A significant characteristic of all emulsions is that gravity separation of contaminants will not occur. The entire fuel system must be able to swallow the dirt carried by the emulsion, which probably cannot be filtered with anything finer than a 40 micron filter. Filter area may have to be increased wherever possible to avoid a pressure drop increase to relief pressure in a short time because of contaminant collection, and fuel system components should be designed to operate with contaminated fuel without damage. Significant long term operation of fuel systems is required to evaluate the total impact of handling this increased quantity of dirt. The damage caused to the T55 fuel control by contamination was an abnormal situation, illustrative only of what can happen if filters go into bypass and allow dirt to be ingested in a fuel system not designed for it.

The accurate measurement of flow of emulsion, either solid or broken down, has been experimentally difficult. The time-weight method has been most successful, but it is time consuming, cumbersome, and inaccurate. There should be significant effort expended to develop both laboratory and aircraft fuel flow meters adequate to measure emulsion flow rate.

CONCLUSION

Avco Lycoming engines have been operated for short periods of time on emulsified JP-4, and fuel sensitive components have been more intensively tested. The indications are that atomizing combustor versions of these engines will operate satisfactorily with emulsions which are not corrosive and which can readily be de-emulsified in passing through the fuel system. With present emulsions, the operational envelope of current engine models will probably be reduced. This can be compensated for, at least in part, by modifications within the present state of the art, and detailed environmental studies of combustors and fuel system components with the optimum emulsions are needed to delineate the degree of modification required. Considerably more testing is required before an engine can be considered operationally flightworthy on emulsified fuel, but there is reason to believe that the chances for eventual success are good.

ACKNOWLEDGMENTS

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