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SMALL-SCALE IMPACT TESTS OF CRASH-SAFE TURBINE FUELS

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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 ignitibility, 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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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-γ-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 afore-mentioned 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 character-istics 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 flamma-bility 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

STYROFOAM PLUG
8" O.D. x 9" LENGTH

POLYURETHANE HOLLOW PLUG (FUEL RESISTANT)
8" O.D. x 9" LENGTH (7.5" DEEP CAVITY, 0.75"
WALL THICKNESS

TAPE - NYLON REINFORCEMENT
1" WIDE

POLYETHYLENE BAG
12" WIDE x 24" LENGTH x 0.0017"
THICK. QUANTITY - 3

BREECH OF GUN (OUT OF VIEW)
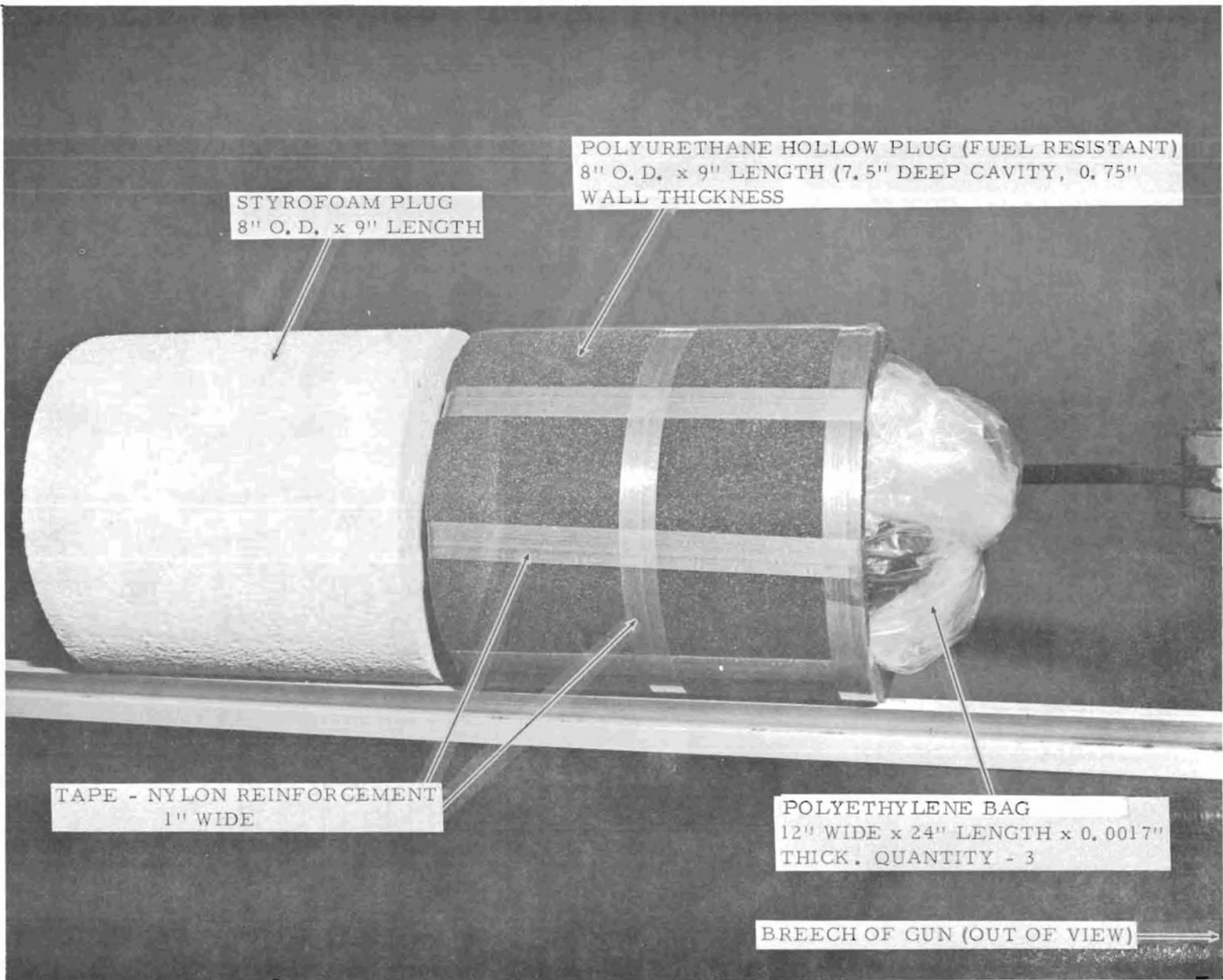
FIGURE 1 - FUEL SPECIMEN PACKAGED FOR AIR GUN TEST

24'-0"

12'-0"

9'-0"

FIBERGLASS MEASUREMENT SCREEN

RADIOMETER (3)

3'-0"

2'-0"

C

B

A

4'-0"

OPEN FIRE

9'-0"

SEE NOTE

8'-0"

SUPPORT STAND FOR
STEEL GRID

2" x 4" OPENING
STEEL GRID

OPEN FIRE

8'-0"

4'-0"

8" I.D. GUN BARREL
(LOCATED 5'-0" ABOVE SURFACE)

20'-0"

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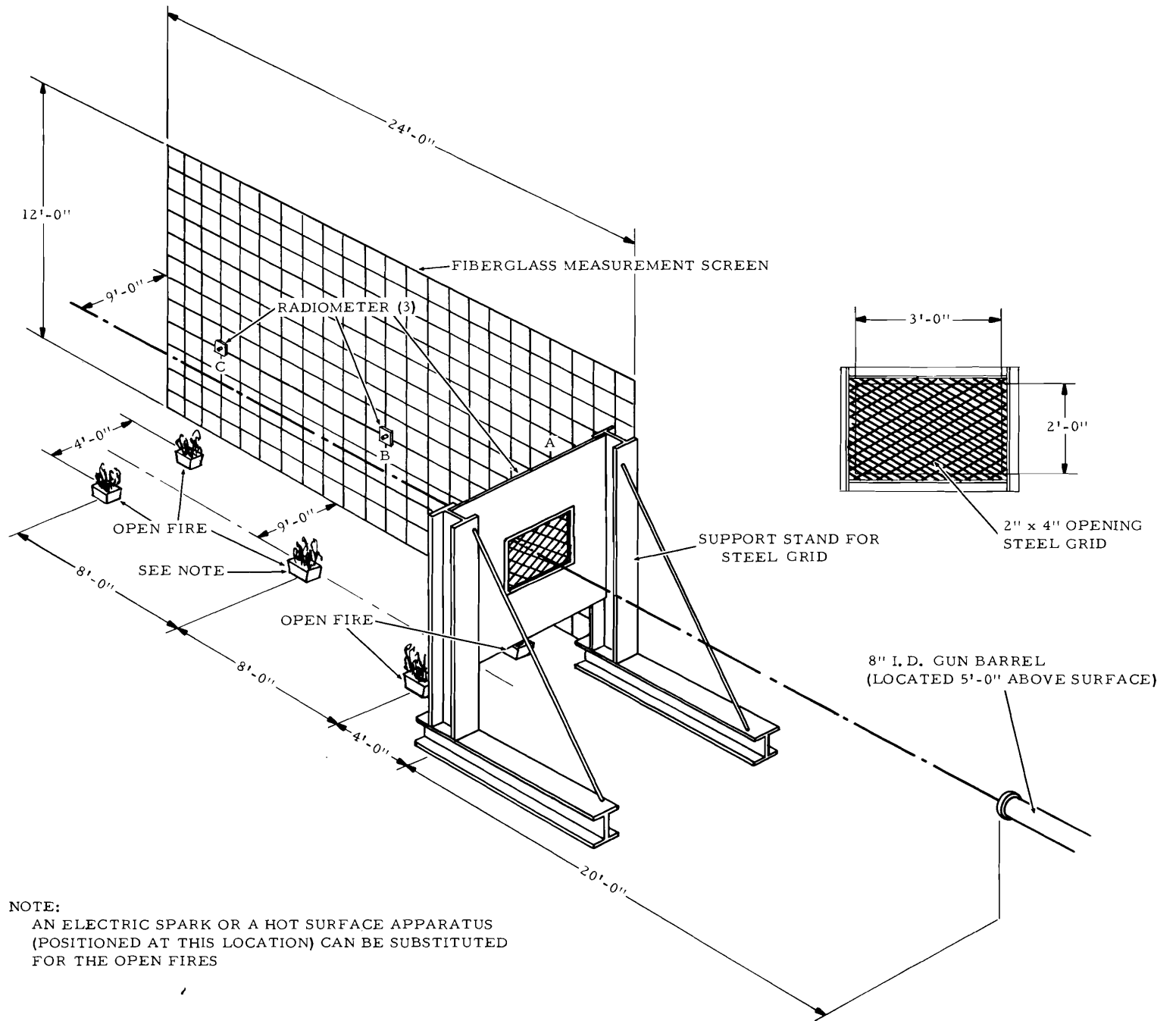   FOR THE OPEN FIRES

4

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 ($900^\circ F$ - $1400^\circ F$) 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 $\cong 800$ dynes/cm^2 and gels with apparent viscosities $\cong 8,000$ centipoises

AIR GUN BARREL

12 ft REF.

10 ft REF.

22.5 ft REF

23 in DIA. REF

LIGHT SHIELD TUBE

PRESSURE RELIEF PORTS (7)

SUPPORT STAND FOR STEEL GRID

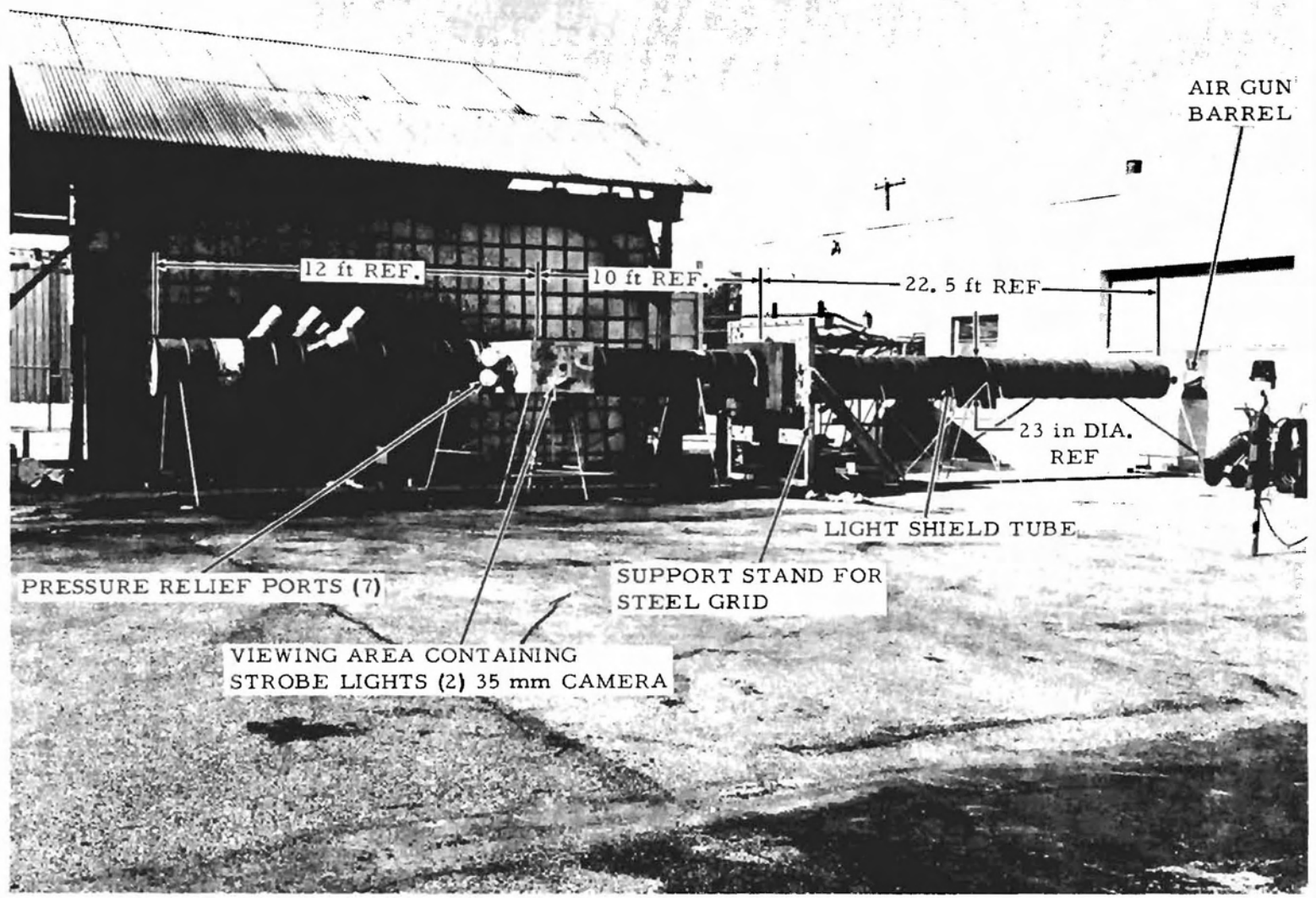VIEWING AREA CONTAINING STROBE LIGHTS (2) 35 mm CAMERA

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

NO.	FUEL TYPE
1	NEAT JP-4 (14)
2	NEAT JP-8 (6)
3	NEAT JET A (14)
4	JP - 4 EMULSION (16)
5	JET A EMULSION (11)
6	JP - 4 GELLED (15)
7	JET A GELLED (34)
8	JP - 8 EMULSION (5)
9	JP -5 FLUORINATED (7)
10	POLYURETHANE FOAM FILLED WITH JP - 4 (4)
11	NAPHTHALENE (GRANULAR) (2)
12	JET A GELLED(DILATANT PROPERTIES)(8)

RADIANT HEAT FLUX $- \dfrac{Btu}{ft^2 - sec}$
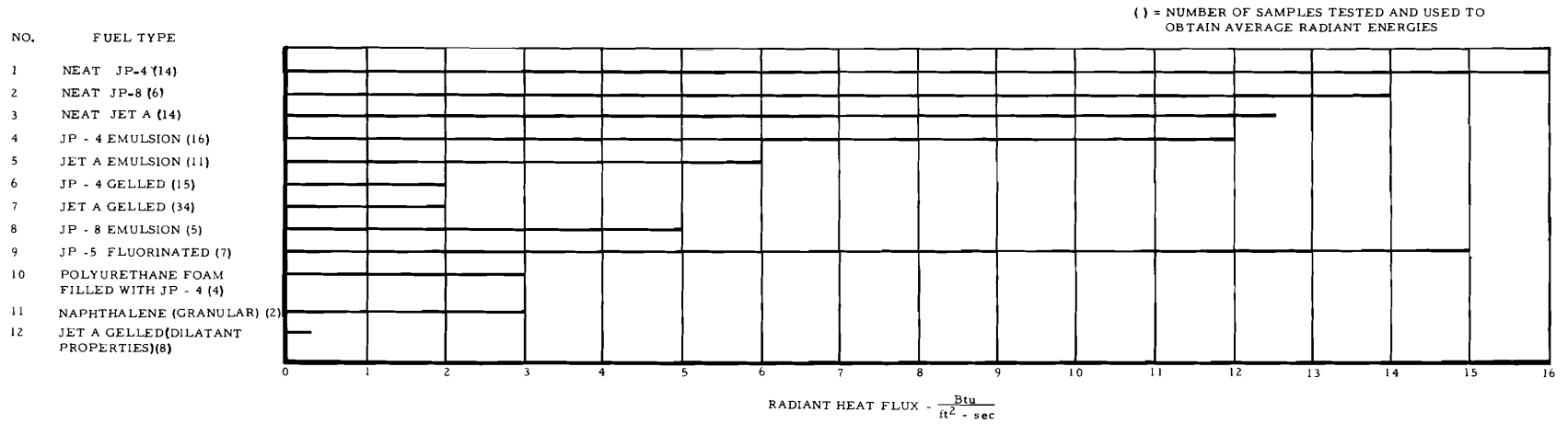
FIGURE 4 – RADIANT ENERGIES RELEASED BY VARIOUS FUELS –
AIR GUN TEST

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 characterisitics
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

NON-BURNING FUEL MIST

2

DANGER
KEEP CLEAR
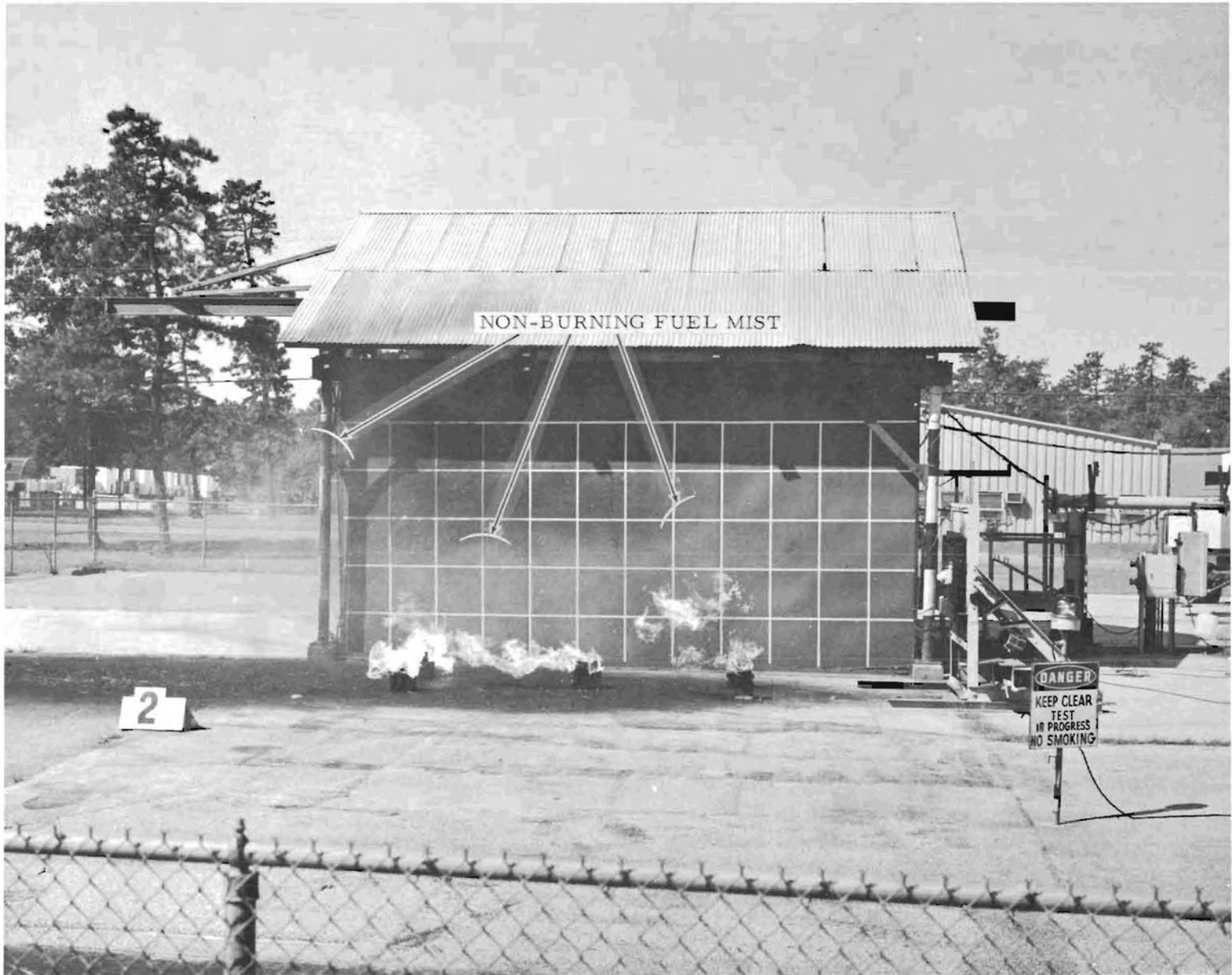TEST
IN PROGRESS
NO SMOKING

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
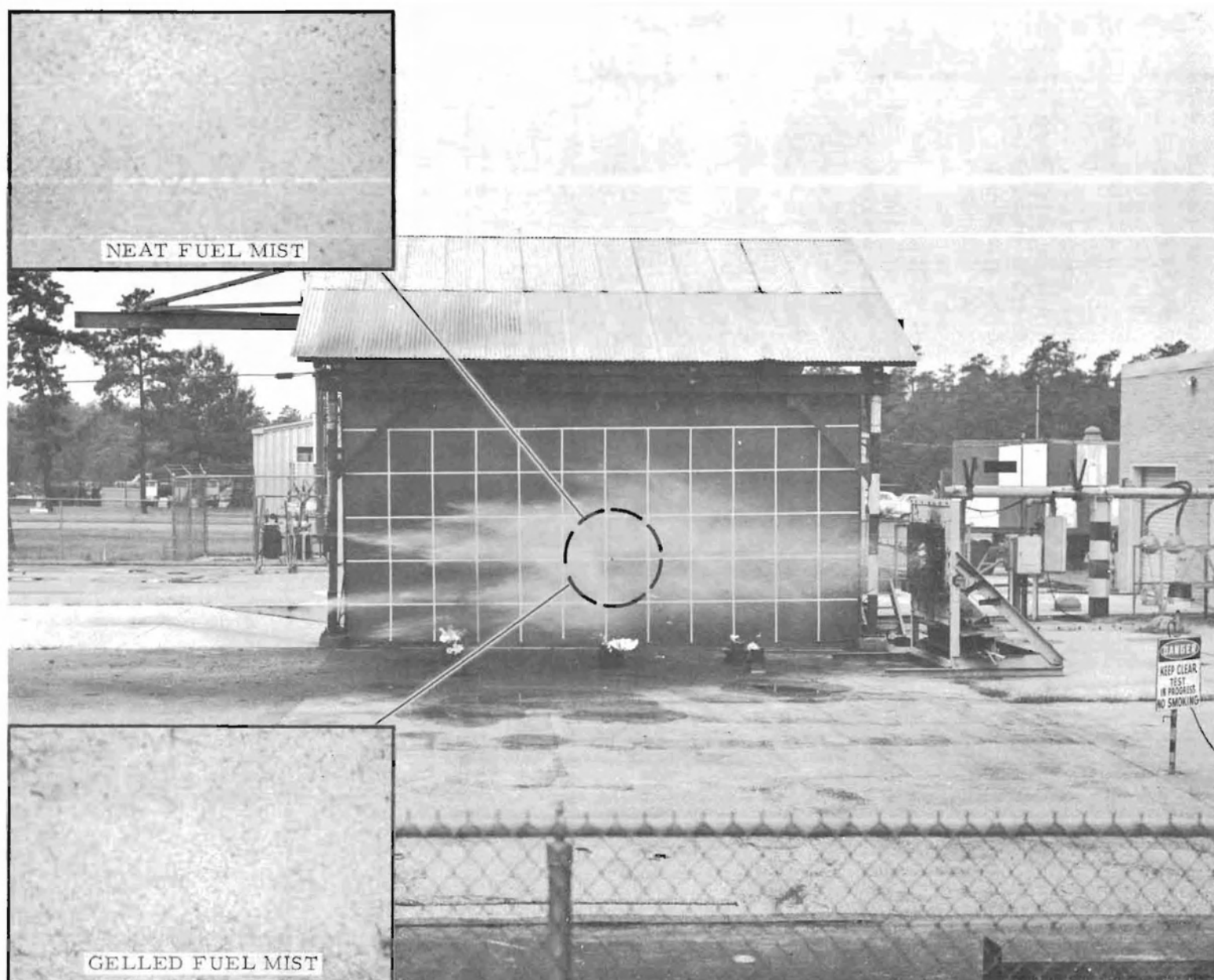
13

NEAT FUEL MIST

GELLED FUEL MIST

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

EXISTING SWAY BRACE (2)

24"

3"

1" 1"

SAW CUTS (6)
(SEE NOTE)

BULKHEAD (2)

8" (4 EACH)

NOTE:
3" WIDE TAPE WAS USED TO SEAL
OFF SAW CUTS (NOT SHOWN)

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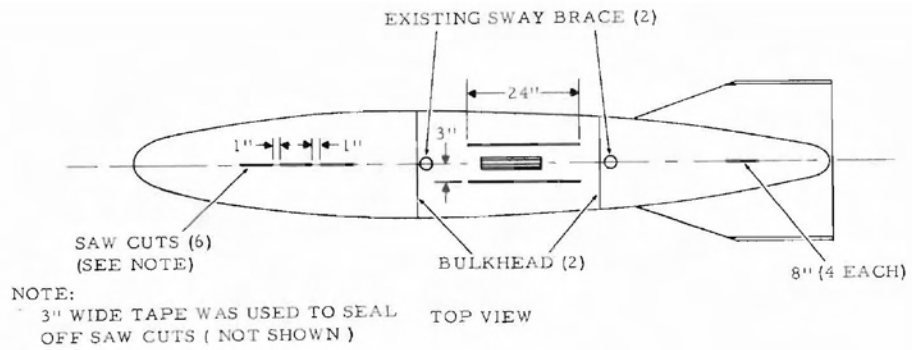
FIGURE 8 - STRUCTURAL MODIFICATIONS TO F-86 FUEL TANK - VERTICAL DROP TEST

PRESSURE TRANSDUCER (2)
(LOCATED FORE & AFT)

ELECTRICAL/MECHANICAL
QUICK RELEASE

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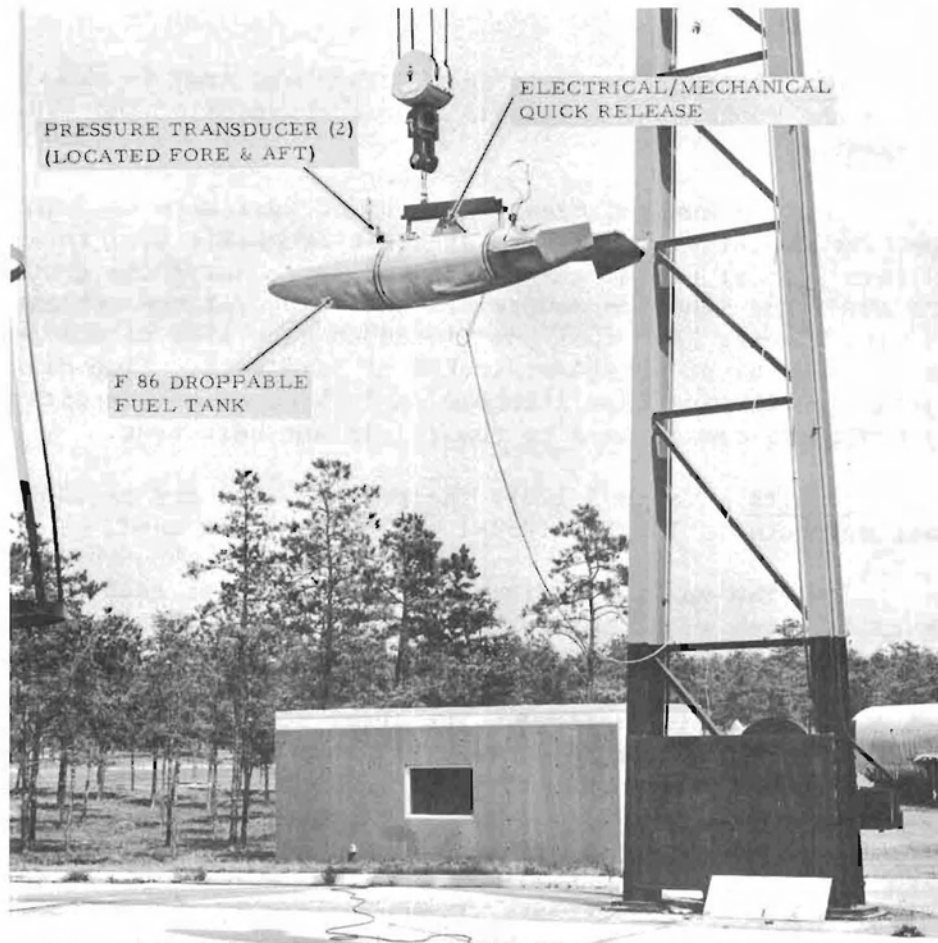
FIGURE 9 - DROP TEST FACILITY FOR F-86 FUEL TANKS

15

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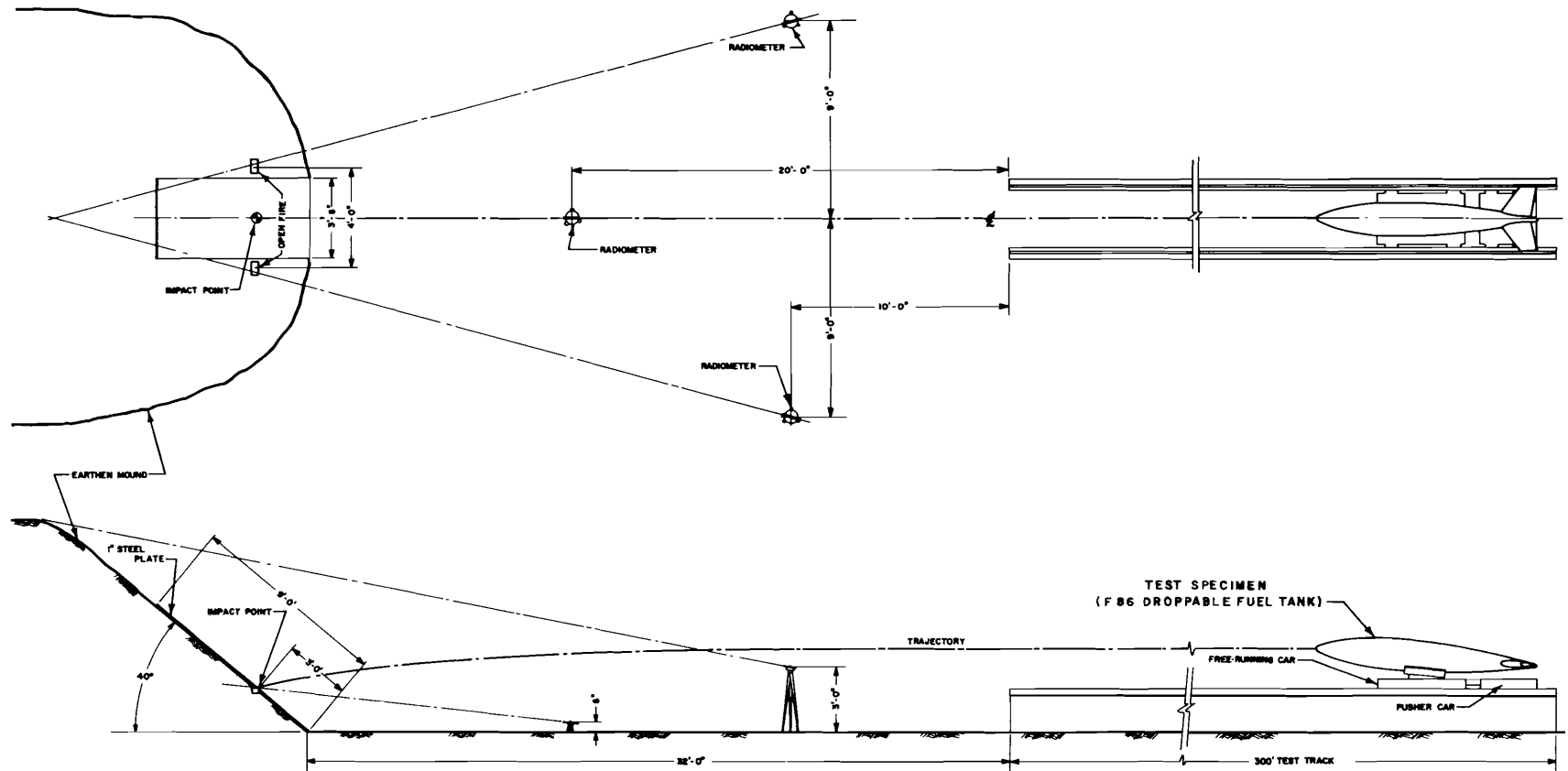
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FIGURE 10 – CATAPULT TEST FACILITY FOR F-86 FUEL TANKS

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TABLE 3.--CATAPULT CRASH TEST DATA

Test No.	Type of Fuel	Fuel Temp. ($^{\circ}$F)	Air Temp. ($^{\circ}$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.
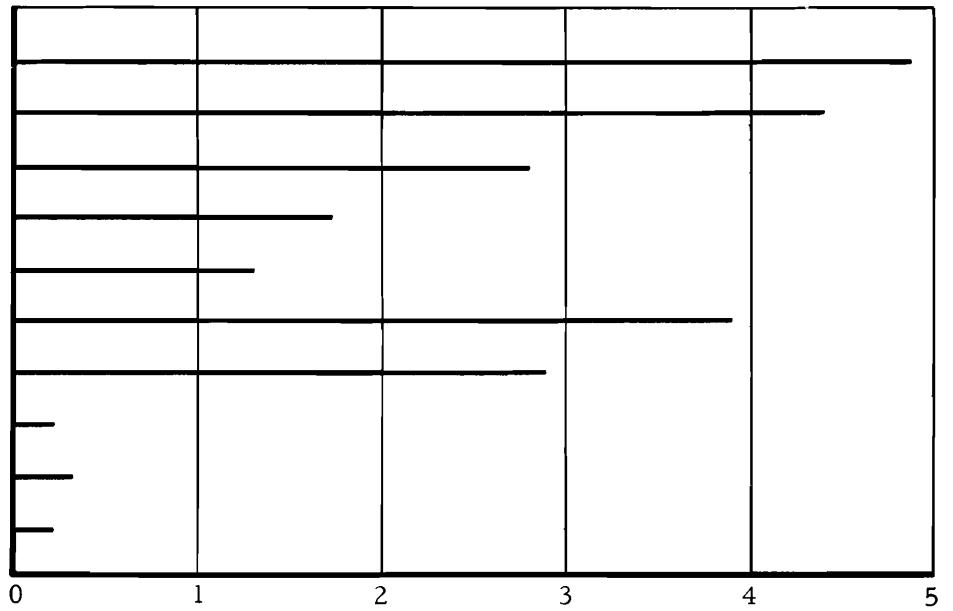
(a) CATAPULT TEST METHOD
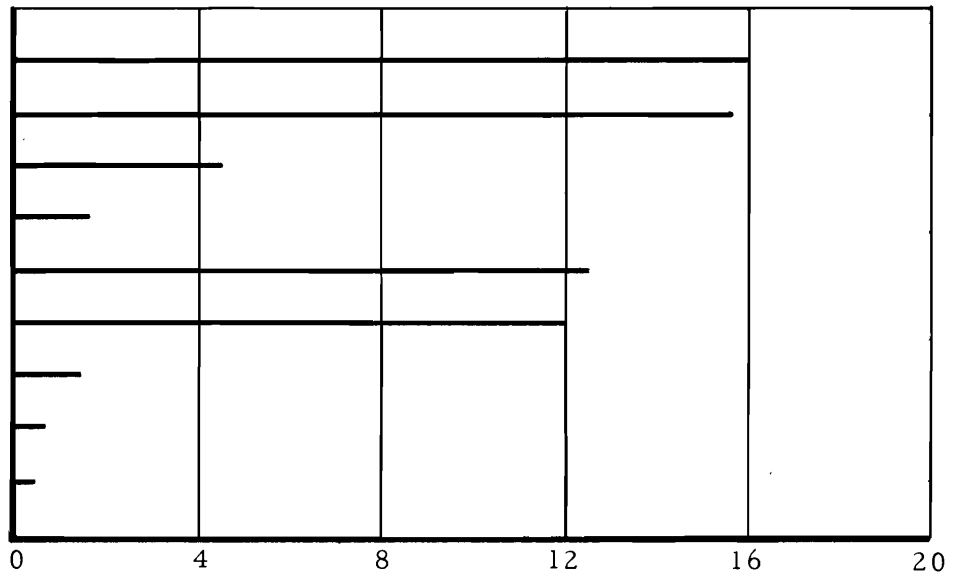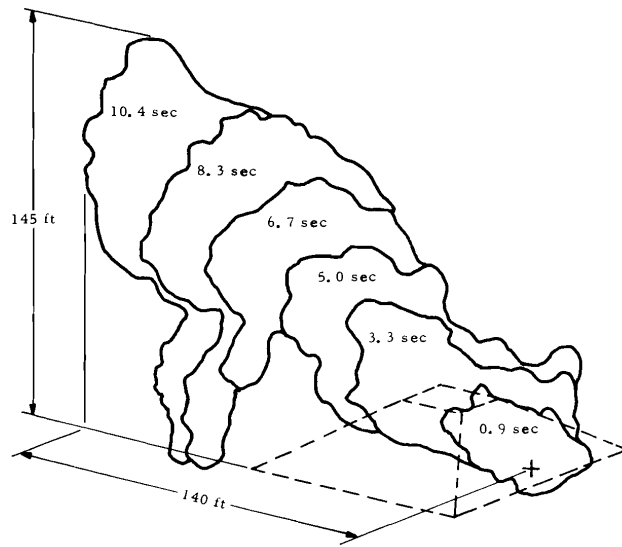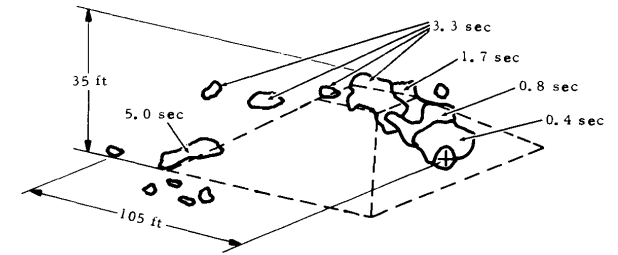
(b) AIR GUN TEST METHOD

$$\text{MAXIMUM RADIANT HEAT FLUX} = \frac{\text{Btu}}{\text{ft}^2 - \text{sec}}$$
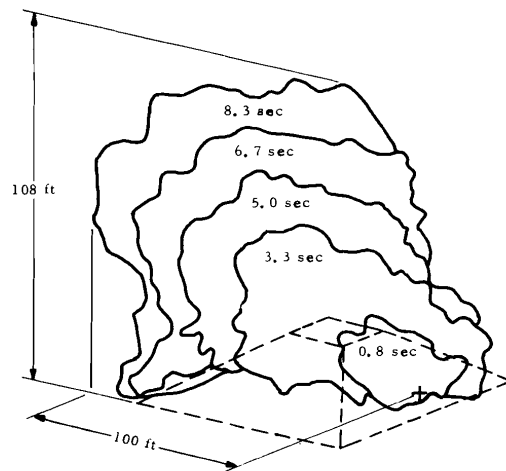
FIGURE 11 – RADIANT HEAT INCIDENT – CATAPULT VS AIR GUN TEST RESULTS
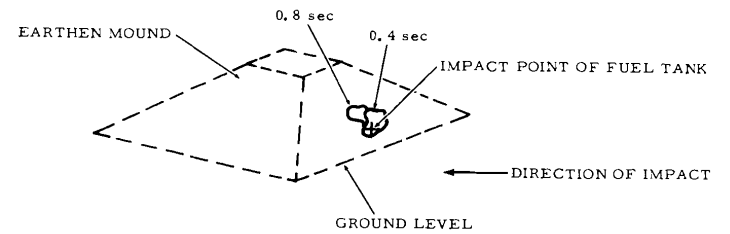
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(a) NEAT JP-4

(d) 1.5% GELLED JP-4

(c) NEAT JET A

(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.

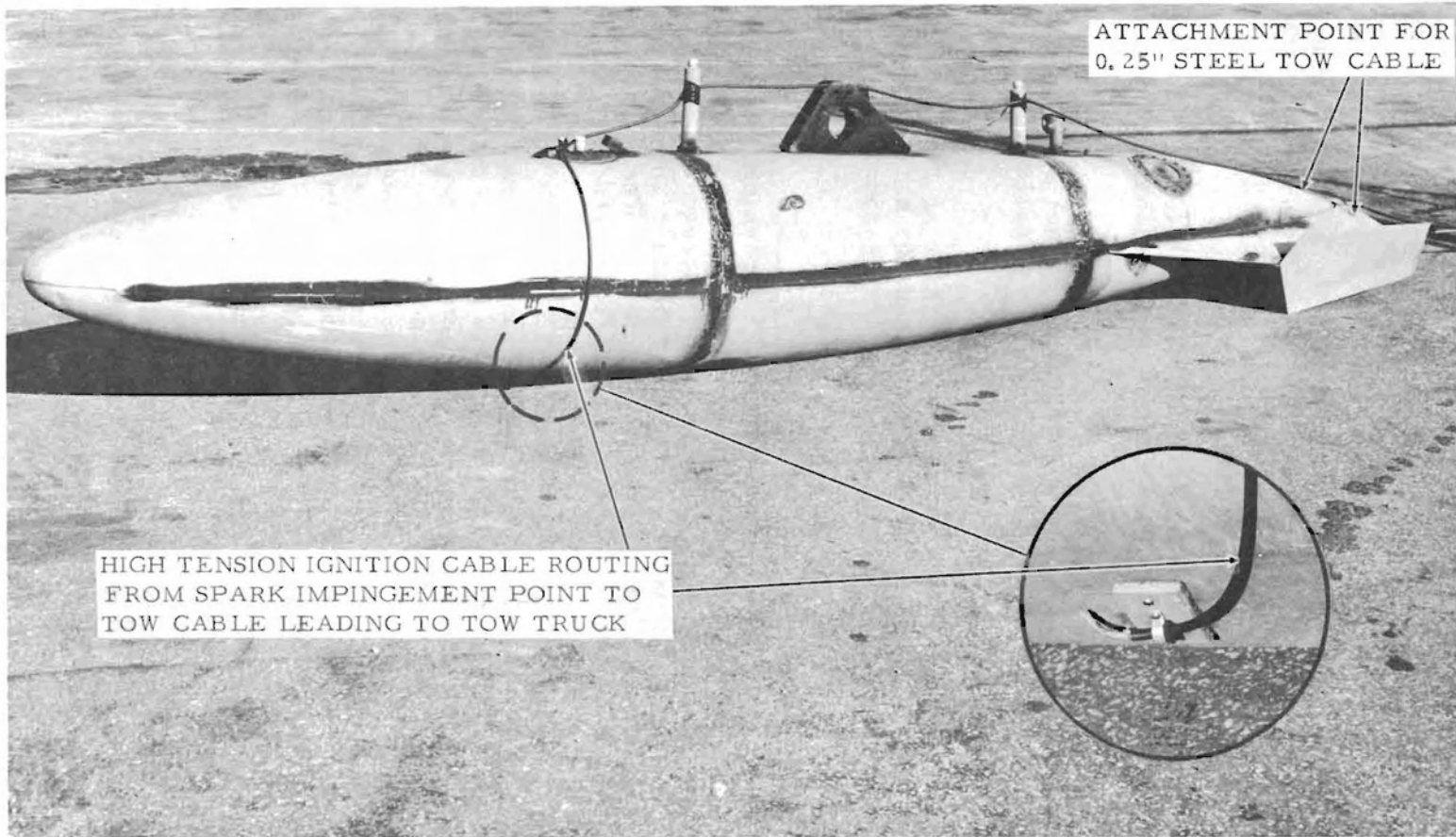Figure 14 is a composite map showing fire size of each test.

21

ATTACHMENT POINT FOR
0.25" STEEL TOW CABLE

HIGH TENSION IGNITION CABLE ROUTING
FROM SPARK IMPINGEMENT POINT TO
TOW CABLE LEADING TO TOW TRUCK

FIGURE 13 - F-86 FUEL TANK CONFIGURATION - DRAG TEST

TABLE 4.--DRAG TEST DATA

Test No.	Type of Fuel	Fuel Temp. (°F)	Air Temp. (°F)	Events from Static Position (sec)		Est. Fire Reduction % Test No. 1	Est. Fuel Ignited %
				Fuel Leakage	Fuel Ignition		
1	JP-4	63	69	8.7	10.4		100.0
2	Jet A	67	72	3.8	10.8	99.0	1.0
3	0.5% JP-4 Gel	62	73	5.5	16.4	99.0	Note
4	1.5% JP-4 Gel	62	72	5.8	10.3	99.9	Note

Note: Fuel continued to burn after tank had stopped moving and fire had to be extinguished.

23

LEGEND
▼ FUEL IGNITED
▽ FUEL LEAKAGE ON RUNWAY

(FIRE)

8'

STEEL SPIKES (5) 8" APART

4'

(FIRE)

1200'

10'

12'

350'   275'   75'   0

TEST NUMBER 1

TANK AT REST

TANK IN MOTION

TOW CABLE

2'

1200'

12'

350'   120' 75'   0

FINISH

START

TEST NUMBER 2

24

10"

1'-9"

1200'

4'

350'   175'   75'   0

TEST NUMBER 3

10"

1'-6"

1200'

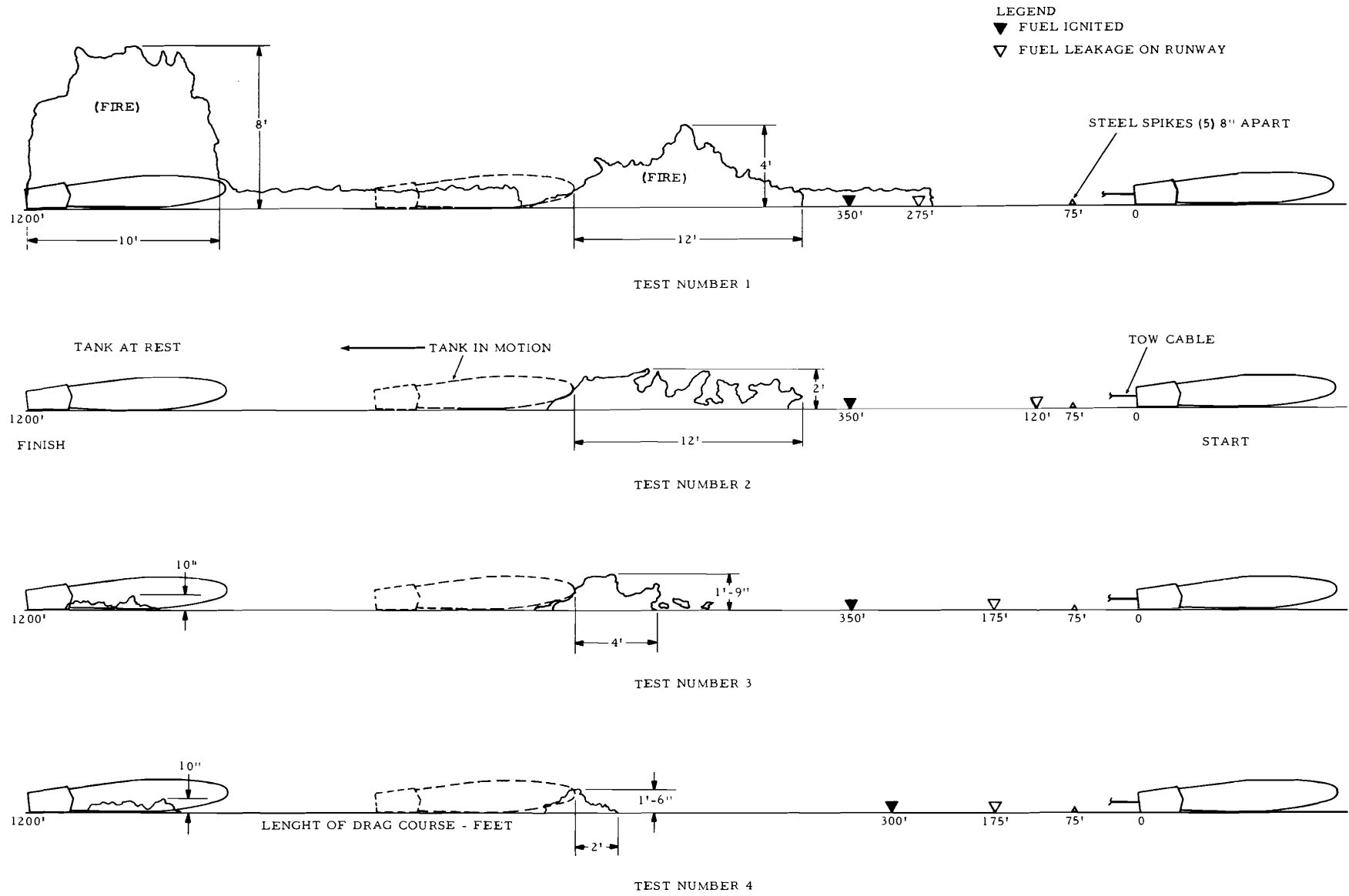LENGHT OF DRAG COURSE - FEET

2'

300'   175'   75'   0

TEST NUMBER 4

FIGURE 14 - MAP OF FIRE PROGRESS - DRAG TEST

In Test No. 1 the JP-4 fuel ignited 1.7 seconds after fuel started to seep from the moving tank. The fire propagated in the direction the tank was being towed and in the opposite direction where fuel had wetted the runway prior to ignition. A ribbon of flame, 925 feet long, continued to burn after the tank had come to rest. All fuel drained from the tank and would have been consumed by fire had not protein foam been used to extinguish the fire.

In Test No. 2 the Jet A fuel ignited 7 seconds after fuel started to seep from the moving tank. A 12-foot-long flame trailed the moving tank; and when the tank came to rest, the flame extinguished itself. All fuel drained from the tank. A 10-inch-wide by 1080-foot-long area of concrete saturated with the Jet A fuel remained after the test.

Tests Nos. 3 and 4 using 0.5 percent and 1.5 percent gelled JP-4, respectively, produced similar results inasmuch as a flame trailed the moving tank(s). When the tank(s) came to rest, the fuel continued to burn directly adjacent to the tank but did not propagate down the fuel-wetted area created by the fuel seeping from the dragged tank(s). The fuel remaining in the tank in both tests would have been completely consumed by fire had not the flames been extinguished. Protein foam was employed in Test No. 3 and a water spray in Test No. 4. The fuel-wetted area remaining on the runway was spotty and accounted for the flame not propagating. Due to the temperature-sensitive characteristic of the FAA 1069-1 gel, there was neat JP-4 fuel seeping from the tank along with the gelled JP-4, and therefore, the results obtained from Tests Nos. 3 and 4 are not all conclusive because of the nonhomogeneous nature of the gel structure.

The total loss of fuel from the tank due to seepage for both tests amounted to approximately 8 gallons.

Spill Method

Test Procedures - This test showed a fuel's ability to spread on a flat surface and the time required for fire to envelop the surface of the spread fuel.

A 3-gallon quantity of fuel was held in a container (Figure 15) 3 feet above a flat surface. An 8- by 1 1/4-inch slot in the bottom of the container was sealed off on the underside with a rip panel made of fuel resistant tape. The fuel was released through the slot by ripping off the tape. The spilled fuel pattern was outlined with chalk at the 30- and 120-second interval after its release. The fuel was also ignited at the 120-second time interval. The time required for the surface to become fully engulfed in flames was recorded as a part of this test.

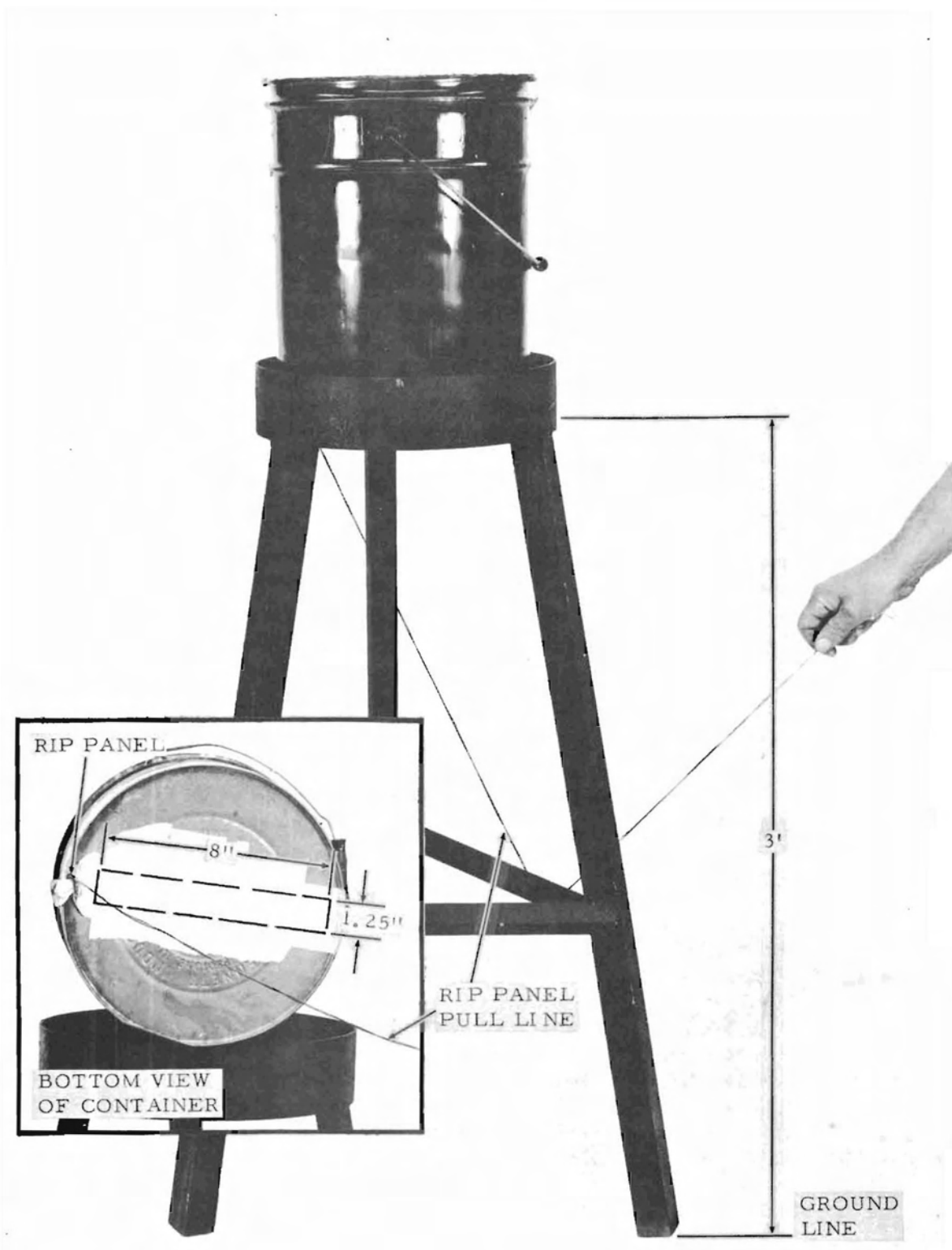Results - Figure 16 shows comparative spreads of the neat and gelled fuels on a concrete surface.

25

RIP PANEL

8"

1.25"

BOTTOM VIEW
OF CONTAINER

RIP PANEL
PULL LINE

3'

GROUND
LINE

FIGURE 15 - FUEL CONTAINER - SPILL TEST

26

NOTES:

TEMPERATURES

NEAT JET A FUEL	84°F
GELLED JET A FUEL	82°F
AMBIENT AIR	86°F
FUEL QUANTITY	3 gal

FUEL WAS DROPPED FROM A
HEIGHT OF 3 ft THROUGH A
SLOT (8" x 1.25")

JET A FUEL

GELLED JET A FUEL
17,000 CENTIPOISES

2'

4'

6'

8'
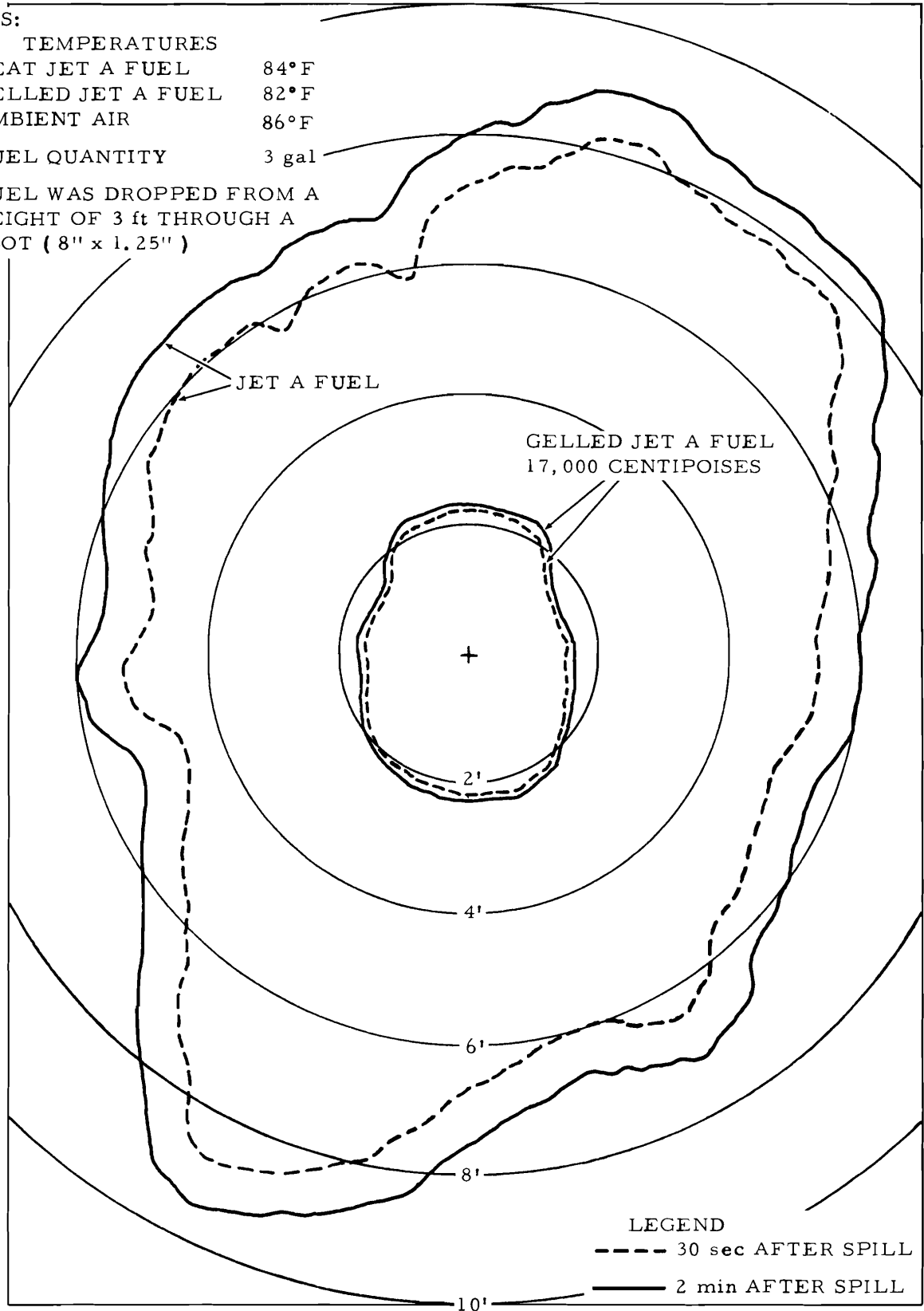
10'

LEGEND
- - - - 30 sec AFTER SPILL
———— 2 min AFTER SPILL

FIGURE 16 - SPILLED FUEL PATTERNS

27

The outward flow of the neat fuel had stopped at
2 minutes after spill; however, the gelled fuel continued to flow at a
very slow rate.

Both fuel spills were ignited on the upwind side (2 mph)
at the 2-minute time period. Flames covered the neat fuel spill in
47 seconds and the gelled fuel spill in 70 seconds.

The area wetted by the gelled fuel equalled a 92-percent
reduction over the area wetted by the neat fuel for the 2-minute time
period.

SUMMARY OF RESULTS

The results obtained during the evaluation of numerous modified
turbine fuels to determine their behavior under simulated crash fire
conditions are:

1. Pseudoplastic gelled Jet A turbine fuels with apparent
viscosities between 400-800 centipoises (RVT Brookfield, No. 3 spindle at
10 rpm), when exposed to open flames while in an aerosol state, reduced the
fire hazard by 97 percent as compared to the neat Jet A fuel under similar
air gun test conditions.

2. The highly viscous gelled fuel (1.5 percent FAA 1069-1) used
in the 35-foot-vertical drop test improved the tank's structural
integrity and fuel containment ability.

3. The four different viscosities of both the FAA 1069-1 gelled
JP-4 and the Jet A fuels, when impacted horizontally in the presence of
open flames, showed varying degrees of reduced ignitibility characteristics,
as compared to the two neat fuels, under similar conditions. The higher
viscous fuels (1.0 to 1.5 percent) provided the greatest advantage. The
gelled Jet A fuels were approximately 30 percent more effective in reducing
the fire hazard than like viscosities of gelled JP-4 fuels tested.

4. Neat Jet A fuel performed decidedly better than the neat
JP-4 fuel in the drag tests on the basis that a conflagration did not occur
with the Jet A fuel; whereas, one did occur with the JP-4 fuel. No state-
ment could be made regarding the drag tests of the two different
viscosities of gelled JP-4 since a mixture of the neat and gelled fuel was
involved rather than a homogeneous gel as intended.

5. As evidenced by the spill tests, a fuel having viscosities
higher than regular fuel will form a smaller area when spilled on a
relatively flat concrete surface.

6. The air gun test method produced results that were repro-
ducible and that could be correlated with the larger scale catapult tests.

CONCLUSIONS

Based upon tests performed, it is concluded that:

1. Higher viscosity fuels reduce the fire hazard potential of fuel misting, the rate of fuel spill from ruptured tanks and piping, and area of fuel spill. However, the level of fluidity required for aircraft compatibility will not permit their use.

2. The pseudoplastic gelled Jet A turbine fuel with dilatant properties shows the most potential for being able to significantly resist ignition and propagation of flame when in an aerosol state while still possessing a suitable degree of fluidity.

3. The air gun test method is a reliable means of screening candidate fuels to evaluate their ignition and burning characteristics in the mist form only, and to determine whether or not a particular fuel should be subjected to more sophisticated tests.

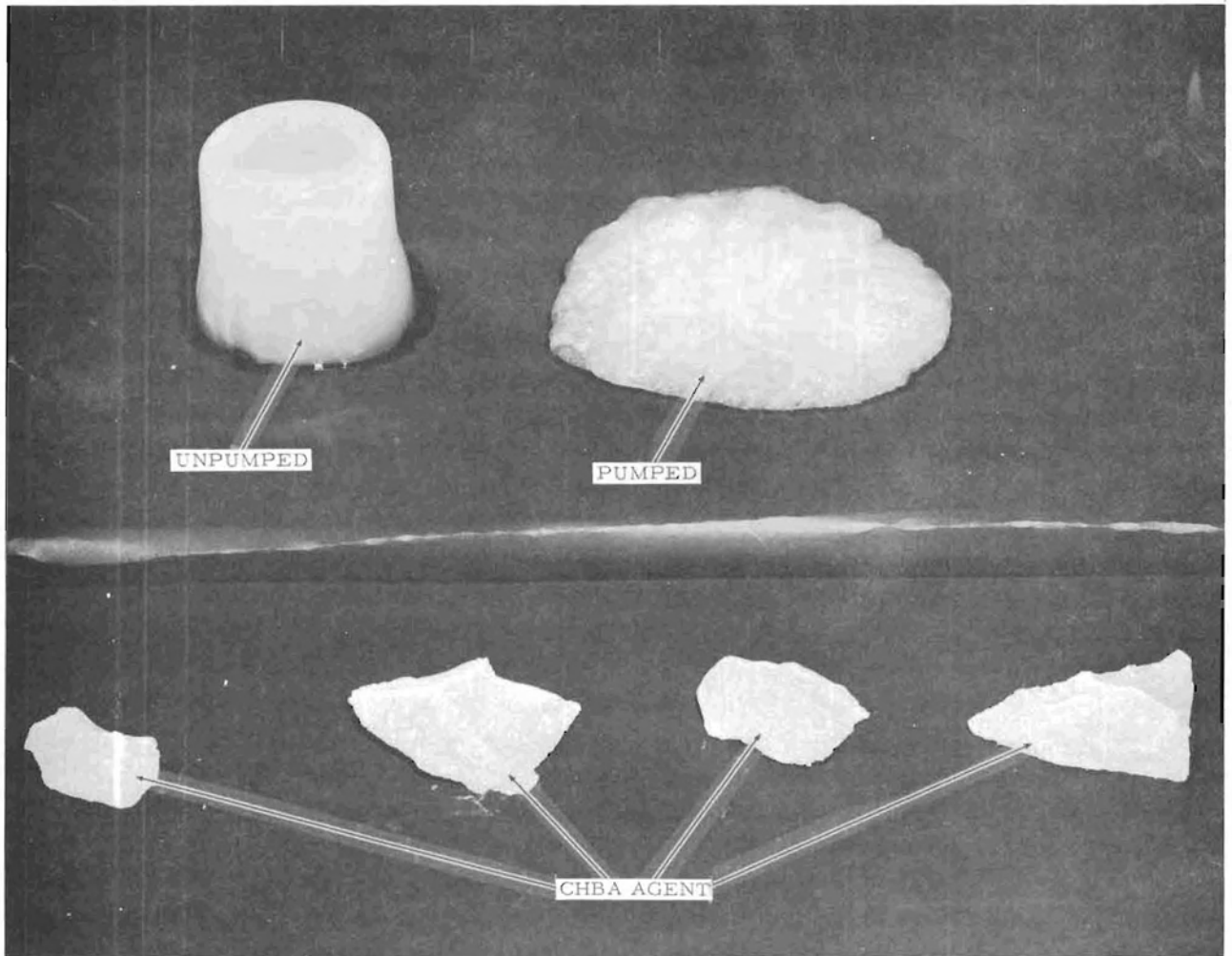GELLED FUEL COMPOSITION FAA 1069-1 AND THICKENING AGENT

FIGURE 1-1 - 1.5 PERCENT GELLED JET A TURBINE FUEL AND CHBA ADDITIVE

APPENDIX B

CRASH-FIRE HAZARD RATING SYSTEM AND TEST PROCEDURES

The rating system outline below is applicable to hydrocarbon-type aircraft fuels. A maximum overall rating of 95 is possible for the fuel with the most desirable properties under the proposed scheme.

Crash-Fire Hazard Rating System

1. **Minimum Temperature for Hot Surface Ignition**

   Minimum AIT by ASTM D2155-66 Method

   Rating Value = $10 \left(\dfrac{AIT-100}{1000}\right)$; Zero Rating at AIT $\leq 100^\circ$F;
   Maximum Rating (10) at AIT $\geq 1100^\circ$F

2. **Minimum Temperature for Formation of Flammable Mixtures**

   Flash Point by Modified ASTM D-56-64 Method

   Rating Value = $10 \left(\dfrac{F.Pt.}{200}\right)$; Zero Rating at F.Pt. $\leq 0^\circ$F;
   Maximum Rating (10) at F.Pt. $\geq 200^\circ$F

3. **Relative Volatility Rate or Time for Formation of Flammable Mixtures**

   Time to attain 1/2 psig at 100°F by modified Reid Vapor Pressure Method, ASTM D323-58.

   Rating Value = $10 \left(1 - 2.5/t\right)$; Zero Rating at t $\leq$ 2.5 min.

4. **Relative Self-Spread Rate**

   Rate of self spread following ignition in "Slope Test" at 70°F

   Rating Value = $15 \left(1 - R/5\right)$; Zero Rating at R $\geq$ in/sec.

5. **Regression or Burning Rate of Bulk Fuel**

   Regression rate of fuel ignited in 8-in diameter burning tray.

   Rating Value = $10 \left(1 - \dfrac{R}{0.1}\right)$; Zero Rating at R $\geq$ 0.1 in/min.

6. **Horizontal Flame Spread Rate Under Static Conditions**

   Horizontal flame spread rate of fuel ignited in 3-in angle trough.

   Rating Value = $10 \left(1 - R/5\right)$; Zero Rating at R $\geq$ 5 ft/sec.

7. Fireball Size Under Impact Conditions

Height and width of fireball in "Fuel Drop Test" with 5 lbs of fuel at a drop height of 20 ft.

Maximum width (W_1) within 1 second after ignition:
Rating Value = $10 (1 - W_1/20)$; Zero Rating at $W_1 \geq 20$ ft.

Maximum width (W_2) within 10 seconds after ignition:
Rating Value = $10 (1 - W_2/20)$; Zero Rating at $W_2 \geq 20$ ft.

Maximum height (H_2) within 10 seconds after ignition:
Rating Value = $10 (1 - H_2/12)$; Zero Rating at $H_2 \geq 12$ ft.

The test methods for determining the fuel properties used in the previously outlined rating system are described as follows:

Crash Fire Hazard Rating System Test Procedures

1. Minimum Temperature for Hot Surface Ignition

Minimum autoignition temperatures of the fuels are determined (see Figure 2-1) in air by the standard ASTM D2155-66 method (Reference 11) with two minor modifications. (1) The thickened fuels are taken at room temperature ($70^\circ \pm 10^\circ$F) and passed through a wire screen of approximately 10 mesh prior to use and (2) they are injected into the test flask (200 cc Pyrex Erlenmeyer) with the needle of the hypodermic syringe removed. These modifications are recommended to facilitate fuel injection and they should have little or no effect on the minimum AIT's expected for the fuels of interest.

FIGURE 2-1 - APPARATUS FOR DETERMINING AUTOIGNITION TEMPERATURE

2. Minimum Temperature for Formation of Flammable Mixtures

Flash points of the fuels (see Figure 2-2) are determined by the ASTM D56-64 method (Tag Closed Cup) (Reference 12) with certain modifications in procedure. The thickened fuels have relatively low-thermal conductivity and fluidity and, therefore, considerable thermal lag can exist between the fuel sample and the sample container or bath in a flash point tester. A low-heating rate of approximately $0.3^\circ F$/min is required to overcome this difficulty and to obtain a uniform sample temperature. For the JP-4 type thickened fuels, the Tag Closed Cup apparatus must be modified to permit circulation of low-temperature fluids. This was done by adding an inlet port opposite to the outlet port and near the bottom of the bath container; also, the sides of the bath container are covered with insulation to reduce heat leaks. In a determination, the sample is cooled to $20^\circ F$ below the expected flash point. A bath temperature equal to or slightly below the sample temperature is necessary to allow for heat loss differences and to achieve the optimum heating rate of $0.3^\circ F$/min. The thickened fuels should be passed through a 1/4-inch or $\sim$ No. 3 wire mesh screen before use.

FIGURE 2-2 - APPARATUS FOR DETERMINING FLASH POINT

3. <u>Relative Volatility Rate or Time for Formation of Flammable Mixtures</u>

Modifications of the ASTM Reid Vapor Pressure Test Method (ASTM D323-58)
(Reference 13) are made to compare the relative rates at which fuels form
flammable vapor-air mixtures at 100°F. The time required for a fuel to
attain a vapor pressure of 1/2 psig was selected since the corresponding
fuel concentration will fall well within the flammable range for the fuels
of interest. The data are obtained by (see Figure 2-3) a method similar
to that of the Standard ASTM procedure but with a few exceptions. Liquid
fuels are loaded into the sample chamber according to the ASTM procedure,
but thickened fuels are loaded by means of a cooled piston-type injector
(32°F). The fuels, precooled to 32°F, are forced through an ~ No. 3
wire mesh and through a nozzle extending to the bottom of the chamber.
This chamber is maintained at 32°F and is immediately assembled with the
air chamber which is at a temperature of 100°F; the chambers are fitted
with a screw-type connector for quick assembly. The air chamber and the
fuel container are not shaken during a determination, and precautions
are taken to prevent any liquid spill from the fuel container into the
air chamber. Pressure measurements are made using a transducer although
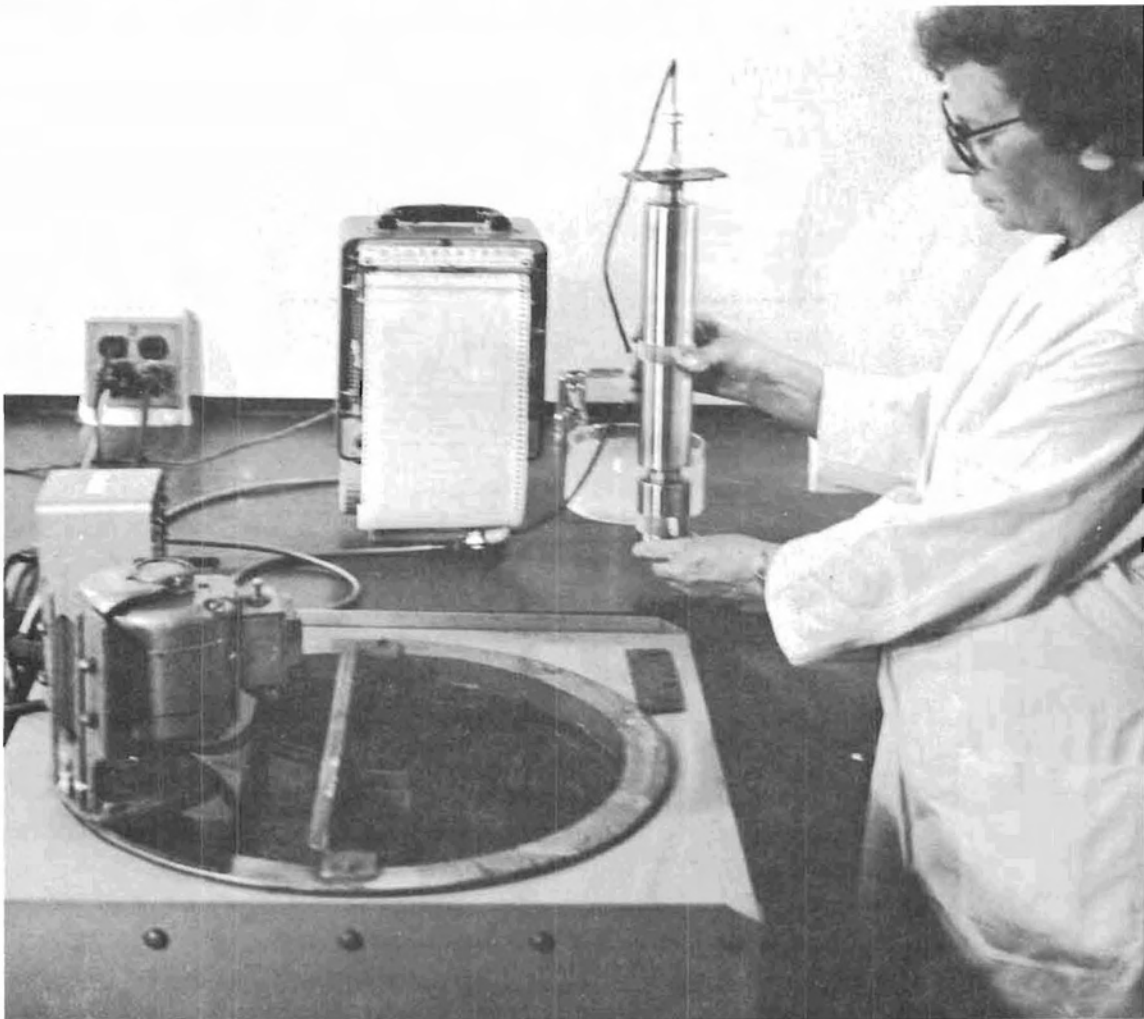precision-type Bourdon gages can also be used.

FIGURE 2-3 - APPARATUS FOR DETERMINING VAPOR PRESSURE (REID METHOD)

2-5

4. Relative Self-Spread Rate

A "Slope Test" (see Figure 2-4) was designed to measure the relative ease with which a thickened fuel, once ignited, can soften and flow to increase the potential size of the fire. In this test, a 4-foot-long metal trough, sloped at a 2° angle, is used; 3-inch aluminum angle is recommended for the trough. One and one-half inches of the upper end of the trough is filled evenly with the fuel and the top surface of the fuel is ignited with a torch. For fuels that do not hold in place, an aluminum V-shaped wedge contains the fuel until it is ignited. In the case of the kerosene-type fuels, a wick is required to ignite the fuel; a 1-inch length of 8mm pipe stem cleaner is adequate. The time required for the fuel to travel 2 feet down the trough is then measured from the time of ignition. Fuel and ambient temperatures should be $70^{\circ} \pm 5^{\circ}F$ and the thickened fuels should be passed through an $\sim$No. 3 wire mesh before use.
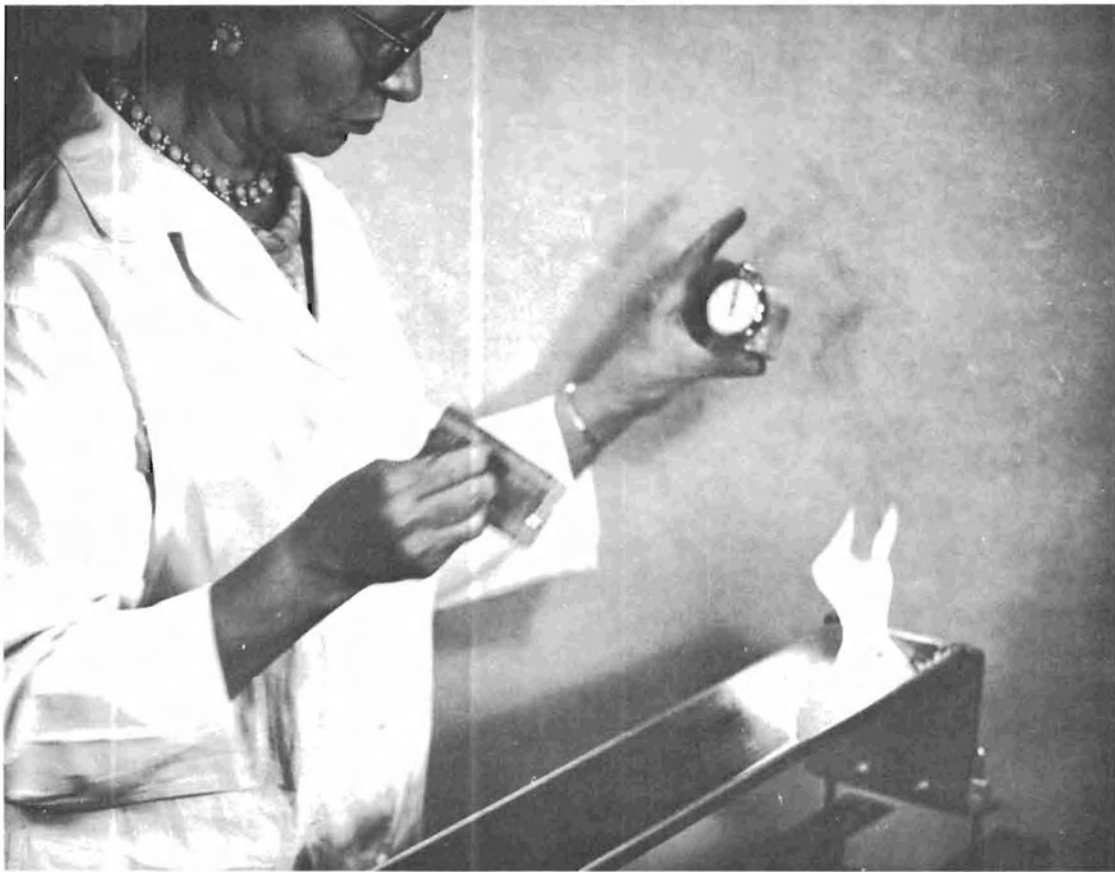

FIGURE 2-4 - BURNING GELLED FUEL BEING TESTED IN SELF-SPREAD RATE
APPARATUS

5. Regression of Burning Rate

The regression of burning rates of the fuels are determined in
8-inch-diameter metal trays with a total depth of 1 1/2 inches
(see Figure 2-5). Aluminum or steel trays are recommended and they should
be filled to a height 1/2 inch from the top. Any irregular or uneven fuel
surfaces are leveled to provide a uniform surface area, and the fuel is
ignited by a torch. The average regression rate is determined by measur-
ing the burning time for a fuel depth of 1 inch. The rates can be
measured by visual observation, by pressure-load transducers, or by other
devices whose output can provide a change of fuel weight and fuel depth
with time. Fuel and ambient temperatures should be $70^\circ \pm 10^\circ F$.

FIGURE 2-5 - TRAY CONTAINING EMULSIFIED FUEL DURING BURNING RATE TEST

2-7

6. Horizontal Flame Spread Rate Under Static Conditions

The flame spread rates should be determined in a metal trough (see Figure 2-6) at least 4 1/2 feet in length; 3-inch aluminum angle is recommended for this test. The trough is filled with the thickened fuel (or liquid fuel) and any irregular or uneven fuel surfaces are leveled to provide a uniform surface area. The fuel is ignited with a torch at one end of the trough and flame propagation is measured over a 4-foot distance. Flame propagation can be measured by the use of fuse wires (1/2 amp) and a suitable timer or recorder; the first fuse wire should be about 6 inches from the point of ignition. Fuel and ambient temperatures should be $70^{\circ} \pm 5^{\circ}F$, and the thickened fuels should be passed through an $\sim$ No. 3 wire mesh before use.
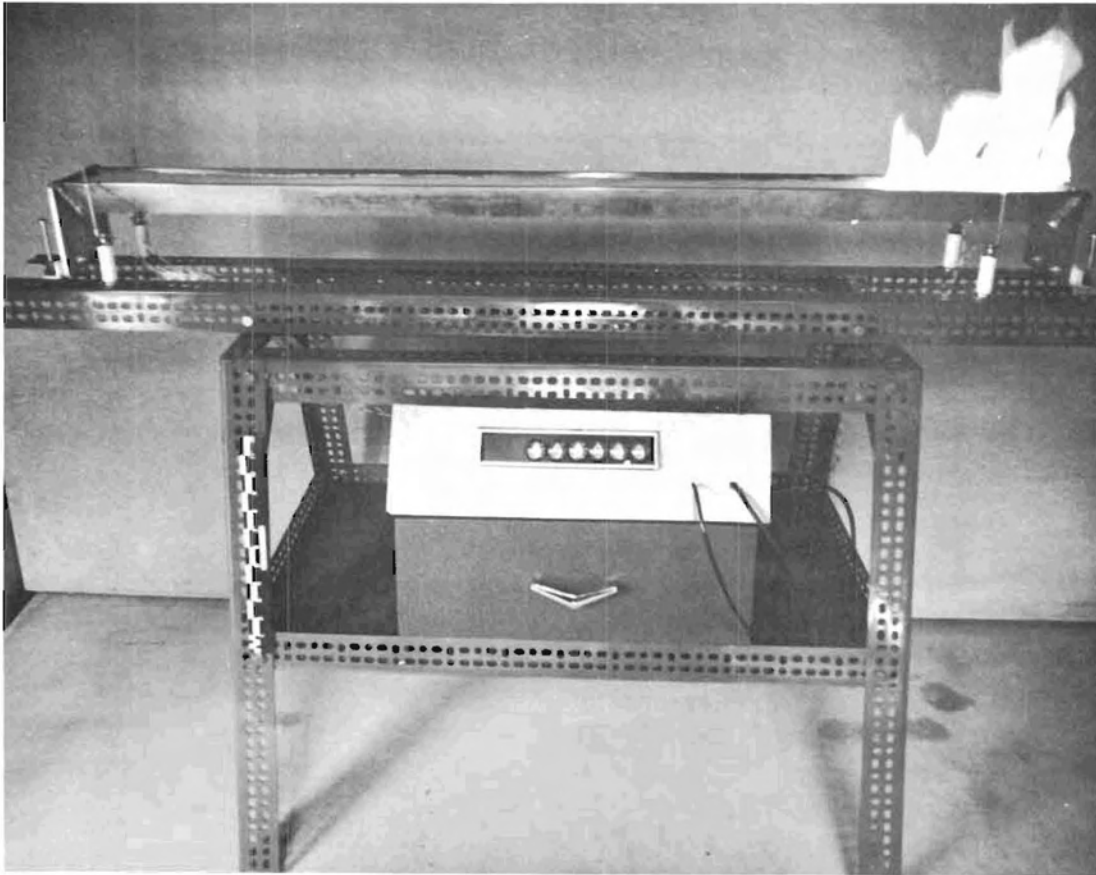

FIGURE 2-6 - APPARATUS FOR DETERMINING HORIZONTAL FLAME SPREAD

7. Fireball Size or Radiation Intensity Under Impact Conditions

A "Fuel Drop Fire Test" was designed for comparing the relative fire hazard which may be associated with the fuels in ignitions under impact conditions. For this purpose, 5 pounds of fuel contained in a 3000-ml Pyrex flask are dropped from a height of 20 feet onto a concrete or asphalt surface; the shape of the flask appears to be unimportant since the results are essentially the same with Erlenmeyer and round bottom flasks. A torch is positioned near the point of impact to effect immediate ignition and is removed after ignition. The flame spread and size of fireball produced are recorded by a motion picture camera; a metal frame grid is mounted in the background to facilitate the fireball measurements. The maximum width of the fireball within 1 second is measured to observe flame spread differences which can be attributed to increased vapor formation, mist formation, or fuel spread under impact conditions. The maximum height and width attained within 10 seconds are also measured. An alternate method for comparing the fireball hazard is the measurement of the thermal radiation. A bismuth-silver thermopile equipped with a calcium fluoride window is mounted 3 feet above ground level and 30 feet from the point of impact. Output of the thermopile is recorded by a direct writing oscillograph. Fuel and ambient temperatures should be $70^o \pm 10^oF$, and the thickened fuels should be passed through an $\sim$ No. 3 wire mesh before use. In addition, the experiments should be conducted under minimum wind conditions because of the great effect this factor can have on the flame spread. Figure 2-7 shows the fire resulting from a test made on JP-4 emulsified fuel.

FIGURE 2-7 - DROP TEST AREA FOR MEASURING FIRE SIZE OF IMPACTED FUELS

APPENDIX C

DEFINITIONS OF GEL AND EMULSIFIED FUELS

Gels: A typical gel has a structure in which a semisolid very open network is filled with a liquid that is immobilized to an extent that the normal flow properties of the liquid are masked. The structural network enclosing the liquid is formed by the addition of solid materials dispersed in the liquid. The dispersed phase exists as particles or fibers which are in contact with each other. A gel is most likely a non-Newtonian fluid and may be further classified as (1) pseudo-plastic if the stress increases more rapidly at low rates of shear rather than at high rates of shear; (2) plastic when the rate of shear does not acquire a finite value until the shear stress exceeds a yield value, and (3) dilatant when the shear stress increases faster than the rate of shear.

The three fluids just described are "time-independent" since their flow properties are independent of time. The rate of shear at any point in the fluid is a function of the shear stress at that point. Figure 3-1 depicts characteristic rheograms in which shear stress is plotted against rate of shear.

The flow properties of the other two non-Newtonian materials, i.e., thixotropic and rheopectic, are dependent on time. The apparent viscosity of these two more complex fluids depend not only on the magnitude of the shear rate but also on the length of time during which shear has been applied.
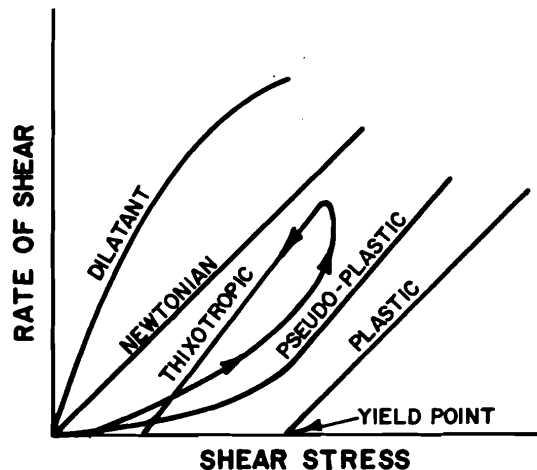

FIGURE 3-1 - FLOW CHARACTERISTICS OF VARIOUS MATERIALS

3-1

Emul: Emulsions are a two-phase liquid system in which small droplets of one phase are dispersed throughout a second continuous phase. The dispersed phase in emulsions consists of particles which mutually repel and stand off from each other in contrast to the dispersed phase in gels. Emulsions are considered non-Newtonian fluids and can be classified into the five categories described under Gels.

Inhib: Inhibited fuels contain chemical additives such as halogenated hydrocarbons which interfere with the combustion process.

APPENDIX D

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