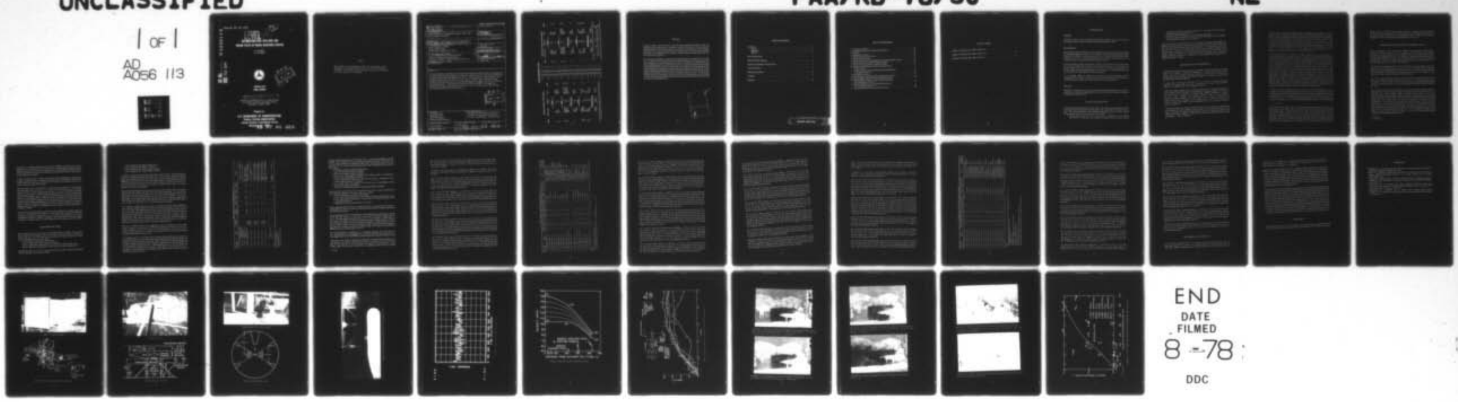
AD-A056 113 NAVAL WEAPONS CENTER CHINA LAKE CALIF F/G 21/2
ANTIMISTING FUEL SPILLAGE/AIR SHEAR TESTS AT NAVAL WEAPONS CENT--ETC(U)
MAR 78 A SAN MIGUEL , M D WILLIAMS DOT-FA76WAI-589
UNCLASSIFIED FAA/RD-78/50 NL

1 OF 1
AD
A056 113



END
DATE
FILMED
8-78
DDC

Report No. FAA - RD - 78-50

ANTIMISTING FUEL SPILLAGE/AIR SHEAR TESTS AT NAVAL WEAPONS CENTER

A. San Miguel
M. D. Williams

MARCH 1978
FINAL REPORT

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA/RD-78/50		

4. Title and Subtitle
Antimisting Fuel Spillage/Air Shear Tests At Naval Weapons Center

5. Report Date
Mar[redacted]78

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
Anthony San Miguel [redacted] Marion D. Williams

9. Performing Organization Name and Address
Naval Weapons Center
Range Department
China Lake, California 93555

10. Work Unit No. (TRAIS)
181-520

11. Contract or Grant No.
DOT-FA76WAI-589

12. Sponsoring Agency Name and Address
U. S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D. C. 20591

13. Type of Report and Period Covered
Final rept.
Sep[redacted] 75-Dec[redacted] 77

14. Sponsoring Agency Code
ARD-520

15. Supplementary Notes

16. Abstract

A test apparatus consisting of a large-scale airfoil located within a temperature-velocity-controlled airstream was used to evaluate the fire suppression afforded by FM9 antimisting fuel additive in Jet A. A homogeneous low turbulence airstream between 100 and 170 knots was used to obtain crash-survivable antimisting fuel kinematic data. It was demonstrated that FM9 could be an effective antimisting agent. The failure envelope for FM9 in 27°C Jet A fuel was measured for agent concentrations from 0.3 to 0.5 percent and 32°C airflow velocities between 100 and 170 knots.

17. Key Words	18. Distribution Statement
Aircraft Fires Modified Fuels Fire Prevention Antimisting Kerosene	Document is available to the public through the National Information service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	35	

METRIC CONVERSION FACTORS

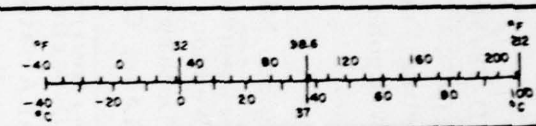
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The goal to develop a "fire safe" fuel for a survivable aircraft crash landing is difficult to attain in an absolute sense since commercial fuels, once ignited, readily burn. The problem is to alter the kinematic physical properties of a fuel in such a manner so as not to affect its commercial value. This report presents test results of Jet A fuel incorporating FM-9 polymer antimisting agent. A wing test apparatus is described which utilizes a fuel expulsive airfoil in an airstream to simulate a full-scale survivable crash. Results from three series of tests are presented.

The cooperation and assistance of a number of people and organizations were invaluable. Drs. R. F. Landel and S. T. J. Peng of the Jet Propulsion Laboratory provided helpful discussions on rheology measurements, Dr. R. Mannheimer of Southwest Research Institute and Mr. A. Woodman of the Naval Weapons Center (NWC) contributed laboratory measurements, Mr. H. Brooks of Imperial Chemical Industries assisted with antimisting agent preparation, and Mr. T. Horeff and Mr. John Van Dyke of the Federal Aviation Administration gave guidance in identifying the pertinent problem areas addressed in this study. The Civil Aviation Authority, Royal Aircraft Establishment and Imperial Chemical Industries of the United Kingdom not only supplied the FM-9 additive, but also provided for its shipment to this country. The U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, through an inter-agency agreement with the FAA, engaged Southwest Research Institute to make rheological measurements and analyses at the test site and in their laboratories.

TABLE OF CONTENTS

PRECEDING PAGE BLANK

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

PURPOSE

The purpose of this study was to establish the kinematic flame propagation response of antimisting fuels when released in airflow conditions representative of impact-survivable aircraft crashes.

BACKGROUND

Studies and tests aimed at development of a safer fuel have always been of interest to the Federal Aviation Administration (Reference (1)). One recent outgrowth of such work is the development of polymer "thickening" fuel additives to suppress the misting property of Jet A fuel. The practical objective stated in Reference (2) to be met by such antimisting agents during a survivable crash is to eliminate the mist of fuels under dynamic conditions and decrease the probability of ignition.

Candidate antimisting materials were evaluated in full-scale crash tests (Reference (3)) utilizing Navy A-3 and Air Force RB-66 aircraft. These tests were performed during 1972-73 at the Naval Air Test Facility, Lakehurst, New Jersey. One objective of these tests was to determine how representative air gun and catapult tests with antimisting fuels were of actual crashes. It was concluded (Reference (2)) that such tests were not representative of full-scale crash conditions.

A new potentially scalable fuel spillage test was developed at the National Aviation Facilities Experimental Center (NAFEC). A prototype test apparatus was constructed at NAFEC and sent to the Naval Weapons Center (NWC) where further development and testing was undertaken.

OBJECTIVE

The objective of this study was to conduct aircraft crash survivable fuel spillage/air shear tests with antimisting fuels to establish the interrelationships between fire and variables such as additive concentration, fuel temperature, and airflow velocity.

STATE-OF-THE-ART REVIEW

A review of the antimist fuel literature and other related activity was presented recently (Reference (4)). This excellent review summarized the then-current work being conducted by the U.S. Army, Air Force, Navy, FAA, and the U.K. Royal Aircraft Establishment. Observations made in this review, which are directly pertinent to the subject matter in this report, are as follows:

1. Antimist agents are effective to prevent the formation of flammable mist of low volatility fuels (JP-5, Jet A, JP-8) under many conditions of high-shear exposure. However, different

concentrations in the fuel, ranging from about 0.1 to 0.7%, are required for the various agents to attain equivalent antimist effectiveness.

2. Antimist effectiveness is lowered by shear force action (varies among agents).
3. The precise physical mechanism by which the polymeric antimist agents exert their influence on misting phenomena are subject to some conjecture.

Laboratory tests have not yet been shown to be representative of full-scale crash conditions. The problem is that previous full-scale crash tests have not been designed to obtain significant quantitative data such as local particle velocities, droplet shear deformations, etc. The large-scale tests have usually been of the fire-no fire variety. Laboratory tests on the other hand are designed to measure, within traditional ranges, parameters such as deformation fields that probably are not representative of those actually occurring in full-scale tests. It is evident, then, that a requirement exists to measure the significant phenomena occurring in a full-scale test so that small-scale laboratory apparatus can be designed in the range of interest.

AIRFLOW FACILITY/TEST APPARATUS

Air temperature significantly affects the ignition and sustenance of fuel fire and therefore an airflow facility must be capable of controlling air temperatures. A reasonable dynamic range would be between -20°C and the minimum flash point temperature of Jet A (38°C). The T-range air augmentation facility at NWC is capable of controlling air temperatures in this range in conjunction with fire testing of full-scale aircraft components.

The basic facility at T-range was constructed in 1973 and consists of several air storage tanks, compressors to charge these tanks, and a heater to regulate airflow temperature. Data acquisition is similar to, and compatible with, any fully instrumented facility.

T-range was originally designed to test air-breathing propulsion units for tactical sized missiles. Air can be delivered at flow rates between 5 and 90 kgm/sec, temperatures between -20 and 2500°C, and pressures from 0 to 55 kgm/cm^2. The existing storage capability is equivalent to a 50 kgm/sec flow for 3 minutes. Hardware data acquisition capability includes 36 strain gauges, 12 accelerometers/pressure transducers, and 24 thermocouple channels. An option is to use a 14-track magnetic tape recorder in conjunction with a multiplex system to record 50 data channels on 10 tape tracks. Another 150 channels of assorted instrumentation readily can be provided if required by means of a telemetry van.

A feature of the facility is its control of airflow temperature. The air is heated by a propane heating source utilizing the storage air. Make-up oxygen is restored to the airstream after heating. The air, oxygen, and propane gas mixing is manually operated. Flow rate is measured by a choked venturi and turbine flow meters. Maximum cold flow time of operations can be varied between 74 seconds and 90 kgm/sec to 2 hours at 1 kgm/sec.

A modular low velocity diffuser was designed which is compatible with the T-range air source. The diffuser is shown in Figure 1. The design was optimized for 100-knot flow. However, its dynamic range is between 0 and 200 knots. Supersonic airflow is brought into the aft end of the diffuser by a 15.25-cm inside diameter (ID) steel pipe. The general features of the diffuser are shown in Figure 2. The length of the diffuser is 6.1 m. The aft square cone housing is 1.83 m long, 1.6 X 1.6 m aft and 0.86 X 0.86 m forward (each side converging 12°). Contained in the center of the square cone is the diffuser element. It consists of a 1.83-m-long cylinder whose periphery consists of a 12-pointed star with an outside diameter (OD) of 45.7 cm and an ID of 38.1 cm. The thickness of the steel cylinder walls is 0.95 cm. There are 72 2.54-cm-diameter holes symmetrically located on the periphery. A cone 30.48 cm long caps one end of the diffuser element.

A 1.22-m-long mixing section is bolted to the square cylinder. This is in turn attached to a 0.61-m-long square section containing six screens of 2.54- and 1.77-cm wire mesh. These screens are placed in pairs 30.48 cm apart. Next, another 91.4-cm-long mixing section is bolted on. Finally, a 1.52-m-long section containing egg crate configuration straighteners (each cell is 109 cm^2) is bolted to the adjacent mixing section. The test airfoil is shown in Figure 3. The pertinent dimensions of the test airfoil apparatus are shown in Figure 4. The airfoil chord is 213.4 cm, its thickness is 36.9 cm, and its length is 152.4 cm. On the leading edge midway along the length protrudes a 15.2-cm ID fuel exit tube. The airfoil is 93.9 cm above the ground and is placed in the center of a square 90.5 X 90.5 cm airstream, 217.2 cm aft of the exit plane of the diffuser (Figure 2). At the lower airflow boundary is located a propane torch (Figure 5). During a given test the propane torch is ignited (pulsed) at intervals approximately 1.5 sec apart, with durations of the order of 0.1 sec. The flame volume, in the absence of fuel in the airstream, is about 1000 cm^3. In the body of the airfoil (installed for test series 2-3) is located a 16-mm camera, protected by a water jacketed container. A wide-angle (3-mm) lens was used that viewed a 94° field. The distorted view seen by the lens is shown in Figure 6 together with some significant dimensions. The quality of the airflow over the airfoil was ascertained by means of a water vapor technique. Movies taken of the water vapor flow confirmed the homogeneous low turbulent flow produced by the diffuser (Figure 7).

It is important to always match the turbulence numbers from a wind tunnel apparatus to that for free-flight, in addition to matching Reynold's numbers. The reason for controlling turbulent flow is to minimize initial rotational motion intensities by intrinsic momentum exchanges between adjacent air particles moving from one streamline into another. Low turbulence was induced by the use of screens (see Figure 2), six of which were sufficient. Quantitative verification of homogeneous low turbulence was obtained by use of the NWC packaged Rosemount Mach probe using the relationship

$$V = 215.8 \sqrt{p} \qquad (1)$$

where V (knots) is the velocity and p is the differential pressure (psi) measured by the probe. Data were obtained at three stations. The first station was at the exit plane of the diffuser. Figure 8 shows typical variation of p with respect to time for 100-knot airflows. Longitudinal turbulence at the diffuser exit plane is typified by variations of ±6 and ±5 knots at 100- and 150-knot airflows, respectively. Longitudinal turbulence at the airfoil loading edge is typified by variations of ±6 and ±10 knots at 100- and 150-knot airflows, respectively. The airfoil was placed in position and velocity measurements were made 31 cm below the trailing edge, where ignited fuel propagation paths were known to pass. The longitudinal velocity turbulence below the aft trailing airfoil edge is typified by

±20 and ±25 knots at 100- and 150-knot airflows, respectively. Average velocity data is plotted in Figure 9 and shows how the velocity flow attenuates with increases in turbulence and distance from the diffuser exit plane. The data show that the longitudinal velocity turbulence is low (<10%) and homogeneous (<5 knots). Airflows could be repeated within 5% from test to test.

PREPARATION AND HANDLING OF ANTIMISTING FUELS

Of prime consideration in the preparation and handling of antimisting fuels is their potential to degrade. The antimisting property of such fuels containing high molecular weight polymer additives will degrade if the long molecules can be mechanically severed. A concurrent study at Southwest Research Institute (SWRI), San Antonio, Texas, discusses this degradation problem in Reference (5). Experience gained during the first series of tests at NWC during March 1976 was used to assure that there would be no possible mechanical degradation during the second and third series of tests performed during October 1976 and July 1977, respectively.

The preparation and handling procedures used for the first series of tests during March 1976 were as follows. Jet A fuel was purchased in sealed 208-l* drums from Chevron. AM-1 and FM-4 antimisting agents were obtained from NAFEC in unsealed 208-l drums. No attempt was made to chemically analyze the materials. It was known that the antimisting agents were over two years old and that a "white in solution" precipitate was visible, perhaps due to water contamination.

Two types of pumps were used to transfer and mix the antimist concentrate with the fuel. One pump was a paddle pump (Sears model 563/26461) turned by a 0.4-kW motor (Sears model 113.12540) at 1725 rpm (19 l/min).** The second pump was a centrifugal pump (Crane Deming Pumps model DC 496381-CZO) turned by a 0.75-kW motor (Reliance model C56E 1503P-C4) at 3450 rpm (38 l/min).

Since the density of the neat fuel was assumed to be that of the neat fuel used in the concentrate, mixing proportions were based on a volume basis. Neat fuel was removed from the 208-l drums in 21-l increments using a plastic measuring container. Concentrate was then added to the neat fuel drum using another graduated plastic container. The residue concentrate attached to the plastic container was removed by hand resulting in a wiped-clean container. Three such 208-l drums were then located adjacent to each other. Each set of three drums contained the antimisting fuel of given concentration to be tested. Fuel and concentrate were mixed by means of one of the pumps described above. Lines (1.9-cm) were attached in series to the three tanks. The pump withdrew the fuel from the bottom of the first drum and deposited it at the top of the third drum. An electric blanket was placed over and secured to the three drums. The barrels were then heated at a rate of about 5°C/hr until the desired temperature was reached, e.g., 35°C. A temperature controller was used. Mixing of the fuel was made overnight for about 12 to 14 hours. The fuel was then transferred by the pump to the fuel supply tank prior to testing.

* *208 liters*

** *19 liters/min*

The question of antimisting degradation was posed after completion of the first series of tests. Originally, it was not believed that a total of 50 passes in 14 hours through the pumps used would significantly degrade the fuel. However, subsequent study of the mechanical degradation associated with the above mixing procedure revealed unexpected results (Reference (5)), e.g., a greater percent of larger molecules were generated.

In order to circumvent trying to explain the unexpected results consequential to using the above handling and mixing procedure, a conservative approach was used for mixing AM-1 and FM-9 for the second and third test series, executed in October 1976 and July 1977, respectively. In essence, the procedure was that previously used at NAFEC.

Two mixers similar to those used at NAFEC were built. These mixers consisted of a 76-cm-long shaft with three blades, each 10 cm long by 2.5 cm wide. Two of the blades were placed 180 degrees apart at the end of the shaft. The shaft was attached to a cover of a 208-l barrel and remotely rotated by an electric motor at 100 rpm. Mixing was performed at 25°C for 30 min. A weight rather than a volume measuring basis was used with a Toledo scale. Samples of the mixed fuel were collected in 1-gal samples and sent to SWRI for laboratory evaluation. This method and procedure was used to mix the AM-1 antimisting fuels for the second test series. It was also used to mix (10-min duration) the FM-9 antimisting fuels for the third test series. The mixed fuel was then either heated or cooled to the desired test temperature by means of an electric blanket or by storage in a refrigerated shed, respectively. The conditioned fuel was then elevated to the fuel hopper (Figure 2) by means of a forklift.

In many instances the above mixers were not used to mix the FM-9, since this agent readily mixes with Jet A. Concentrations were determined on a weight basis using a Toledo scale. Mixing was accomplished by mixing the additive with a 1.5-m rod under the direct supervision of an Imperial Chemical Industries (ICI) Ltd. (England) representative. The fuel was heated with an electric blanket or cooled in a refrigerated shed prior to being transferred to the fuel hopper by means of a forklift.

DATA FROM NWC TESTS

The test plan used for the first series of tests performed between 19-31 March 1976 to evaluate AM-1 and FM-4 was recommended to NWC by FAA based on previous experience at NAFEC. The AM-1 test plan was to use 35°C airflow and fuel temperatures. The agent concentration and airflow velocity combinations to be used were as follows:

1. 0.3% concentration and 120-knot airflow velocity.
2. If test 1 passes, increase airflow velocity to 150 knots.
3. If test 2 passes, reduce concentration to 0.2% and repeat at 120-knot airflow velocity.
4. If test 1 fails, increase concentration to 0.4% and repeat at 120-knot airflow velocity.

The FM-4 test plan was to use 35°C airflow temperatures. The agent concentration and airflow velocity combinations to be used were as follows:

1. 0.4% concentrations and 100-knot airflow velocity
2. If test 1 passes, increase airflow to 110 knots
3. 0.3% concentration and 100 knots (failed at NAFEC)
4. 0.4% concentration and 120 knots (failed at NAFEC)

A summary of the first series of tests performed at NWC is given in Table 1. The general observation is that the concentration levels and airflow velocities at 35°C used in the test plan represent fuel fire ignition states. Fireballs developed for each of the tests on the first ignition pulse. Test 5 differed significantly from the other tests in that a huge fireball (perhaps 15 m high and wide) engulfed the airfoil. The radiant heat from this test was great enough to char rags, tape, and paper as far as 12 m away from the edge of the fireball. Tests 6 through 10 exhibited relatively modest, but still large fireballs of lower radiant energy intensity.

High response thermocouples (TC) were placed around the airfoil as shown in Figure 10 to identify fire flow paths. TC4 and TC8 were placed 115.5 cm aft of the leading edge, 7.5 cm off from the airfoil surface. TC1 and TC6 were located 39 cm aft of TC4 and TC8, respectively. These two TCs were likewise 7.5 cm from the airfoil surface. TC3 was 62 cm aft of TC1 and TC6, 3.6 cm from the trailing edge. TC5 was located within the ejection duct, whereas TC7 was within the propane igniter. If the reference time is taken as that of first response to fire from TC7, then initial heating times in test 5 for TC8, 6, 3, 4 and 1 were 15, 35, 45, 130, and 130 msec, respectively.

Test 5 exhibited a burning path typical of neat Jet A misted fuel. The fire quickly engulfed the entire airfoil with explosive violence. The distance between the propane igniter exit plane and TC8 was 79.5 cm. Hence, the average flame front velocity in the 152-knot airflow between the igniter and TC8 was 53 m/sec; between TC8 and TC6 it was 19.5 m/sec; and between TC6 and TC3 it was 62 m/sec. Average velocities under the airfoil of 50-60 m/sec are typical of neat or ineffective antimisting fuel tests. Tests in which obvious benefit is derived from antimisting agents are characterized by much lower average velocities, as will be demonstrated below. The simultaneous heating of TC4 and TC1 is due to classical bound vortex flow around the edges of the airfoil. The heat flow path described here is typical for unacceptable antimisting fuel tests.

NWC tests 1 through 3 (Table 1) are representative of the tests performed to evaluate airflow velocity and quality of flow intrinsic to the NWC diffuser design discussed elsewhere in this report. Airflow calibrations were made on the basis of pitot probes placed at various locations in the airstream. It was learned from these tests that the static pressure in the airstream *must* be measured to compute velocity with an accuracy of 10%.

A considerable amount of 16-mm film footage at 24, 400, 1,000, and 5,000 frames per second from cameras placed 10-40 m from the airfoil was extensively analyzed in detail for fuel flow patterns and ignition/fire formation phenomena. Unfortunately, aside from confirming antimisting phenomena and fire ignition, detailed information needed for analytical modeling was scarce. The basic problem with the film coverage was scene obscurity due to three-dimensional fuel flow. It was demonstrated that this obscurity could be greatly reduced by placing a camera within the fuel flow under the airfoil. A consequence of the demonstration was to repackage a camera (Figures 4 and 6) within the airfoil for the second and third series of tests.

TABLE 1. Results of Tests Performed at NWC in March 1976.

Test no.	Test date	Test objective	Additive concentration (%)	Kinematic viscosity (centistokes/°C)	Fuel volume (l)	Diffuser air temp. (°C)	Fuel temp. (°C)	Air velocity (knots)	Remarks
1	4/3/76	System checkout air flow calibration	...	...	0	...	...	...	T-range modifications checkout.
2	12/3/76	Diffuser flow characterization	...	...	0	...	...	...	Diffuser evaluation/calibration.
3	12/3/76	Static pressure influence	...	...	0	35.0	...	...	Static pressure evaluation.
4	17/3/76	Airfoil water dump	...	0.68 /37.8	568	35.0	22.7	152	All-up system checkout.
5	19/3/76	AM-1 data point	0.10[a] 0.16[b] 0.12[c]	2.81 /37.8	568	35.0	38.3	152	Huge fireball on first pulse pumped fuel (minor degradation).
6	22/3/76	AM-1 data point	0.29[a]	6.36 /37.8	190	35.0	36.7	144	Fuel did not dump apparently due to air pressure.
7	30/3/76	AM-1 data point	0.26[a] 0.28[b] 0.22[c]	4.42 /37.8	568	38.3	36.7	144	Large fireball on first pulse pumped fuel (minor degradation).
8	30/3/76	FM-4 data point	0.26[a]	2.84 /37.8	568	41.7	35.6	127	Large fireball on first pulse pumped fuel (minor degradation).
9	31/3/76	AM-1 data point	0.37[a] 0.32[b] 0.34[c]	7.39 /37.8	568	33.3	41.1	96	Large fireball on first pulse pumped fuel (no apparent degradation).
10	31/3/76	FM-4 data point	0.39[a]	3.56 /37.8	568	32.2	35.6	96	Large fireball on first pulse pumped fuel (no apparent degradation).
...	...	FM-4 (NAFEC supplied)	0.4 [a]	4.46 /37.8	1				
...	...	Neat Jet-A		1.5 /37.8					NWC measured s.g. = 0.805 gm/cc (20°C).

[a] In the field measurement.

[b] NWC gum measurement.

[c] SWRI steam jet gun measurement.

Utilizing the experience gained from the first series of tests, a second series was designed to test AM-1 and FM-9. The test plan used for the second series of tests (performed between 13-20 October 1976) to evaluate AM-1 and FM-9 was recommended to NWC by FAA. The second test plan was to use 27°C airflow and 30°C fuel. The agent concentration and airflow velocity combinations to be used for FM-9 were as follows:

1. 0.3% FM-9 concentration and 120-knot airflow velocity.
2. If test 1 passes, increase air velocity to 140 knots.
3. If test 2 passes, increase air velocity to 160 knots.
4. If test 1, 2, or 3 fails, increase concentration to 0.4% FM-9 and repeat at corresponding air velocity and increased velocities up to 160 knots.
5. If test 4 fails, increase concentration to 0.5% FM-9 and repeat at corresponding air velocity and increased velocities up to 160 knots.
6. If test 5 fails, reduce fuel temperature to 20°C and repeat at corresponding air velocity and increased velocities up to 160 knots.
7. If test 3, 4, 5, or 6 passes, repeat with 30% of fuel quantity degraded by pumping.

The second AM-1 test plan was to use 27°C airflow and 30°C fuel. The agent concentration and airflow velocity combinations to be used for AM-1 were as follows:

1. 0.3% AM-1 concentration and 100-knot airflow velocity.
2. If test 1 fails, increase concentration to 0.4% AM-1 and repeat at 100-knot airflow velocity.
3. If test 2 fails, reduce fuel temperature to 20°C and repeat at 0.4% AM-1 and 100 knots. If test 3 fails, conclude AM-1 tests.
4. If either test 2 or 3 passes, increase air velocity to 120 knots.

Another significant difference between the second and first series of tests was that 190-1* batches of antimisting fuel were used instead of 568-1. The above test plan was used only as a guide. On-site changes were made with FAA approval.

A basis for judging the degree of fire suppression for the antimisting fuel was developed after reviewing all test films. The outcome of a single torch ignition pulse was designated a pass if either no fire or only self-extinguishing fireballs occurred, or if the torch behaved as a flame holder and the flame did not propagate. The outcome was designated a fail if a fireball(s) initiated a pool fire by either escaping from the airstream or by producing an airstream fire of sufficient intensity to ignite a pool fire. Figure 11 depicts an example of a single torch ignition pulse outcome that was designated a pass. Figures 12-14 depict an outcome that was designated a fail. For comparison, the flame propagation exhibited by neat Jet A is shown in Figures 15 and 16.

The overall effectiveness of antimisting fuel was designated a pass for a test if each pulse was a pass. The effectiveness was called marginal if one or more pulses were fail(s), but the airfoil did not become engulfed in flames. The effectiveness was designated fail if the airfoil became enveloped in flames.

Another factor to be considered in rating the fire effectiveness of antimisting fuels is the dump rate into the airstream at the time of a given pulse. The dump rate is a function of the airstream velocity head, the fuel head, and the exit hole diameter in the airfoil. It was observed that at airstream velocities greater than 120 knots the dump rate was significantly reduced. This was reasonably

* *190 liters*

overcome in test series 2 and 3 by loosely placing a sheet metal cover over the exit tube. The fuel dump rate was also modified to some extent by varying the volume of fuel dumped from 190 to 568-l. The primary consequence of using more fuel was to extend the time of test so that more fire pulses could be examined.

A summary of the second series of tests performed at NWC is given in Table 2. The general observation is that FM-9 is effective in reducing fire propagation. A detailed summary of each test follows.

Test 11 used 0.3% FM-9 concentrate in a 190-l batch of 28.2°C Jet A fuel. The average fuel dump rate into the 26.8°C, 99-knot airflow was 25.0 l/sec. This dump rate was lower than that expected (60 l/sec) because of the pneumatic plunger sticking. The propane igniter was pulsed at 4.1, 5.5, 6.7, and 8.2 sec. Three small self-extinguishing fire ignitions were recorded by the airfoil camera; they traveled about 26, 25, and 45 cm in 70, 60, and 40 msec, respectively. Test 11 was judged to pass the fire self-extinguishing requirement.

Test 12 used 0.3% FM-9 concentrate in a 190-l batch of 36.1°C Jet A fuel. The average fuel dump rate into the 26.1°C, 100-knot airflow was 59 l/sec. The propane igniter was pulsed at 4.0, 5.0, and 5.9 sec. Two small fire ignitions, that self-extinguished in a distance of about 30 cm, were recorded by the airfoil camera. Only one of these self-extinguishing fires was observed by the overall viewing 16-mm camera. Test 12 was judged to pass the fire self-extinguishing requirement.

Test 13 used 0.3% FM-9 concentrate in a 190-l batch of 33.3°C Jet A fuel. The average fuel dump rate into the 25.0°C, 125-knot airflow was 39 l/sec. The dump rate was less than that expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head on the airfoil fuel exit. The propane igniter was pulsed at 4.3, 6.2, and 8.5 sec. One moderate fire ignition, that did not propagate but traveled downstream some 6 to 10 m, was observed by the overall viewing 16-mm camera. The airfoil camera jammed. Test 13 was judged to pass the fire self-extinguishing requirement.

Test 14 used 0.3% FM-9 concentrate in a 190-l batch of 26.7°C Jet A fuel. The average fuel dump rate into the 24.4°C, 122-knot airflow was 9 l/sec. The dump rate was much less than that expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head on the airfoil fuel exit. The propane igniter was pulsed at 15.0, 16.8, 19.0, 22.0, 24.7, 27.9, 31.3, 34.4, and 36.7 sec. The overall viewing 16-mm camera did not record any fire. The airfoil cameras detected one small fireball, which self-extinguished before leaving the wide-angle viewing area (about 60 cm). Test 14 was judged to pass the fire self-extinguishing requirement. Note that this test may be considered a no-test on the basis of the low fuel dump.

Test 15 used 0.3% FM-9 concentrate in a 190-l batch of 31.3°C Jet A fuel. The average fuel dump rate into the 25.0°C, 123-knot airflow was 41 l/sec. The dump rate was less than expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head at the airfoil fuel exit. The propane igniter was pulsed at 4.7, 5.9, and 8.2 sec. The overall viewing 16-mm camera recorded a moderate firefall, which did not propagate within the fuel flow field, resulting in a modest ground fire some 6 to 9 m behind the airfoil. Test 15 was judged to be marginal with respect to the fire self-extinguishing requirement.

TABLE 2. Results of Tests Performed at NWC in October 1976.

Test no.	Test date	Test objective	Additive concen. (%)	Fuel volume (l)	Diffuser air temp. (°C)	Fuel temp. (°C)	Air velocity (knots)	Number pulses	Dump rate (l/sec)	Degree fuel wetting of pan	Ignition pulses Passed	Ignition pulses Failed	Remarks	Antimisting effectiveness
11	13/10/76	FM-9 data point	0.3	190	26.8	28.2	99	4	25	Minor	4	0	Small fire ignitions self-extinguished.	Pass
12	13/10/76	FM-9 data point	0.3	190	26.1	36.1	100	3	59	Modest	3	0	Small fire ignitions self-extinguished.	Pass
13	13/10/76	FM-9 data point	0.3	190	25.0	33.3	125	3	39	Considerable	3	0	Modest fireballs traveled downstream.	Pass
14	14/10/76	FM-9 data point	0.3	190	24.4	26.7	122	9	9	Minor	9	0	Small fire ignition self-extinguished.	Marginal (no-test)
15	14/10/76	FM-9 data point	0.3	190	25.0	31.1	123	3	41	Considerable	3	0	Modest fireball resulted in pool fire.	Marginal
16	15/10/76	FM-9 data point	0.3	190	26.1	27.8	141	6	9	Minor	6	0	No fire ignitions detected by cameras.	Pass (no-test)
17	15/10/76	FM-9 data point	0.3	190	-9.4	27.8	130	3	25	Minor	3	0	No fire ignitions detected by cameras.	Pass (no-test)
18	18/10/76	FM-9 data point	0.3	190	27.2	33.3	140	3	39	Modest	3	0	Small fire ignitions self-extinguished.	Pass
19	18/10/76	Jet A data point	...	190	25.0	31.1	147	1	39	Modest	0	1	Huge fireball, over 40 ft high.	Fail
20	18/10/76	AM-1(old) data point	0.3	190	27.2	26.7	126	2	56	Considerable	1	1	Pool fire contributed to failure.	Fail
21	19/10/76	FM-9 data point	0.3	190	...	...	...	...	...	...	...	...	No test results due to aerodynamic back pressure.	...
22	19/10/76	FM-9 data point	0.3	190	25.0	36.1	142	1	57	Considerable	0	1	Pool fire contributed to failure.	Fail
23	19/10/76	AM-1(old) data point	0.3	190	22.2	30.6	101	2	58	Considerable	2	0	Modest fireballs traveled downstream.	Pass
24	19/10/76	AM-1(new) data point	0.3	190	26.7	33.3	100	1	59	Considerable	0	1	Pool fire contributed to failure.	Fail
25	20/10/76	FM-9 data point	0.3	190	27.8	29.4	122	2	59	Considerable	0	2	Pool fire contributed to failure.	Fail
26	20/10/76	FM-9 data point	0.4	190	28.3	28.9	122	3	54	Modest	3	0	Modest fireballs traveled downstream.	Pass
27	20/10/76	FM-9 data point	0.4	190	26.7	26.7	143	2	61	Considerable	0	2	Pool fire contributed to failure.	Fail
28	20/10/76	FM-9 data point	0.3	190	27.2	26.7	122	2	59	Modest	0	2	Pool fire contributed to failure.	Fail

NOTES:
1. AM-1 fuels mixed by SWRI personnel.
2. A cover was used on the discharge duct for tests 22 through 28.
3. Weather conditions were excellent: low humidity (~30%), temperature about 27°C, no wind.

Test 16 used 0.3% FM-9 concentrate in a 190-l batch of 27.8°C Jet A fuel. The average fuel dump rate into the 26.1°C, 141-knot airflow was 9 l/sec. The dump rate was less than expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head at the airfoil fuel exit. The propane igniter was pulsed at 5.5, 6.7, 9.7, 12.4, 15.1, and 18.1 sec. The overall viewing 16-mm camera and the airfoil camera did not observe any fire. Test 16 was judged to pass the fire self-extinguishing requirement. Note that this test may be considered a no-test on the basis of the low fuel dump.

Test 17 used 0.3% FM-9 concentrate in a 190-l batch of 27.8°C Jet A fuel. The average fuel dump rate into the −9.4°C, 130-knot airflow was 25 l/sec. The dump rate was less than expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher air stream head at the airfoil fuel exit. The propane igniter was pulsed at 7.7, 10.2, and 12.7 sec. The overall viewing 16-mm camera did not observe any fire. The airfoil camera film was lost during processing. Test 17 was judged to pass the fire self-extinguishing requirement. Note that this test may be considered a no-test on the basis of the low fuel dump and low air temperature.

Test 18 used 0.3% FM-9 concentrate in a 190-l batch of 33.3°C Jet A fuel. The average fuel dump rate into the 27.2°C, 140-knot airflow was 39 l/sec. The dump rate was less than expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head at the airfoil fuel exit. The propane igniter was pulsed at 4.3, 5.9, and 8.0 sec. The overall viewing 16-mm camera did not function properly. The airfoil camera recorded the first two pulses as very small (2- to 8-cm diameter) self-extinguishing swirling fireballs. The first pulse fireball rotated about 180° in the field of view, i.e., 4090°/sec. The external 70-mm fuel flow field film was lost during processing. Test 18 was judged to pass the fire self-extinguishing requirement.

Test 19 used a 190-l batch of 31.1°C Jet A fuel. The average fuel dump rate into the 25.0°C, 147-knot airflow was 39 l/sec. The dump rate was less than expected (60 l/sec) because of the pneumatic plunger sticking, in combination with the higher airstream head at the airfoil fuel exit. Prior to ignition, spray waves (a meter apart) were traveling about 50 knots over the airfoil. The propane igniter was pulsed at 4.2 sec. The overall viewing 16-mm camera recorded a great fireball some 12 m high. Fire engulfed the entire airfoil. The airfoil camera recorded the fire growth as fire traveled across the lens in 0.011 sec. Test 19 served to demonstrate that neat Jet A is highly flammable for the given test conditions.

Test 20 used 0.3% AM-1 (old concentrate prepared by SWRI) in a 190-l batch of 26.7°C Jet A fuel. The average fuel dump rate into the 27.2°C, 126-knot airflow was 56 l/sec. Prior to ignition, the leading edge of a typical spray wave was traveling about 50 knots over the airfoil. The propane igniter was pulsed at 3.8 and 5.2 sec. The overall viewing 16-mm camera recorded a small fireball which self-extinguished. Its duration in the field of view was 0.17 sec. The second pulse resulted in a fire much less severe than that for test 19. The airfoil camera recorded both pulses. Test 20 was judged to be a failure with respect to the fire self-extinguishing requirement.

Test 22 used 0.3% FM-9 concentrate in a 190-l batch of 36.1°C Jet A fuel. The average fuel dump rate into the 25°C, 142-knot airflow was estimated as 57 l/sec. The propane igniter was pulsed at 3.5 sec. The overall viewing 16-mm camera recorded the severe fire development. Good fire coverage was also obtained from the airfoil camera. Complete fire engulfment of the airfoil was attained within 0.2 sec. Test 22 was judged to be a failure with respect to the fire self-extinguishing requirement.

Test 23 used 0.3% AM-1 (old concentrate prepared by SWRI) in a 190-l batch of 30.6°C Jet A fuel. The average fuel dump rate into the 22.2°C, 101-knot airflow was 58 l/sec. The propane igniter was pulsed at 4.2 and 5.6 sec. The overall viewing 16-mm camera recorded one pulse that self-extinguished. The airfoil camera recorded both self-extinguishing fire fronts. Test 23 was judged to pass the fire self-extinguishing requirement.

Test 24 used 0.3% AM-1 (new concentrate prepared by SWRI) in a 190-l batch of 33.3°C Jet A fuel. The average fuel dump rate into the 26.7°C, 100-knot airflow was estimated to be 59 l/sec. The propane igniter was pulsed at 3.4 sec. The overall viewing 16-mm camera recorded the fire engulfment initiated by the first pulse. Good fire coverage was also obtained from the airfoil camera. Complete fire engulfment of the airfoil was attained within 200 msec. Test 24 was judged not to pass the fire self-extinguishing requirement.

Test 25 used 0.3% FM-9 concentrate in a 190-l batch of 29.4°C Jet A fuel. The average fuel dump rate into the 27.8°C, 122-knot airflow was 59 l/sec. The propane igniter was pulsed at 4.0 and 5.4 sec. The overall viewing 16-mm camera recorded fire engulfment development. The airfoil camera recorded a very small fire ignition on the first pulse. The fire ignition and propagations were dramatic with the second pulse. Complete fire engulfment of the airfoil was never observed, as in the case for Jet A fuel alone. Test 25 was judged not to pass the fire self-extinguishing requirement.

Test 26 used 0.4% FM-9 concentrate in a 190-l batch of 28.9°C Jet A fuel. The average fuel dump rate into the 28.3°C, 122-knot airflow was 54 l/sec. The propane igniter was pulsed at 3.6, 5.1, and 6.2 sec. The overall viewing 16-mm camera recorded one pulse traveling downstream. The airfoil camera recorded three ignitions. The first ignition was extremely small. The second and third ignitions were well defined. Test 26 was judged to pass the fire self-extinguishing requirement.

Test 27 used 0.4% FM-9 concentrate in a 190-l batch of 26.7°C Jet A fuel. The average fuel dump rate into the 26.7°C, 143-knot airflow was 61 l/sec. The propane igniter was pulsed at 4.7 and 6.0 sec. The overall viewing 16-mm camera recorded both pulses. The first pulse initiated a fire downstream. The second pulse caused the fire to propagate forward on the airfoil. The airfoil camera similarly recorded the two pulses. The glow caused by the downstream fire was quite apparent before the second pulse induced fire engulfment of the airfoil. Test 27 was judged not to pass the fire self-extinguishing requirement.

Test 28 used 0.3% FM-9 concentrate in a 190-l batch of 26.7°C Jet A fuel. The average fuel dump rate into the 27.2°C, 122-knot airflow was 59 l/sec. The propane igniter was pulsed at 3.7 and 5.0 sec. The overall viewing 16-mm camera recorded both ignitions, as did the airfoil camera. Test 28 was judged not to pass the fire self-extinguishing requirement.

Utilizing the experience gained from the second series of tests, a third series was designed to further test FM-9. The plan used for this series of tests (performed between 19-26 July 1977) to evaluate FM-9 was recommended to NWC by the FAA. The third test plan was to use 33°C airflow and 27°C fuel. The objective was to establish the failure envelope for FM-9 for concentrations between 0.3 and 0.5% and airflow velocities (at the diffuser exit plane) between 100 and 170 knots.

Again, as in the second test series, both 190-l and 568-l batches of antimisting fuel were used. The same cover plate used in the second test series (tests 22-28) was employed to minimize the head pressure effects of the airstream on the initial fuel expulsion from the airfoil (see test 6, Table 1 and test 21, Table 2).

A summary of the third series of tests performed at NWC is given in Table 3. The general observation is that sufficient data was collected to define the FM-9 failure envelope for the stated conditions. A detailed summary of each test follows.

Test 29 used 0.3% FM-9 concentrate hand-mixed in a 190-l batch of 28.6°C Jet A fuel. The average fuel dump rate into the 22.4°C, 109-knot airflow was 38 l/sec. The propane igniter was pulsed at 11.3 and 12.3 sec. The first pulse self-extinguished immediately within the field of view of the airfoil camera. The second pulse created simultaneously both a pool and an airstream fire resulting in a fireball diameter of about 9 m. A runaway condition was experienced by the test apparatus. By the second pulse the air velocity reached 118 knots and the air temperature was 36.4°C. The first pulse passed the fire self-extinguishing requirement. The second pulse was a failure point. Test 29 was judged to fail the fire self-extinguishing requirement or to be a no-test.

Test 30 used 0.3% FM-9 concentrate hand-mixed in a 190-l batch of 27.4°C Jet A fuel. The average fuel dump rate into the 38.1°C, 98-knot airflow was 55 l/sec. The propane igniter was pulsed at 24.9, 26.1, 27.5, and 29.1 sec. The first two pulses self-extinguished within the field of view of the airfoil camera. The third pulse also self-extinguished but manifested itself as one of long duration (0.23 sec). The fourth pulse also was of long duration, except that a fireball was also observed to go downstream resulting in a pool fire that self-contained by quickly reducing from about a 3-m height to about 3 cm, some 8 m aft of the airfoil. The first three pulses passed the fire self-extinguishing requirement. The fourth pulse did not pass the fire self-extinguishing requirement. Test 30 was judged to marginally pass the fire self-extinguishing requirement.

Test 31 used 0.4% FM-9 concentrate hand-mixed in a 190-l batch of 28°C Jet A fuel. The average fuel dump rate into the 31.7°C, 117-knot airflow was 60 l/sec. The propane igniter was pulsed at 22.9, 24.1, and 25.7 sec. All three pulses self-extinguished immediately within the field of view of the airfoil camera. The fire pulse duration of the second pulse was 0.1 sec. Test 31 was judged to pass the fire self-extinguishing requirement.

Test 32 used 0.5% FM-9 concentrate hand-mixed in a 190-l batch of 28.6°C Jet A fuel. The average fuel dump rate into the 30.2°C, 132-knot airflow was 53 l/sec. The propane igniter was pulsed at 30.5, 31.7, and 33.3 sec. All three pulses self-extinguished immediately within the field of view of the airfoil camera. The fire pulse duration of the second pulse was 0.1 sec. Test 32 was judged to pass the fire self-extinguishing requirement.

Test 33 used 0.5% FM-9 concentrate hand-mixed in a 190-l batch of 25.2°C Jet A fuel. The average fuel dump rate into the 34.2°C, 158-knot airflow was 30 l/sec. The propane igniter was pulsed at 32.3, 33.5, 34.9, 36.5, 38.1, and 39.7 sec. All six pulses self-extinguished immediately within the field of view of the airfoil camera. Test 33 was judged to pass the fire self-extinguishing requirement.

TABLE 3. Results of Tests Performed at NWC in July 1977.

Test no.	Test date	Test objective	Additive concen. (%)	Fuel volume (l)	Diffuser air temp. (°C)	Fuel temp. (°C)	Air velocity (knots)	Number pulses	Dump rate (l/sec)	Degree fuel wetting of pan	Ignition pulses		Remarks	Antimisting effectiveness
											Passed	Failed		
29	18/7/77	FM-9 data point[a]	0.3	190	22.4[b]	28.6	109[c]	2	38[f]	Modest	1	1	Failure probably due to apparatus malfunction.	Fail (no-test)
30	19/7/77	FM-9 data point(a)	0.3	190	38.1	27.4	98	4	55	Considerable	3	1	Downstream pool fire self-contained.	Marginal
31	19/7/77	FM-9 data point[a]	0.4	190	31.7	28.0	117	3	60	Considerable	3	0	Small fire ignitions self-extinguished.	Pass
32	19/7/77	FM-9 data point[a]	0.5	190	30.2	28.6	132	3	53	Considerable	3	0	Small fire ignitions self-extinguished.	Pass
33	20/7/77	FM-9 data point[a]	0.5	190	34.2	25.2	158	6	30[f]	Considerable	6	0	Small fire ignitions self-extinguished.	Pass
34	20/7/77	FM-9 data point[a]	0.4	568	30.8	26.3	120	5	75	Considerable	5	0	Small fire ignitions self-extinguished.	Pass
35	20/7/77	FM-9 data point[a]	0.3	568	33.6	26.9	100	5	79	Considerable	4	1	Downstream pool fire self-contained.	Marginal
36	21/7/77	FM-9 data point[a]	0.5	568	29.7	25.2	161	7	41[f]	Considerable	7	0	Small fire ignitions self-extinguished.	Pass
37	21/7/77	FM-9 data point[a]	0.4	568	29.7	28.0	142	2	70	Considerable	0	2	Pool fire contributed to failure.	Fail
38	22/7/77	FM-9 data point[a]	0.4	568	29.1	25.8	129	6	72	Considerable	5	1	Downstream pool fire self-contained.	Marginal
39	22/7/77	FM-9 data point[a]	0.3	568	32.5	26.3	110	3	74	Considerable	1	2	Pool fire contributed to failure.	Fail
40	22/7/77	FM-9 data point[d]	0.3	190	29.7	28.0	109	3	58	Considerable	2	1	Pool fire contributed to failure.	Fail
41	25/7/77	FM-9 data point[a]	0.35	568	30.8	25.7	122	5	74	Considerable	1	4	Downstream pool fire self-contained.	Marginal
42	25/7/77	FM-9 data point[a]	0.35	568	31.3	26.3	110	6	77	Considerable	6	0	Modest fireball traveled downstream.	Pass
43	25/7/77	FM-9 data point[d]	0.3	190	30.2	28.0	98	4[e]	48	Considerable	3	1	Fuel flow almost exhausted for pulse 4.	Marginal (no-test)
44	26/7/77	FM-9 data point[a]	0.45	379	29.1	25.8	159	5	56	Considerable	0	5	Downstream pool fire self-contained.	Marginal
45	26/7/77	FM-9 data point[a]	0.45	379	35.8	28.6	169	2	54	Considerable	0	2	Pool fire contributed to failure.	Fail

NOTE:
Weather conditions were excellent: low humidity (~30%), temperatures between 27-38°C, no wind.
Antimisting fuel flash point, 49-52°C.

[a] Hand-mixed (10 min).

[b] Diffuser air temperature rose after first pulse.

[c] Air velocity rose after first pulse.

[d] Machine-mixed (100 rpm, 10 min).

[e] The fourth pulse occurred in a non-representative flow field.

[f] Dump rates lower than expected, perhaps due to fuel release cylinder malfunction.

Test 34 used 0.4% FM-9 concentrate hand-mixed in a 568-l batch of 26.3°C Jet A fuel. The average fuel dump rate into the 30.8°C, 120-knot airflow was 75 l/sec. The propane igniter was pulsed at 27.3, 28.3, 29.9, 31.7, and 32.9 sec. All five pulses self-extinguished within the field of view of the airfoil camera. The fire pulse duration of the third pulse was 0.3 sec. Test 34 was judged to pass the fire self-extinguishing requirement.

Test 35 used 0.3% FM-9 concentrate hand-mixed in a 568-l batch of 26.9°C Jet A fuel. The average fuel dump rate into the 33.6°C, 100-knot airflow was 79 l/sec. The propane igniter was pulsed at 31.7, 32.9, 34.3, 35.7, and 37.3 sec. The first four pulses passed the fire self-extinguishing requirement. The pulse duration of pulses four and five were about 1.2 sec. The fifth pulse exhibited a fireball that resulted in a pool fire that self-contained by quickly reducing from about a 3-m height to about 3 cm, some 8 m aft of the airfoil (similar to test 30). Test 35 was judged to marginally pass the fire self-extinguishing requirement.

Test 36 used 0.5% FM-9 concentrate hand-mixed in a 568-l batch of 25.2°C Jet A fuel. The average fuel dump rate into the 29.7°C, 161-knot airflow was 41 l/sec. The propane igniter was pulsed at 26.1, 27.3, 28.9, 30.3, 31.7, 33.3, and 34.7 sec. All but the third pulse self-extinguished within the field of view of the airfoil camera. A 10-cm fireball was observed to pass through the field of view on the fourth pulse. However, the ball was not observed by the overview camera. Hence it must have self-extinguished near the trailing edge. Test 36 was judged to pass the fire self-extinguishing requirement.

Test 37 used 0.4% FM-9 concentrate hand-mixed in a 568-l batch of 28°C Jet A fuel. The average fuel dump rate into the 29.7°C, 142-knot airflow was 70 l/sec. The propane igniter was pulsed at 16.7 and 18.2 sec. The first pulse resulted in a fireball in the airstream starting a pool fire some 7 m behind the airfoil. The second pulse initiated a fire in the airstream. Test 37 was judged not to pass the fire self-extinguishing requirement.

Test 38 used 0.4% FM-9 concentrate hand-mixed in a 568-l batch of 25.8°C Jet A fuel. The average fuel dump rate into the 29.1°C, 129-knot airflow was 72 l/sec. The propane igniter was pulsed at 24.3, 25.5, 27.1, 28.5, 30.1, and 31.5 sec. All pulses except the third and fifth self-extinguished within the field of view of the airfoil camera. Pulse three self-extinguished some 3 m behind the airfoil. Pulse five resulted in a pool fire under the wing to some 10 m aft of the airfoil. This pool fire self-contained. Test 38 was judged to marginally pass the fire self-extinguishing requirement.

Test 39 used 0.3% FM-9 concentrate hand-mixed in a 568-l batch of 26.3°C Jet A fuel. The average fuel dump rate into the 32.5°C, 110-knot airflow was 74 l/sec. The propane igniter was pulsed at 20.3, 21.5, and 23.1 sec. The first pulse resulted in a pool fire under the trailing edge of the airfoil. This pool fire retreated some 3 m resulting in a pool fire some 8 m high. The second pulse self-extinguished in the field of view under the airfoil. The third pulse resulted in a full fire field. Test 39 was judged not to pass the fire self-extinguishing requirement.

Test 40 used 0.3% FM-9 concentrate machine-mixed in a 190-l batch of 28°C Jet A fuel. The average fuel dump rate into the 29.7°C, 109-knot airflow was 58 l/sec. The propane igniter was pulsed at 26.3, 27.7, and 29.3 sec. The first and second pulses self-extinguished within the field of view of the airfoil camera. Their fire pulse time was about 0.27 sec each. The third pulse resulted in a pool fire under the airfoil. Test 40 was judged not to pass the fire self-extinguishing requirement.

Test 41 used 0.35% FM-9 concentrate hand-mixed in a 568-l batch of 25.7°C Jet A fuel. The average fuel dump rate into the 30.8°C, 122-knot airflow was 74 l/sec. The propane igniter was pulsed at 14.7, 15.7, 17.3, 18.7, and 20.3 sec. The first pulse self-extinguished immediately within the field of view of the airfoil camera. The next three pulses failed to contain the fireball within the airstream. The fifth fireball resulted in a pool fire aft of the airfoil. This fire was significantly different from other pool fires in that it was of low heat intensity. Test 41 was judged to marginally pass the fire self-extinguishing requirement.

Test 42 used 0.35% FM-9 concentrate hand-mixed in a 568-l batch of 26.3°C Jet A fuel. The average fuel dump rate into the 31.3°C, 110-knot airflow was 77 l/sec. The propane igniter was pulsed at 8.7, 10.1, 11.3, 12.7, 14.3, and 15.7 sec. The first four pulses self-extinguished within the field of view of the airfoil camera. The fifth pulse resulted in a fireball that self-extinguished some 6 m behind the airfoil. The sixth pulse self-extinguished within the field of view of the airfoil camera. Test 42 was judged to pass the fire self-extinguishing requirement.

Test 43 used 0.3% FM-9 concentrate machine-mixed in a 190-l batch of 28.0°C Jet A fuel. The average fuel dump rate into the 30.2°C, 98-knot airflow was 58 l/sec. The propane igniter was pulsed at 13.5, 14.7, 16.5, and 17.7 sec. The first three pulses self-extinguished within the field of view of the airfoil camera. The fourth pulse, however, resulted in a pool fire. This event was judged invalid on the basis that the fuel flow was almost exhausted. Test 43 was judged to marginally pass the fire self-extinguishing requirement or to be a no-test.

Test 44 used 0.45% FM-9 concentrate hand-mixed in a 379-l batch of 25.8°C Jet A fuel. The average fuel dump rate into the 29.1°C, 159-knot airflow was 56 l/sec. The propane igniter was pulsed at 29.9, 31.3, 32.7, 34.1, and 35.7 sec. Fireballs, about 1-5 cm, were observed to pass through the field of view of the airfoil camera for every pulse. A pool fire resulted aft of the airfoil after the first pulse. The fire was never seen throughout the test by the airfoil camera. Test 44 was judged to marginally pass the fire self-extinguishing requirement.

Test 45 used 0.45% FM-9 concentrate hand-mixed in a 379-l batch of 28.6°C Jet A fuel. The average fuel dump rate into the 35.8-plus, 169-knot airflow was 54 l/sec. The propane igniter was pulsed at 20.9 and 22.1 sec. Both pulses resulted in a pool fire. Test 45 was judged not to pass the fire self-extinguishing requirement.

DISCUSSION OF TEST RESULTS

Test 19 (Table 2) demonstrated that, for an airstream velocity of 147 knots, neat Jet A will mist and release intense heat as a result of an air explosion initiated by the propane igniter under the airfoil. Test 5 (Table 1) demonstrated that a small percentage (<0.16%) of AM-1 additive does not significantly reduce the released heat rate for higher airstream velocities (152 knots). Test 18 (Table 2) demonstrated that the addition of 0.3% FM-9 to neat Jet A significantly decreases the fuel's propensity to support a fire initiated by the propane igniter.

Based on the test results in Tables 2 and 3, it is conclusive that FM-9 fuel additive in concentrations of at least 0.3% is effective in reducing neat Jet A's propensity to support fire in an airstream analogous to that in a survivable aircraft crash landing. Figure 17 shows a fire suppression effectiveness envelope derived from the test data in Tables 2 and 3. The area above the curve is designated pass and represents conditions for which the antimisting fuel was completely effective in suppressing fire. The area below the curve is designated marginal/fail and represents conditions for which the antimisting fuel did not completely suppress fire or was ineffective. (Tests in which the airfoil fuel outlet cover was not used are not plotted in Figure 17.) It is emphasized that none of the test failures ever exhibited the fierce heat intensity or ignition explosion observed using neat Jet A.

It is apparent that more than one mechanism determined the travel of a fireball under the wing. In many instances the fireball was contained within the airstream and ejected to the ground, either under the wing apparatus or several meters downstream. The fireball would sometimes then ignite the pool fuel on the ground. The pool fuel fire would then spread rapidly due to the airstream-whipped surface air. Generally, the pool fire would progress on the ground toward the wing apparatus. Heat from the progressing pool fire would then ignite the antimisting fuel in the airstream above the fire. The heat intensity of the pool fire was obviously much greater than that of the propane torch. Such a chain of events was not judged as a failure for the antimisting agent to self-extinguish fuel fire unless the airfoil was engulfed by fire. Had the propane torch been replaced with a heat source equivalent to a developed pool fire under the airfoil, it is probable that all tests would have resulted in failure of the antimisting agent to suppress fire. On the other hand, such a heat source may be unrealistic for a survivable aircraft crash landing. It is pointed out that the intrinsic failure envelope could also be a function of antimisting agent storage life, height of the airfoil above ground, fuel dump density rate, air humidity, ground temperature, etc.

CONCLUSION

FM-9 antimisting agent in 0.3% to 0.5% concentration in Jet A fuel is effective in suppressing the fireball that so often results from severe ruptures of wing fuel tanks during impact survivable aircraft crashes.

REFERENCES

1. Hansberry, H. L., "Aircraft Fire Protection Developments by the Federal Aviation Administration" (1940-1970), available AD 70A36847, May 1970.
2. Horeff, T. G., "Research and Development of Modified Fuels for Reduction of the Postcrash Fire Hazard," *Aircraft Crashworthiness*, Saczaski, K., et al., editors, University Press of Virginia, Charlottesville (1975).
3. Ahlers, R. H., "Full-Scale Aircraft Crash Tests of Modified Jet Fuel," Technical Report Number FAA-RD-77-13, U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C., January 1977.
4. Weatherford, W. D. Jr., and Wright, B. R., "Status of Research on Antimist Aircraft Turbine Engine Fuels in the United States," ARARD/NATO 45th Meeting, Propulsion and Energetics Panel, "Aircraft Fire Safety," Rome, Italy, 7-11 April 1975.
5. Mannheimer, R. J., "Rheology Study of Antimist Fuels," Technical Report Number FAA-RD-77-10, U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C., January 1977.

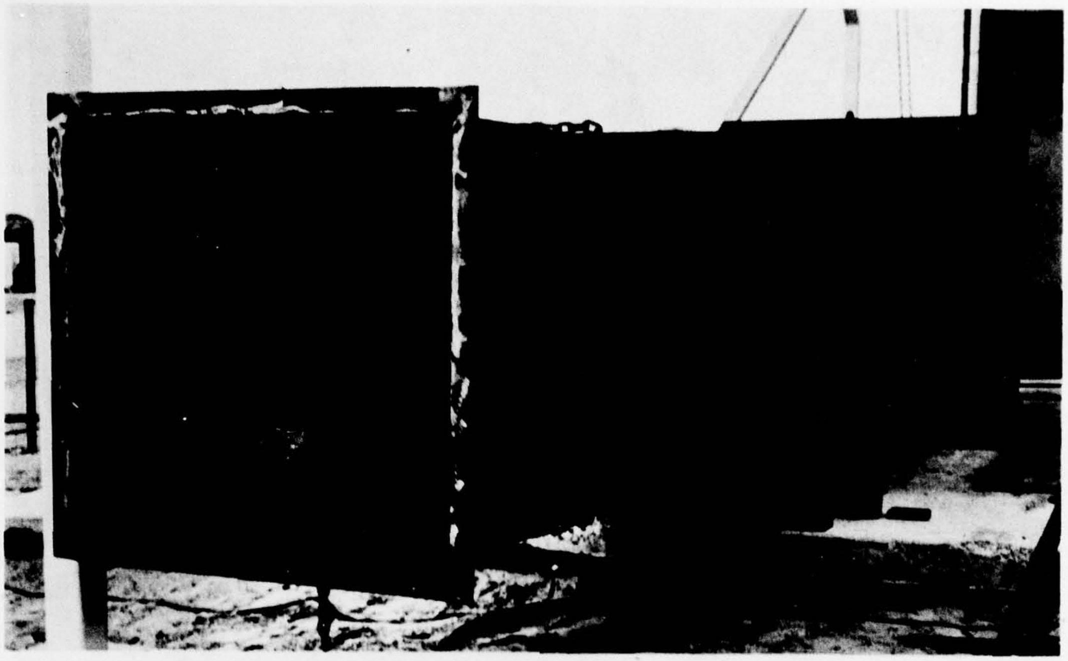


FIGURE 1. Low Velocity Air Diffuser.

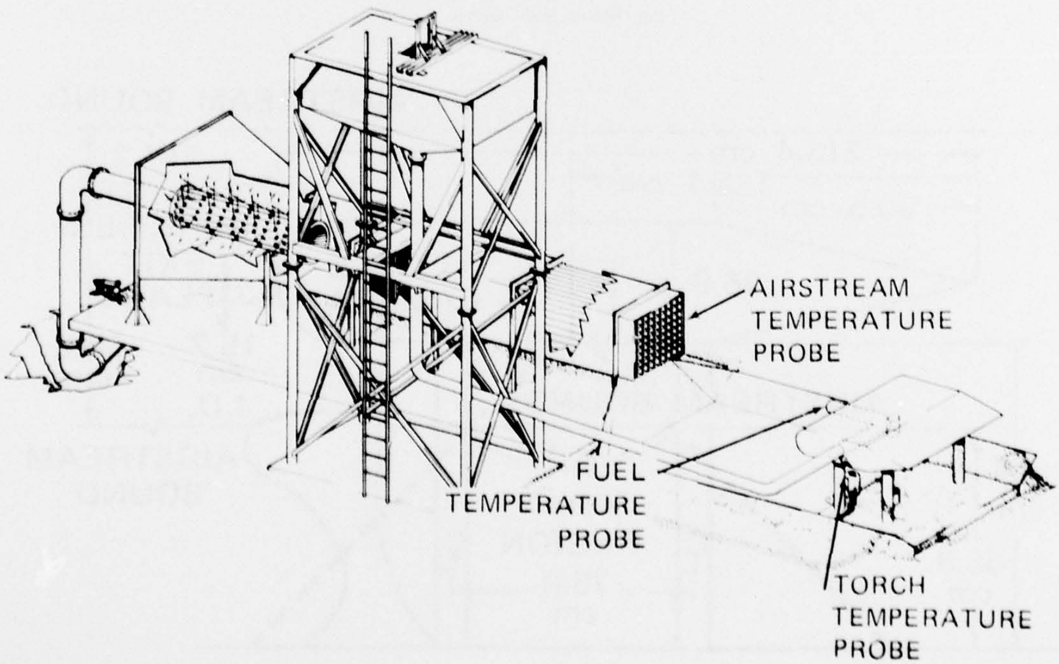


FIGURE 2. T-Range Low Velocity Flow Facility with Airfoil in Place.

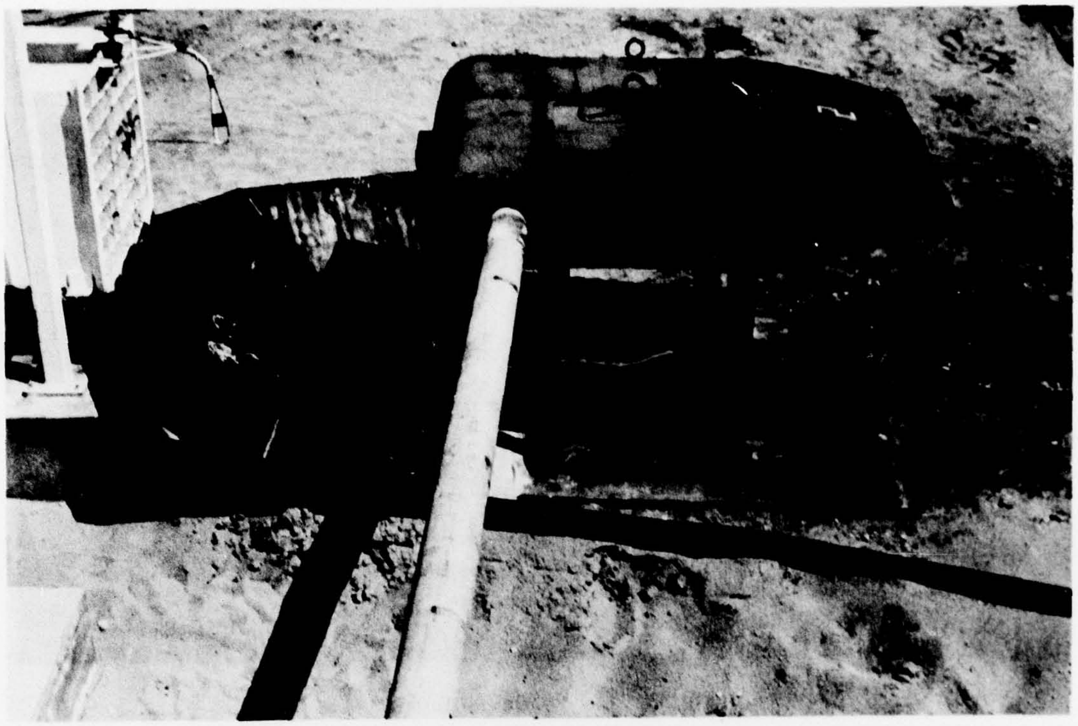


FIGURE 3. Test Airfoil.

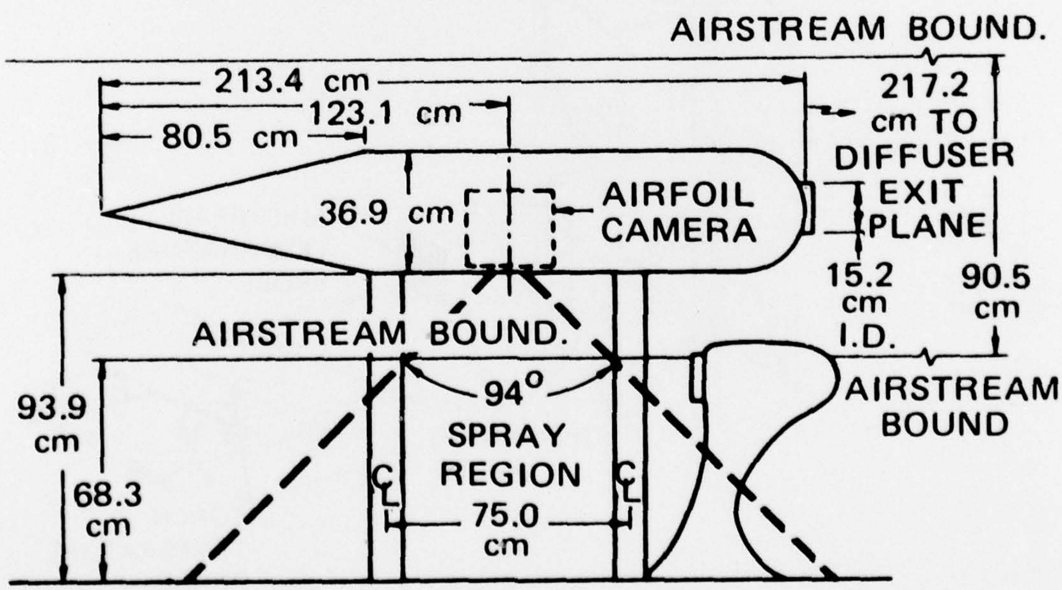


FIGURE 4. Dimensions of Test Airfoil.

FIGURE 5. Propane Torch Located Under Airfoil.

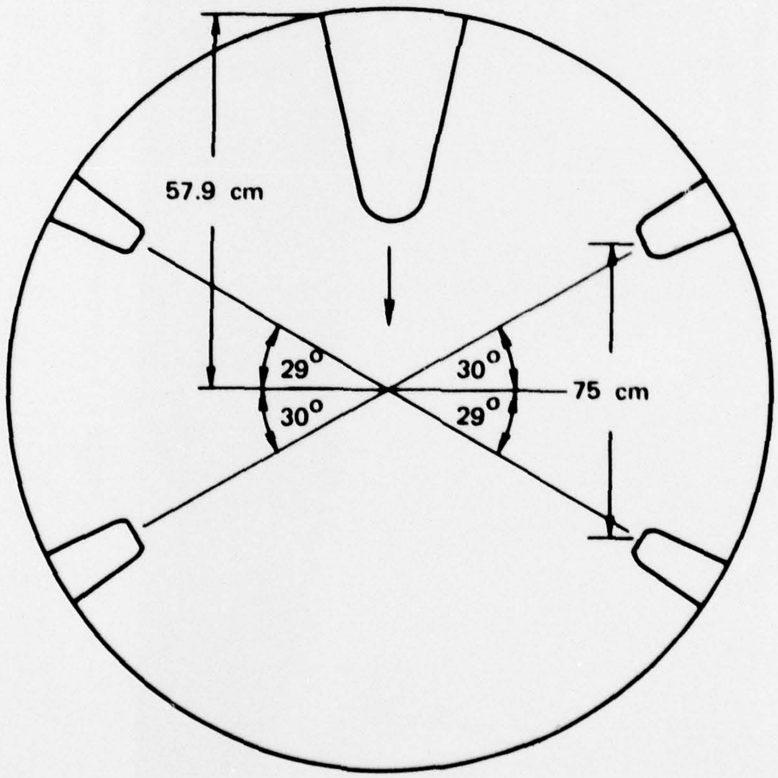


FIGURE 6. Airfoil Camera Field of View.

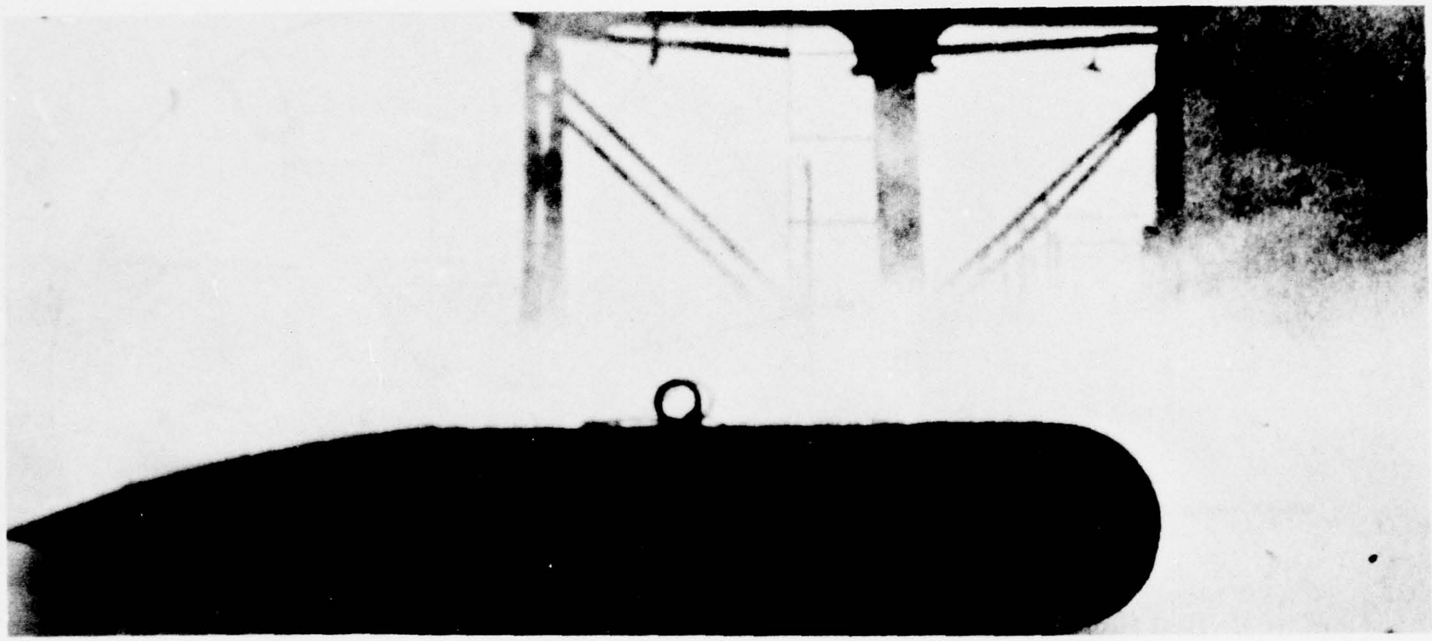


FIGURE 7. Water Vapor Demonstration of Homogeneous Low Turbulent 100-knot Air Flow.

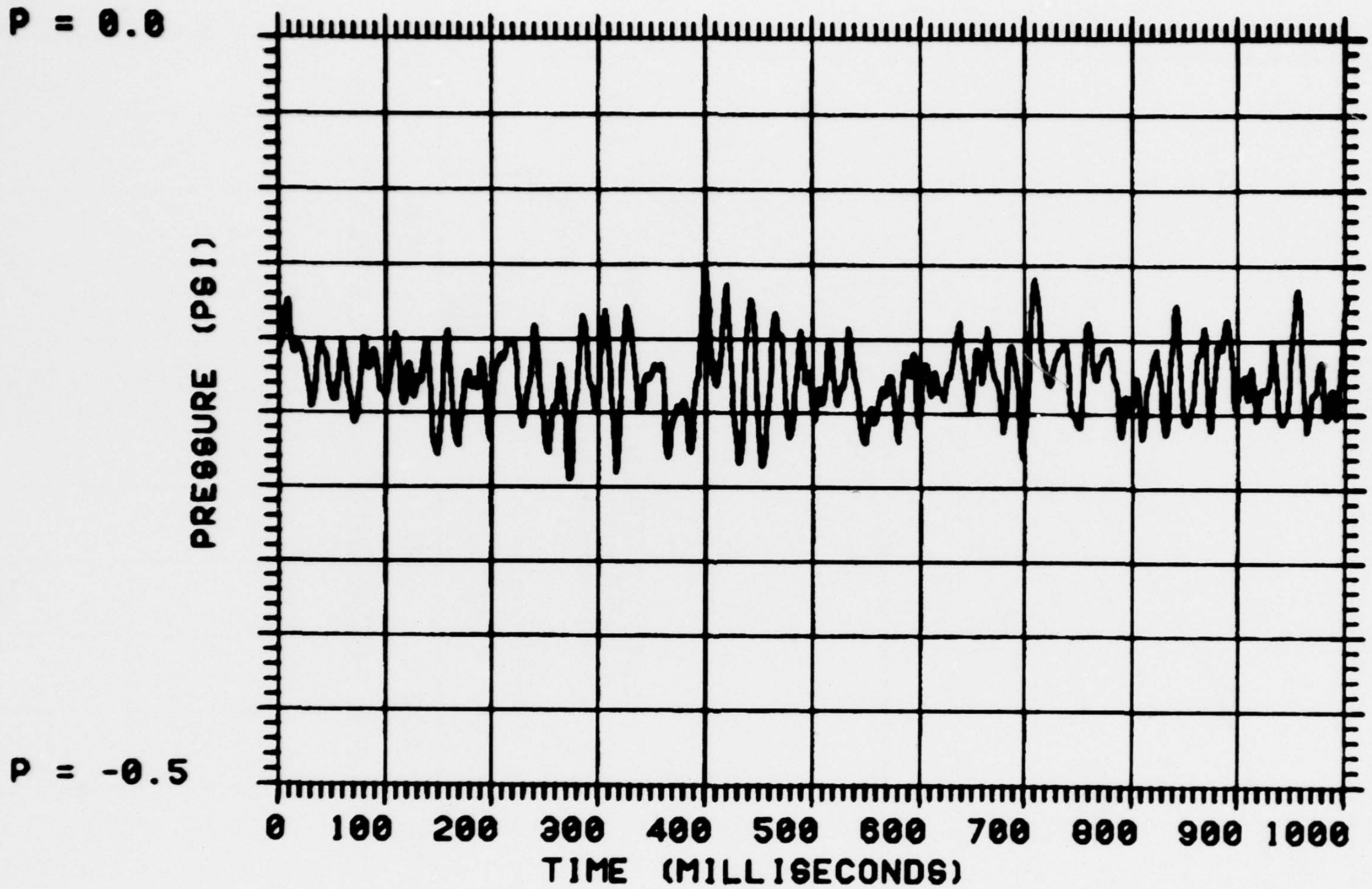


FIGURE 8. Turbulent Air Pressure at Diffuser Exit Plane (100 knots).

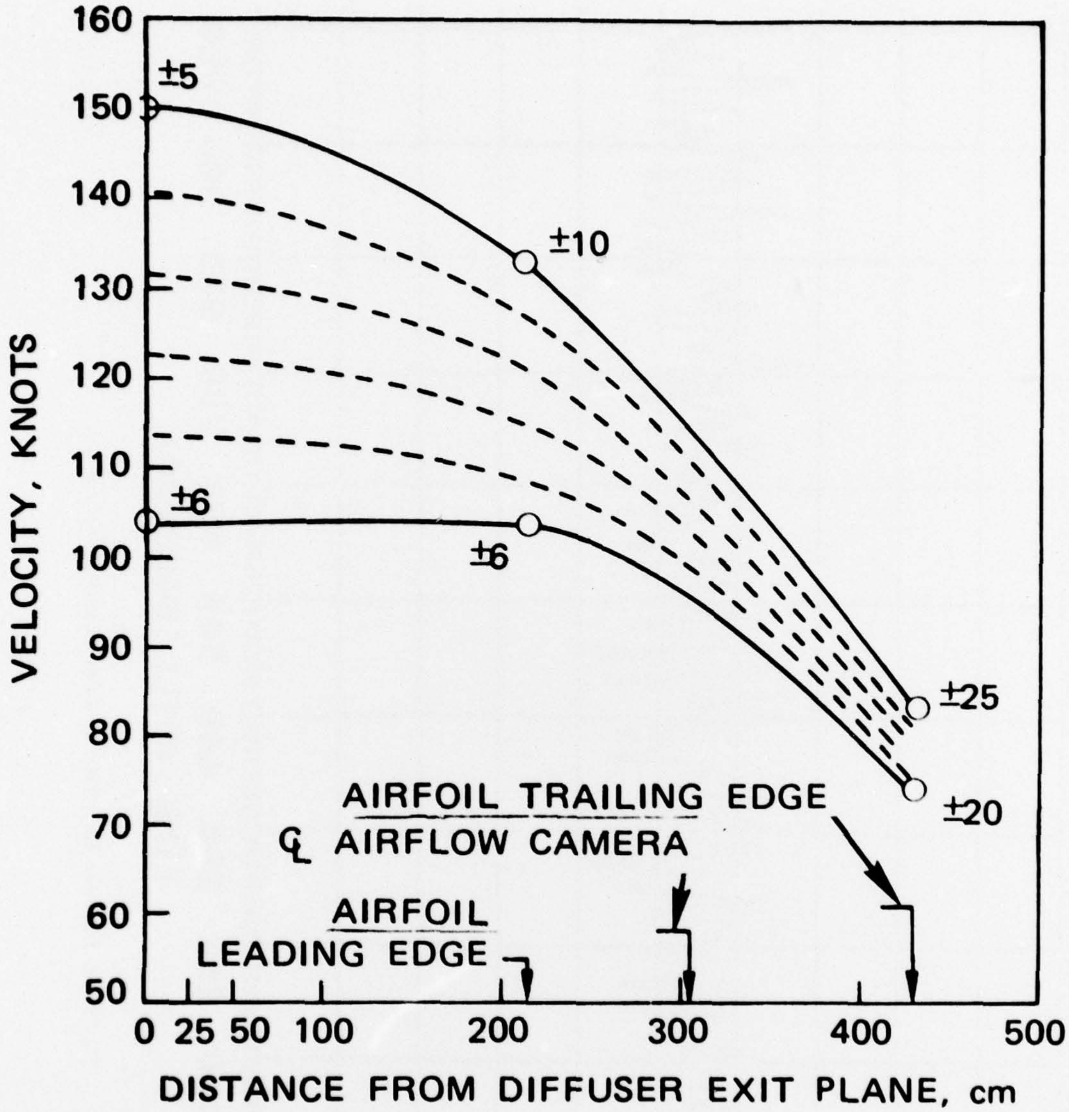


FIGURE 9. Airflow Velocity Attenuation From Diffuser Exit Plane.

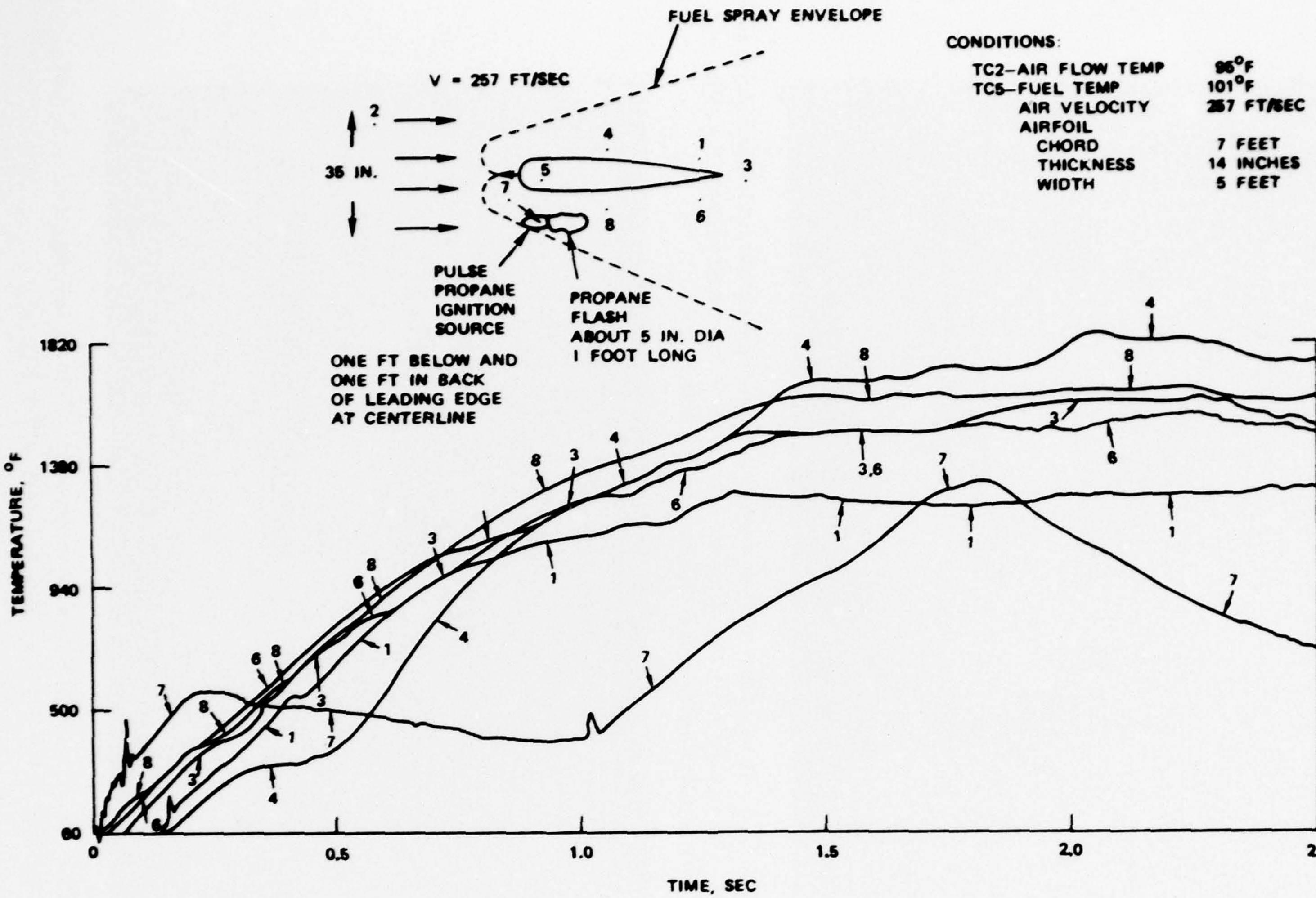


FIGURE 10. Temperature–Time Response of Thermocouples Located in the Vicinity of Airfoil.

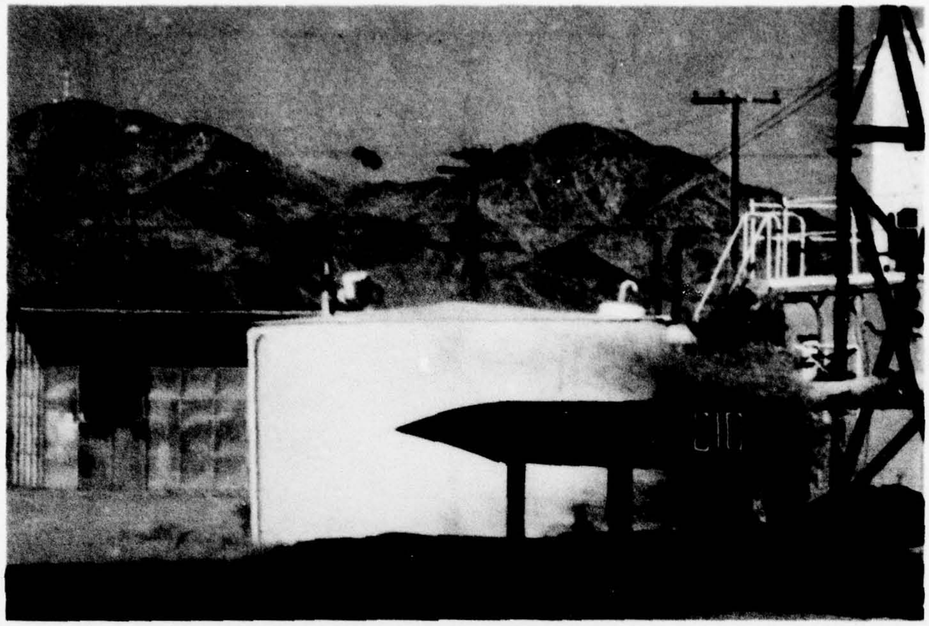


FIGURE 11. Fuel flow pattern approximately one second after fuel release and torch ignition, test no. 38 (FM 9 concentration - 0.4%, air velocity - 129 knots, fuel volume - 568 liters).

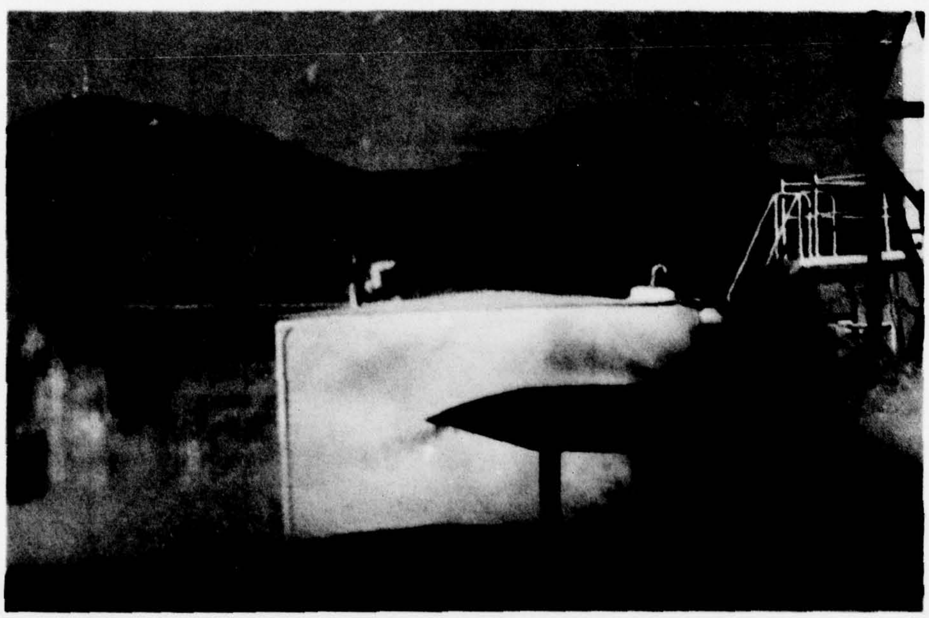


FIGURE 12. Torch ignition, test no. 41 (FM9 concentration - 0.35%, air velocity - 122 knots, fuel volume - 568 liters).

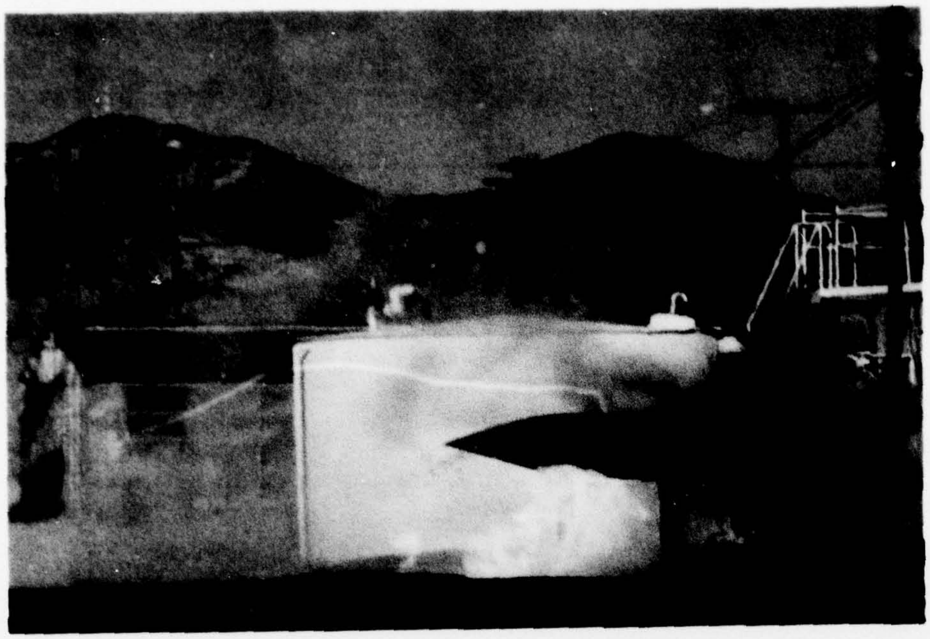


FIGURE 13. Flame propagation one-half second after torch ignition, test no. 41 (FM9 concentration - 0.35%, air velocity - 122 knots, fuel volume - 568 liters).

FIGURE 14. Flame propagation one second after torch ignition, test no. 41.

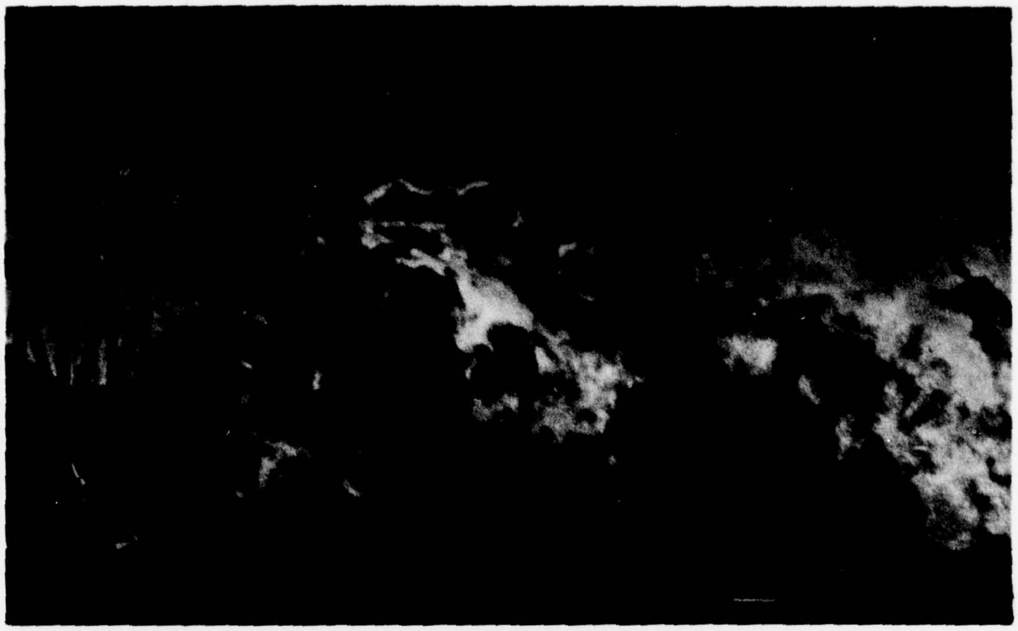
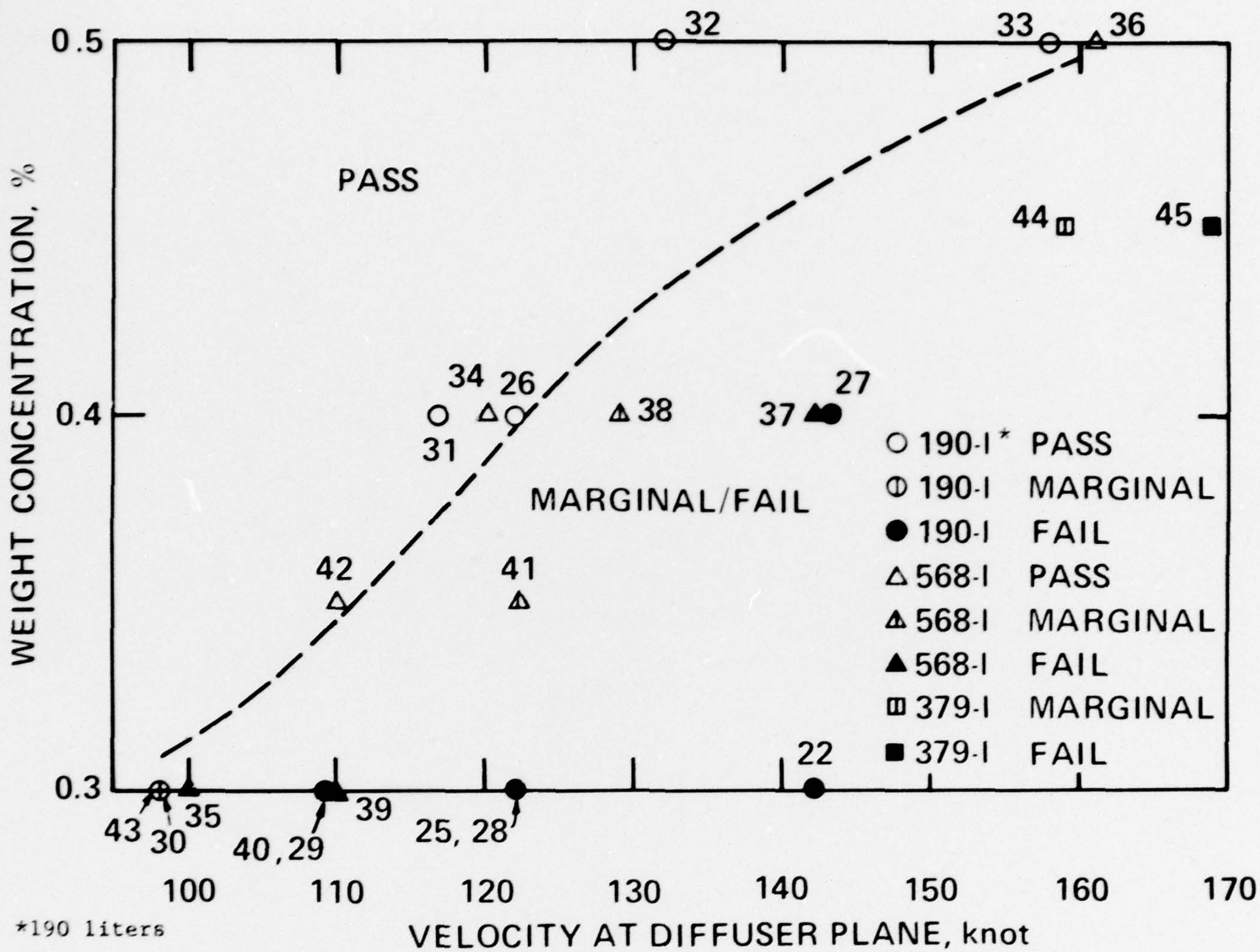


FIGURE 15. Flame propagation of neat Jet A approximately one-half second after torch ignition, test no. 19 (no FM9, air velocity - 147 knots, fuel volume - 190 liters).

FIGURE 16. Flame propagation of neat Jet A approximately one second after torch ignition, test no. 19.



*190 liters

Figure 17. Fire Suppression Effectiveness Envelope for FM-9 in Jet A.