

SMALL-SCALE IMPACT TESTS OF CRASH-SAFE TURBINE FUELS

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FINAL REPORT

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16. Abstract A variety of regular and modified hydrocarbon-turbine fuels, one nonhydrocarbon fuel, and reticulated polyurethane foam filled with neat fuel was subjected to small-scale impact tests to determine burning, misting, and splatter characteristics of the fuels. The results of this study conclude that it is entirely feasible to retard the ignitability, combustibility, and flow characteristics of current hydrocarbon fuels by increasing their apparent viscosity. The study showed that non-Newtonian gelled fuels performed better than other modified fuel candidates and better than the reticulated polyurethane foams filled with neat fuel.			
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PREFACE

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INTRODUCTION

Purpose

The purpose of this project was to determine the burning characteristics of all available modified fuels under simulated crash-fire conditions as part of an overall program to develop a turbine fuel that will not burn when inadvertently released during a crash.

Background

The Federal Aviation Administration (FAA) initiated a program in 1964 to determine the feasibility of whether a thickened turbine fuel could provide reduced fire hazards under aircraft ground-crash conditions and yet, in its thickened state, be compatible with existing jet transport fuel systems and burn directly in a turbine engine. The initial project was carried out under contract with The Western Company, Richardson, Texas. The effort produced a thickening agent known as N-coco-7-hydroxybutyramide (CHBA) (formulation FAA 1069-1) (Reference 1). The CHBA agent when mixed with turbine fuels at a temperature of 130°F created a non-Newtonian gelled fuel (Appendix A) which was reasonably compatible with turbine engines and pumps of conventional design if the fuels were force fed to the pumps. The project brought to light under small-scale simulated crash conditions the fact that the fire reduction benefits of fuel thickeners resulted from their ability to physically bind the fuel and thus reduce the rate of vaporization and the exposed surface area available to support a fire.

Part way through the initial program, it was tentatively established by small-scale simulated crash tests that thickened turbine fuels presented less of a fire hazard than standard fuels. As a result the project discussed in this report was initiated to determine the burning characteristics of CHBA and various other candidate fuels as they became available.

When further testing showed that the CHBA agent was not compatible with aircraft fuel systems because of its poor fluidity, corrosiveness, and its instability due to varying temperatures and degrees of aging, a second contract (Reference 2) was initiated with the Western Company to identify the best fuel-modifier system which would provide improved fuel safety. Concurrently with the second effort, a third contract (Reference 3), with the Bureau of Mines, got underway to develop a laboratory method of rating the potential crash-fire hazards of hydrocarbon-type aircraft fuels, both regular and modified. The crash-fire hazard rating system (see Appendix B) was essential to The Western Company during the screening of fuel modifiers in its effort to find candidate fuels that could reduce aircraft post-crash ground fires. The Al-2-ethylhexanoate (aluminum octoate) gel was selected as the best of the 55 modified fuels tested. The aluminum octoate gel was tested in a J47-GE-25 turbine engine (Reference 4) and found to possess spray properties which prevented proper atomization at the burner-can nozzle

and was thereby withdrawn as a potential candidate. The two aforementioned contractual efforts, designed to select a suitable turbine fuel modifier, both proposed a candidate employing the "gelling" rather than the "emulsifying" technique. Refer to Appendix C for definitions of gels and emulsions.

Although the FAA-sponsored research programs failed to produce suitable crash-safe fuel candidates, candidates were continually being received for evaluation from industry-sponsored in-house programs.

Every known turbine fuel suspected of being in the category of a crash-safe fuel was sought after from both the military and industry, tested to some degree, and reported on herein.

DISCUSSION

General

Methods and procedures were designed to perform small-scale static and dynamic tests to determine the fire severity of regular and modified fuels under simulated crash conditions.

Small-scale tests, described below, were developed at the National Aviation Experimental Center (NAFEC) to determine fire hazard characteristics of fuels in the mist and liquid form. Special emphasis was placed on fuel misting since it has been determined to be extremely hazardous in aircraft crash situations (References 5, 6, 7, and 8).

Test Procedure and Results

Air Gun Method

Test Procedures - This test showed (1) the degree to which a fuel would become an aerosol after being air sheared and (2) the flammability characteristic of the aerosol fuel in the presence of an open flame, electric arc, or a hot surface. One gallon (6.7 pounds) of fuel, regular or modified, was packaged in a frangible container (Figure 1) and propelled horizontally at a speed of 90 ± 5 miles per hour against a steel grid (Figure 2). The packaging container was arrested at the grid where the specimen of fuel was squeezed from the container and extruded through the grid. The fuel was sheared by its interaction with the still air to form a fuel-mist cloud. The center of the cloud reached zero forward velocity approximately 12 feet beyond the steel grid. The impact speed provided complete atomization of a 1-gallon specimen of the neat fuel by expanding the .134 cubic foot of liquid into a fuel-air cloud of approximately 2,000 cubic feet in size in a time period of 0.27 second thereby subjecting the fuel to an average longitudinal deceleration of approximately 20 g.

For the open flame test, five 4- by 7-inch rectangular pans positioned 8 inches above the ground (Figure 2) presented a total fire area of 140 square inches, to which the cloud of fuel mist was

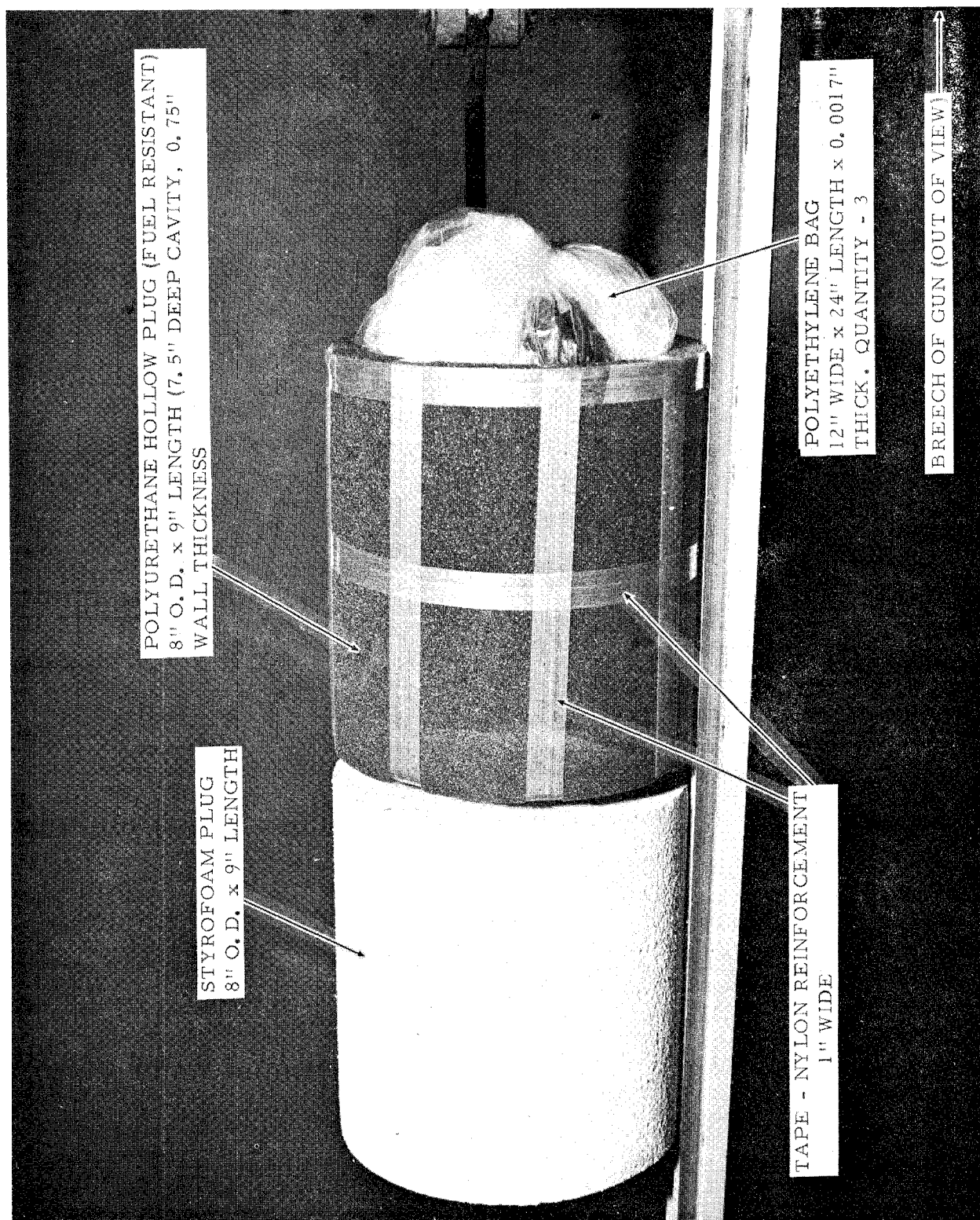
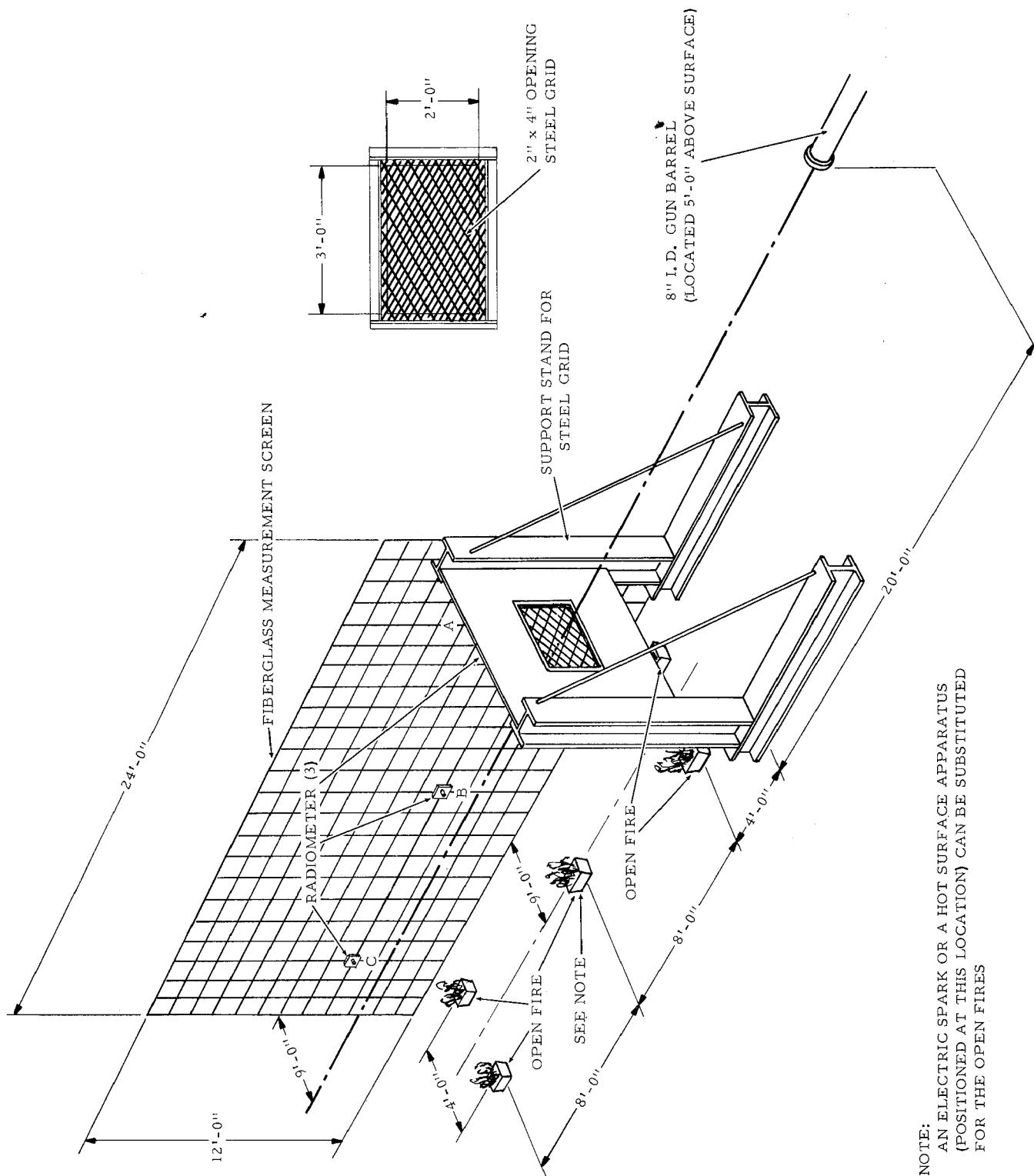


FIGURE 1 - FUEL SPECIMEN PACKAGED FOR AIR GUN TEST



NOTE:
AN ELECTRIC SPARK OR A HOT SURFACE APPARATUS
(POSITIONED AT THIS LOCATION) CAN BE SUBSTITUTED
FOR THE OPEN FIRES

FIGURE 2 - AIR GUN IMPACT TEST FACILITY

exposed. Open flame was predominantly used since it was considered to be more severe than the other two types of ignition sources; namely, the electric spark and the hot surface.

For the electric arc test a 3/8-inch-long arc was provided as noted in Figure 2. An ignition vibrator unit from a turbine engine, Model No. J47-GE25, supplied the high pulsating voltage.

The hot-surface apparatus (Figure 2, see note) consisted of a 1/4-inch-thick stainless steel plate (11 by 14 inches) supported horizontally and covered with an oval-shaped steel hood curved on a 7 inch radius. One end of the hood was closed off with a steel plate, and the open end faced the air gun. Eleven thermocouples were embedded in the horizontal plate, and a twelfth was suspended in the airspace within the hood area. A gas-fired plumber's furnace heated the horizontal plate from beneath and was shut off when the desired plate temperature (900°F - 1400°F) was attained and before the fuel sample was fired.

Time history data of a fuel's ability to burn under any one of the three test conditions were recorded by three Heat Technology radiometers (Model GR20-32P) and two cameras operating at speeds of 1000 frames per second. A 70-millimeter camera was employed on occasion.

The droplet size within the fuel-mist cloud produced by the air gun test method was determined with the apparatus shown in Figure 3.

Results - Table 1 lists 32 types of the neat and modified fuels and four fuel containment methods tested by the air gun method during this program. Many of the fuel types were furnished in varying formulations, each requiring an individual test. The number of fuels tested totaled 275.

The modified fuels are listed as either a Gel (gelling agents), Emul (emulsifier), Inhib (inhibited), or as a Dilat (dilatant gel) along with descriptive data. As indicated, there were 12 different suppliers participating in the program, three of whom were continuing development formulations of modified fuels as this project ended.

The types of fuels were grouped into 12 categories and are shown in Figure 4 with the average ratings received in terms of radiant energies; a direct indication as to the size of the fireball that the ignited fuel produced. Fluidity of the formulations was not considered in the early stages of the program since manufacturers submitting fuels were primarily interested in determining whether they could produce a turbine fuel that would be less vulnerable to ignition in a simulated crash environment and yet possess the heat of combustion required. Therefore, the majority of the fuels tested under Items 4, 5, 6, 7, and 8 were highly viscous, i.e., emulsions with yield stresses ≥ 800 dynes/cm² and gels with apparent viscosities $\geq 8,000$ centipoises

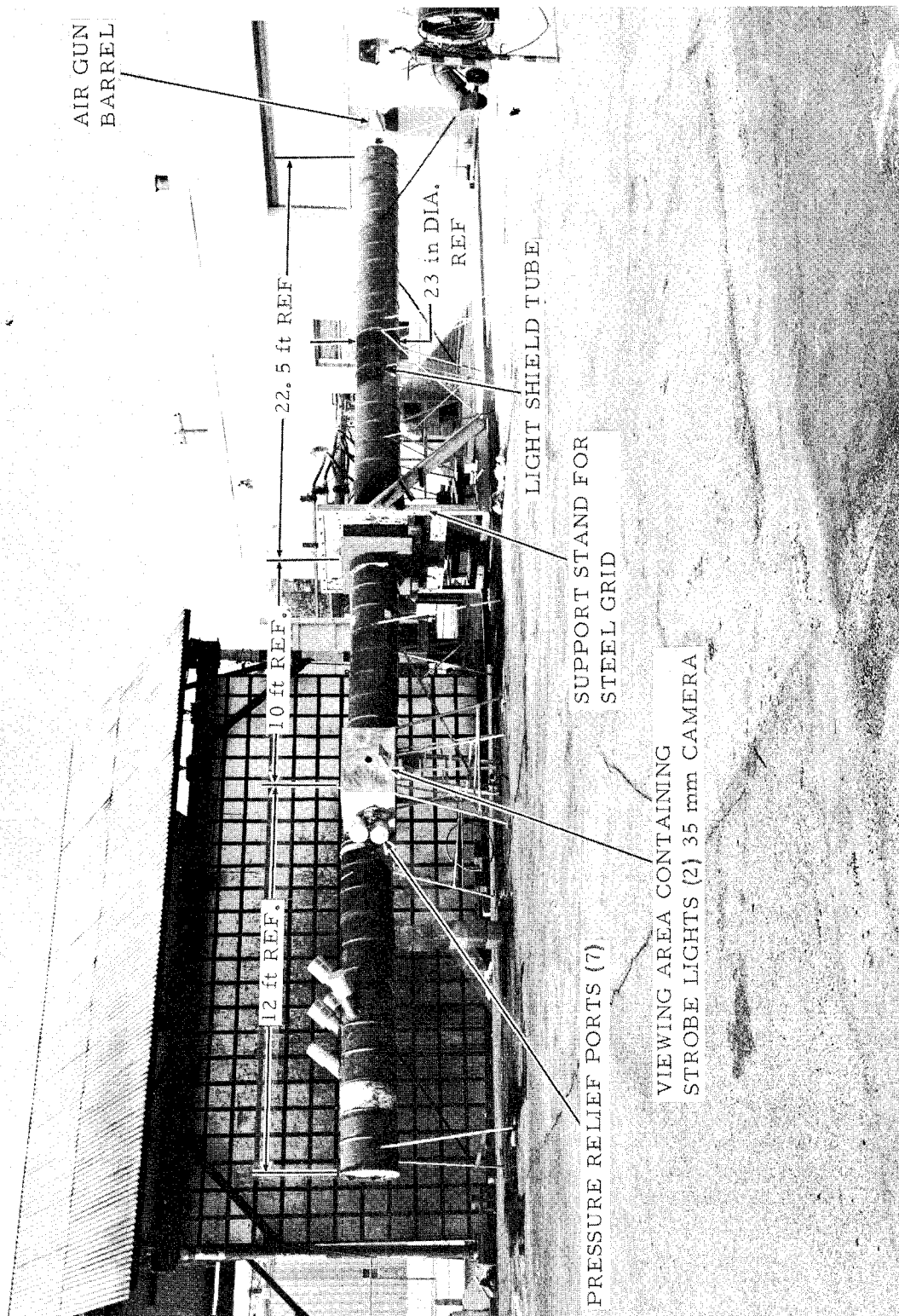


FIGURE 3 - FUEL-MIST ANALYSING APPARATUS

(RVT Brookfield, Number 6 spindle at 10 rpm). However, thickened fuels in the viscosity ranges mentioned have since been determined by Reference 9 to be incompatible with commercial jet transport fuel systems.

TABLE 1.--TYPES OF PRODUCTS TESTED BY THE AIR GUN METHOD

No.	Type	Description	Base Fuel	Mfr.
1966				
1		Turbine Engine Fuel (Jet A-1)		
2		Turbine Engine Fuel (JP-4)		
3		Turbine Engine Fuel (JP-5)		
4	Gel	N-coco- γ -gamma-hydroxybutyramide (FA-1069-1)	JP-4	A
5	Gel	N-coco- γ -gamma-hydroxybutyramide (FA-1069-1)	JP-4	A
6		Diesel Fuel		
7	Emul	Proprietary	JP-4	B
8	Gel	Proprietary	JP-4	B
9	Inhib	Dibromodifluoromethane (12B2) (9.5%)	JP-5	C
10	Inhib	Bromotrifluoromethane (1201) (1.0%)	JP-5	C
11	Inhib	Dibromodifluoromethane + Bromotrifluoromethane (0.5% + 0.5%)	JP-5	C
12	Emul	Proprietary	JP-4	A
13	Emul	Proprietary	JP-5	A
14	Emul	Proprietary	JP-4	D
15	Emul	Proprietary	Jet A	D
16	Emul	Proprietary	JP-4	D
17		Polyurethane Foam (80 pores per inch)	JP-4	E

TABLE 1.--TYPES OF PRODUCTS TESTED BY THE AIR GUN METHOD (Continued)

No.	Type	Description	Base Fuel	Mfr.
18		Polyurethane Foam (20 pores per inch)	JP-4	E
19		Polyurethane Foam (60 pores per inch)	JP-4	E
20		Polyurethane Foam (10 pores per inch)	JP-4	E
1967				
21	Emul	Proprietary	JP-4	F
22	Dilat	Proprietary	JP-4	A
23	Compound	Naphthalene (granular-liquifies 160°F - ignites at 500°F)		G
24	Gel	Hydrocarbon resin	JP-4	H
25	Gel	Hydrocarbon resin	Jet A-1	H
1968				
26	Gel	Al-2-ethylhexanoate (aluminum octoate)	Jet A	A
27	Gel	Hydrocarbon resin	Jet A-1	H
28	Gel	Polyglucan derivative	Jet A	I
1969				
29	Gel	Proprietary		J
30	Gel	Hydrocarbon Resin		H
31	Emul	Proprietary	JP-4	F
32	Inhib	Dibromotetrafluoroethane (2402) (5.0%)	JP-5	K
1970				
33		Turbine Engine Fuel (JP-8)		
34	Gel	Proprietary	Jet A	F
35	Emul	Proprietary	JP-8	F
36	Emul	Proprietary	Jet A-1	L

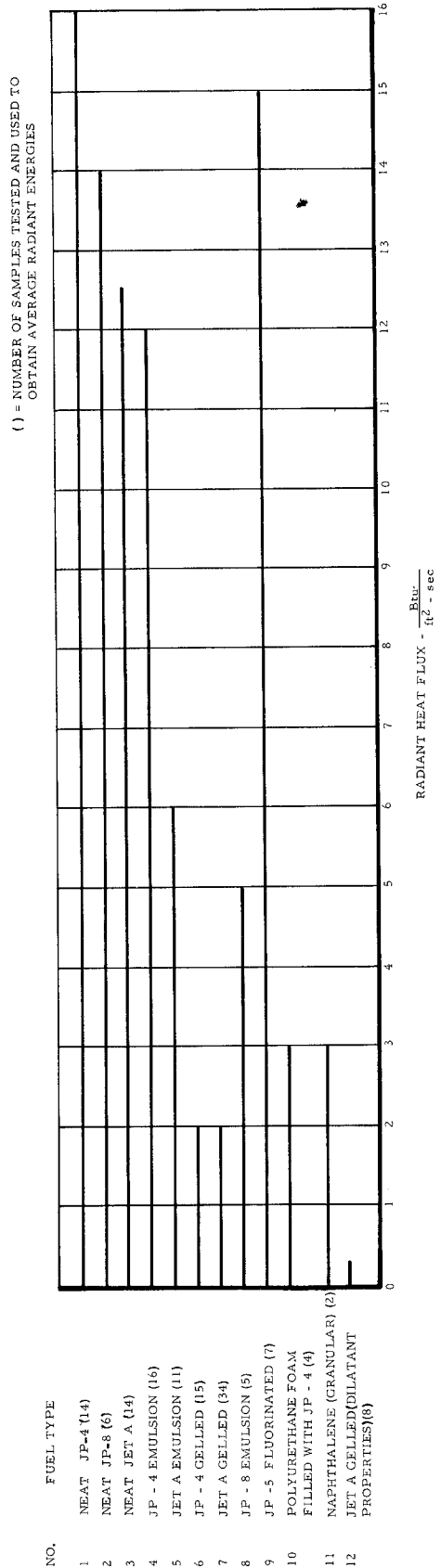


FIGURE 4 - RADIANT ENERGIES RELEASED BY VARIOUS FUELS -
AIR GUN TEST

The fluorocarbons used in Item 9, Figure 4, are listed in Table 1 as Items 9, 10, 11, and 32. The mixtures when in an aerosol state and in the presence of an open flame produced adverse results as shown.

The result of using reticulated polyurethane foam of different porosities filled with neat JP-4 fuel (Reference Table 1, Items 17 through 20) reduced the fuel misting which provided an 81-percent reduction in the radiant heat flux as compared to the neat JP-4 alone. The 80-pore-per-inch foam retained 25 percent of the fuel after impact and thereby allowed a smaller amount of fuel to become an aerosol. However, in each of the four tests the fuel misted over the first pair of open fires, and the fire flashed back to the liquid fuel on the ground at the base of the steel grid (Figure 2), a situation which never occurred with gelled fuels.

The naphthalene compound, Item 11, of Figure 4, was tested in granular form. As shown, there was a like reduction in the radiant heat flux as compared to Item 10; however, there was no ignition of the compound on the ground. The material reportedly liquifies at 160°F and will ignite at 500°F.

As this program progressed, it became evident from References 4, 9, and 10 that the thickened fuels would have to be more fluid in order to reduce the problems encountered in moving the fuel throughout an aircraft's fuel system. When the emphasis was placed on increasing the fluidity of the fuels, the air gun test results showed that those fuels would ignite readily. Certain manufacturers rectified the situation by adding to the lower viscous gels a viscoelastic and/or dilatant property which greatly improved the fire-resistant properties of the fuel when in the aerosol state.

Item 12 of Figure 4 was comprised of Jet A gels with viscoelastic and dilatant properties and low apparent viscosities of 400 to 800 centipoises (RVT Brookfield, Number 3 spindle at 10 rpm), and as shown, received a very low radiant heat rating.

The degree to which the fire hazardous characteristics of neat turbine fuel in the aerosol state, when in the presence of open flames can be reduced by substituting a higher viscosity fuel is illustrated in Figures 5 and 6. Figure 5 shows fire size as it reaches near maximum proportions throughout a fuel-mist cloud of neat Jet A fuel in approximately 1.4 seconds.

However, an equal quantity of neat Jet A fuel modified to be more viscous will support a reduced amount of combustion as shown in Figure 6, and a shorter burning time which in this test represents .5 second.

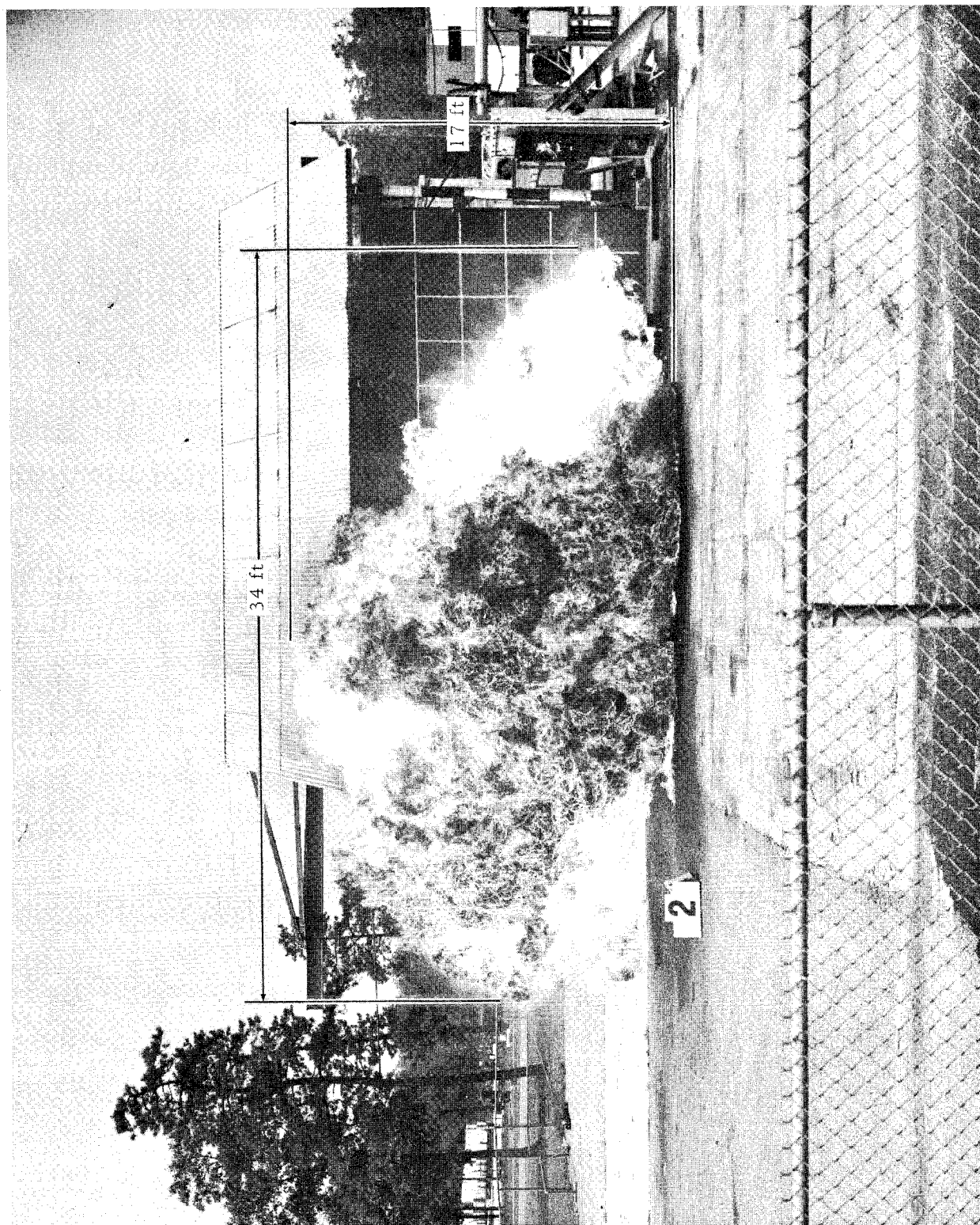


FIGURE 5 - JET A FUEL-MIST EXPOSED TO OPEN FLAMES -
AIR GUN TEST

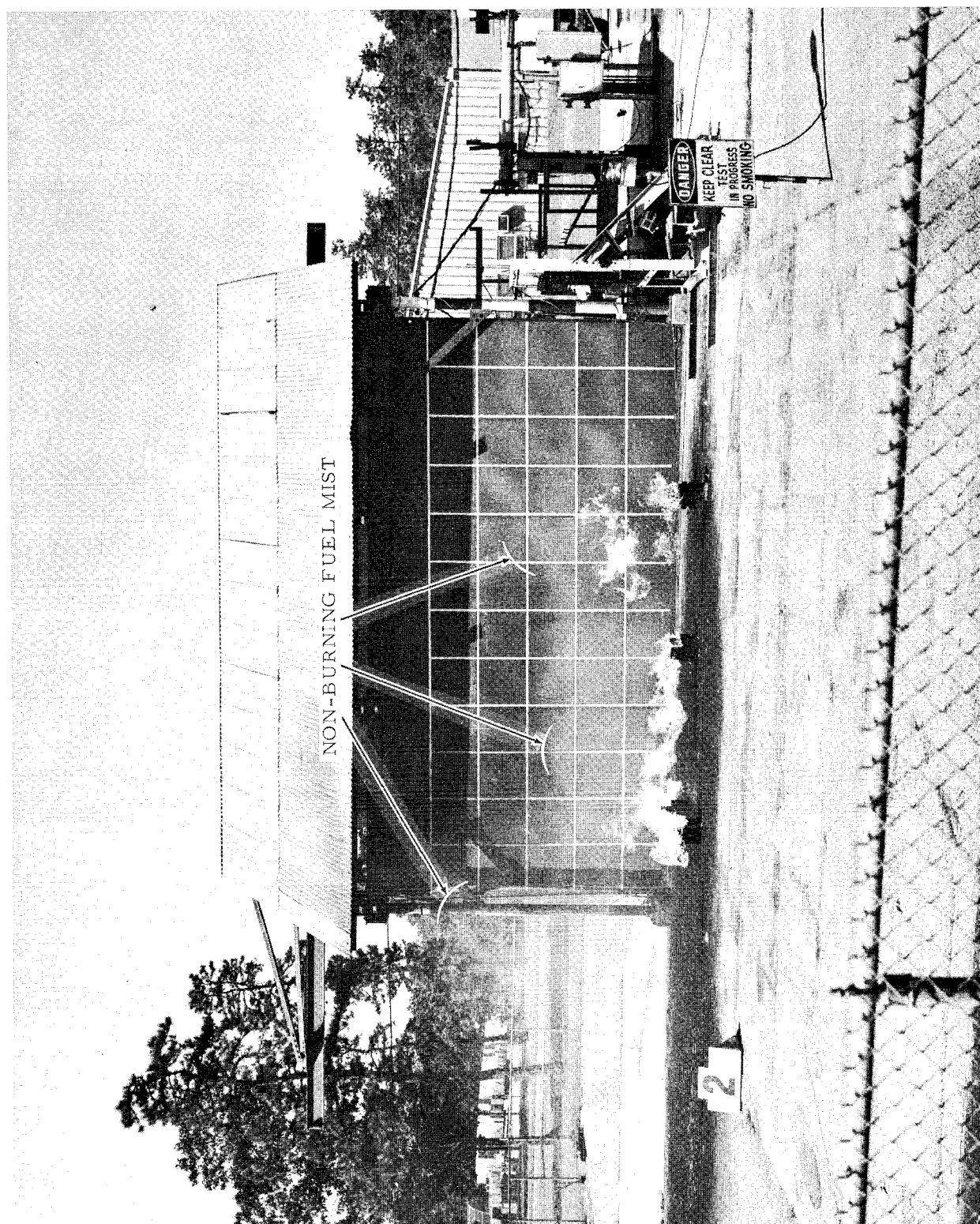


FIGURE 6 - GELLED JET A FUEL-MIST EXPOSED TO OPEN FLAMES -
AIR GUN TEST

The droplet size of the neat and modified fuels within the fuel-mist cloud for a typical air gun test is shown in Figure 7.

Vertical Drop Method

Test Procedures - This test method demonstrated fuel spill resulting from vertical impact. One hundred twenty gallons of fuel were used in this method. The fuel was contained in F-86 aircraft droppable fuel tanks which were structurally weakened (Figure 8), to provide for greater breakup of the tanks when dropped from a height of 35 feet from the NAFEC Drop Facility (Figure 9). Time history data of the fuel spill were recorded by two motion picture cameras operating at 500 frames per second. One camera viewed the impact from atop the tower, and the second camera was positioned off to one side. Pressure transducers located on top of the tank were also used to record internal fuel pressures.

Results - One drop test was conducted using the neat JP-4 fuel and one using JP-4 fuel gelled with 1.5 percent of the FAA 1069.1 additive. Table 2 lists the results that are pertinent to the two tests.

TABLE 2.--VERTICAL DROP TEST DATA

Test No.	Type of Fuel	Pressure in Tank (psig)	Ground Area Wetted by Fuel (sq ft)	Plume Height of Released Fuel (ft)	Fuel Released from Tank (gal)
1	JP-4	36	476	15	120
2	Gelled JP-4	0	10 (see Note 1)	(see Note 2)	4

Note: 1. Represents sum of many scattered wetted areas.
2. Small globules of fuel raised a maximum of 8 feet.

One-hundred-percent loss of fuel from the tank was experienced with the neat fuel, while only an estimated 4 gallons or .033 percent of the gelled JP-4 fuel escaped from the ruptured tank.

The tank containing the JP-4 fuel was completely ripped open and flattened in the test while the tank containing the gelled fuel

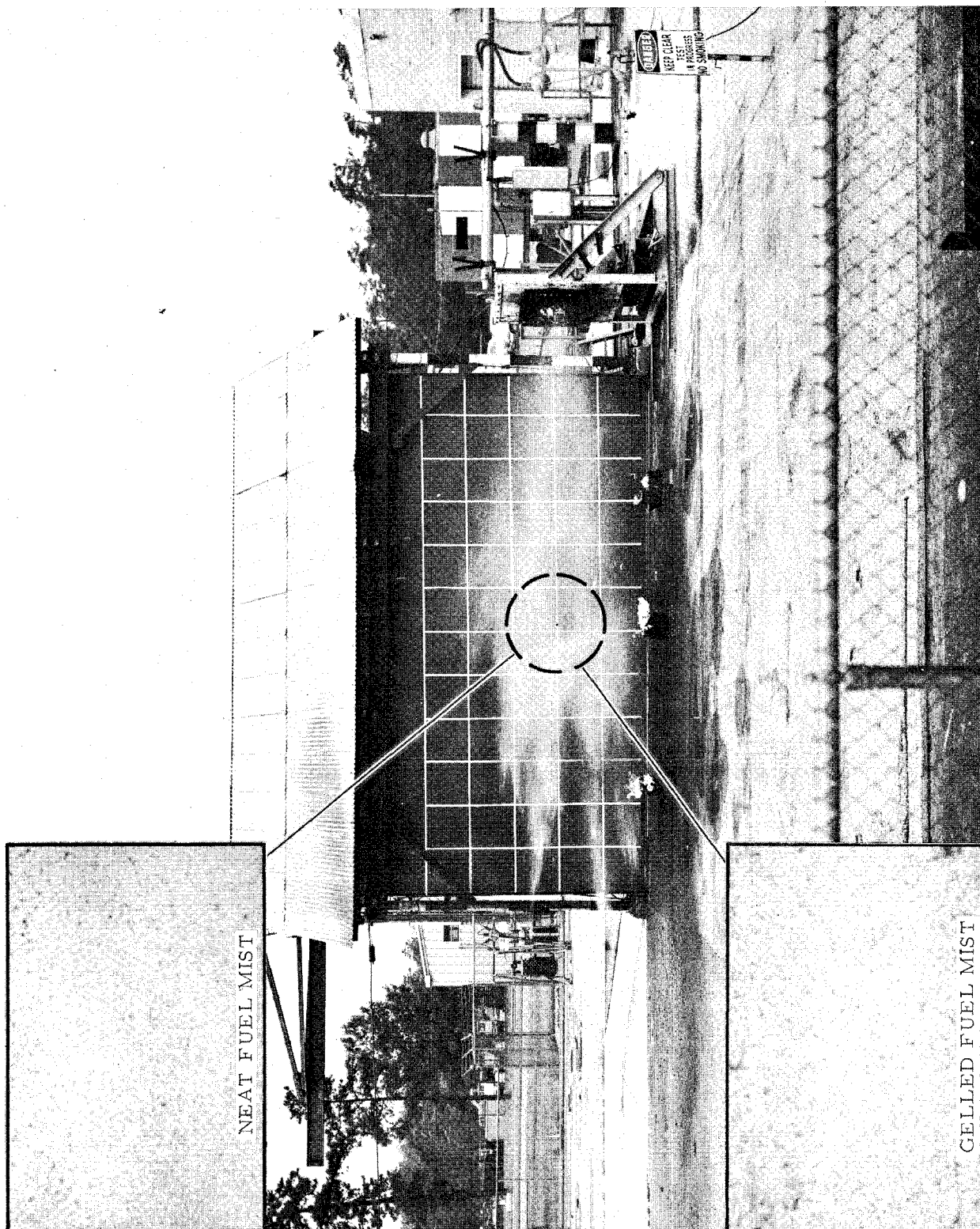


FIGURE 7 - DROPLET SIZE OF NEAT AND GELLED FUELS -
AIR GUN TEST

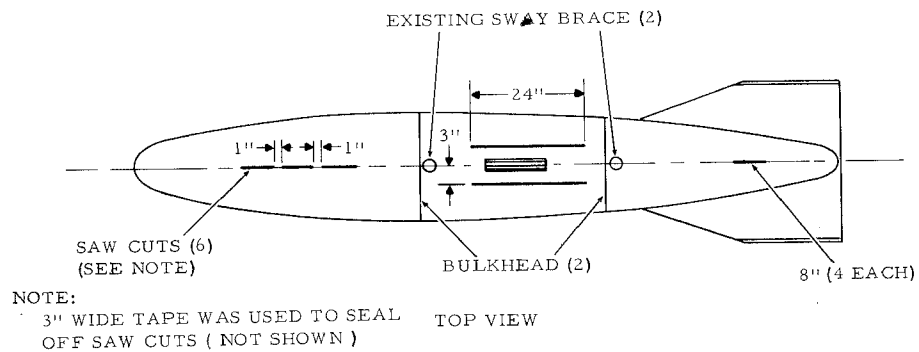


FIGURE 8 - STRUCTURAL MODIFICATIONS TO F-86 FUEL TANK -
VERTICAL DROP TEST

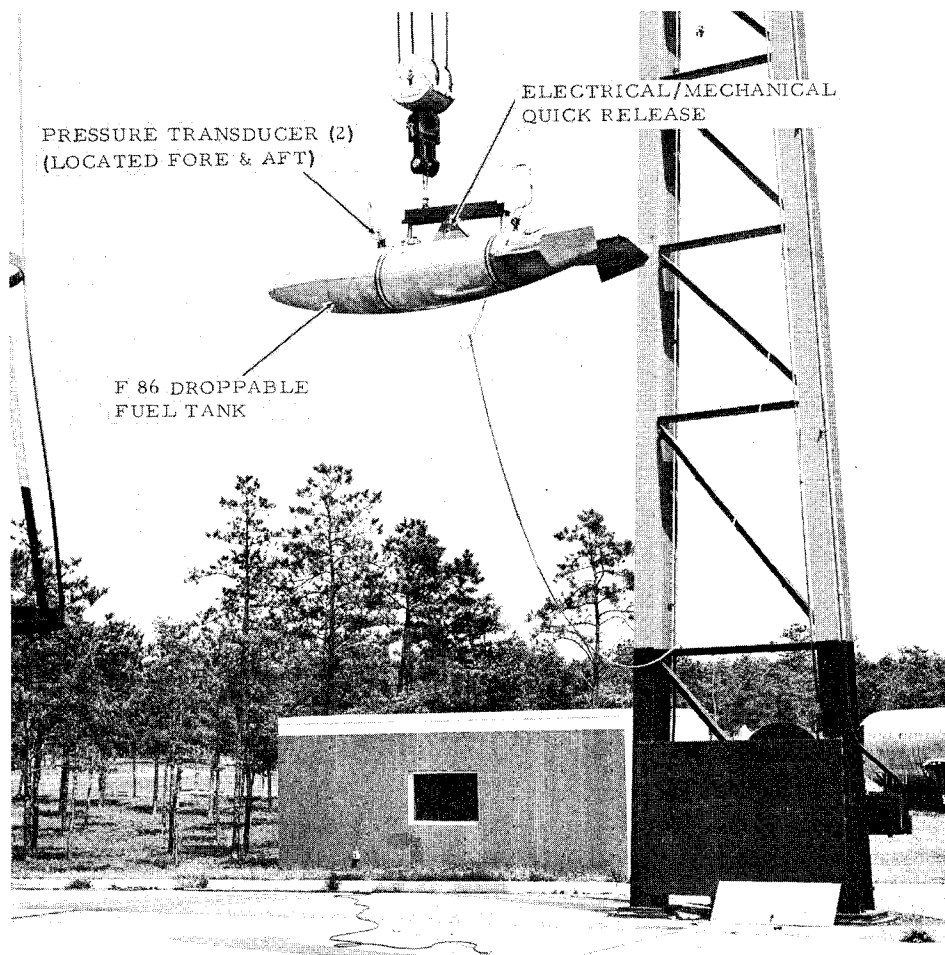


FIGURE 9 - DROP TEST FACILITY FOR F-86 FUEL TANKS

received a 1-foot-long lateral split in the outer skin at each of the two bulkhead locations (Reference Figure 8). Also the structural integrity of the gelled fuel tank was sufficiently intact to allow the tank and its contents to be lifted onto a truck for disposal.

The tank in Test No. 1 impacted hard and stopped abruptly while the tank in Test No. 2 impacted then rocked upward to 18 inches high at the front, settled downward, then rocked upward to 10 inches high at the rear before becoming motionless.

Tapes were torn from the slots (Figure 8) in Test No. 1 but remained intact in Test No. 2.

The neat fuel spilled out of the crashed tank and wetted an area 47 times larger than the area wetted by gelled fuel.

The plume of the neat fuel that rose from the impact of the tank was fringed with a fuel mist; whereas, the spilled gelled fuel did not aerosol.

Catapult Method

Test Procedures - This test method was used to show fuel dispersion and subsequent flammable characteristics of the dispersed fuel after impact.

One hundred twenty gallons of fuel were used in each test. The fuel was contained in an F-86 aircraft droppable fuel tank and catapulted into a steel plate raised at a 40° angle above the ground line (Figure 10). The ignition source was one 4- by 7-inch-rectangular pan filled with burning JP-4 fuel positioned on each side of the point of impact for a total of 56 square inches of fire area. Time history data of the fuel's behavior were recorded on high-speed motion picture film and by employing radiometers to record radiant heat flux.

Results - Table 3 lists the results that are pertinent to the 10 tests conducted. The FAA-1069-1 gelled fuel was used.

The maximum radiant heat recorded for each test is plotted in Figure 11 along with similar data taken for the air gun test wherein 1-gallon quantities of similar fuel were used. The dual plot shows the similarity of the results from the two test methods even though the ratio of fuel quantity used was 120:1. The lower heat flux values for the catapult tests are due to the relative location of the radiometers to the impact zone.

Figure 12 shows a map of the fire propagation and the maximum fire size attained for the two base fuels (JP-4 and Jet A) and for the two FAA-1069-1 gelled base fuels at the highest viscosity (1.5 percent) at which they were tested. In each test, it was characteristic for the tank to split in two parts at impact and for the forward portion of the tank to

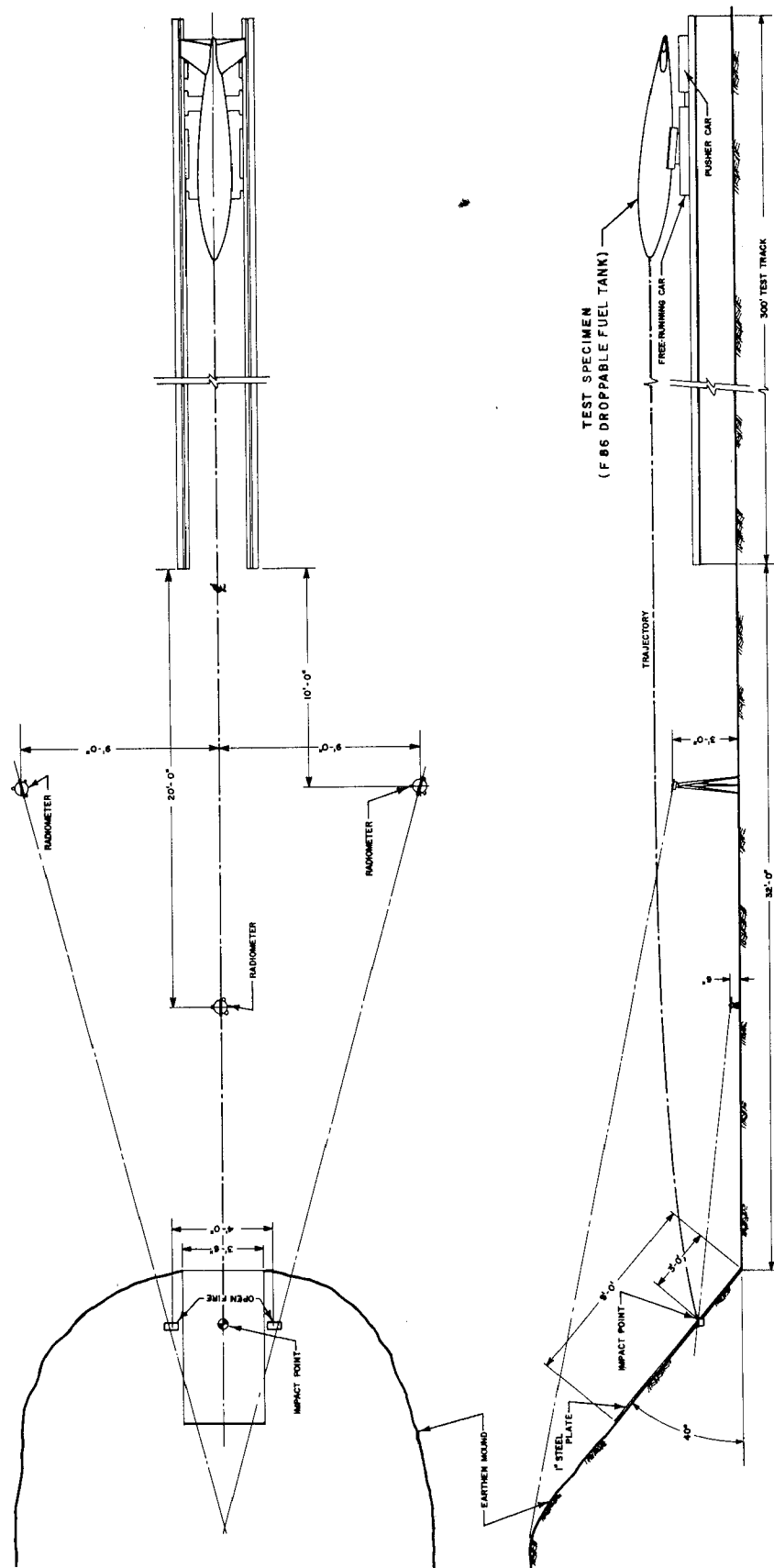


FIGURE 10 - CATAPULT TEST FACILITY FOR F-86 FUEL TANKS

TABLE 3.--CATAPULT CRASH TEST DATA

Test No.	Type of Fuel	Fuel Temp. (°F)	Air Temp. (°F)	Speed of Tank (mph)	Max Radiant Heat (Btu/ft ² /sec)	Fire * Reduction (% Test No. 1)	Fire Beyond Impact Point
1	Neat JP-4	45	52	80	4.9	0	Yes
2	Neat Jet A	45	52	79	3.9	10	Yes
3	1.5% Jet A Gel	45	54	80	0.2	97	No
4	1.5% JP-4 Gel	48	62	81	1.3	75	Yes
5	1.0% JP-4 Gel	49	60	81	1.7	65	Yes
6	1.0% Jet A Gel	45	56	80	0.4	92	No
7	0.5% JP-4 Gel	45	52	79	2.8	47	Yes
8	0.5% Jet A Gel	48	51	80	0.2	89	No
9	0.2% JP-4 Gel	47	52	80	4.4	10	Yes
10	0.2% Jet A Gel	46	53	81	2.9	40	No

Note: * Based on analysis of photographic and radiant heat data.

FUEL TYPE

NEAT JP - 4

0.2% GELLED JP - 4

0.5% GELLED JP - 4

1.0% GELLED JP - 4

1.5% GELLED JP - 4

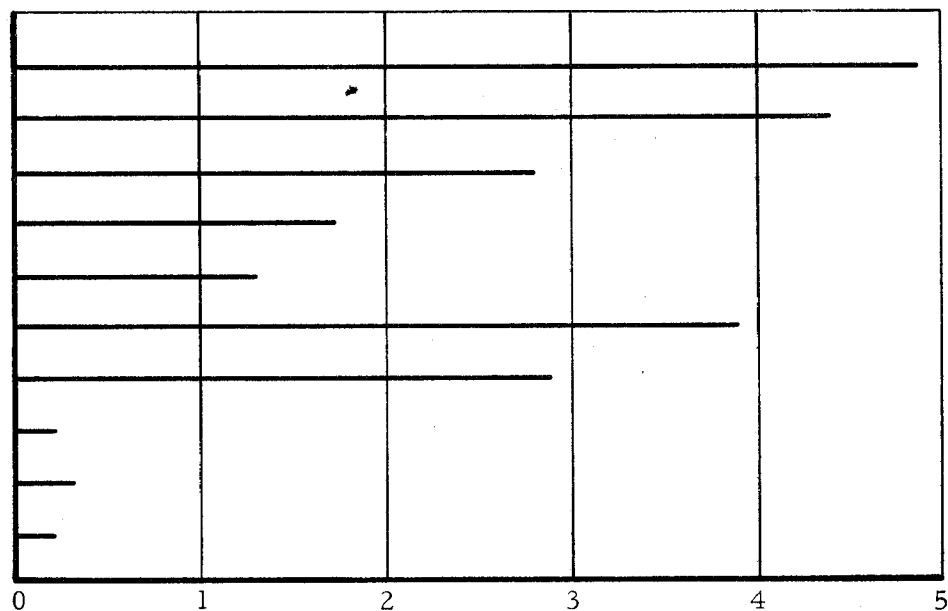
NEAT JET A

0.2% GELLED JET A

0.5% GELLED JET A

1.0% GELLED JET A

1.5% GELLED JET A



(a) CATAPULT TEST METHOD

NEAT JP - 4

0.2% GELLED JP - 4

0.5% GELLED JP - 4

1.0% GELLED JP - 4

1.5% GELLED JP - 4

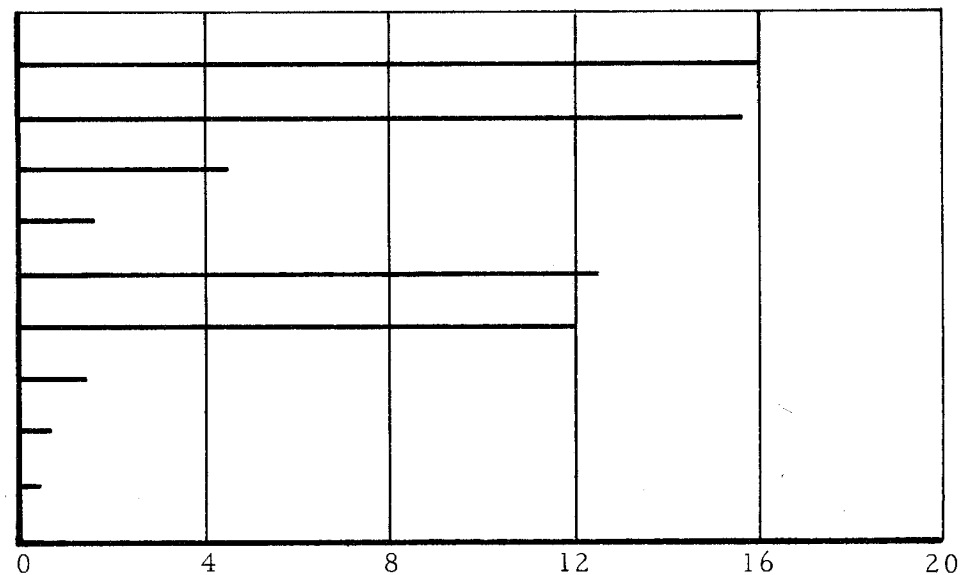
NEAT JET A

0.2% GELLED JET A

0.5% GELLED JET A

1.0% GELLED JET A

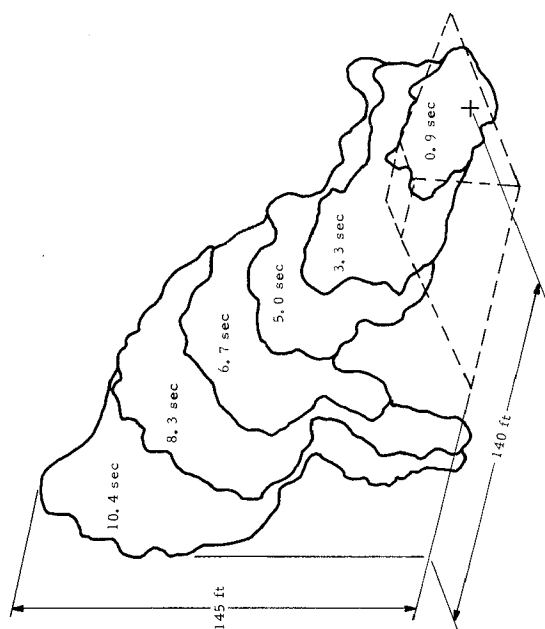
1.5% GELLED JET A



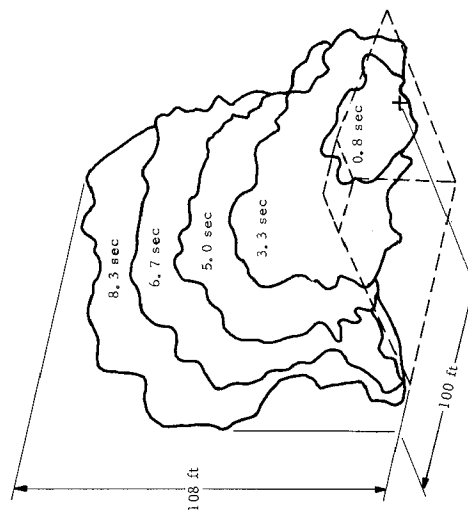
(b) AIR GUN TEST METHOD

$$\text{MAXIMUM RADIANT HEAT FLUX} = \frac{\text{Btu}}{\text{ft}^2 - \text{sec}}$$

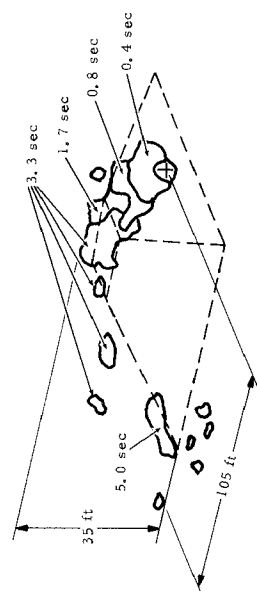
FIGURE 11 - RADIANT HEAT INCIDENT - CATAPULT VS AIR GUN TEST RESULTS



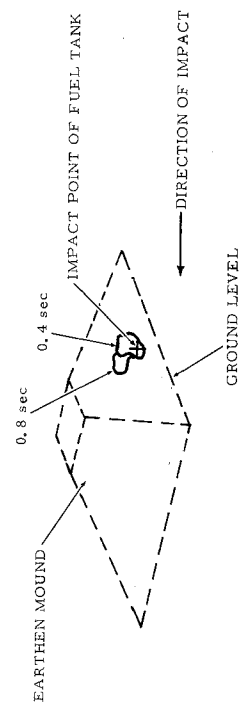
(a) NEAT JP-4



(c) NEAT JET A



(d) 1.5% GELLED JP-4



(b) 1.5% GELLED JET A

FIGURE 12 - MAP OF FIRE PROGRESS - CATAPULT TEST

continue over the mound and impact from 100 to 200 feet beyond the initial point of impact. As much as 30 to 50 percent of the gelled fuel would be carried by the broken-off forward tank section.

In Test No. 2 (neat Jet A), the ground adjacent to the impact point was saturated with unburned fuel. High-speed photography showed large quantities of nonburning fuel flowing downward over the impact zone during the height of the fire.

Burning fuel was confined to the impact side of the mound in all four tests when different viscosities of Jet A turbine fuel were used.

Burning fuel was not confined to the impact side of the mound in the four tests when the varying viscosities of gelled JP-4 turbine fuel were used.

After impact for the various viscosities of the gelled JP-4 fuels and (but much less severe) for the gelled Jet A fuels, the fuel separated into burning globules resembling raining napalm.

Drag Method

Test Procedures - This test showed fuel dispersion and subsequent flammable characteristics of the dispersed fuel when a tank ruptures after being dragged over a row of spikes and on a concrete surface for a distance of 1200 feet. At a point 75 feet from the start and across the drag course, five 1-inch-high spikes were positioned 8 inches apart in the runway for the purpose of cutting through the bottom surface of the tank.

One hundred twenty gallons of fuel were used in each test. The fuel was contained in an F-86 aircraft fuel tank (Figure 13) and dragged behind a vehicle by means of a steel cable and electrical/mechanical quick-disconnect assembly. The ignition source was an electric arc on the underside of and at the rear of the tank (Figure 13). The spark generator, described earlier under "Air Gun Test," was carried in the tow vehicle with a high-tension ignition wire running along the tow cable to the tank. The electrical arc was energized continually only while the tank was being dragged.

Time history data of the fuel's behavior were recorded by motion picture photography.

Results - Neat JP-4 and Jet A turbine fuels and two JP-4 FAA-1069-1 gels were tested. Table 4 lists pertinent results for the four tests.

Figure 14 is a composite map showing fire size of each test.