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THE CONTINUAL SEARCH of the military services and industry for ways to reduce the fire hazards of aircraft engine fuels has led to the investigation and development of emulsified fuels. This development has currently reached the stage where gas turbine engine fuels can be satisfactorily pumped and metered in the emulsified state with standard engine fuel system components. A demonstration of this capability was recently accomplished on an Allison gas turbine Model T63 engine in a feasibility program sponsored by the U.S. Army. This engine is used in the U.S. Army OH-6A helicopter and several commercial versions of that basic design. The test methods and results are presented in this paper.

Reference can be made to the 1966 Proceedings of the Aircraft Fluids Fire Hazard Symposium, and particularly the paper presented by F. P. McCourt entitled "U.S. Army Fire Hazard R. and D. Activities," for further explanation and documentation of the safety characteristics of the fuel type tested.

An emulsion lies in the realm of collodial chemistry and is a dispersion or mixture of two immiscible liquids and a surface active agent. Collodial chemistry deals with dispersions of particles which are microscopic and submicroscopic in size. The dispersion of solid in a liquid is known as a gel; a liquid in a mutually immiscible liquid, an emulsion; a solid in a gas, a smoke; and a liquid in a gas, a fog. All these dispersions and their formations involve no chemical reaction, but are solely described by surface chemistry.

Emulsions often occur in every day life, and the most common emulsifying agents are soaps. Dirty dish water is partially an emulsion of grease in water. Milk is a thin emulsion of butter fats in water while cream is a thicker but similar emulsion. Some hand soaps are emulsions almost identical to the fuel tested, but with the addition of perfumes, lanolin, and the substitution of a cheaper grade of kerosene.

The particular emulsion employed in this test was a dispersion of fuel in water. The emulsion consisted of minute droplets of JP-4 covered with a thin skin or balloon of water. The emulsifier bonds the water to the fuel and allows such a method of mixing to occur. The fuel is then known as the interior phase and the water, as the exterior phase. It is important to note that the chemical composition of the fuel has not been changed -- only the physical state.

The safety aspect of this fuel results primarily from the fact that the liquid JP-4 has no surface exposed to air; it is all contained within a skin of water. As a result, the rate of fuel vaporization is very much lower than that of free liquid fuel. This implies that, in an airplane crash, even if a fuel tank has burst, a vapor cloud of fuel will not form. (This vapor cloud, when ignited by some stray spark, becomes the

ABSTRACT

The development of aircraft engine fuels with improved safety characteristics is of considerable importance to both military and commercial users. Preliminary evaluation of such a fuel has recently been completed by the Allison Div. of General Motors Corp. under contract with the U.S. Army.

This evaluation compared an emulsified mixture of JP-4 fuel in water with standard JP-4 jet engine fuel in the Model T63 gas turbine engine. The results of this testing on both bench test and full scale engine test demonstrated the feasibility of such a safety fuel in this or an engine of similar type. In fact, the fuel appears to have a very good potential for military application.

inevitable fireball.) Rather, a slow, controlled burning takes place on the surface of the emulsion when it is in bulk form.

A secondary consideration is the greatly increased (approximately times 10^6) viscosity of emulsified fuel which implies that the emulsified fuel will not slosh, splash, or disperse as readily as the liquid. Fuel system leaks would be readily detectable because the emulsion would extrude much like toothpaste. The much higher viscosity also affects flow properties, however. The emulsion moves in discrete "plug flow" -- a completely laminar plug moving on a very thin boundary layer of liquid fuel.

In the course of testing, two different blends of emulsion were prepared. The bench test was run using a mixture of 96% JP-4, 3.5% water, and 0.5% emulsifying agent by volume. Based on test results from another company, a blend of 96.85% JP-4, 2.5% water, and 0.65% emulsifying agent by volume was used in engine testing. An Allison Material Services Lab Report indicated a low temperature tolerance of -10 F and tolerance to -40 F was reported by another agency, but at that point in development, batch-to-batch variation was high. The change in blend between bench and engine testing, however, was not sufficient to affect the pressures, flows, or spray angles which were recorded. Essentially, the change affected only the amount of free fuel in the emulsion supply drum.

TEST APPROACH

BENCH TESTING - The complete engine fuel system was set up in the following configuration: the fuel pump and fuel control were mounted on the driven pads in the test cell in the usual manner; regulated shop air was connected to the P_c port of the fuel control; the pump and control were plumbed together as in an engine installation; and the test fluid was supplied to the pump inlet.

The fuel nozzle was mounted in a holding fixture in the dome of a nozzle spray visualization rig. This rig consisted of a 35 gal stainless steel catch drum covered by a steel top or dome. The dome had a viewing port and two 100 w lamps spaced approximately 120 deg apart. In this manner, the nozzle spray could be back-lighted and photographed through the viewing port. The outlet of the control was connected to the nozzle inlet through a 1/8 in. turbine flowmeter. The flowmeter readout was on an EPUT event counter through a 10 X amplifier. The test bench provided a readout of fuel control rpm on a second EPUT. Pressures were read at appropriate points in the fuel system on the test bench pressure gages. A diagram of the bench test setup is shown in Fig. 1 and a photograph of the test setup is shown in Fig. 2.

The first series of tests was run by flowing standard test fluid MIL-F-7024-IIA, a fluid very similar to JP-4 in viscosity and density, but with much less flammability. Ten points on the fuel control acceleration schedule were chosen and test condition inputs were set in the same order throughout the test. Finally, the nozzle spray at each test point was observed and photographed with a Polaroid camera. Nozzle spray angles were measured from the Polaroid snapshots. Emulsified JP-4 was then supplied to the fuel pump inlet from the emulsion supply tank by means of a piston type air-driven pump suspended in the 55 gal supply drum. The supply rig (Fig. 3), in which both the JP-4 was emulsified and the emulsion was pumped or supplied, was capable of supplying emulsion to the engine pump in a range between 0 and approximately 80 psig. The pump was the same type used to pump heavy oil or grease for grease guns. Based on the experience of the emulsified fuel supplier, a pump supply pressure of approximately 30 psig was used.

Instrumentation was provided to indicate the pressure drop across the engine pump filter, and the pressure readings were high enough to indicate that the filter bypass valve had moved open. Instabilities in nozzle flow, spray angle, and system pressures were also noted, and the turbine meter would not perform satisfactorily. As a result of this first run the pump filter was removed. It was found that while the paper filter

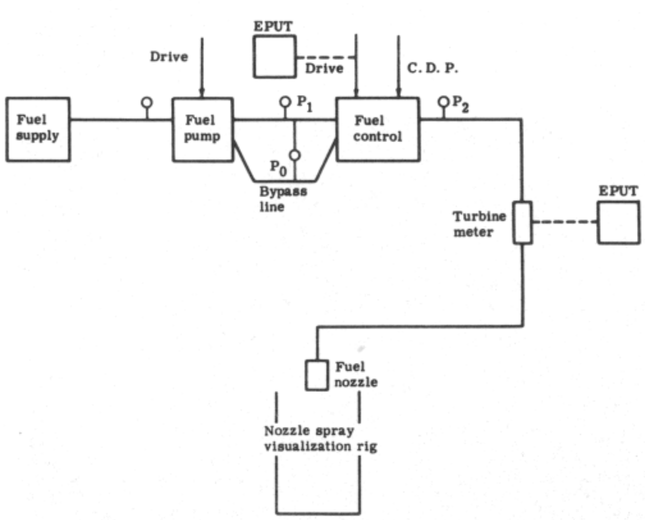

Fig. 1 - Block diagram showing bench test setup of engine fuel system

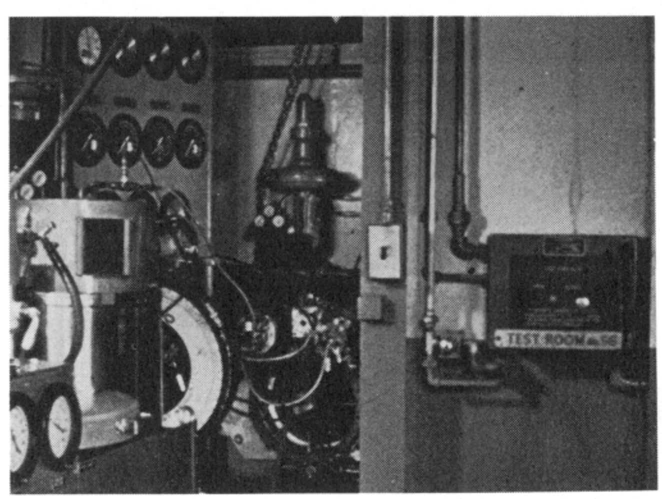

Fig. 2 - Bench test setup of engine fuel system

For the third attempt the fuel system was again flushed and primed with liquid JP-4 as before. The P_c line to the fuel control was broken and capped, and regulated shop air was supplied to the P_c port of the fuel control. This allowed a false input to be given to the fuel control so that it could be made to supply more fuel than it ordinarily would for a given engine-supplied input. This was done in light of the bench test results which indicated a lean fuel schedule when emulsified JP-4 was flowed. Engine speed control was still provided by the governor function of the control, however. In this configuration the engine successfully started and sustained fire when the emulsion reached the nozzle and began burning. The same steady-state points were run for this (and the remainder of the test) as had been run for the liquid JP-4 performance calibration.

The false P_c was then removed and the fuel control metering schedule was enriched by an external orifice adjustment. Satisfactory transition from liquid to emulsified fuel burning was accomplished. Subsequently, the engine starting cycles were performed successfully using emulsified fuel with no liquid priming after shutdowns of up to 2 hr. Smoke issued from the engine exhaust and slight afterfires were present for several shutdowns. Occasionally, a small explosion was heard in the combustion section on fireup, but this was undoubtedly due to the fuel nozzle leaking fuel during and after shutdown, as observed during bench testing.

The engine continued to be started and run at the same series of steady-state points and through transients until approximately 4 hr of emulsified fuel running time had been accumulated. From this point, intermittent difficulty was encountered with what appeared to be control "sticking" or "hang-up" on fireups and transitions with both liquid and emulsified fuel.

The fuel nozzle was removed from the engine for inspection. Disassembly revealed the nozzle screen to be nearly covered with rust particles, what appeared to be white fibers, and paint of the type coating the inside of the drum in the emulsion supply rig. The white fiber-like material proved to be polymer strings created by the emulsifier. The nozzle tip showed normal carbon buildup, but some abrasive wear was apparent in the nozzle passages. The nozzle was cleaned and subjected to an E. D. S. check at this time and then reassembled on the engine.

A fresh supply of emulsified fuel was provided and after an ambient soak of approximately 4 hr, the engine started satisfactorily on emulsion only. After a warmup period, transients between ground idle and take-off were again performed. Finally, the engine was run at take-off for approximately 15 minutes and then at ground idle for the required 2 minute cool-off period. This concluded the engine running on emulsified JP-4; approximately 6.5 hr of total running time on emulsion were completed.

After removal of the engine from the test chamber, the fuel pump and fuel control were returned to bench test for post-test calibration.

TEST RESULTS

For ease of explanation, the two phases of the emulsified fuel feasibility test will be dealt with separately, that is, Bench Test and Engine Test. The most critical problem area indicated by both phases of this test was the corrosive nature of this fuel. This one undesirable fuel property resulted in the majority of the subsequent test difficulties, but perhaps could be corrected in this case by a small percentage of some additive such as sodium bromide.

BENCH TESTING - Taking the components of the fuel system in order, the fuel pump will be discussed first. As mentioned in the procedure section, the 10-micron pleated-paper filter incorporated in the fuel pump will filter and pass emulsified JP-4, but with a pressure drop sufficient to keep the pump filter bypass valve open. Laboratory tests conducted by the fuel supplier have shown that normal fuel system pressures can collapse both paper filters and thin metal screens when a large quantity of contamination is present in the emulsified fuel being delivered.

With reference to Fig. 5, the pump appeared to contribute a slightly smaller pressure increase at low and high speed on emulsified as compared to liquid JP-4. Otherwise, pump operation was completely satisfactory during the test. The post-test E. D. S. check showed the pump to have deteriorated beyond acceptable limits, however. The pump flow capacity was just below the lower acceptable limit. Fig. 6 shows that, for the same settings, the fuel control flowed a leaner schedule on emulsified than on liquid JP-4. In general, the control tended to meter in the same fashion, and the liquid and emulsified plots were roughly parallel. The fuel control appeared to have depreciated in metered flow during the test as well. The orifice adjustment made on the engine test stand should have produced a higher flow rate than the post-test calibration indicated. This may also indicate that, with some enrichment in the start and acceleration to idle range, the engine could have been made to perform adequately as it did towards the end of the test with a control set to the high limit of the E. D. S. As this test was only in-

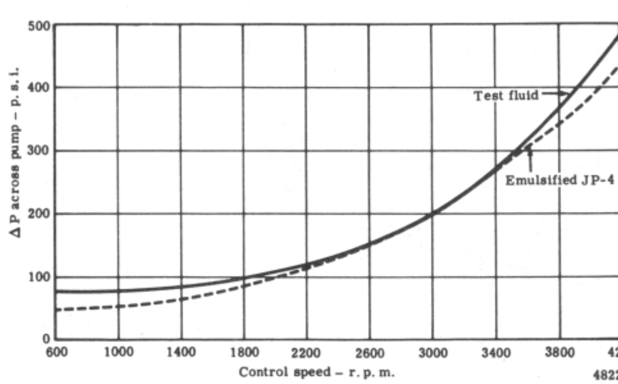

Fig. 5 - Increase in fuel pressure supplied by engine-driven fuel pump versus speed while flowing test fluid and emulsified JP-4

tended to indicate feasibility, no further tailoring of fuel control characteristics was attempted.

The fuel nozzle was affected to the greatest extent of any of the fuel system components. As mentioned previously, a nozzle spray angle fluctuation of 10-20 deg and a very poor spray quality were obtained with the first nozzle tested on the bench when emulsion was flowed. The spray cone appeared alternately to adhere to the air shroud and then to separate. This was, perhaps, due to a surface tension effect between the fuel spray and the wetted shroud. The problem was corrected for most part by the substitution of the new nozzle, but a spray angle fluctuation of some 5 deg was still present at low flows. Fig. 7 is not very conclusive, but it does indicate that the nozzle spray angle, when flowing emulsion, was wider at low pressures and narrower at high pressures than when liquid JP-4 was flowed. Also indicated is the depreciation of the spray angle after engine test. The nozzle remained within acceptable limits, however, and the effect was only slight.

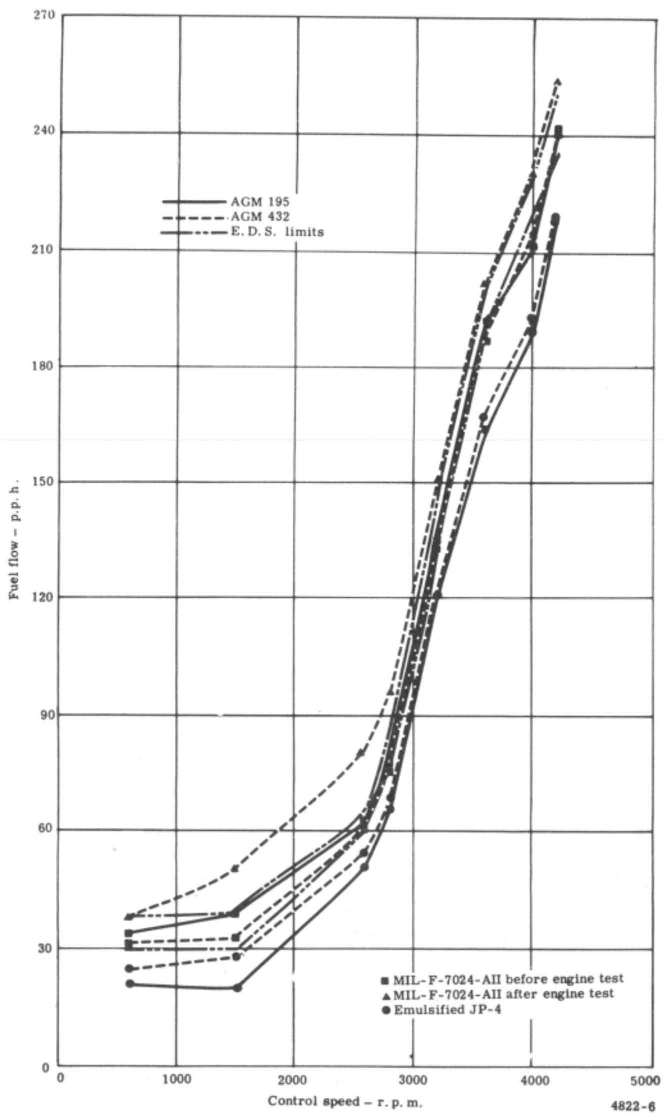

Fig. 6 - Fuel flow metered by fuel control versus control speed while flowing test fluid and emulsified JP-4

Fig. 8 indicates that the flowing of emulsion caused fuel nozzles to run lean also. The effect on engine operation was to create higher pressure levels throughout the fuel system. Depreciation with emulsion use was also evident here as shown by the post-test calibration of the nozzle. The spray pattern of the nozzle was uneven and beyond E. D. S. limits after operation with emulsion. This indicates that wear in the nozzle passages was significant after passing emulsion for less than a total of 10 hr of operation. The wear was most likely due to small particles of rust entrained in the fuel which acted as an abrasive. Photographs of the nozzle spray of the two fuels at take-off conditions are shown in Figs. 9 and 10. As can be seen, the spray quality was essentially the same in either case at higher flow rates.

After the test, disassembly of the fuel control was necessary to remove all the emulsion from the passages, even though the control had been flushed with liquid fuel after removal from the engine. The only rust evident was on the cutoff valve. Considerable rust was found in and on the outside of the fuel nozzle, as mentioned previously. Partial teardown of the fuel pump also disclosed rust on the steel parts; the pump drive shafts and the end plates were removed and found to be rusted and pitted.

Besides the compressible nature of the fuel, due to the entrained air, bench testing revealed that the emulsion was atomized as an emulsion and that spraying did not cause significant breakdown. Lab testing and the experience of the fuel supplier indicated that the emulsion will breakdown and return to the liquid phase between 100 and 200 F, depending on the container material. This may indicate that an unsuccessful light-off on a cold engine would result in a mass of nondrainable emulsion remaining in the burner can. Enough residual heat should be present in a warm or hot engine to liquify any unburned emulsion and allow it to drain from the burner as a liquid, but cold start attempts are a potential safety harzard.

ENGINE TESTING -

Performance - The results of the engine performance calibrations are shown in Figs. 11-13. The emulsion was prepared from the same supply of JP-4 that the preliminary liquid fuel base line was run on.

From a performance standpoint, the only effect of the

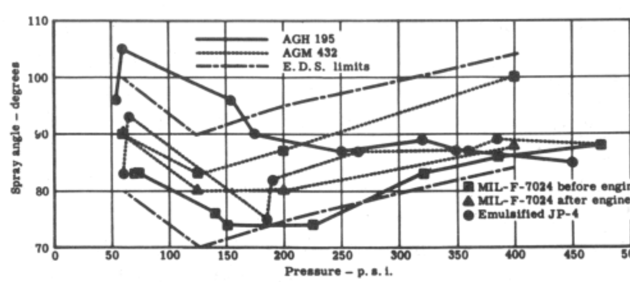

Fig. 7 - Fuel nozzle spray angle versus inlet pressure while flowing test fluid and emulsified JP-4

emulsified fuel appears to be a slightly higher fuel flow level and specific fuel consumption. This can be explained by the fact that 2.5% of the fuel weight is inactive water. The emulsifying agent itself is organic and has some heating value. A second loss results from the fact that the thin skin of water surrounding each droplet of fuel must be broken away by shear, but for the greater part by heat, before the fuel inside is available to be burned. Within the accuracy of this test these two considerations account for the total increase in fuel consumption.

Operation - Figs. 14-19 are reproduced sections of Offner Recorder tape with the parameters described previously. They allow comparisons between transient conditions burning liquid and emulsion. Figs. 20-22 are typical of the be-

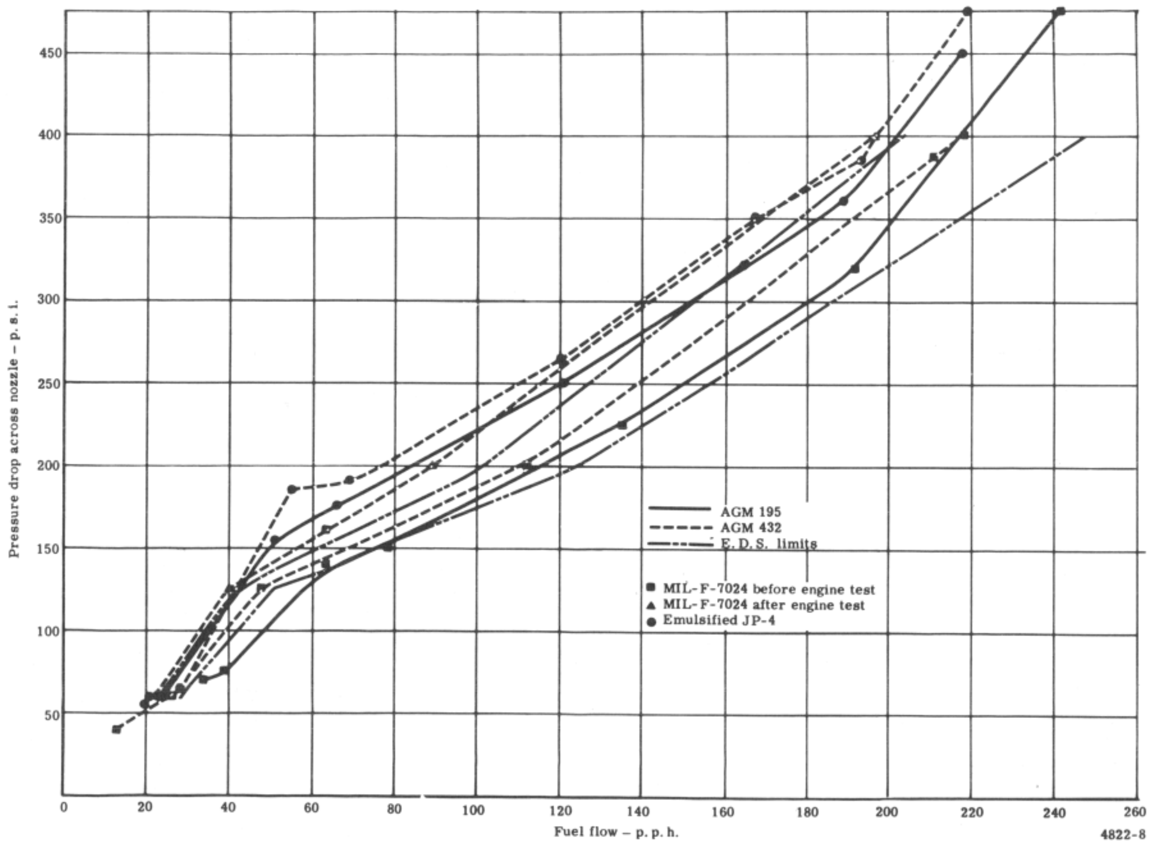

Fig. 8 - Fuel nozzle flow versus pressure drop while flowing test fluid and emulsified JP-4

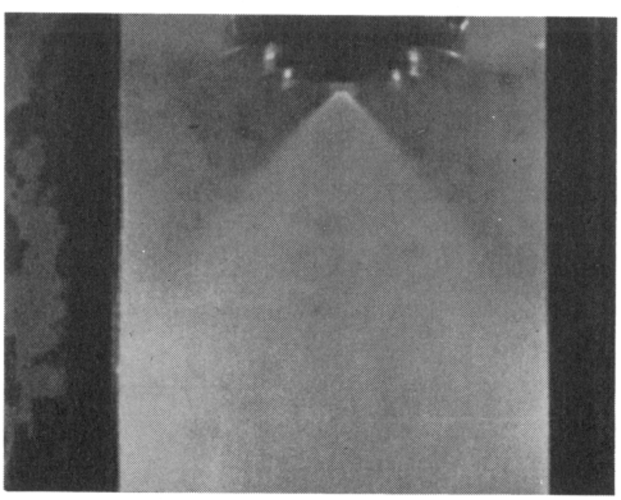

Fig. 9 - Engine fuel nozzle spray flowing fluid JP-4 at take-off conditions, approximately 240 pph

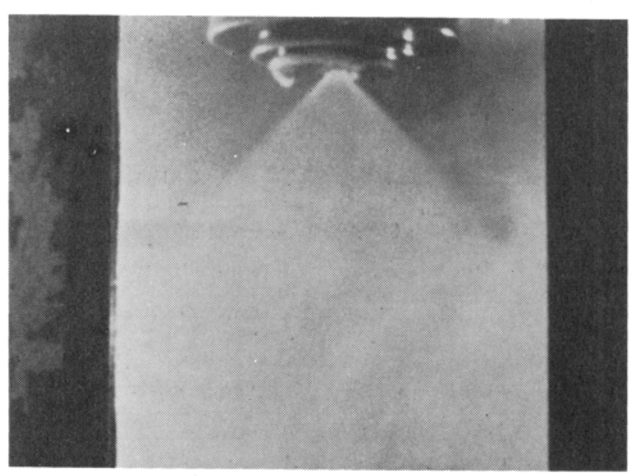

Fig. 10 - Engine fuel nozzle spray flowing emulsified JP-4 at take-off conditions, approximately 220 pph

havior of the same measured parameters during steady-state operation.

The first comparison can be made between fireups on the two fuel forms. The fireup recording on liquid shown here occurred after the fuel control orifice was adjusted. The fireup recording on emulsion occurred with the system totally filled with emulsion. There were four main points of difference between the two fuels. The time to stabilize N_1 generally took 2-6 sec longer with emulsion.

Likewise, the peak T. O. T. was generally the same or slightly lower. Emulsion starts also resulted in a lower nozzle pressure than did liquid starts, and lastly, the pressure fluctuations were sometimes half again as large as those with liquid in the system. All these effects could be accounted for by either the decreased heat release per pound of emulsified fuel or the compressibility factor.

Figs. 16 and 17 allow a rough comparison of rapid accelerations on the two fuel types. Again it took slightly longer when using emulsion, but the variety of conditions did not allow a specific time band to be estimated. The air in the fuel causes the typical nozzle pressure level for emulsion, also characteristic of any condition above ground idle. This was due in part to the partial clogging of the nozzle screen with rust, paint, and such, as mentioned earlier. Bench test indicated that a somewhat higher pressure level should be anticipated, however, due to the nature of the emulsion.

Figs. 18 and 19 are recordings of rapid decelerations. Once more the emulsified fuel appeared to slow down the engine response, and the effect on elapsed time was easily

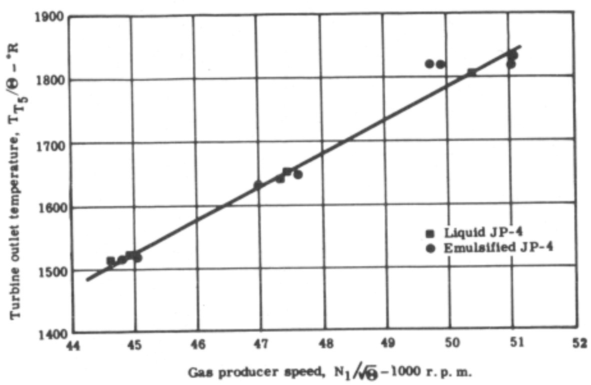

Fig. 11 - Turbine outlet temperature versus gas producer rpm burning liquid and emulsified JP-4

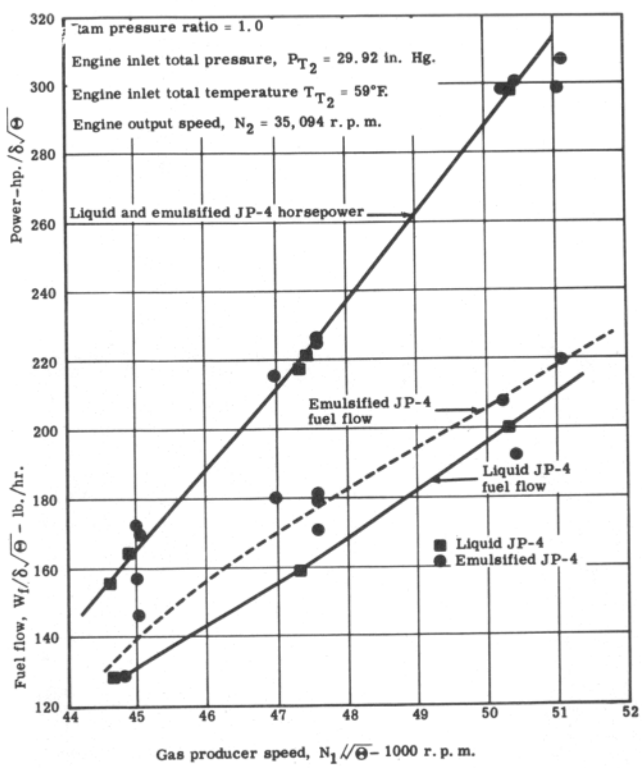

Fig. 12 - Both horsepower and fuel flow versus gas producer rpm while burning liquid and emulsified JP-4

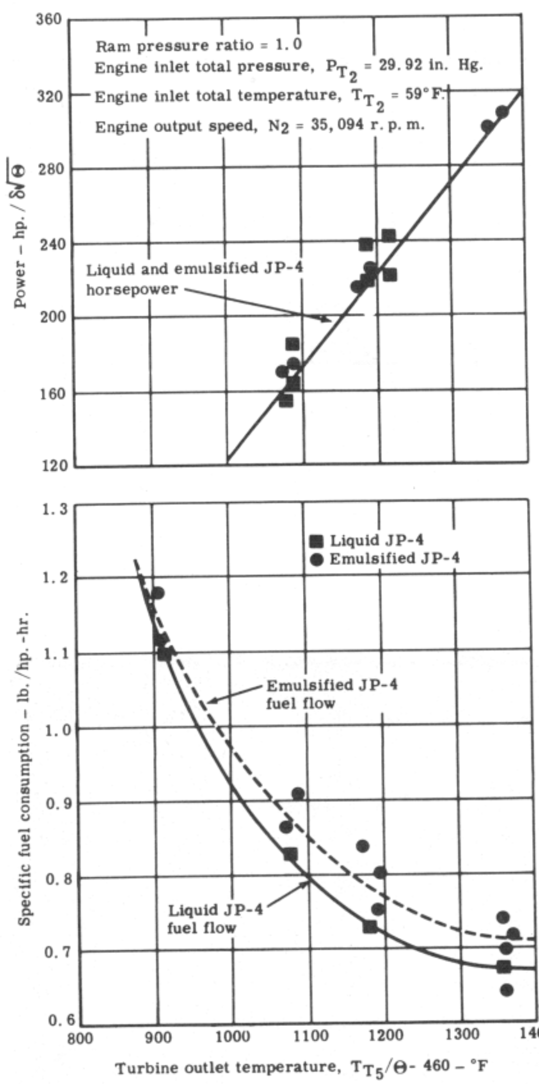

Fig. 13 - Both horsepower and specific fuel consumption versus turbine outlet temperature while burning liquid and emulsified JP-4

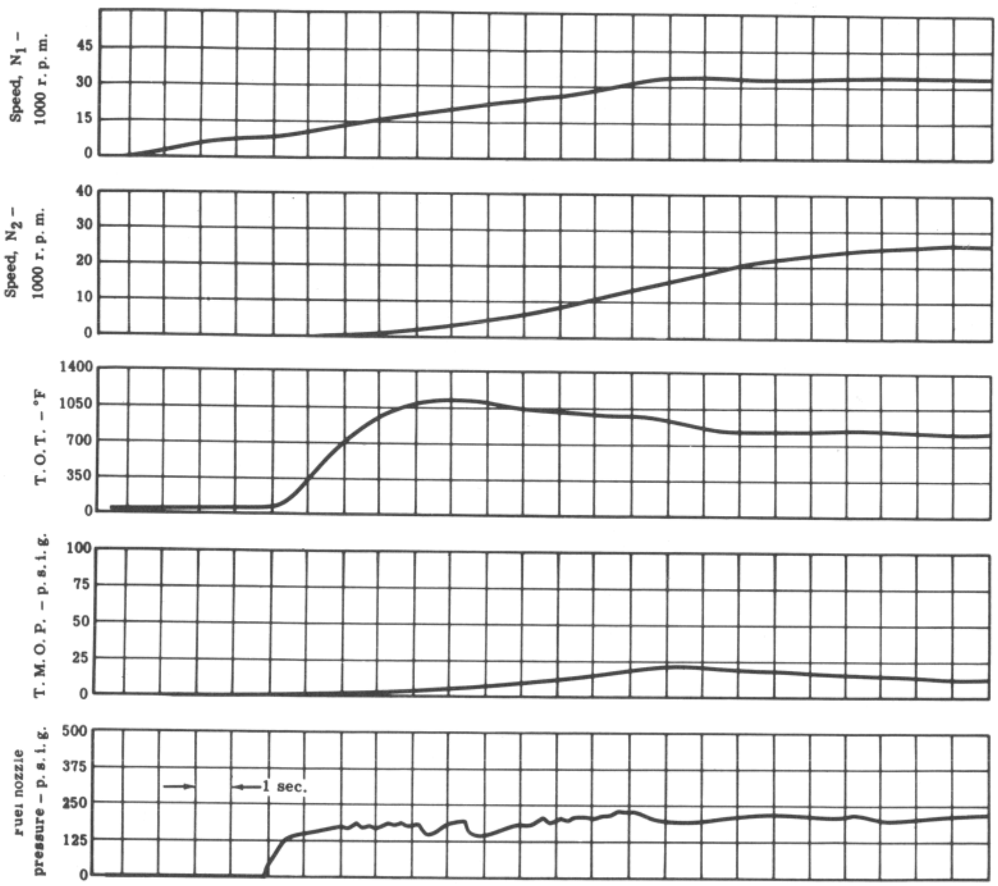

Fig. 14 - Reproduction of recorder chart showing five engine parameters versus time during fire-up to ground idle while burning liquid JP-4

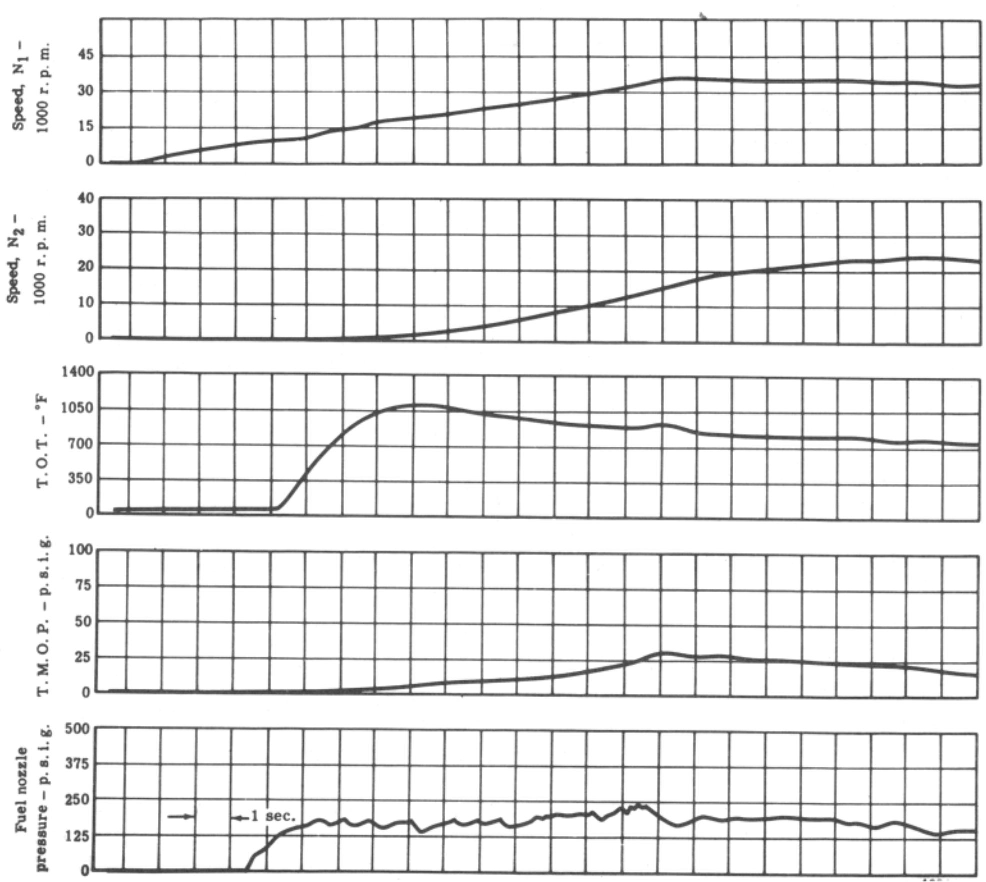

Fig. 15 - Reproduction of recorder chart showing five engine parameters versus time during fire-up to ground idle while burning emulsified JP-4

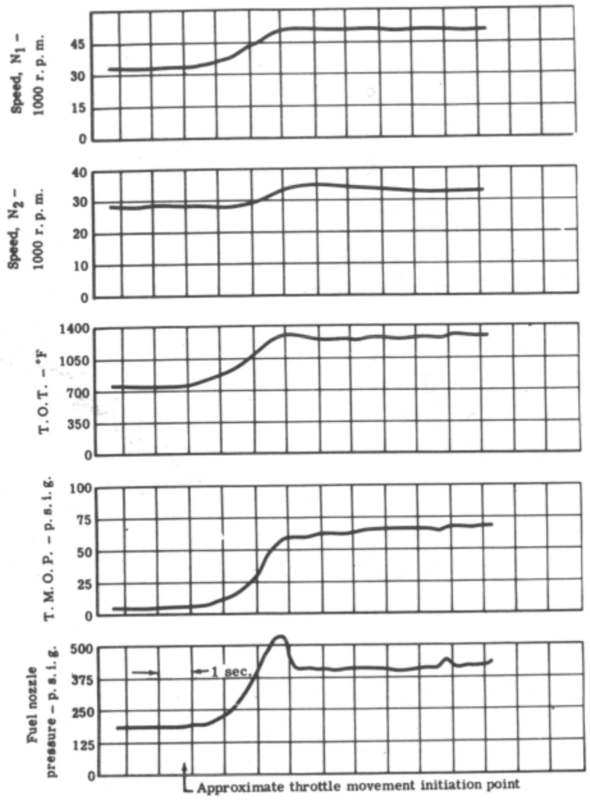

Fig. 16 - Reproduction of recorder chart showing five engine parameters versus time during a rapid acceleration from ground idle to take-off while burning liquid JP-4

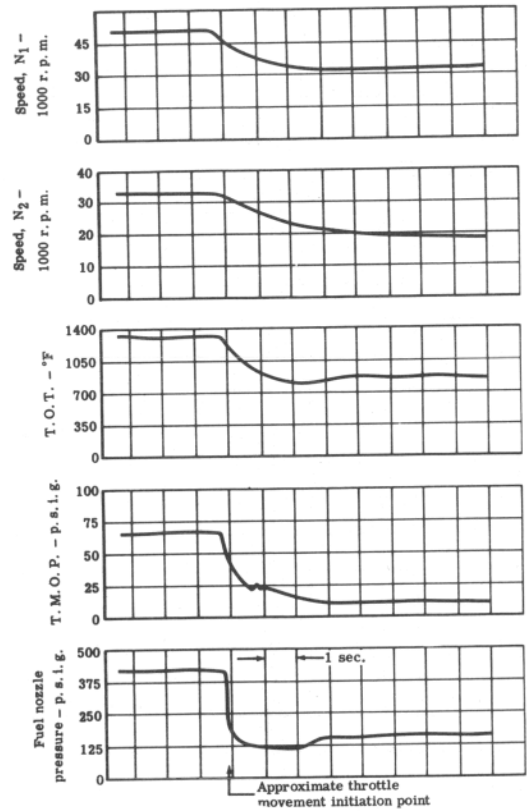

Fig. 18 - Reproduction of recorder chart showing five engine parameters versus time during rapid acceleration from take-off to ground idle while burning liquid JP-4

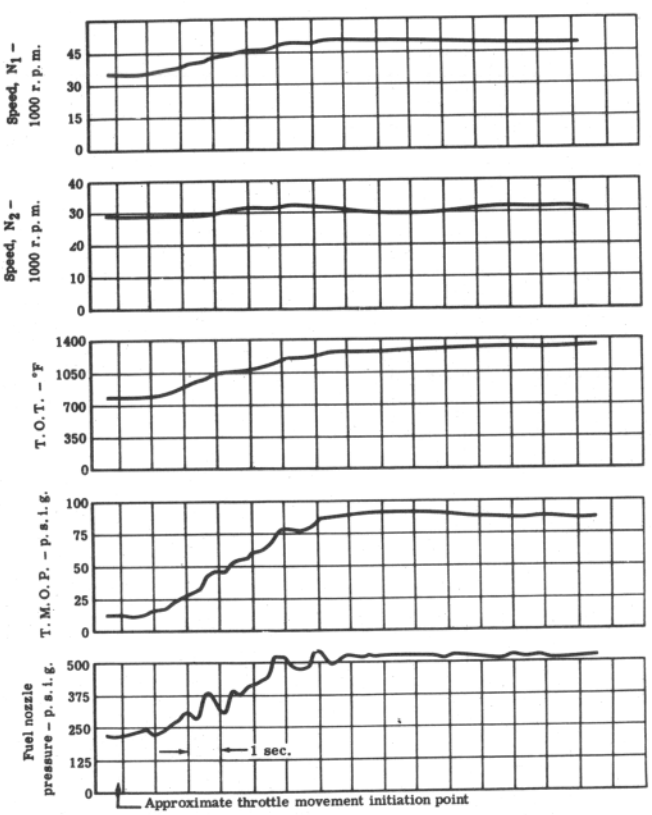

Fig. 17 - Reproduction of recorder chart showing five engine parameters versus time during rapid acceleration from ground idle to take-off while burning emulsified JP-4

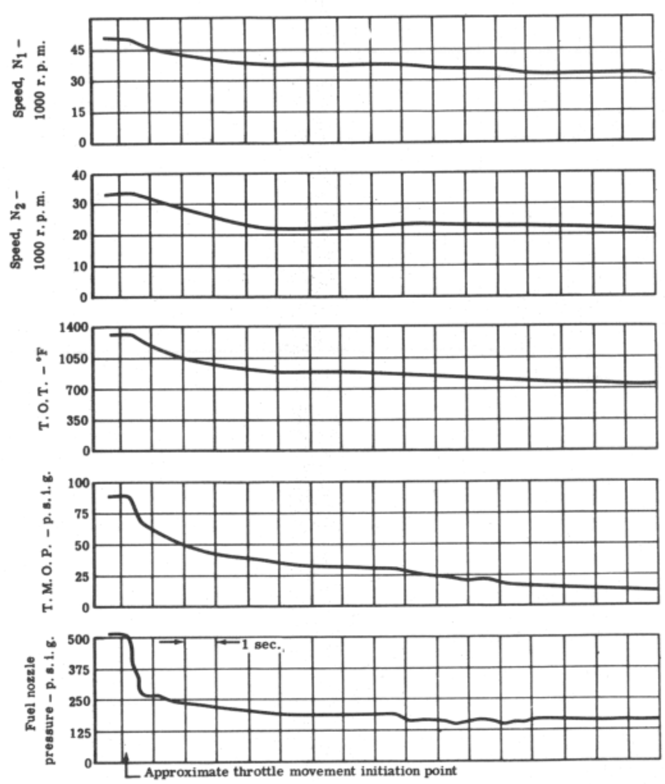

Fig. 19 - Reproduction of recorder chart showing five engine parameters versus time during rapid deceleration from take-off to ground idle while burning emulsified JP-4

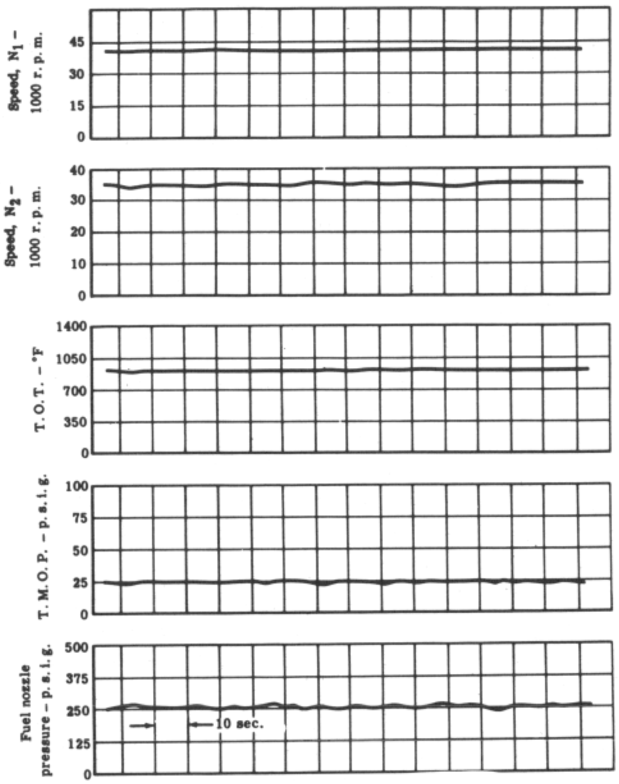

Fig. 20 - Reproduction of recorder chart showing five engine parameters while running at part throttle, 40, 346 gas producer rpm, while burning emulsified JP-4

the greater than for any other transient. All these increased times may be explained by the fact that the compressibility of the fuel causes a delay in nozzle line pressure level change and a resulting delay in nozzle inlet pressure change. In general, the emulsion did not cause an excessively sluggish "feel," but the lack of engine response was evident to the operator.

Figs. 20 and 21 show steady-state performance at two widely spaced levels. In both cases the fluctuations in nozzle pressure are again evident. Similar traces for JP-4 burning showed that nozzle pressure remained steady. Note that the other parameters are stable, however, and that the pressure instability does not result in engine instability.

A better comparison between liquid and emulsion running can be observed in Fig. 22. The transition between liquid and emulsion occurred at ground idle. As can be seen, the top four parameters changed level slightly but remain constant. Nozzle pressure alone became erratic after the emulsion filled the system.

Fuel Handling - Engine disassembly revealed that the combustion chamber, turbine blades, vanes, and associated parts washed by engine exhaust gases were either rusted or coated with and abraded by a substance similar to jeweler's rouge but believed to be very fine rust particles. There was no evidence of excessively burned vanes or blades. The performance calibration performed on liquid JP-4 during the last hour of emulsified fuel running time indicated that no serious performance depreciation occurred as a result of the

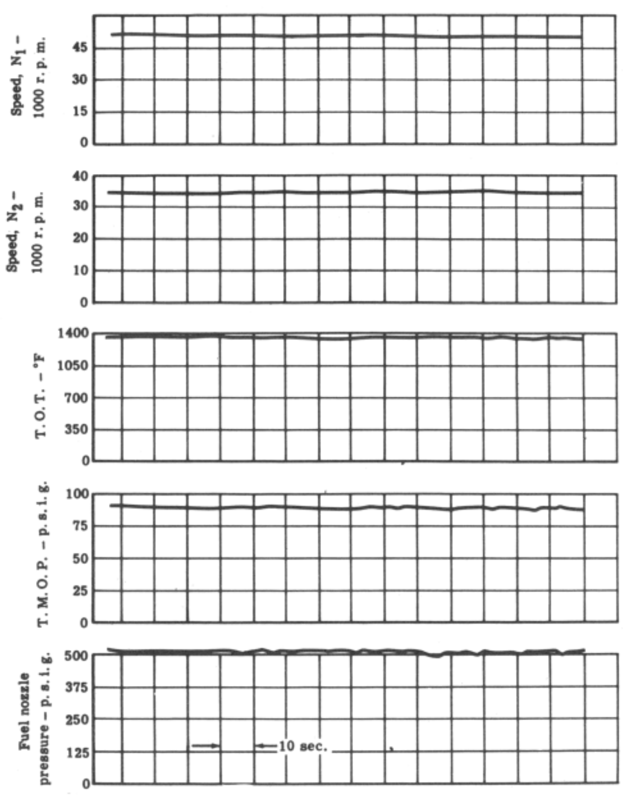

Fig. 21 - Reproduction of recorder chart showing five engine parameters running at take-off, 50, 993 gas producer rpm, while burning emulsified JP-4

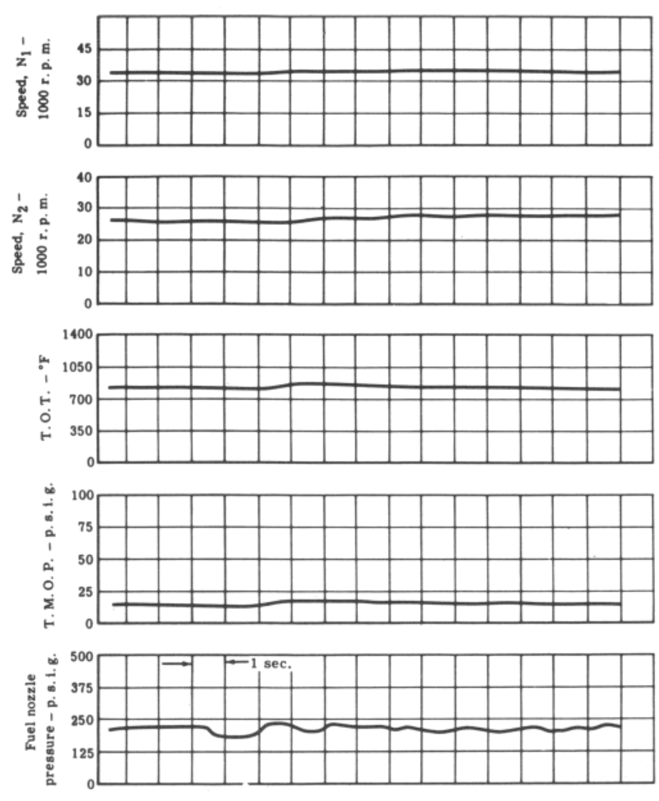

Fig. 22 - Reproduction of recorder chart showing transition from liquid to emulsified JP-4 while running at ground idle

operation on the emulsion. Unfortunately the emulsified fuel washed rust particles originating from the emulsion supply rig and some of the test stand fuel system fittings into the engine.

SUMMARY

It can be said that it is feasible to operate a gas turbine engine, specifically the T63, on an emulsion of JP-4 fuel. Satisfactory engine operation using this particular emulsion was obtained with the following conditions or exceptions:

1. The emulsified fuel and water, as tested, corroded materials susceptible to rust or attack by free water. Rust particles carried in the fuel were abrasive to fuel system components, and, to a lesser degree, internal engine components in the hot gas path. Sufficient quantities of rust were present to clog fuel system screens and filters after a few hours of operation.
2. The metered fuel flow by weight was less through a given system for emulsion than for liquid. This resulted in lean fuel schedules when liquid JP-4 control settings were retained and emulsion flowed.
3. There was no detectable power sacrifice involved in using emulsified fuel in sufficient quantity. Satisfactory engine stability was also achieved.
4. The standard engine fuel system can be used with emulsified fuel with relatively minor adjustments and modifications for standard sea level conditions.
5. The bulk of the fuel remains in the emulsified state through the fuel system and past the point of atomization in the nozzle, even in 100 F ambient conditions.
6. Particular care must be exercised with the entire fuel system and fuel handling equipment to eliminate materials subject to corrosion when in prolonged contact with a fuel having characteristics of the one tested in this program.

SYMBOLS AND ABBREVIATIONS

AGM 195 = Allison Serial Number of older design fuel nozzle employed in beginning of test
AGM 432 = Allison Serial Number of newer design fuel nozzle employed in latter part of test
C.D.P. = Compressor discharge pressure
E.D.S. = Engineering Design Specifications (Allison)
F = Degrees Fahrenheit
N_1 = Gas producer rotational speed in rpm
N_2 = Power turbine rotational speed in rpm
P_c = Compressor discharge pressure signal
pph = Pounds per hour
psi = Pounds per square inch
psig = Pounds per square inch gage (above barometric pressure)
rpm = Revolutions per minute
T.M.O.P. = Torquemeter oil pressure
T.O.T. = Turbine outlet temperature (power turbine inlet temperature)
θ = Standard compressor inlet temperature correction factor
δ = Standard compressor inlet pressure correction factor

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