Non-Newtonian Fuels for Aircraft Safety

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The fire hazard associated with aircraft accidents involving fuel spillage may be minimized by using thickened fuel, which exhibits its original vapor pressure but is rendered safer in three distinct ways: the rate of vaporization per unit area is reduced, the tendency to atomize on impact is much less, and the fuel breaks into discrete gobs preventing rapid flame spread. Consideration of such fuels for aircraft has recently become serious, because of recognition of the facts that emulsion-thickened fuels provide relative ease of removal from tanks, good atomization in engines, constant rheology over wide temperatures, and ability to be demulsified if required. Military requirements for such emulsions are that they contain at least 97% of fuel and be stable in storage between −30° and 130°F. The yield stress can be varied from 1000 to 3500 dynes/cm.[2] Plant-scale batches of such fuels were prepared, but reproducibility from batch to batch has not been satisfactory. Considerable research must still be carried out to determine the feasibility of scaling up emulsions reproducibly. Performance of emulsion in various helicopter engines was determined by other contractors. Engine operation was surprisingly close to normal when a steady supply of clean fuel reached the engine, and modifications required to insure this proved to be minor. Beyond bench-type testing, fire safety must still be demonstrated.

Introduction

THIS paper is a review of the material presented at the Aircraft Fluids Fire Hazard Symposium, Ft. Monroe, Va., on June 7–8, 1966, and at the National Aeronautical Meeting of Society of Automotive Engineers (SAE), April 27, 1967, plus a few other relevant publications. The authors have been forced by the sheer bulk of the material to concentrate on what appear to be the key points of each paper, and the serious reader is urged to examine the original reports.

The Federal Aviation Agency (FAA) has funded work on the use of gels, which were first considered as an emergency in-flight means to render the fuel rapidly immobile, but are now being considered as flight fuels.[5] More recently, the U.S. Army Aviation Material Labs has funded a broad program to formulate and evaluate emulsions as safety fuels.[6] The immediate goal was recovering usable JP-4 after safely transporting it, and the secondary but now principal goal was using it in flight. The two programs differ also in that the Army is mainly concerned with the relatively simple fuel systems in helicopters, but has to contend with 0.50 caliber incendiary ground fire as well as crashes. Both groups feel that the results to date are promising enough to justify continuation of the program.

Table 1 Goals of army fuel emulsion contract

Property	Minimum target
Fuel value	97% of JP-4
Stability	30 days storage
Operability	−20° to 130°F
(Desired	−65° to 160°F)
Impact shock	150 g for 1 msec
Vibration resistance	0–32 cps @ 0.4 g
Compatibility	Aircraft materials
Microorganisms	Inhibit growth

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The principal goals of the Army program are summarized in Table 1. Although not so explicitly stated, the FAA goals are essentially the same. The question immediately arises as to the definition of "operability," which convers a vast range of actual operations under a wide variety of conditions. To a large extent, the work reviewed below constitutes an organized effort to work out practical answers to this question.

Fuel Formulation Studies

Structure of Gels and Emulsions

The question of gels vs emulsions is still open, though at present the emphasis is largely on the latter. Historically, control of burning rate by gelation is well established, both for safety and incendiary purposes. Though the past formulations require reoptimization for use in aircraft, much can be drawn from past technology to aid in this process.[1] On the other hand, emulsions of the type under consideration were scarcely thought of ten years ago,[4] and the comparison of merits is accordingly incomplete.[2]

The definition of "gel" prepared by the Interagency Chemical Rocket Propulsion Group, and adopted by the American Society for Testing Materials (ASTM) as D 2507-66T,[14] is: "A gel is a liquid containing a colloidal structural network that forms a continuous matrix and completely encloses the liquid phase. A gel deforms elastically upon application of shear forces less than the yield stress. At shear forces above the yield stress, the flow properties are principally determined by the gel matrix." This definition could be made more precise by changing "encloses" to "pervades," but it essentially describes these candidates for safety fuel use. One must bear in mind that "gel" is a much-abused word, and that many so-called gels do not meet this definition. For instance, Napalm is a viscoelastic fluid with no yield stress and is totally unsuitable for use in an engine. The material known as FAA 1069.1 does conform to this description; its colloidal structural network consists of N-coco-gamma-hydroxybutyramide (CHBA).[17] It is important to realize that both the fuel and the CHBA are continuous phases and that both contact the walls of any vessel containing the gel. The flow-resistance of the gel is due to the adhesion of minute elongated crystallites of CHBA to one another where they cross in the gel matrix. This adhesion is due

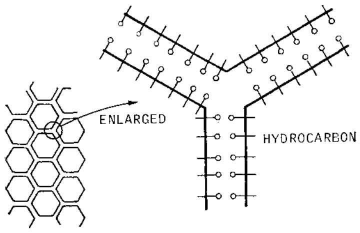


Fig. 1 Emulsion structure (HIPR).

to "van der Waal's forces," which is the general term for the intermolecular forces due to: 1) nonpolar interactions, 2) hydrogen bonding, and 3) dipole moment. The hydrogen bonding component is believed to dominate in this case.

Emulsions are defined[14] as follows: "An emulsion is a two-phase liquid system in which small droplets of one liquid (the internal phase) are immiscible in, and are dispersed uniformly throughout, a second, continuous liquid phase (the external phase)." The word "uniformly" must not be taken too strictly, since some degree of nonuniformity exists in all real emulsions. To this general definition, we must add Lissant's "high internal phase ratio" (HIPR).[4] Most of the emulsions encountered have internal phase ratios below 74% by volume and, hence, are liquids. Above this critical ratio, a structural strength develops, which is due to the deformation of the droplets from spheres to polyhedra. At the 97% level, these are tetrakaidecahedra[16] and provide a yield stress comparable to that of a moderately stiff gel. Their structure is indicated in Fig. 1; the hexagonal pattern is that expected from crosscutting dodecahedra.

Rheology of Gels and Emulsions

The flow properties of these two classes of thickened fuels are illustrated in Fig. 2, in comparison with unthickened JP-4, a heavy fuel (JP-5) (which has also been proposed as a safety fuel), and Napalm (or other viscoelastic fluids). The important difference is that the gel yields rather abruptly at about 1000 dynes/cm² to a free-flowing fluid, whereas the emulsion starts to yield at about 1000 dynes/cm², but resists flow to a greater extent above this yield stress. In the ASTM definitions, the CHBA gel would be essentially "plastic," the emulsion "pseudoplastic."

Several other flow effects not shown in Fig. 2 are important and will be further discussed under Fuel System Studies. These include:

1) In Fig. 2, it is assumed that the flow test is made in equipment that is wetted by the continuous phase of the emulsion, which typically is "hydrophilic" in nature and so wets metal, glass, etc. It does not wet "lipophilic" surfaces such as polyethylene or polyperfluoroethylene since the lipophilic fuel is not continuous and slides along tubes lined with these materials like a nearly frictionless piston. Gels do not exhibit this flow (unless they are so cohesive as to be elastic and, hence, very difficult to atomize in the engine) because both the solid and liquid phases are in contact with the surface.

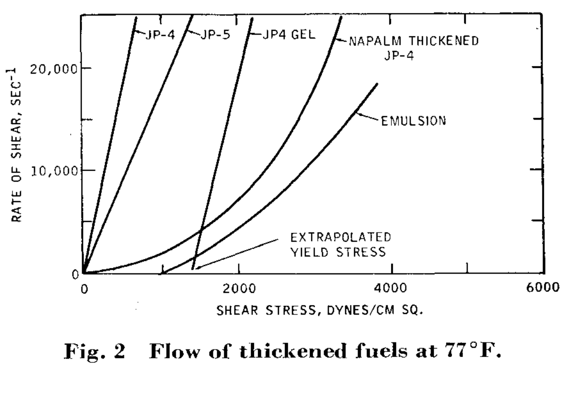


Fig. 2 Flow of thickened fuels at 77°F.

2) The effect of temperature on gels has long been known to be very important; it is due to the variation in strength of the van der Waal's forces that hold the structural network together and provide the yield stress. These forces increase at low temperatures, so that intolerable stiffness results. At a moderately elevated temperature, they are reduced to the point where the gel melts to a liquid. Neither of these effects is observed in an emulsion, whose yield stress is due to geometry rather than chemical forces. As long as neither phase separates from the emulsion, the yield stress is essentially independent of temperature.

3) The behavior on handling is also quite different. Gels tend to break down nearly to liquids on shearing; some degree of "thixotropic" recovery may take place, but this is often a slow process. Emulsions, on the contrary, show a mild "dilatancy" or thickening on initial shearing. This is believed to be due to rearrangement of the continuous phase, which tends to flow towards the corners (Fig. 1) during storage, but is easily reworked into the more strained position between the faces of the polyhedra. It is the increase in strain energy that causes the stiffening. A considerably larger amount of working can then be tolerated without visible effect, but at a certain critical energy level, inversion of the emulsion starts. The result is the temporary generation of a "double" emulsion, consisting of chunks of depleted fuel-in-hydrophil emulsion dispersed in fuel. The chunks soon coalesce, leaving clear fuel. The amount of separated fuel depends on the energy input per unit volume up to about 3×10^6 ergs/cm³, after which an equilibrium amount appears to remain in the dispersed form. Details are discussed under Nozzles below.

Formation and Properties of Emulsions

Six emulsion formulations have reached the status of publication (Table 2), out of several thousand of potential candidates,[4] and there is no reason to feel that the possibilities are exhausted. There is reason, however, to expect that there will be no major change in the engineering properties as these are derived in large part from the geometry rather than the chemistry of the system. Thus, the values in Table 3 may be regarded as typical of the whole class, past and future, though relating specifically to WSX-7063 as formulated under Army Contract DA-44-177 AMC-387(T). Some discussion of these points is required.

The yield stress of the various emulsions in Tables 2 and 3 has varied, sometimes because of problems in either production or stability, and sometimes deliberately. The optimum value of this property is dependent on the outcome of future tests; it is expected that about 2000 dynes/cm² will resist bullets and crashes adequately, while still being operable in slightly modified aircraft systems (see below). It seems probable that all compositions can be adjusted to the final optimum value.

The vapor pressure difference is known to be due to loss of light hydrocarbons during preparation of the test batches of emulsions and can be expected to vanish as preparation becomes more efficient. A continuous process would have the greatest potential for circumventing this problem.

The specific gravity and Btu values are based on the use of a specific JP-4 fuel. Changes in this base stock will change all the details but not their relations to each other. It is of interest that the net Btu per unit volume is essentially the same

Table 2 Emulsion formulations

Code	Continuous phase	Yield stress,[a] dynes/cm²	Gallons produced	References
JD-1	Water	1500	Thousands	2, 3, 8, 10–12
EF4-101	Water-glycol	1000	Thousands	4, 12, 13
WSX-7063	Nonaqueous	2000	Thousands	7, 12, 15
"Aqueous"	Water-glycol	2000	Lab only	7
H26D	Water-glycol	1500	Hundreds	9
CS130	Water-glycol	1000	Lab only	9

[a] Approximate.

Table 3 Engineering properties of aircraft fuel emulsion

Property	JP-4	Emulsion
Yield stress	0	2,000
Vapor pressure	2.3	1.9
Conductivity	10^{-13}	1.6×10^{-6}
Dielectric constant	2.0	3.5
Specific gravity	0.770	0.782
Btu/lb—net	19,166	18,938
Btu/lb—gross	20,356	19,654
4-Ball wear	0.45	0.73
Flame spread (relative)	100	2

for the JP-4 because of the higher density of the emulsifiers and continuous phase, and their lower hydrogen content. (JD-1, made with water alone, would show a slightly lower Btu value than the others.)

The 4-Ball wear value shown for emulsion is the highest of several reported; in some cases, the emulsion showed less wear than JP-4. No specification exists for this property, though work is under way to define wear limits for JP-4 [Contract AF-33(615)-2828]. However, it is reassuring to know that emulsion hydraulic fluids with wear rates as high as 0.75 have shown satisfactory performance at over 1000 psi in close-clearance pumps for many months.

The chemical properties shown in Table 4 may be regarded as targets, though they all have been met by one or more of the fuels in Table 2. Further discussion of compatibility will be required under Fuel System Studies.

Stability of all candidate fuels in storage at −20° to +130°F and under conditions of temperature cycle or vibration, has been excellent when the materials are prepared in laboratory quantities. Large batches of material produced by various scale-up techniques have had stability problems up to this point. This area must be given immediate attention before larger scale tests can get under way and the results of such tests can be considered meaningful.

Fire-Resistance Testing of Thickened Fuels

So far, there have been relatively few tests on a scale approaching service conditions, either in the crash or bullet-fire areas. Data that are available support the view that either gel or emulsion is capable of reducing the incidence of fires. This work has been carried out by various government agencies and is not covered in detail here.[5,6]

The various nongovernment laboratories involved have devised a large number of bench-type tests attempting to simulate service conditions. These are summarized in Table 5 in three groups. It is generally realized that no one test of this type can be truly representative of the sort of hazard to be encountered in service, and FAA has announced plans to fund a study to select test methods and devise a system of weighting the results to provide a scale for rating the safety of various fuels. In the meantime, the authors can only state that most of the data from this type of testing indicate

Table 4 Chemical properties of fuel emulsion

Property	Results
Ash content	<0.005%
S content	<200 ppm
Na content	<1 ppm
Resistant to (30 days)	Aereobacter Aerogenes Psuedomonas Aeruginosa Cladosporium Resinal
Compatibility	
Metals—pass	Al, Mg, Cu, Ti, Fe, SS
Elastomers—pass	CR, NBR, FPM, PTFE, PE, PM[20]
Elastomers—fail	IIR, NR, Si

Table 5 Bench-type tests for fire resistance

Group of tests	Description of test	Safety ratio to JP-4	References
Ignition	Flash point (ASTM D 92)	High	9
	Autogenous ignition (modified ASTM D 2155)	Minor	15
	Evaporation rate (modified ASTM D 972)	10–20 times	7, 9
	Explosivity of vapor space	4–5 times	4, 9
Propagation	Flame travel down trough	10–100 times	2, 4, 6, 7
Impact—splash	"Molotov cocktail" impact	>3 times	4
	Air gun (impact on grating at 340 mph)	2–6 times	2, 6
	Flow from simulated bullet hole	High	3, 7
	Vapor space explosion	Infinite	4

a decrease in fire hazard of about tenfold relative to JP-4. One exception is in the autogenous ignition temperature; this is to be expected as the test conditions essentially insure that the fuel is in the vapor phase. Other methods give more encouraging results. It should be noted that although the investigators indicate that the problem of the vapor space becoming explosive is improved only to the extent that a longer time will be required, the vapor explosion always failed to ignite emulsion but always ignited JP-4. The variation in relative evaporation rate is shown in Fig. 3 to be essentially independent of temperature but a function of the percent evaporated.

Corrosion and Contamination

The entire group of engine laboratories working with the emulsions reported trouble with rust or dirt, or both, unless special precautions were taken. Of the emulsions tested, only nonaqueous emulsion[12] received no criticism on the score of corrosion. The water content of the other candidate fuels appears to be largely to blame. Rust inhibitors are being investigated to solve this problem.

There was no way of clearly defining the contamination problem in the presence of corrosion products, but the reports on nonaqueous emulsion left no doubt that the worst fears expressed at the 1966 Symposium had been verified. Past experience with emulsion hydraulic fluid had demonstrated that emulsions not only scavenge all the dirt from a contaminated system, but also carry it in suspension indefinitely. Even with JP-4, from which most of the contaminants will settle in a few hours, control has been a million-dollar headache; the fact that emulsions do not settle clean will surely complicate the picture. In addition, the established test methods such as ASTM D 2276-66T[14] are not applicable, and early experience indicated that filtration of emulsions led to partial demulsification.

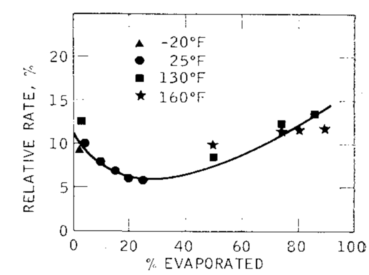


Fig. 3 Evaporation rate of fuel emulsion vs JP-4.

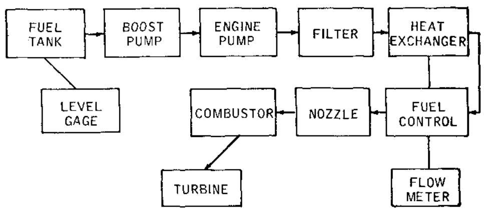


Fig. 4 Typical fuel system for turbine aircraft.

A further complication has been the generation of fiberlike particles of the emulsifier during the separation process in the nozzle. This has only been reported twice: once[10] as contributing to nozzle plugging and by the present authors who obtained similar material from a used nozzle supplied by the author of Ref. 12. These "fibers" resembled shredded coconut, being yellow-white and ribbonlike in shape. They could be distinguished from regular textile fibers by their ready solubility in isopropanol or acetone. They have not been a general problem, but might assume more importance as cleaner emulsions become available.

Steps to alleviate the situation have included the following:

1) Bringing to the attention of all concerned the "Recommended Practice"[19] for changing over hydraulic systems from petroleum to emulsion fluids, and advising them to follow this for fuel systems.

2) Modification of the ASTM D 2387-65T procedure to include use of an emulsion-breaking chemical to produce a mixture that can be filtered for a gravimetric determination of contaminants. The results are believed to be comparable to D 2276-65T, the method called out in MIL-T-5624G to control the dirt to a maximum of 8 mg/gal at point of receipt. Unfortunately, D 2387-65T is not readily adaptable to field monitoring.

3) Control by modified D 2387-65T has been incorporated into the present authors' quality control procedure, and this practice will presumably be followed by the other manufacturers. The need for precleaning of shipping drums has also been established.

4) The practice of flushing out fuel systems with JP-4 or water has been discouraged, and the use of isopropanol recommended.

5) Modified aircraft fueling procedures using the "Air-Cow" concept will be recommended to avoid picking up airborne dirt. Part of this recommendation is that all tanks be filled through the bottom connection to avoid air entrainment. Air, like dirt, is permanently trapped in an emulsion or gel by the yield stress forces.

Another contamination, troublesome in the past, has been water in the JP-4, which frequently separated out in the form of ice crystals and plugged filters and lines. Water is much less harmful in emulsions, as up to 0.5% merely adds to the continuous phase without adversely affecting yield stress, stability, or corrosion. Larger quantities soften, and extreme doses (25%) liquify the product.

Fuel System Studies

A block diagram of a typical fuel system for a turbine aircraft is shown in Fig. 4. The discussion follows this diagram in the direction of fuel flow, from left to right.

Fuel Tanks

Little data have been reported on actual tank tests. In one case, a standard Army auxiliary fuel tank was successfully used,[11] but most investigators used mixing vessels or shipping drums for test runs. In the present authors' opinion, no tank that has not been coated internally with a lipophilic polymer, such as polyethylene, polypropylene or polytetrafluoroethylene, is likely to show good discharge characteristics on emulsion—and even this will not guarantee good discharge of gel.

Fuel Gages

The authors have studied the gaging problem in as much detail as possible without actual tests and have concluded that the commonly used capacitance gages are capable of giving meaningful readings provided the elements are coated with lipophilic material. No data are available on gels, but the preceding applies to all emulsions. It is probable that several elements would be needed in each tank to compensate for the fact that these fuels do not flow to a level surface, but tend to form mounds reflecting past changes in attitude angle, etc. If, in some unforeseen condition, these gages prove to be inoperable, nuclear gages similar to MIL-O-38338A appear to be completely capable of dealing with all contingencies. They offer the additional advantage of reading out directly in weight of fuel rather than volume.

Pumps

The usual aircraft booster or transfer pump is a small diameter, high-speed centrifugal. This type of unit has generally been able to move thickened fuels, though some tendency to separate emulsions has been noted. In one instance, a major engine test was seriously lowered in validity because part of the pump discharge was released into the tank; the liquid JP-4 that accumulated would have nullified any safety gain. In general, slower moving pumps have handled the emulsion well[11] and are usually employed in its manufacture; gear and vane pumps in particular have proved satisfactory. However, positive displacement pumps require relief, and the relief valve can be even more destructive than the high-speed centrifugal. Low-speed centrifugals, or positive displacement pumps with either variable capacity or speed, are available and could be employed if necessary.

The suction conditions at the pump are vitally important.[19] Users of fire-resistant emulsion hydraulic fluids have had to learn to "build a highway to the pump," and this will be even more important for aircraft system designers. Even unthickened JP-4 becomes border-line in pumpability at 160°F sea level, or 130°F at 20,000 ft because of incipient boiling, so that any pressure drop in the suction line must be minimized. This even includes removal of inlet strainers; in the authors' laboratory, an 8-mesh strainer across the inlet completely prevented pumping WSX-7063 at 77°F and sea level. Careful consideration of the net positive suction head of each system is an absolutely vital step in predicting the operability of emulsion in any given system. As the over-all success of the program depends on the ability to pump the fuel at several points, thorough investigation of the limitations on pump design appears essential.

Filters

The first data on filtration of emulsions indicated that severe breakdown took place, and it was suggested that no filters be used. This was impossible for the reasons discussed

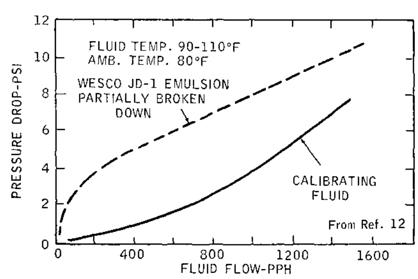


Fig. 5 T55 cooler pressure drop flow characteristic.

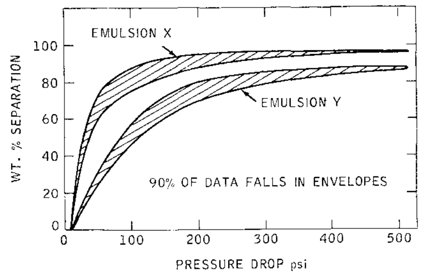


Fig. 6 Separation of JP-4 from emulsions in nozzles.

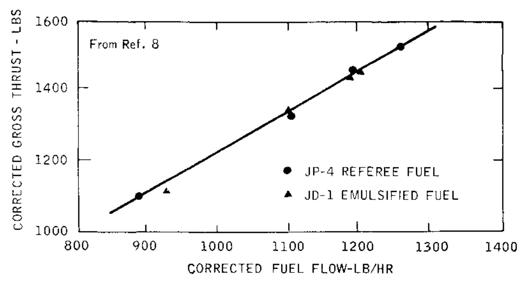


Fig. 8 Corrected gross thrust—corrected fuel flow.

previously. Subsequent work by the present authors and several engine laboratories indicates that filters as fine as 40 μ[12] can be used if the area is large enough to avoid pressure drops of over 5 psi. This would be no problem in the fuel system proper, where flow rates are low. If the filters at the nozzles cause demulsification, this merely aids in the desired effect as discussed below. On the other hand, there may be limitations on in-flight transfer and refueling filtration.

Heat Exchangers

There has been concern over the ability of the emulsions to serve as lubricant coolant in the usual heat exchangers, and with good reason. Non-Newtonian fluids are notorious for their low over-all heat-transfer coefficients, despite their thermal conductivity being about the same as their Newtonian counterparts. The reason lies in the fact that they persist in laminar flow long after a Newtonian fluid would have gone turbulent. They also cause large pressure drops, as shown in Fig. 5, and may cause some deposit formation. At present, use of any thickened fuel except gel (which melts at 130°F) in the heat exchanger must be regarded as an unsolved problem.

Control Valves

Five authors who have reported on engine tests also reported on control valve operation.[3,8,10,11,12] Of these, several were so plagued with contamination and corrosion that their work is difficult to interpret, but in one case the bypass valve tended to remain open, leading to poor starts,[3] and this appeared related to a hard gel accumulation. In another case, flow was below normal,[10] for no specific reason. It was reported that the pump wore out during the test. In the most extensive series of tests,[12] the performance was good on clean emulsions. The only abnormal behavior found was an increase in hysteresis in the spool valve. The conclusion must be drawn that although some problems exist, further research could lead to solutions of them.

Flow Meters

Flow meters so far evaluated have included the turbine type (unsatisfactory),[10] a flow-bridge instrument,[12] a sensing reed,[9] and a "hydromechanical" (inertial).[8] The authors have found that the nutating-plate meter is satisfactory for this type of material, but this design is not commonly available in a light-weight version. The same weight problem may limit the flow-bridge. The sensing reed required recalibration if there was any change in fuel consistency. So far, the hydromechanical unit seems to be the only one free from all deficiencies.

Nozzles

The behavior of various types of nozzles was checked out in the course of the engine tests,[8,10,12] and in a more intensive program in the authors' laboratories. In every instance, the flow vs pressure relationship proved to be essentially the same as for JP-4, indicating turbulent flow. The laboratory whose fuel pump wore out also suffered severe nozzle erosion, but this did not affect the preceding conclusion.[10] They did report a very unusual finding, "that the emulsion was sprayed as an emulsion and that spraying did not cause significant breakdown." This is at variance with the other laboratories, whose data indicated very substantial breakdown. Figure 6 shows the percent separation of JP-4 after passage through the duplex nozzles provided by the authors of Refs. 8, 10, and 12. Emulsions X and Y are experimental formulations representing the extremes of behavior.

The reference to "90% of the data" on Fig. 6 was put in to exclude the data on the simplex starting nozzle of Ref. 12. A high-speed movie presented along with Ref. 12 at the SAE National Meeting showed the same anomalous behavior, in that the breakdown was only about $\frac{2}{3}$ that of the duplex nozzles. No explanation is available—especially since the main bands of Fig. 6 include the data from the simplest of all nozzles, a cylindrical capillary of flowing rating (gallons per hour/100 psi) comparable to those of the duplex nozzles. This anomaly was also found (to a lesser extent) on a few tests of the isolated primary of the nozzle obtained from the author of Ref. 8 by the present authors. It appears to be associated with simplex nozzles of very small capacity, on the basis of the available evidence. The use of off-the-shelf nozzles clearly should be regulated by detailed experiments on the fuel to be used.

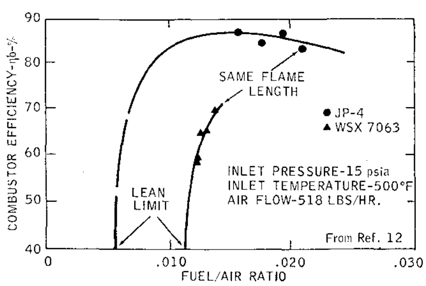


Fig. 7 $2\frac{1}{2}$-in. can combustor performance—Esso WSX-7063 emulsion.

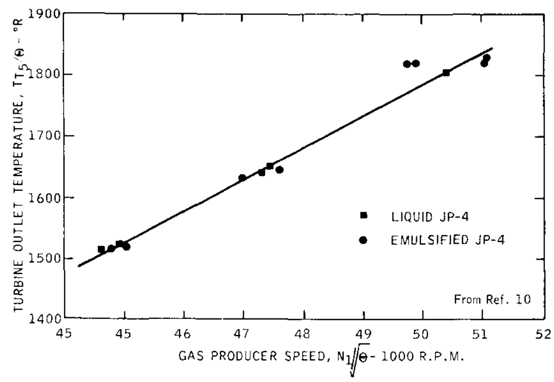
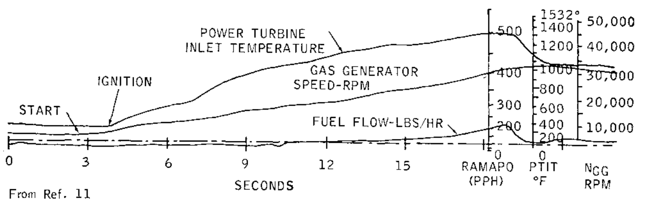
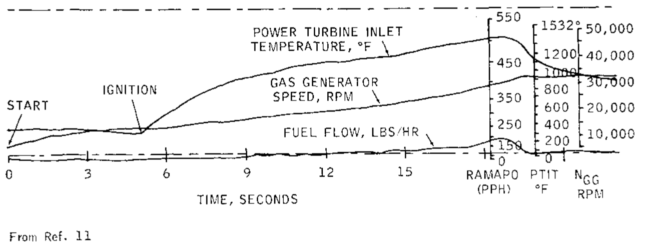


Fig. 9 Turbine outlet temperature vs gas producer RPM burning liquid and emulsified JP-4.



a) Using liquid JP-4 fuel



b) Using emulsified JP-4 fuel

Fig. 10 Transient recording of engine start.

Combustors

Only Ref. 12 made any tests on separate combustors, and his data are complicated by the use of a smaller combustor diameter on the WSX-7063 tests than on the aqueous emulsions. However, both sets of experiments led to the same conclusion, that about a 30% reduction in fuel/air ratio was required to obtain the same flame length as is produced by JP-4 (Fig. 7). This confirms in general the observations in Fig. 6 that some unbroken emulsion will pass through the nozzle. Color photographs of shots with the continuous phase dyed red also indicate that some of the drops are largely composed of the relatively slow-burning components. Whether this calls for longer combustors, or merely for a more positive means of breaking the emulsion in the line to the nozzle, it is evident from Figs. 6 and 7 that under the engine conditions normally used with JP-4, there may be some emulsion burning in the turbine.

Engine Test Results

All of the seven authors have presented a remarkably similar picture: that when thickened fuel is delivered properly through the nozzle, operation is very similar to that with JP-4.[3,8,10–13,18] One laboratory[10] reported blade corrosion, but this was quickly traced to excessive sodium in the fuel and corrective measures taken. Actual plots of exhaust-gas temperature, thrust, corrected rpm, and fuel consumption are shown in Refs. 8 and 10–12 and Figs. 8–11. The only difference found between JP-4 and the emulsions can be attributed to the low fuel value of JD-1 when it was used.

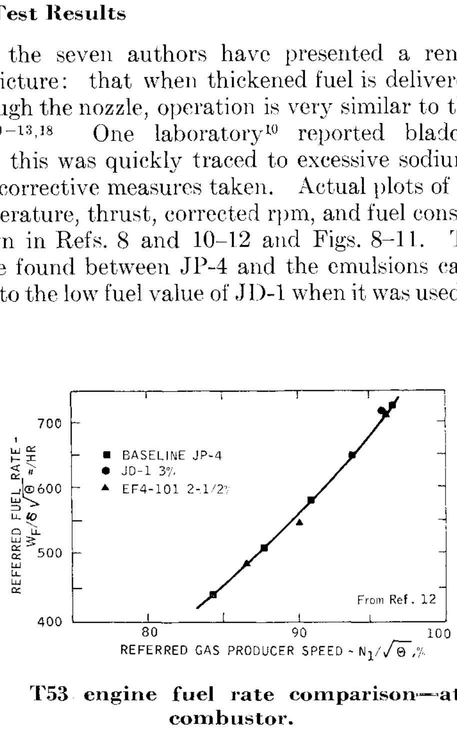


Fig. 11 T53 engine fuel rate comparison—atomizing combustor.

All reports agree that no serious loss of engine efficiency or other performance parameters was experienced. However, there was criticism of fuel clinging to the nozzle[8] and exuding into the combustor,[13] but these were classed as minor problems.

Conclusions

1) Further work is needed to firm up the following areas: scale-up with storage stability, cleanliness control, effect of incendiary bullets, optimization of stability (handling vs nozzle), metering and fuel control problems, combustion under service conditions. 2) No final conclusion can be drawn until these data are obtained and evaluated. 3) It seems quite likely that use of emulsions as safety fuels will be limited to military applications such as helicopters in the foreseeable future.

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