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PHOTOGRAPHIC INVESTIGATION OF MODIFIED FUEL BREAKUP AND IGNITION

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FINAL REPORT

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16. Abstract

Laboratory evaluations were performed to determine the flammability characteristics, physical properties, and rheological profiles of modified fuel sprays. Photographs were made of fuel particles formed by air shearing in the NAFEC Fire Test Facility. Ignition studies of the modified fuel sprays included photographs of typical combustion patterns. Comparisons of shear viscosity, droplet geometries, and ignitability of the different antimisting fuels clarify the effect of polymeric additives on turbine fuel safety, and indicate critical criteria for modified fuel specifications.

The results of this investigation lead to two major conclusions. First, the modified fuel spray consists of particles of large size and highly aspherical geometry. Second, although a modified fuel can be flammable in the presence of an intense ignition source, all modified fuels tested were more difficult to ignite than neat fuel.

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INTRODUCTION

PURPOSE.

The objective of this program was to define the flammability characteristics, physical properties, and rheological profiles of improved modified fuels. Included is photographic documentation of fuel droplet patterns and burning fuel sprays.

BACKGROUND.

Contradictory results in flammability testing of modified fuels in different environments have necessitated additional laboratory and analytical evaluation. Current modified fuel work centers around the "antimisting fuels," which have replaced gelled fuels as promising safety fuel candidates. The antimisting fuels are solutions of large polymers in the neat aviation fuel. In ways not totally clear, the polymer inhibits breakup of fuel streams subjected to air shear. In an aircraft crash, neat fuel forms a highly flammable spray as it emerges from a broken tank and atomizes in air passing over the decelerating aircraft. The antimisting fuel forms a spray of larger particles than the neat fuel, and the likelihood of ignition is reduced. Though the antimisting fuels are more fluid than the older gelled fuels under shearing conditions, the antimisting fuels are more promising in terms of their compatibility with existing aircraft fuel systems and ground handling facilities. A recent survey estimates that an average of up to one-third of the fatalities in impact-survivable crashes could be avoided by minimizing the effects of postcrash fuel fires due to fuel spillage from damaged tanks or severed wings (reference 1).

The status of research on antimisting fuels in both the United States (reference 2) and Great Britain (reference 3) has been thoroughly reviewed. The British have emphasized the catapult and rocket sled tests in their evaluations (references 4, 5, and 6), and have performed extensive compatibility tests with their Imperial Chemical Industries (ICI) additives (FM-4, FM-8, and FM-9) (references 7, 8, and 9). The United States work includes activities by a number of agencies on various fuel additives. Work by military establishments has involved modified fuel development for helicopter applications and for gunfire resistance (reference 2), as well as for fixed-wing aircraft crashes. These efforts have led to the development of a fuel mist flammability test (reference 10) and to explorations of the rheological behavior of the fuels (reference 11). In recent years, the Federal Aviation Administration (FAA) has emphasized the flammability studies. Unfortunately, though all tests devised to date show obvious qualitative differences in burning intensity between the modified fuel fires and neat Jet A fires, inconsistencies exist in the hazard ratings ascribed to the same fuel by different tests. Serious questions also remain as to the applicability of flammability tests to conditions in an aircraft crash.

The most recent full-scale crash demonstration at Lakehurst Naval Air Station, Lakehurst, New Jersey, resulted in ignition of the antimisting fuel. Follow-up tests, wherein a simulated wing was placed in line with a high-volume air supply, are being conducted as representative of full-scale tests. Photographic evaluation of these latter air shear tests indicate that air velocity, ignition source placement, and fuel flow rate all have some influence on ignitability. Consequently, the most recent FAA activities have centered on a more detailed description of the breakup of the modified fuels in air streams. The work described in this report was performed at the National Aviation Facilities Experimental Center (NAFEC).

EXPERIMENTAL OBJECTIVES.

A photographic system was installed in the test section of the NAFEC Fire Test Facility, building 204, to determine the size and shape of fuel particles formed from shearing a fuel stream by a controlled air flow. The resulting spray was subjected to an intense ignition source in an attempt to establish a relationship between spray characteristics and ignitability. The particle photographs were taken at various downstream distances from the fuel entry point in order to document the breakup history. Three modified fuels (Conoco AM-1, Dow XD8132.01, and ICI FM-4), along with neat Jet A were evaluated in detail as to differences.

DISCUSSION

TEST ENVIRONMENT.

Figure 1 shows the Fire Test Facility at NAFEC. This facility is a subsonic, open-circuit, induction-type tunnel. Major features of this facility are an engine room with two J57 turbojet engines to provide ejector pumping, a control room, and a laboratory with buildup area. The cylindrical test section measures 20 feet in length and 5 feet in diameter. This facility is described in detail in reference 12.

An airfoil of 36-inch span and 48-inch chord was installed as shown in figure 2 for the purpose of protective mounting of test equipment from the air stream and fuel spray. This equipment consisted of:

1. A focusing lens and remotely controlled film magazine as part of the photographic complex,

2. A propane control valve and transformer as part of ignition system which utilized a standard oil burner, 10,000-volt-capacity transformer, and spark gap setting of 1/8-inch, and

3. A 1.84-cubic-foot plenum section in the airfoil leading edge with a 4.25-inch by 0.187-inch rectangular nozzle. The nozzle directed air from the plenum pressurized at 1.2 pounds force per square inch gage (lbf/in^2G) along the optical opening at the end of the airfoil and provided an air barrier against the fuel.

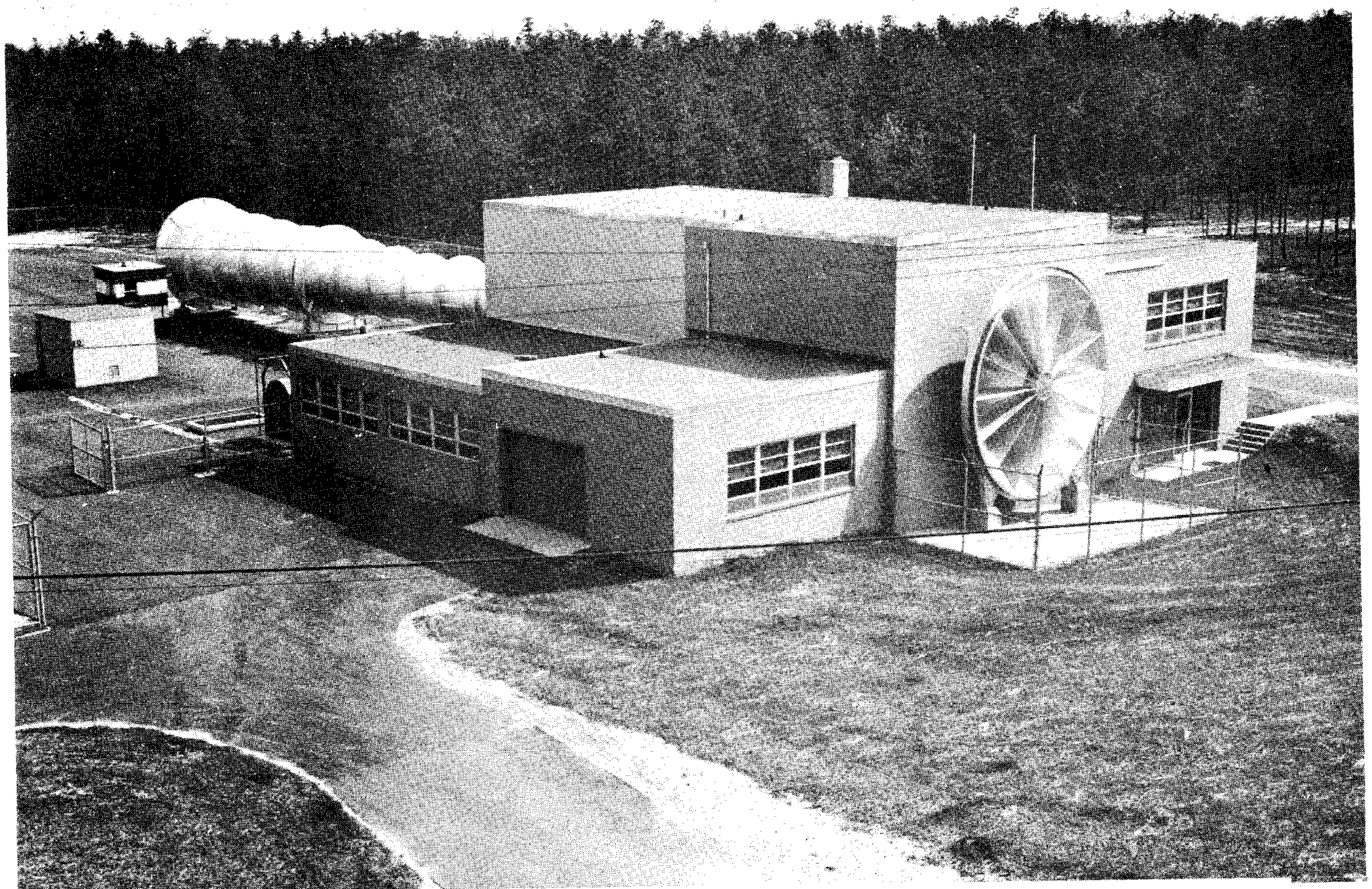

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FIGURE 1.   NAFEC FIRE TEST FACILITY

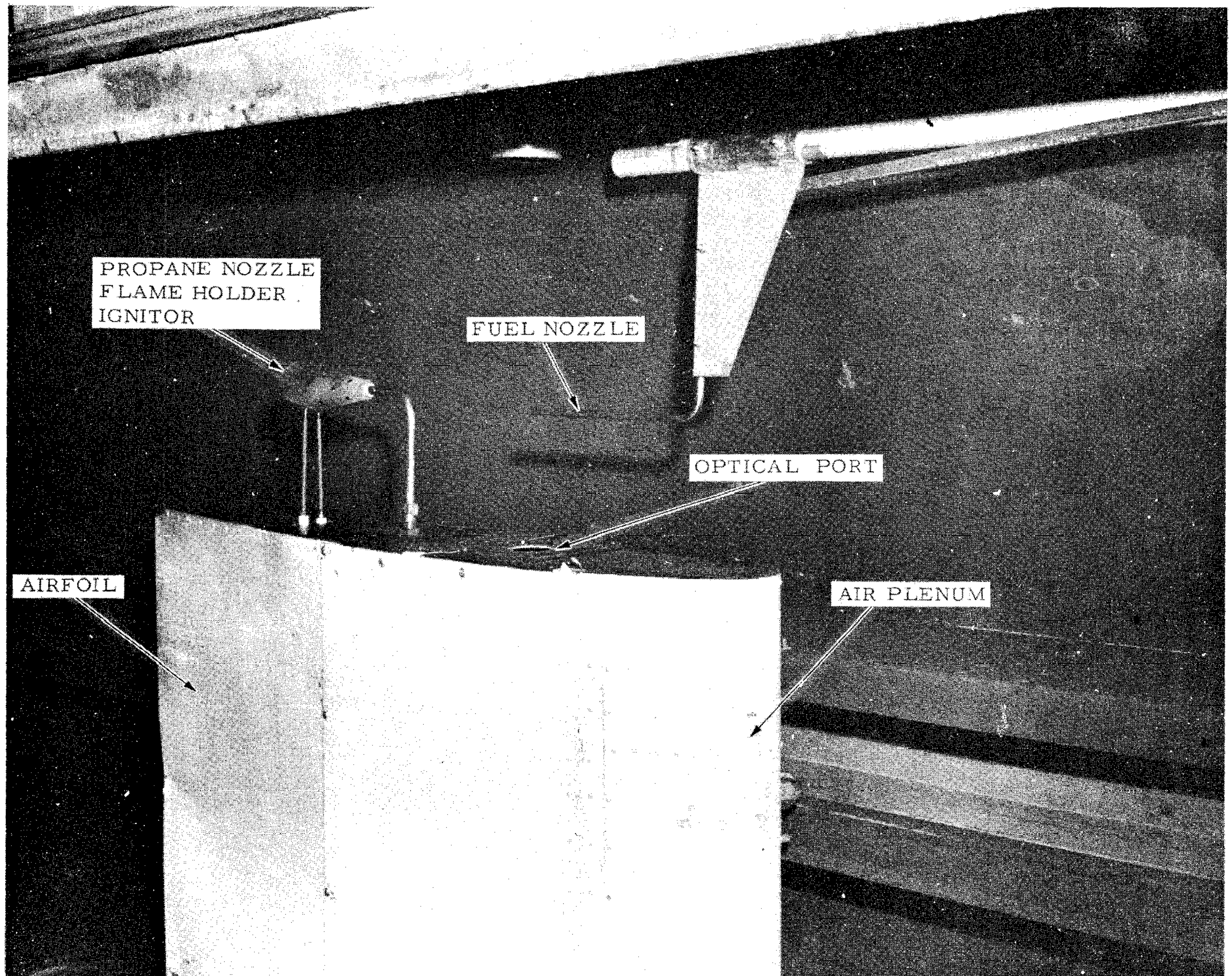


FIGURE 2. TEST SECTION IN TUNNEL-VIEW LOOKING UP

The propane nozzle and flame holder, with igniter, was mounted on the end of the airfoil and downstream of the fuel nozzle. A fuel nozzle support and alignment fixture was mounted on the side of the tunnel. This fixture allowed the nozzle to be moved along the tunnel and permitted variable distances between fuel release and igniter.

The 5/16-inch inner diameter (i.d.) fuel nozzle was attached to a 58.6 foot-long hose of 1/2 inch i.d.

As the fuel enters the tunnel through the nozzle, the high-speed air shears, accelerates, and breaks up the fuel stream. The spray is illuminated by a cylindrical beam of light passing perpendicularly through it. The light source is a 0.5-microsecond (μs) spark which allows stop-action photography of the fast-moving fuel particles. The spark source, from an EG and G model 549 microflash system, passes through a collimating lens. A focusing lens forms images of droplets on the film through a focal depth of 0.12 millimeter (mm). Since the spark duration, rather than a mechanical shutter, controlled the film exposure, all of these photographs were taken at night to eliminate background light. The complete optical system is shown in figure 3.

A motion picture camera was installed downstream of the igniter to record attempted ignition of the fuel sprays. Still pictures of the burning fuel were developed from segments of the developed motion picture film.

Figure 4 shows the fuel storage and pressurized fuel delivery system. This system consisted of four pressure vessels, containing different mixes. The facility compressor provided air for tank pressurization. The fuel was delivered to the test section through an electrically operated solenoid valve in the fuel delivery line at the tunnel wall. This valve was used to start the fuel flow from the control room during testing. Maximum filling of the fuel reservoirs never exceeded 75-percent capacity in order to maintain accumulator capacity.

Figure 5 shows the fuel blending system, consisting of a 55-gallon open top container with a 2 1/2 inch drain outlet and lever- operated quick-opening valve. The cover for this unit incorporated an air-driven motor with a paddle assembly for agitation of the fuel mixtures. The container was placed on a 750-lb capacity platform scale, and Jet A and concentrate were added in accordance with the calculated weight proportions. An average mixing time of 3 hours at 90-100 revolutions per minute (r/min) agitator speed was required at 75° Fahrenheit (F). Mixing time varied with fuel temperature. Minimum mixing temperature of fuel was about 65° F.

The test fuels were blended and loaded into the fuel pumping system. The camera film magazine was loaded and lighting was checked. The pressure regulating valve was adjusted to provide the desired fuel flow.

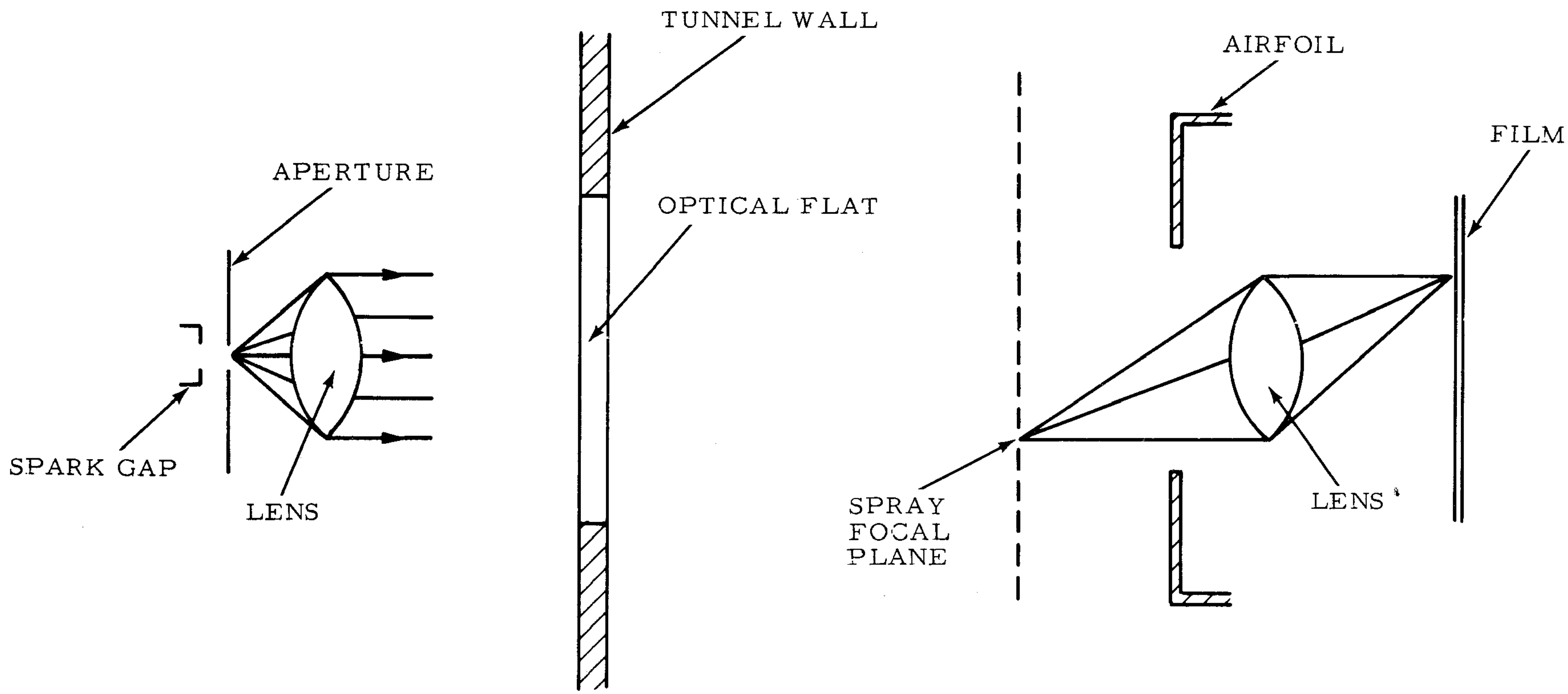
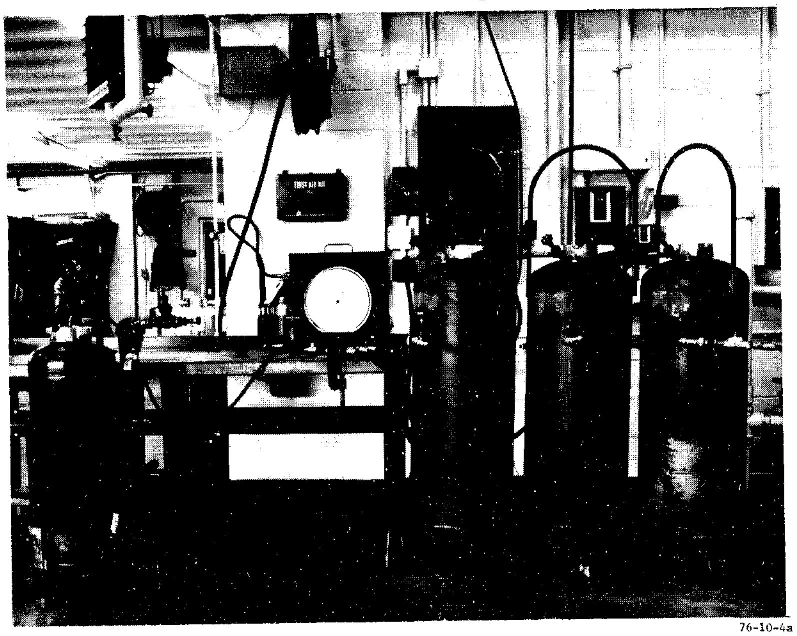


FIGURE 3. PHOTOGRAPHIC SYSTEM



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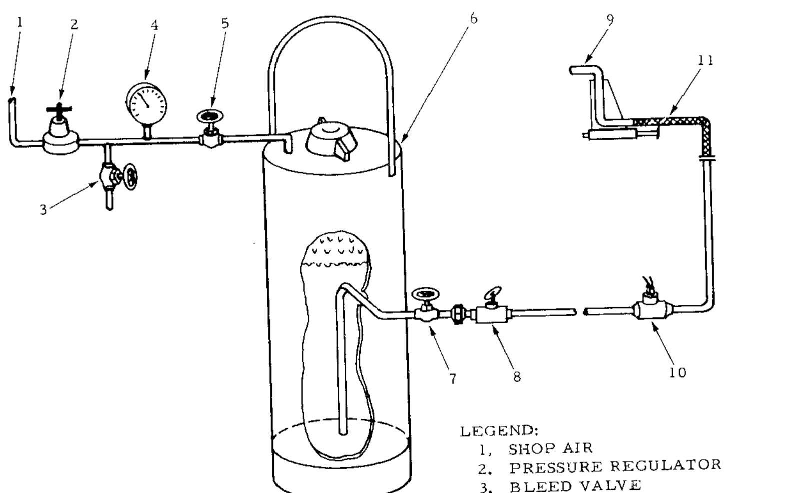

LEGEND:
1. SHOP AIR
2. PRESSURE REGULATOR
3. BLEED VALVE
4. PRESSURE GAGE
5. SHUTOFF VALVE
6. PRESSURE VESSEL
7. SHUTOFF VALVE
8. LEVER OPERATED BALL VALVE
9. FUEL NOZZLE
10. ELECTRIC SOLENOID VALVE
11. FLEXIBLE HOSE

FIGURE 4. FUEL DELIVERY SYSTEM

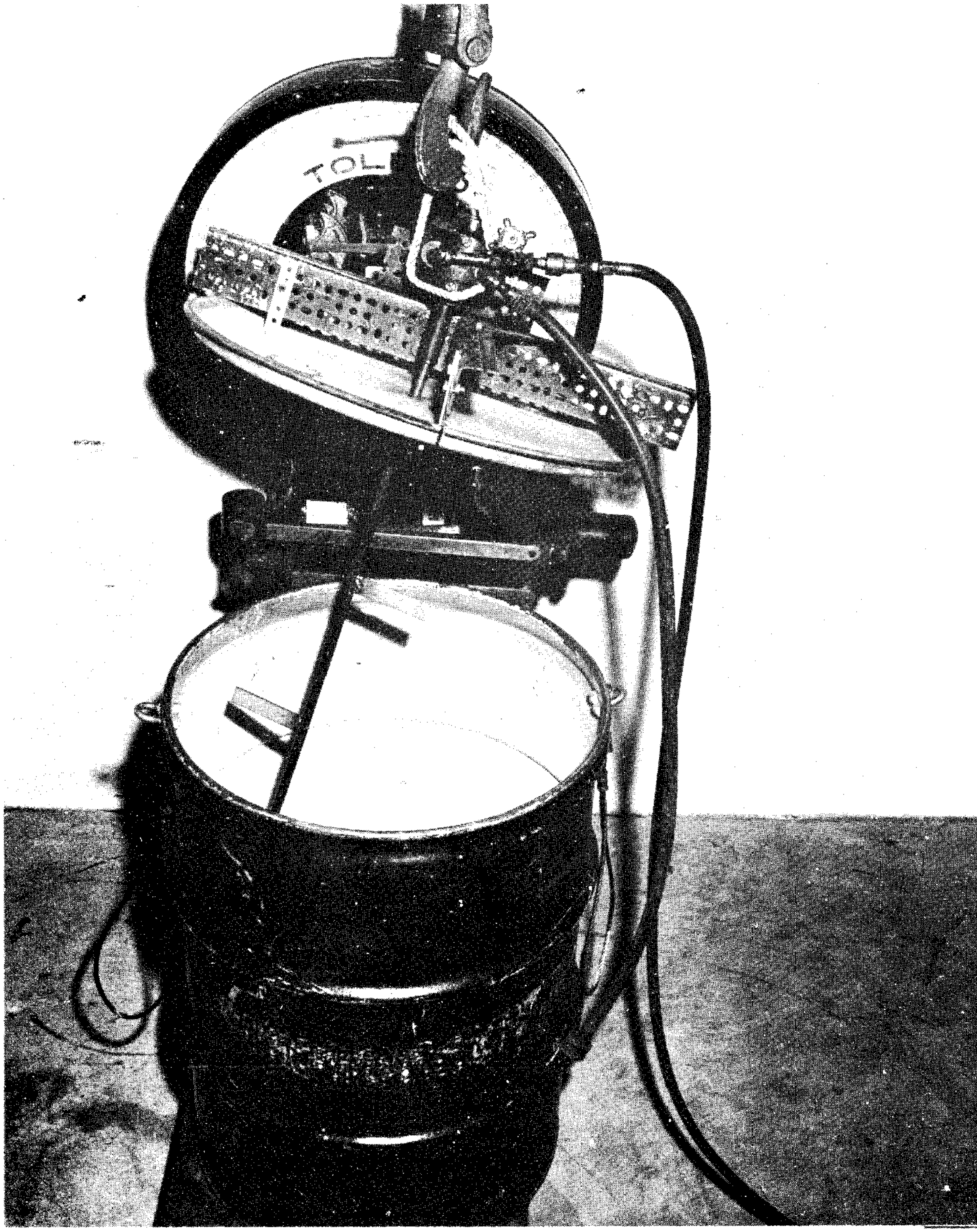

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FIGURE 5. FUEL MIXING APPARATUS

The vertical position of the nozzle varied with the trajectory of the stream. After the airspeed stabilized, fuel was released, and photographs were taken at 5-second intervals. Approximately 30 photographs of each fuel blend were taken at specified airspeeds and nozzle positions. After completion of filming, the igniter was energized. For the modified fuels, a propane flame ignited by spark source was used; however, only the spark source was required to ignite neat fuel spray.

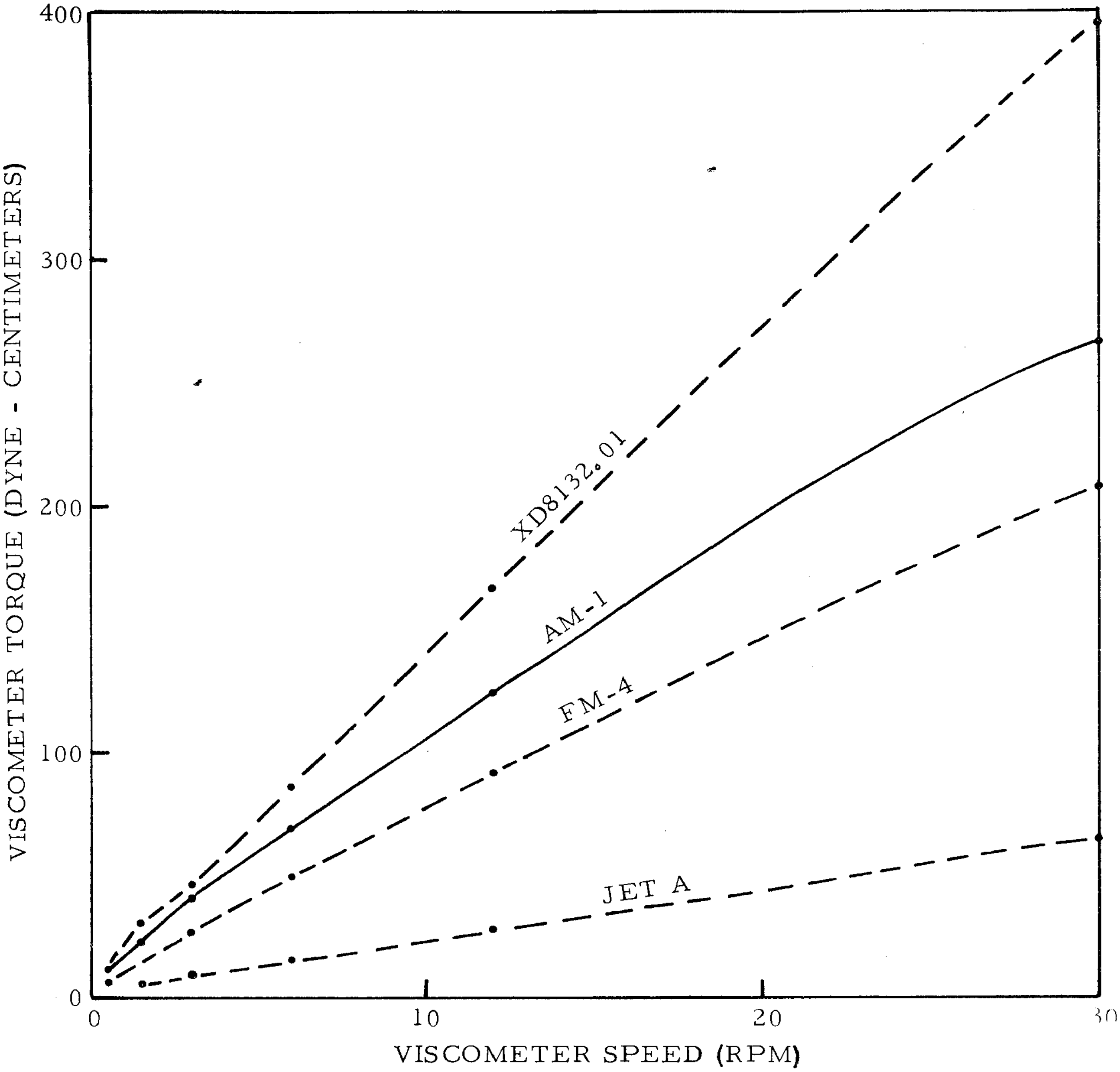
RESULTS.

The modified fuels used in this work were solutions of the same concentrations used in previous testing at NAFEC. The AM=1 was a 0.2-percent solution by weight, while the FM-4 and XD8132.01 were 0.4 percent and 0.7 percent respectively, by weight. Figure 6 shows torque measurements generated by the Brookfield LVT viscometer with a UL adapter. The slope of the lines is a measure of the viscosity, and a straight line is characteristic of a Newtonian fluid. Although all the antimisting fuels evidence mild curvature at the lower viscometer rotational speeds, they flatten out at intermediate rotational speeds. Also listed in figure 6 are the viscosities as measured by a Ubbelohde tube (American Society for Testing and Material designation 1C) for the three modified fuels and for Jet A. These viscosity tests were all performed at room temperature.

The Tag flash points of the fuels as determined by the Tag Closed Tester were 118° F for AM-1, 117° F for FM-4, 122° F for XD8132.01, and 119° F for neat Jet A.

Figure 7 shows the flow rates of the various fuels through the injection system for various reservoir back pressures. While the Jet A is a Newtonian fluid, FM-4 and XD8132.01 show dilatant behavior of increasing shear viscosity with increasing shear rate. The XD8132.01 is further characterized by a leveling of the flow rate for increasing pressures in the fuel reservoir. Additional testing was done on this phenomenon by forcing the modified fuel through a 5-foot length of 1/8-inch tube. The flow rate of the XD8132.01 would also level out with the small tube. However, if pressure was increased further, the flow rate would once again increase. It was further found that as pressure was increased through this relatively constant flow regime, the viscosity decreased for samples collected at the tube outlet. This indicated that the increased work done on the system went into the breakdown of the macromolecules. When the pressure was raised enough to cause the flow rate to increase, the viscosity of the sample collected at the tube outlet was higher than the viscosity of the fluid ejected in the level flow rate regime. The phenomenon is qualitatively shown in figure 8. The overall breakdown of the XD8132.01, from low flow rate to high in the small tube, was characterized by a 3-percent decrease in viscosity. The FM-4 showed a 10-percent decrease in viscosity. The AM-1 remained undegraded in this miniature flow test.

Figures 9, 10, and 11 show photographs of the fuel breakup of FM-4, AM-1, and XD8132.01, respectively. The size relationship is demonstrated by the scale on the photographs. These photographs were taken 6-inches downstream from the fuel nozzle and the nominal air velocity was 110 knots (kn).



FUEL	UBBELOHDE VISCOSITY (CENTIPOISE)
XD8132.01	9.4
FM-4	4.5
AM-1	5.4
JET A	1.5

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FIGURE 6. DYNAMIC VISCOSITY MEASUREMENTS

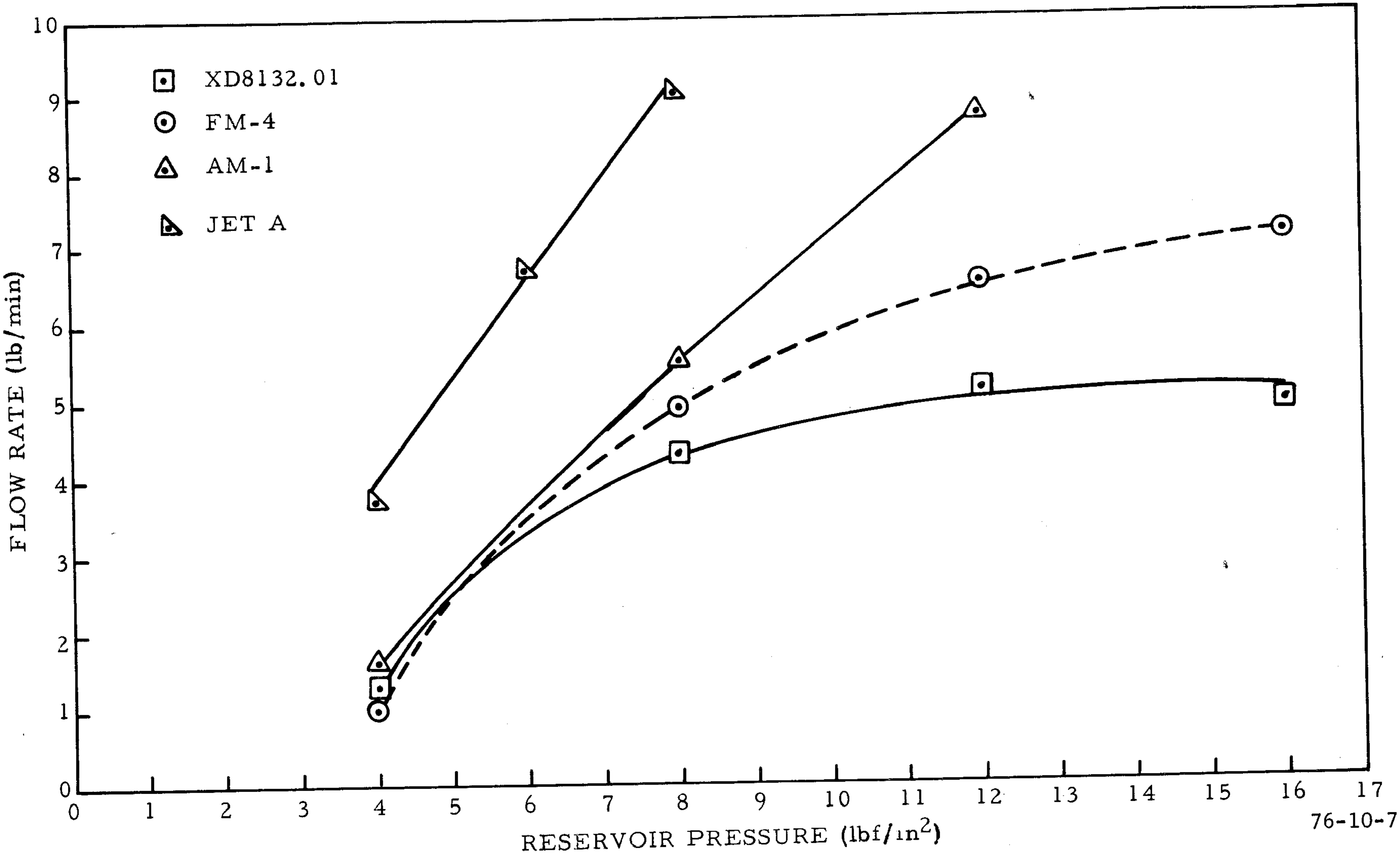

FIGURE 7. FUEL FLOW CALIBRATION

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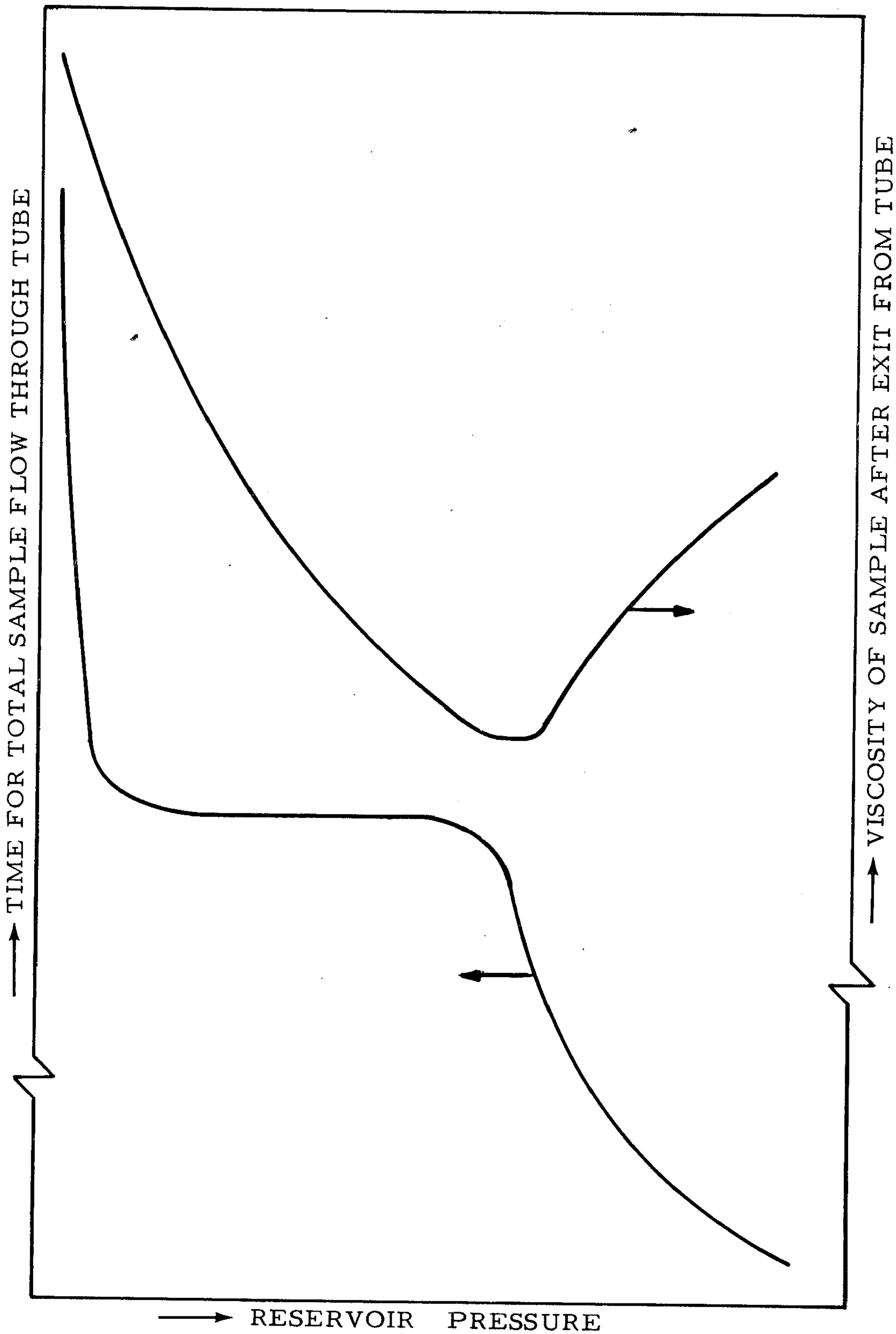


FIGURE 8. XD8132.01 Viscosity Degradation Sketch

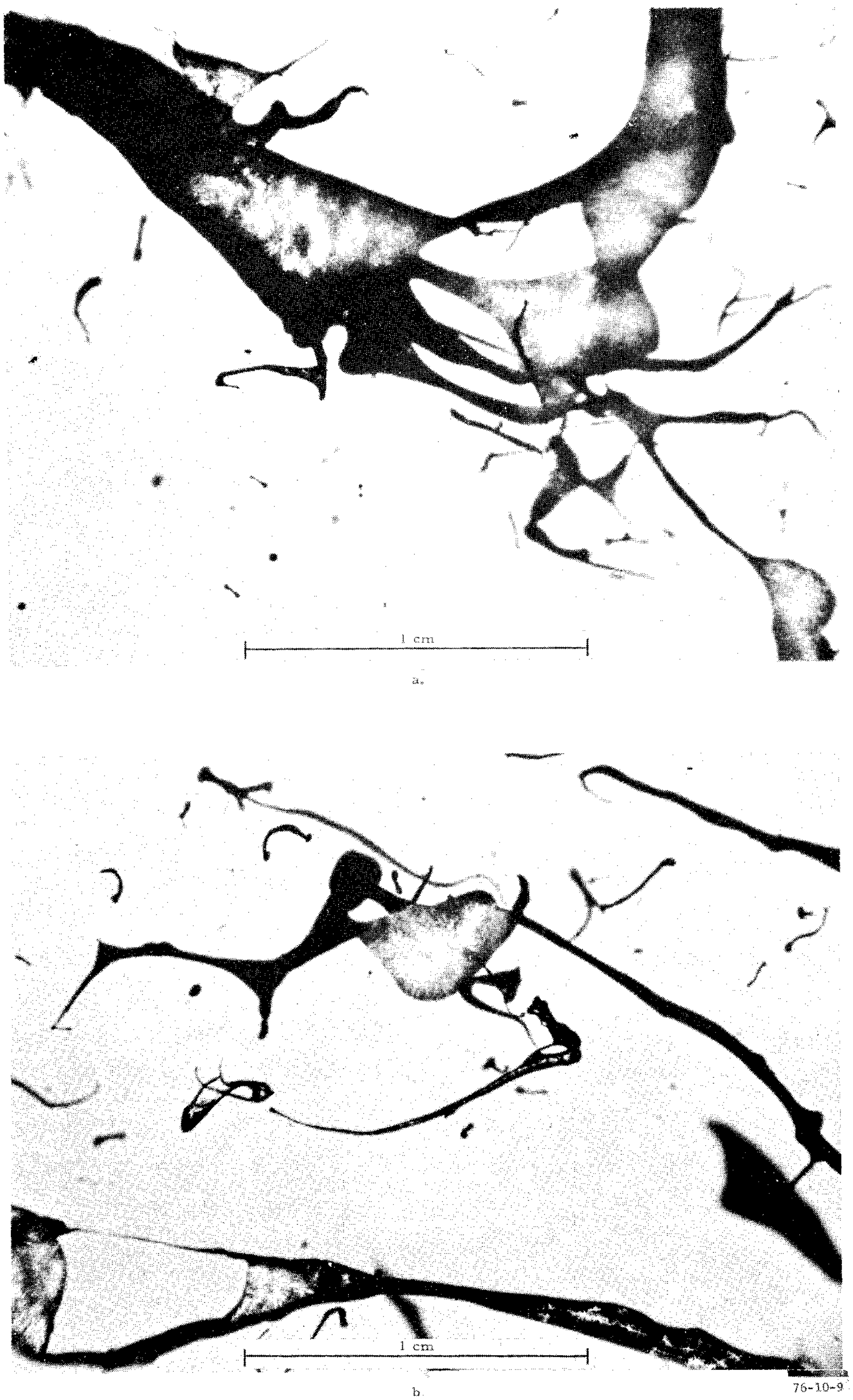
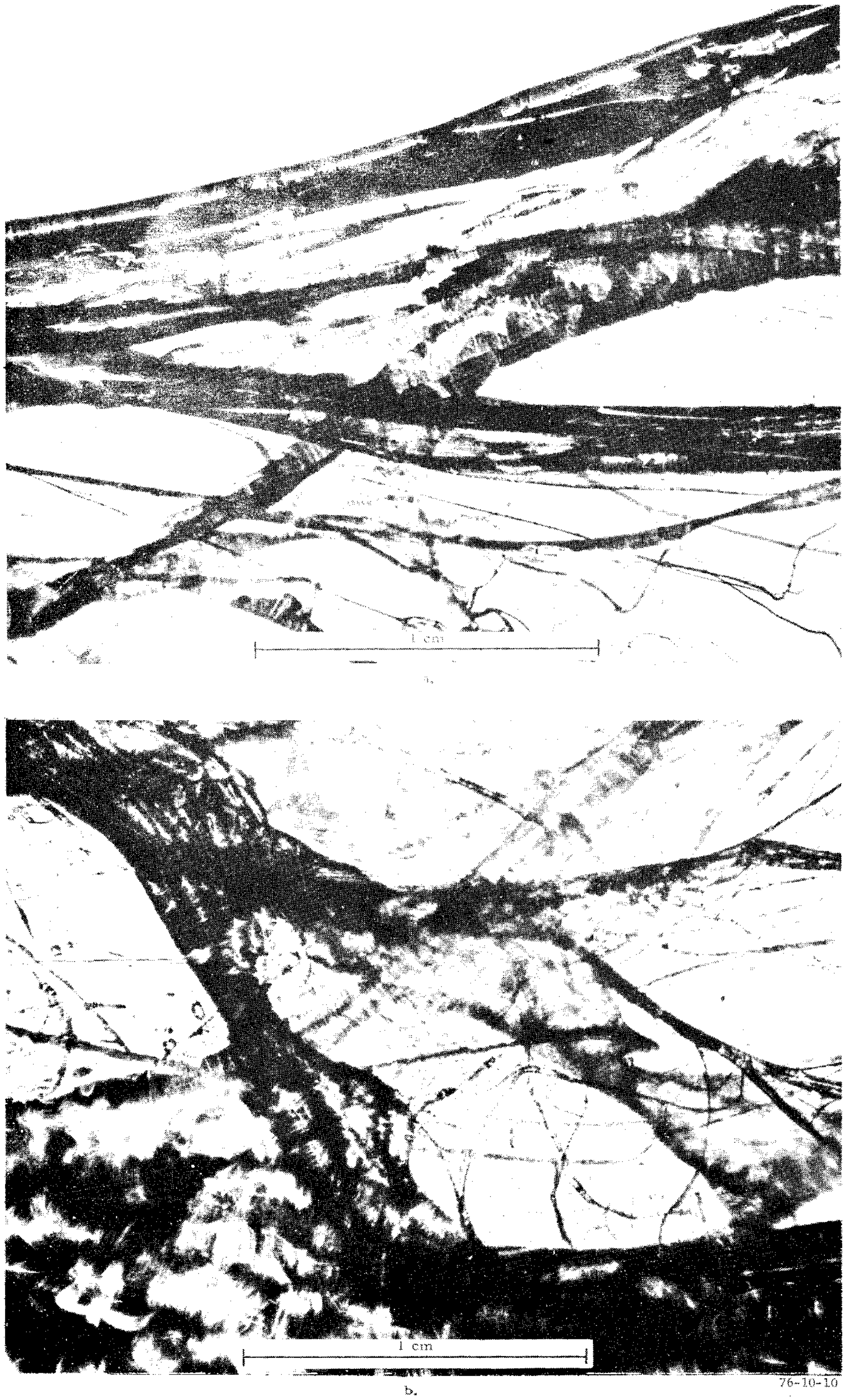


FIGURE 9. FM-4 PARTICLES 6 INCHES FROM NOZZLE



a.

b.

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FIGURE 10. AM-1 PARTICLES 6 INCHES FROM NOZZLE

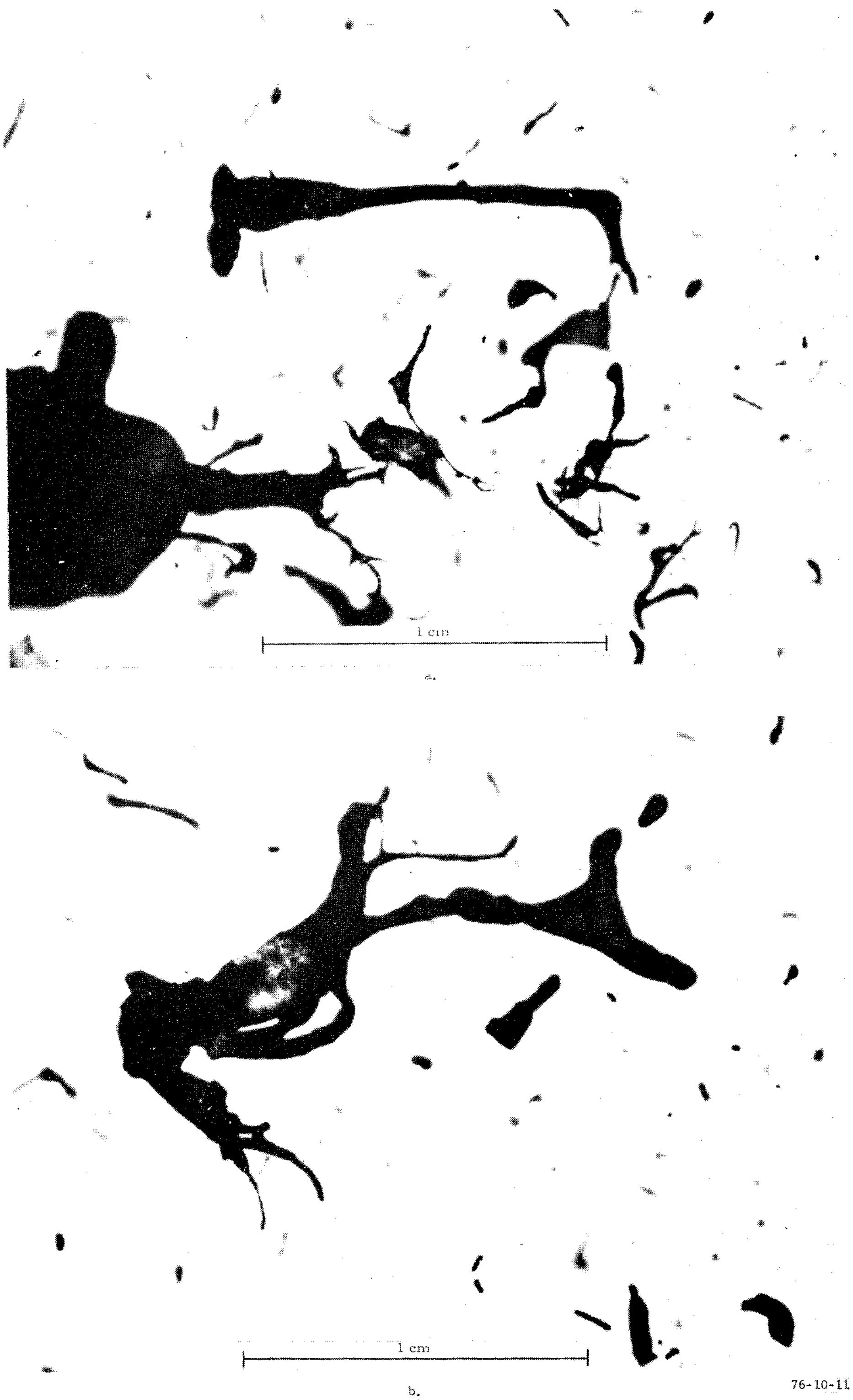


FIGURE 11. XD8132.01 PARTICLES 6 INCHES FROM NOZZLE

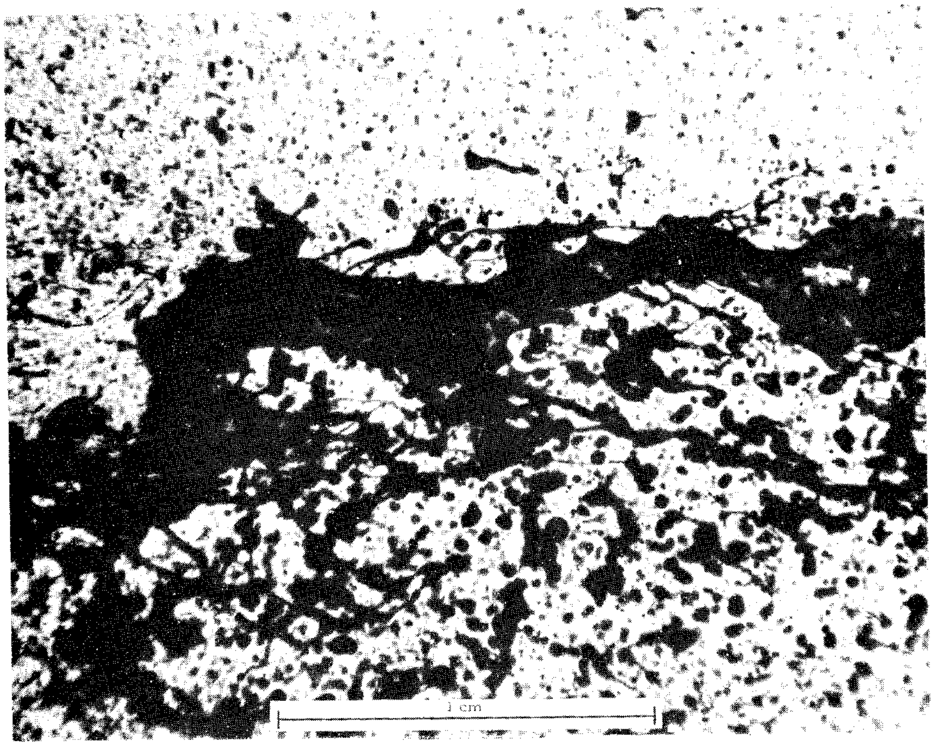
The most obvious feature of the modified fuel particles is large size and variable geometry. Breakup of Newtonian fluids (e.g., water and neat aviation fuel) results in tiny spherical droplets whose final sizes are controlled by the Weber number, a ratio of the surface tension to the dynamic pressure of the flowing gas. Thus, the modified fuel photographs indicate that rheological parameters play a major role in controlling the fuel particle configuration. Both the FM-4 and AM-1 are characterized by sheets and strands with the evidence pointing to a tensile viscosity effect, allowing the fuel to be drawn out in threads by the fast-moving air. The XD8132.01 is characterized by globules of nondescript geometry, and less elasticity is indicated than that shown by the FM-4 and AM-1.

Observation of the overall spreading of the fuel particles perpendicular to the flow axis was that the XD8132.01 tends to spread out in a conical pattern with a cross-section similar to the cone formed by neat Jet A. The FM-4 spreads more than the AM-1, but less than the XD8132.01. This spreading effectively dilutes the local fuel concentration and has a significant bearing on flammability.

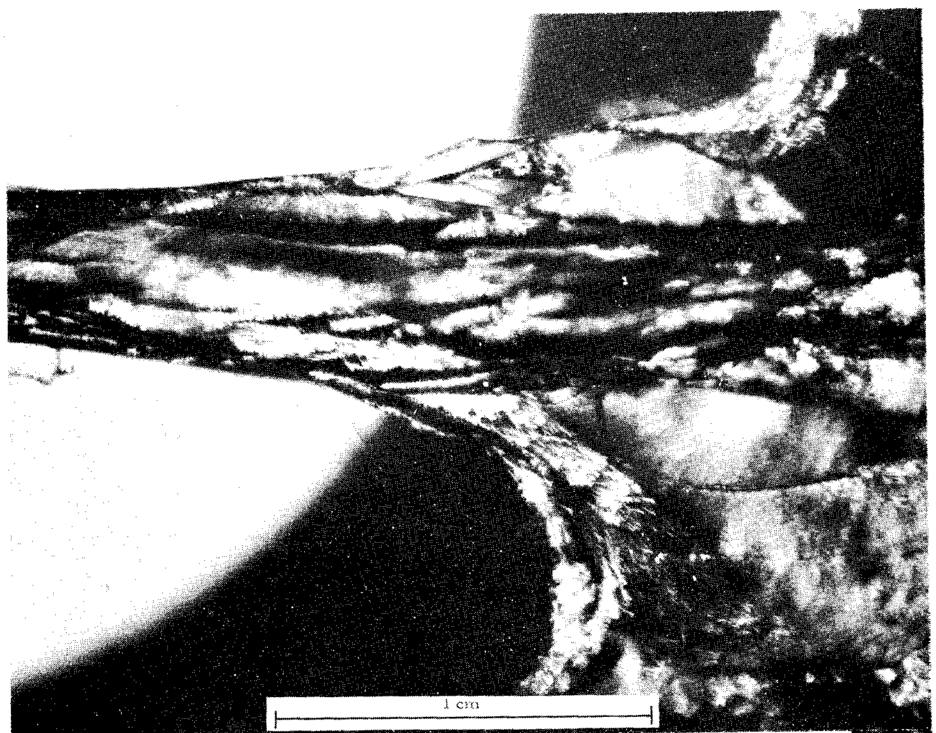
Figures 12 and 13 show photographs of neat Jet A along with FM-4, AM-1, and XD8132.01, at a position 1-inch downstream from the nozzle. The nominal air velocity was 110 kn, and the scale is indicated on the pictures. The rapid disintegration of the neat fuel is evident, and textural similarities between FM-4 and AM-1 are apparent. The thread-like and membranous nature of the FM-4 and AM-1 are distinct from the bulbous form of the XD8132.01.

Figures 14 and 15 show still photographs of Jet A 30-inches downstream from the fuel nozzle, along with pictures of FM-4, AM-1, and XD8132.01 at 46 inches. The air velocity was 110 kn, and the scale is shown on the pictures. The still photographs taken at various distances from the nozzle indicate that the FM-4 and AM-1 continue to show thread-like characteristics, while the XD8132.01 remains in the form of an uneven globule. High-speed motion pictures demonstrated that while the larger modified fuel particles will continue to disintegrate as they are accelerated in the air stream, the geometric characteristics of each will remain.

Ignition of the fuels was observed by use of the propane igniter on the downstream end of the airfoil. Figure 16 shows photographs of ignition attempts on the four fuels. These are typical examples of the type of burning consistently found for the airspeed (110 kn) and fuel flow rate (4 to 7 lb per minute) employed. Jet A consistently ignited easily and burned intensely. Often, ignition of the Jet A was achieved by the electric spark with no assistance from the propane. The FM-4 did not show downstream flame propagation. The spark ignited the propane in the cone, and the propane flame was lengthened by the FM-4 spray by several inches. In contrast to the FM-4, the AM-1 produced a long burning stream. Although the AM-1 required the burning propane as a pilot, the flame was typified by a long and narrow tail. Similar to the FM-4 was the XD8132.01 behavior. The propane flame would lengthen slightly, but no downstream flame propagation occurred. Because of the



a. NEAT JET A



b. FM-4

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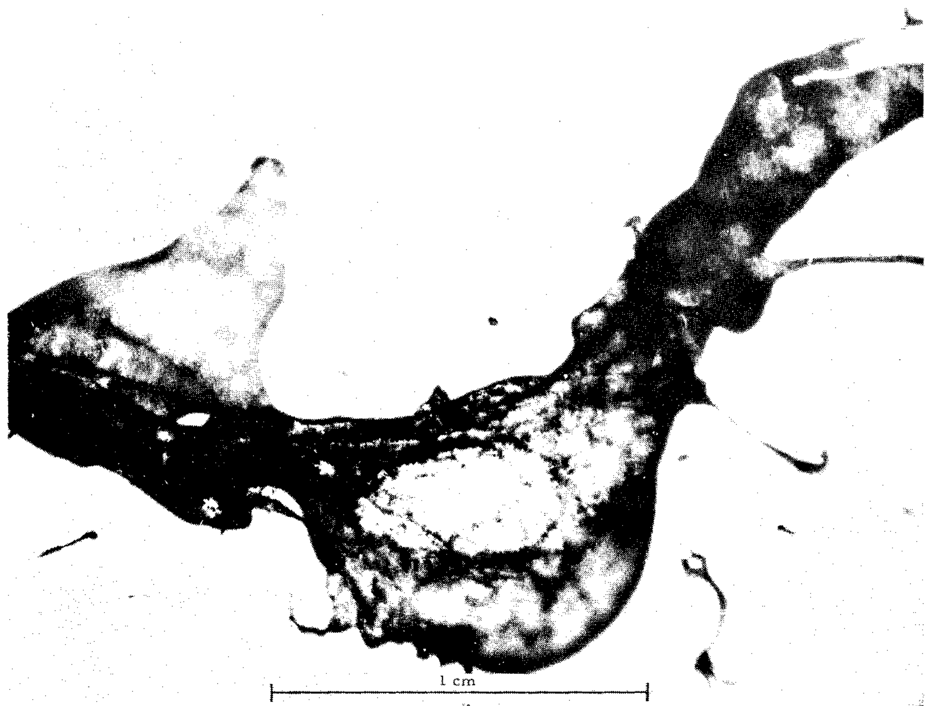
FIGURE 12. NEAT JET A AND FM-4 FUEL DISINTEGRATION 1 INCH FROM NOZZLE

a. AM-1



b. XD8132.01

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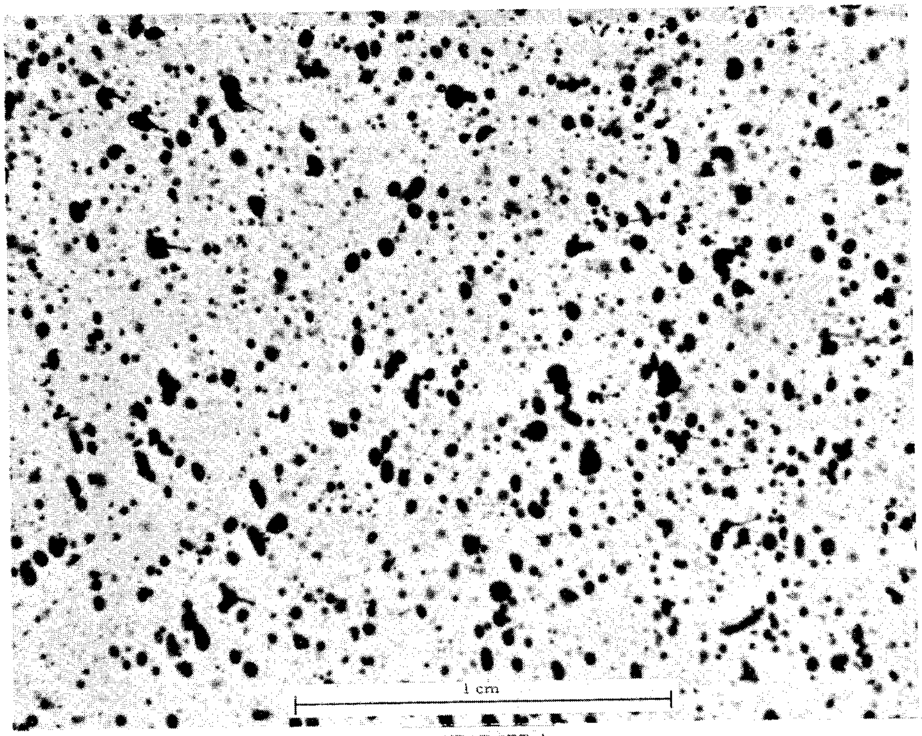
FIGURE 13. AM-1 AND XD8132.01 FUEL DISINTEGRATION 1 INCH FOM NOZZLE



a. NEAT JET A

b. FM-4

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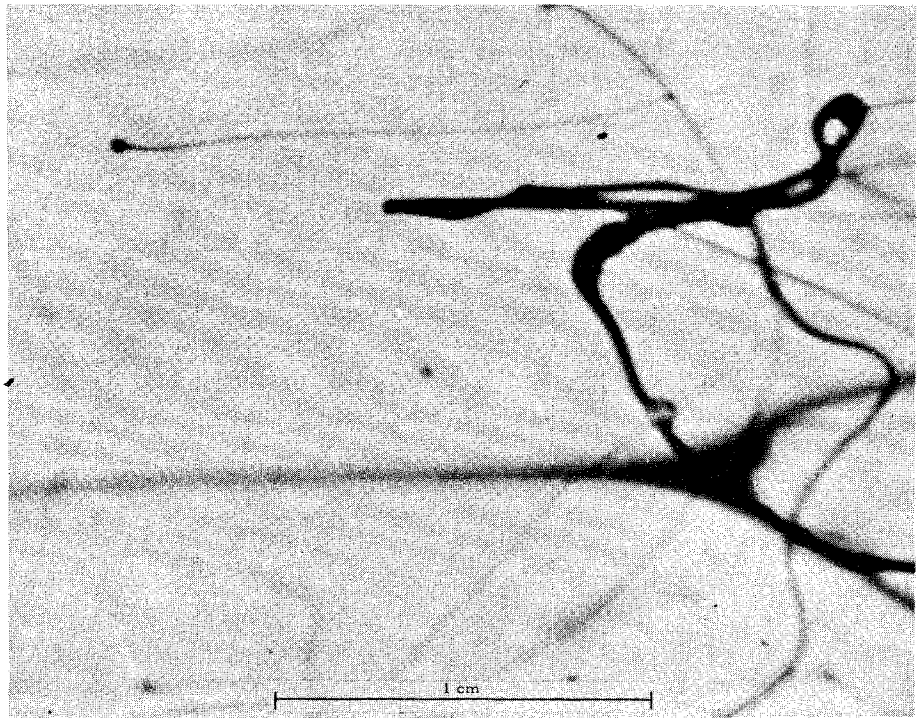
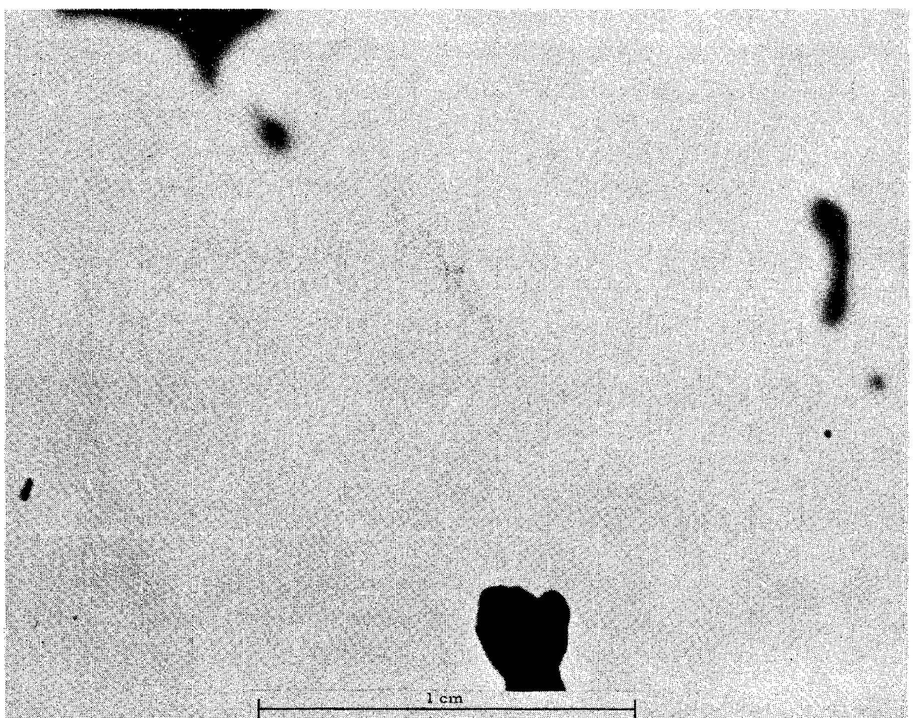
FIGURE 14. NEAT JET A AND FM-4 DOWNSTREAM FUEL PARTICLES



a. AM-1



b. XD8132.01

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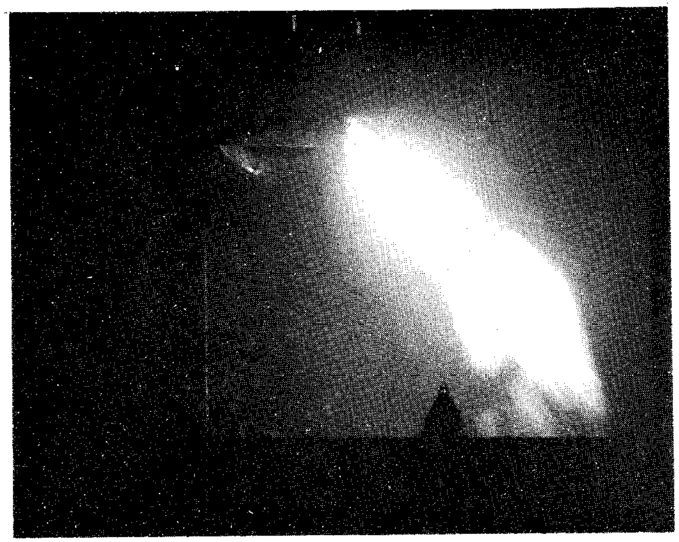
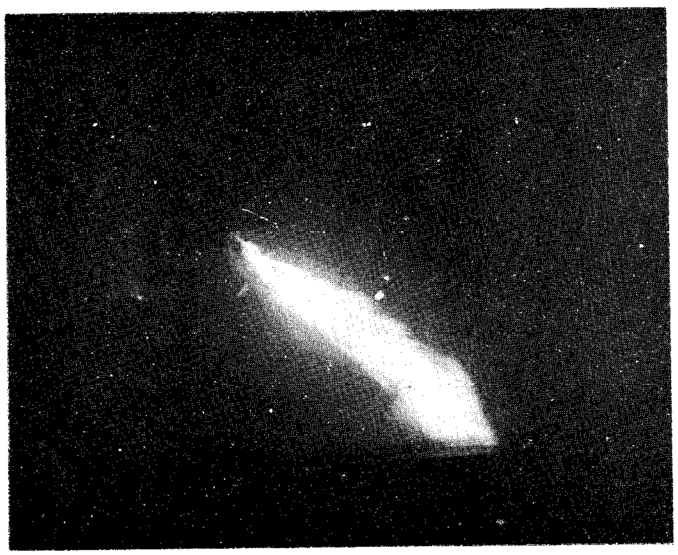
FIGURE 15. AM-1 AND XD8132.01 DOWNSTREAM FUEL PARTICLES



a. NEAT JET A

b. FM-4



c. AM-1

d. XD8132.01

76-10-16

FIGURE 16. BURNING FUEL SPRAYS

difference in spreading among the different fuel jets, no definitive statement can be made regarding the relative hazards of the modified fuels. The relative nonflammability of the FM-4 and XD8132.01 are more likely dominated by their spreading and dilution than by particle geometry. Nevertheless, since none of the modified fuels was ignited by the spark alone, and since none burned as intensely as Jet A, the conclusion can be drawn that all three modified fuels demonstrate less flammability than Jet A. It is noteworthy that the XD8132.01 forms a spray cone of roughly the same angle as Jet A. Because the Jet A is finely divided into small particles, it burns readily. Thus, the likelihood exists that higher overall fuel/air ratios are required for flame propagation into sprays of large particle size.

CONCLUSIONS

The results of this investigation lead to two major conclusions. First, the modified fuel spray consists of particles of large size and highly aspherical geometry. Second, although a modified fuel can be flammable in the presence of an intense ignition source, all modified fuels tested were more difficult to ignite than neat fuel.

The large particle sizes and varying geometry make any laboratory evaluation of flame propagation velocities through modified fuel sprays highly impractical (reference 13). Nevertheless, further testing is needed to elucidate the effect of fuel/air ratio on flammability of modified fuel sprays. While this study showed the AM-1 to be most flammable and the XD8132.01 least flammable at equivalent injection rates, the flammability of the AM-1 could well be due to its tendency to form a narrow cone in the air flow. The lower flammability of XD8132.01, on the other hand, may have been related to its wide cone dispersion. Thus, the results reported may not relate to an actual crash where the fuel release rate is large and the overall air/fuel ratio is not influenced by jet fluid mechanics.

The fluid dynamic and atomization experiments have significant impact both on the development of standard flammability tests and the definition of a modified fuel specification. The photographs of the fuel particles formed by air shear indicate that sprays formed in any bench test apparatus should be analyzed as to particle size and geometry. A bench test that produces particles of sizes and shapes significantly different from those presented here might show radically different spray flammability. The observed flow anomalies must be considered in the establishment of a fuel specification. Tolerable variations of shear viscosity with shear rate must be defined and possible flow anomalies anticipated. Flow tests must be conducted over a range of shear rates sufficient to include all flow regimes found in the aircraft fuel system.

RECOMMENDATIONS

Due to the difficulty of making definitive statements about the relative safety of these modified fuels, we recommend that future safety testing be specifically directed at two problems:

1. The effect of additives on ignitability, and

2. The effect of additive fuel/air ratio on flammability.

At this time the energies required for modified fuel ignition vis-a-vis neat fuel are unknown. In addition, fuel/air ratio has not been successfully defined in any tests to date.

In addition to the work on flammability, we recommend that rheological studies be continued in two areas:

(1) Elucidation of the physical mechanism of modified fuel breakup, and

(2) Pumping, flow, and filtration testing to provide the basis for a modified fuel specification.

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