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DESIGN OF A CASCADE FIRE APPARATUS FOR TESTING COUNTERMEASURE EFFECTIVENESS

NAVAL SURFACE WEAPONS CENTER
WHITE OAK LABORATORY
SILVER SPRING, MARYLAND 20910

AND

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JUNE 1976

FINAL REPORT

Approved for public release; distribution unlimited

DOD AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SYSTEM OFFICE
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

This technical report has been reviewed and is approved.

Julius Singer

JULIUS SINGER, Program Manager
DOD Aircraft Ground Fire Suppression
and Rescue Office (AGFSRO)

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A cascade fire apparatus was designed to be used in the evaluation of agent effectiveness and application techniques in suppressing accidental aircraft ground fires involving fuels which are cascading, spraying, or pouring. The apparatus

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provides for (1) a controllable burning rate, (2) a reproducible fire, (3) a flame geometry that minimizes wind effects, and (4) an adjustable size by virtue of its modular nature. One of the two fuel supply nozzling options yields a smokeless fire; however, the other option has better fire characteristics for evaluating some of the countermeasures.

Suppression tests were conducted using PKP and Monnex dry chemical agents and gaseous Halon 1211. Monnex was slightly more effective on a weight basis in extinguishing the fires. It was not possible to compare the effectiveness of Halon 1211 and the powder agents because of the different application rates and capacities of the extinguishers tested and, therefore, the different required fire size. The apparatus appeared to be well suited for evaluation of agent effectiveness against the kinematic fires and also for training firemen in fighting these fires.

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APPENDIX

ILLUSTRATIONS

1.0 INTRODUCTION

The Phase I report on kinematic jet fuel fires emphasized the prevalence and importance of cascading, spraying, and pouring fuels in aircraft ground fires.[1] Such fires are not amenable to suppression by the foams that constitute the principle systems for aircraft protection; therefore, various auxiliary agents--i.e., powders, chemically active vapors, and inert gasses--are required to cope with these fires. Unfortunately, the evaluation of auxiliary agent effectiveness and application techniques has been hampered by irreproducible fire characteristics and uncertainties regarding the importance of the various fuel and environmental parameters on the fire behavior. Much of the dispersion in the results of past extinguishment tests stems from a lack of satisfactory test fires. Consequently, this program was designed to remove some of these deficiencies by providing (1) a better understanding of cascading fuel fire characteristics and (2) specifications for suitable test fires. Phase I provided simple analytical models for cascading, jetting, and spraying fuel fires and related the fuel and environmental parameters to the experimentally observed fire characteristics. This phase reports the scaling of small laboratory fires up to sizes suitable for testing fire suppression agents, application apparatus, and techniques in extinguishing fires characteristic of aircraft accidents. The scope includes the designs of the fire system, a discussion of refinements made during the development period, and an evaluation of the apparatus performance in a series of extinguishment tests with dry powder chemicals PKP (Purple K Powder, $KHCO_3$) and Monnex $[K(urea)\ CO_3]$, and gaseous Halon 1211 ($CF_2Cl\ Br$).

2.0 BACKGROUND

The initial phase of the project:

- Defined the hazard potential of aircraft crash fires by surveying military aircraft fuel capacity, fuel tank location, and characteristics of the lubrication or hydraulic systems that could contribute to crash fires.
- Defined the hazard history by surveying aircraft accidents involving fires to identify either frequent or highly hazardous gravity-controlled fuel flow fires.
- Developed an analytical description and interpretation of the important parameters for the experimental program and test development.
- Conducted small-scale tests to verify the analysis and identify scaling criteria.

It was found that of the possible types of kinematic fuel fires (cascade fires, rod fires, gas-jet diffusion flames, and droplet spray fires), the cascade and rod fires have received very little attention, and their characteristics are the least understood. Therefore, the cascade fire, which consists of fuel flowing along the surfaces adjacent to fuel reservoirs, was chosen as the kinematic fuel fire to characterize and simulate.

Phase I identified the following features as desirable in a satisfactory test fire:

- A controllable burning rate at values typical of a severe fire with common aircraft fuels such as JP-4 and JP-5 burning at about 0.2 in^3/min per square inch of burning surface (0.125 $gal/min/ft^2$).
- A burning rate reproducible to within 10 percent from fire to fire and constant from top to bottom of the cascade.

- A flame geometry that minimizes wind effects and a testing structure that does not cause unexpected perturbations of agent application.
- An adjustable fire size so that various types and sizes of extinguishing systems can be tested.
- A fire source that produces minimum smoke pollution.

Based on the Phase I results with small (2.25 ft^2) cascade laboratory fires, a full-scale test apparatus was designed to satisfy this list of desirable features. This report describes the development of and the tests performed on the full-scale cascade fire apparatus.

3.0 THE CASCADE FIRE TEST APPARATUS

A schematic drawing of the modular cascade fire testing apparatus is shown in Figure 1. Figure 2 contains three photographs of the cascade fire panel. As can be seen in Figure 2(a), two modules were built, the one on the left being a refinement of the first panel. Figure 3 is a construction drawing of the final design.

3.1 The Cascade Fire Panel

The double-layered panel, approximately four feet wide and eight feet high, consists of a water cooled underplate and support frame covered with a layer of galvanized metal "shingles." These 14 inch by 18 inch shingles hang freely at an angle of about 60 degrees up from the horizontal on hooks welded to our 94-inch lengths of angle iron. Water flows over the back plate during the fire to keep the solid sheet cool and prevent warping. The shingles are not in contact with the water; therefore, these heat up during the fire and aid in evaporating the fuel. This construction permits the shingles to warp without disturbing the entire structure.

A trough located at the bottom of the panel collects unburned fuel [See Figure 2(c)]. When the shingles reach an elevated temperature, all the fuel burns and there is no drainage to the sump. However, some fuel drains off during the initial warm up and again during suppression, especially after the fire is completely extinguished and before the fuel supply is shut off. A small amount of water flows continuously in the trough to cool the excess fuel before it runs through the sump pump and also to carry away any powder extinguishing agent that may fall into the

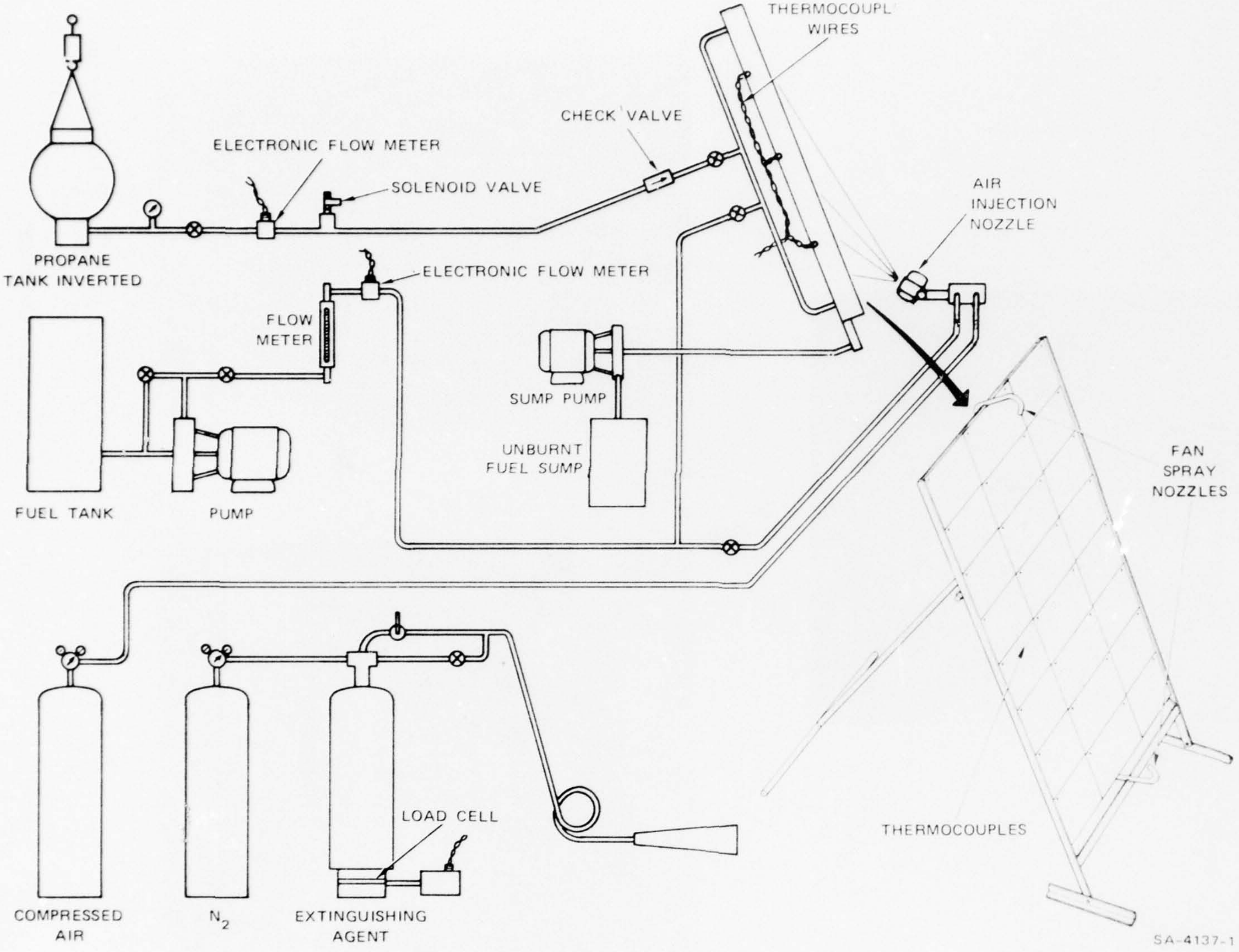

FIGURE 1 SCHEMATIC OF CASCADE FIRE TESTING APPARATUS

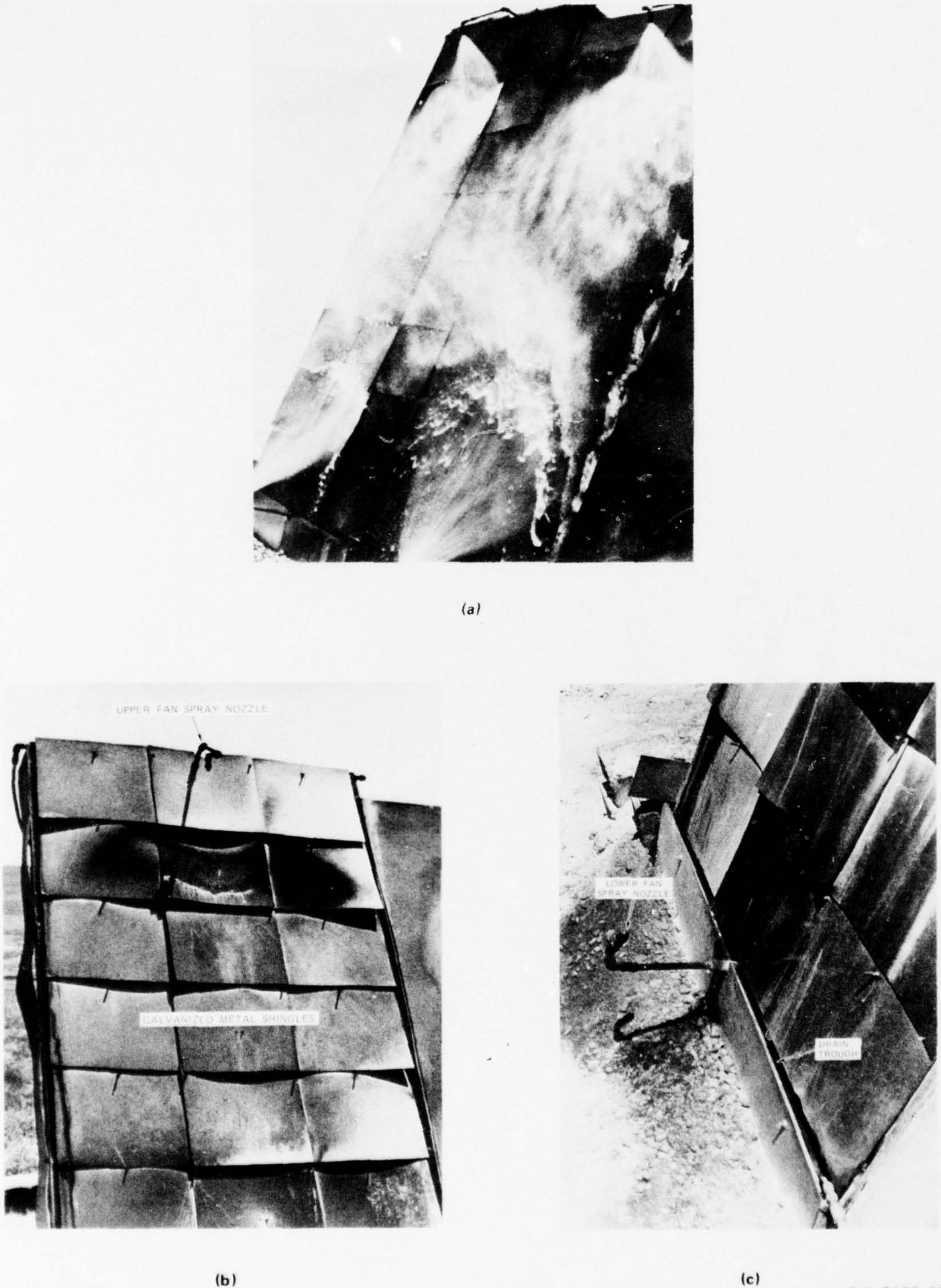

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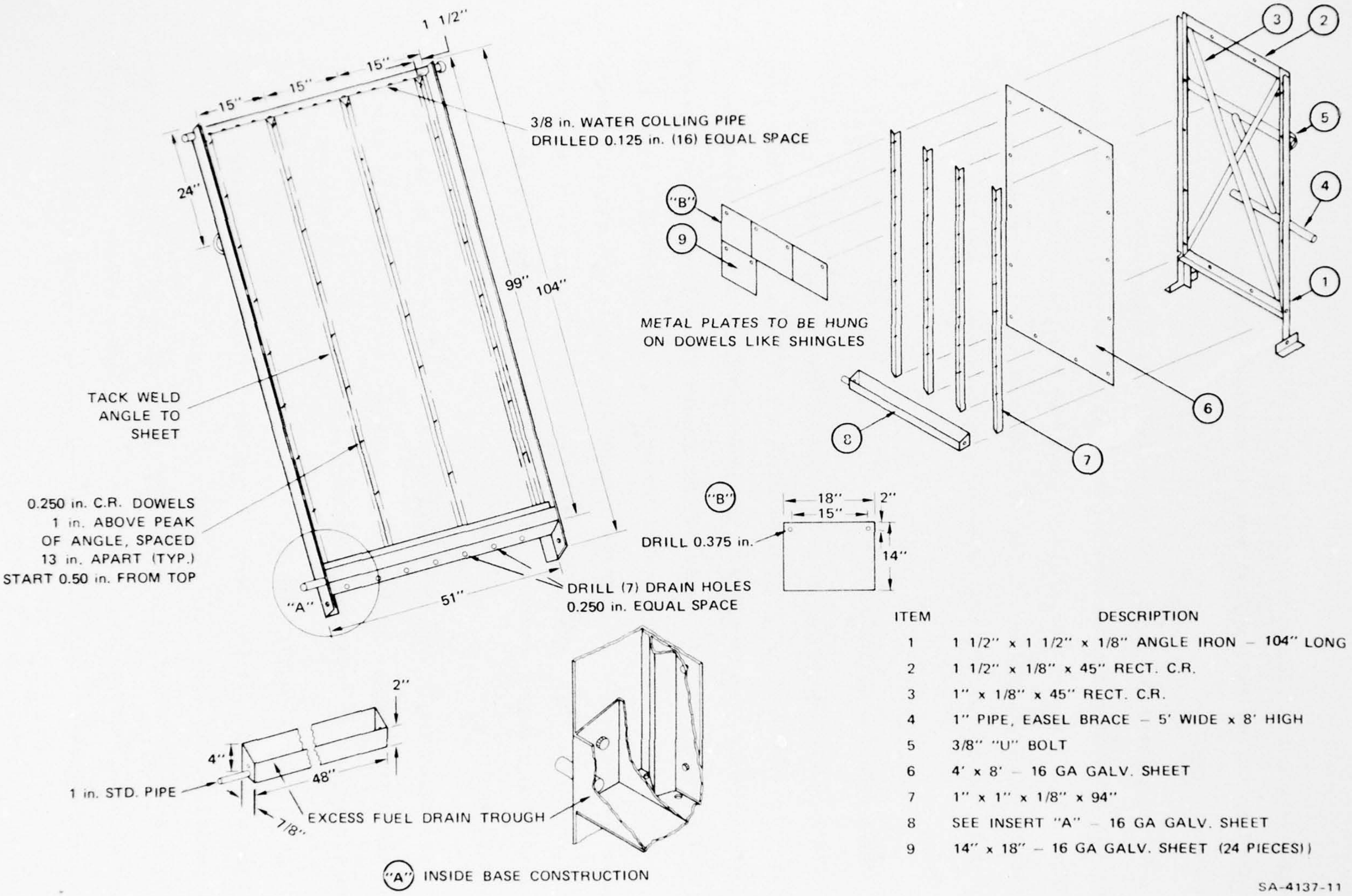
FIGURE 2 PHOTOGRAPHS OF THE CASCADE FIRE PANEL



ITEM	DESCRIPTION
1	1 1/2" x 1 1/2" x 1/8" ANGLE IRON – 104" LONG
2	1 1/2" x 1/8" x 45" RECT. C.R.
3	1" x 1/8" x 45" RECT. C.R.
4	1" PIPE, EASEL BRACE – 5' WIDE x 8' HIGH
5	3/8" "U" BOLT
6	4' x 8' – 16 GA GALV. SHEET
7	1" x 1" x 1/8" x 94"
8	SEE INSERT "A" – 16 GA GALV. SHEET
9	14" x 18" – 16 GA GALV. SHEET (24 PIECES)

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FIGURE 3 CONSTRUCTION DETAILS OF CASCADE FIRE PANEL trough. A gravity flow system may be sufficient to drain the trough if enough drop to the excess fuel sump is provided; however, we needed the sump pump.

The first module, i.e., the right panel in Figure 2(a), followed the thick plate water-cooled design employed in the small laboratory apparatus of Phase I. It was not possible to heat the 1/2-inch-thick steel plate sufficiently to evaporate all the fuel without introducing serious warping. Therefore, the two layer design was adopted for the second module.

3.2 The Fuel Supply Systems

Three liquid fuels, JP-4, JP-5, and methanol, were used in these cascade fire experiments. Also, propane was tried in some of the smokeless fire burns. Unfortunately, the propane fire characteristics did not sufficiently simulate those of the liquid fuels involved in aircraft crash fires; therefore, the use of propane was discontinued. Since the propane fuel vaporized as soon as it left the nozzle and was at atmospheric pressure, the vapors were easily transported away from the plate and the flame geometry could not be controlled as easily as with liquid fuels.

The liquid fuels were pumped at a measured flow rate to the fire panel where two nozzle options were available, normal fan spray nozzles or an air injection nozzle (see Figure 1).

The fan spray nozzles are shown operating in Figure 2(a) before ignition at a flow rate of about 1.6 gpm per nozzle. When using the fan spray nozzles, the fuel supply pipes come through the plate and are extended to about nine inches in front of the plate with the use of nine inches of pipe, and one 45-degree and two 90-degree elbows. The nozzles are aimed so that the downward spray from the top nozzle hits the plate about 1.5 feet below the top of the plate and the upward spray from the bottom nozzle hits the plate about 2 feet above the bottom of the plate plate. The nozzles used give a flat, fan type spray pattern with fine atomization characteristics. Different sized nozzles are used for different flow rates as follows:[*]

Flow Rate Per Nozzle	Nozzle No.	Equivalent Orifice Diameter
less than 1.5 gpm	T9510	5/64 in
1.5 to 2.0 gpm	T9515	3/32 in
2.0 to 2.5 gpm	T9520	7/64 in
2.5 to 3.0	T9530	9/64 in
greater than 3.0 gpm	T9540	5/32 in

To achieve the listed flow rates, the nozzle pressures were varied between 30 and 70 psi. The spray angle is 95 degrees at 40 psi and ranges less than ± 5 degrees for the 30-70 psi pressure range. When the fuel evaporates completely on the hot shingles, the burning rate equals the fuel supply rate. With JP-5, about a one-minute preburn was required to heat the shingles to this total fuel evaporation point; however, less time was required for JP-4 and methanol.

Three fires involving the two fan spray nozzles on the single module are shown in Figure 4. Figure 5 shows fires with two modules and four fan spray nozzles.

The other nozzle option employs a furnace burner and air injection to finely atomize the liquid fuel. The compressed air also supplies part of the oxygen for burning. A single nozzle was placed in front of the fire panel and aimed upward and slightly into the panel as indicated in Figure 1. Air injection nozzle fires with burning rates of 2.1 and 3.95 gpm are shown in Figures 6(a) and 6(b), respectively. No smoke was visible at JP-4 burning rates less than about 3.5 gpm with the compressed

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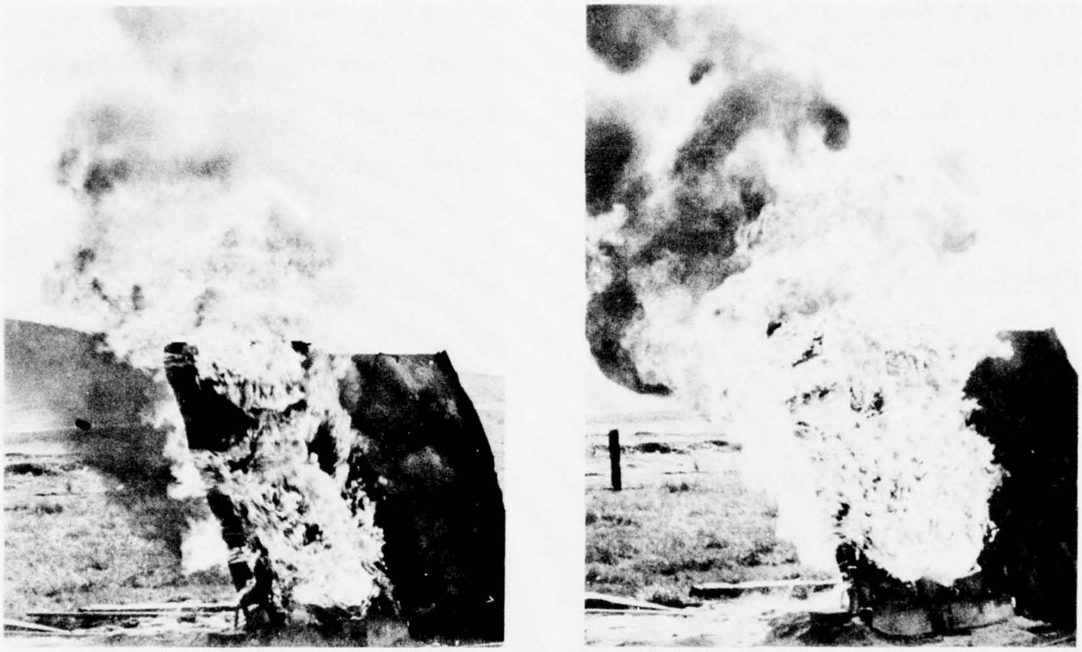
[*] The nozzles were Unijet Nozzles from Spraying Systems Company.



(a)
Fuel flow rate is 1.6 gpm, wind is 5 mph

(b)
Fuel flow rate is 4.5 gpm, wind is 1 mph

(c)
Fuel flow rate is 3.6 gpm, wind is 10 mph

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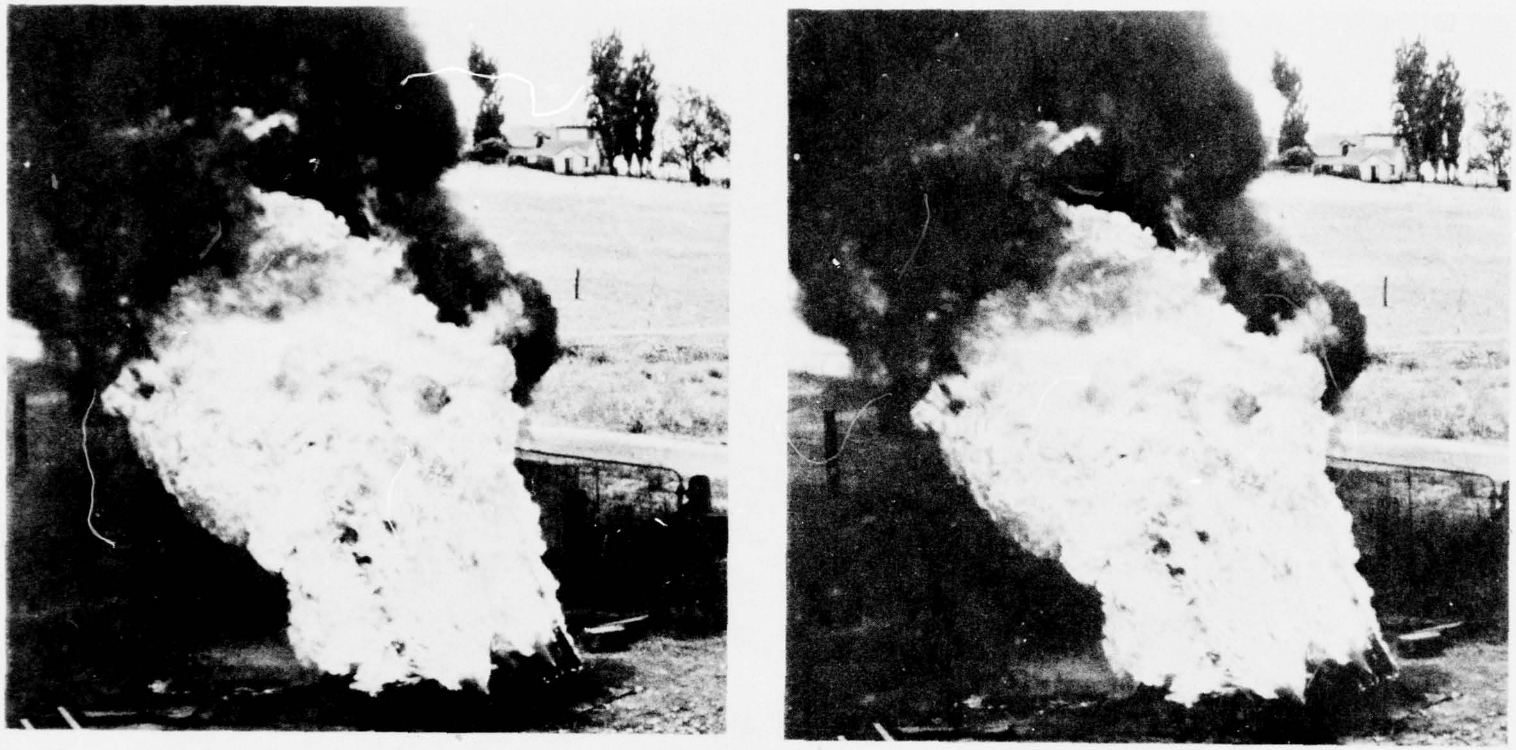
FIGURE 4 PHOTOGRAPHS OF JP-4 ONE-MODULE CASCADE FIRES



(a)
Fuel flow rate is 6.3 gpm, wind is 5 mph

(b)
Fuel flow rate is 8.9 gpm, wind is 3 mph

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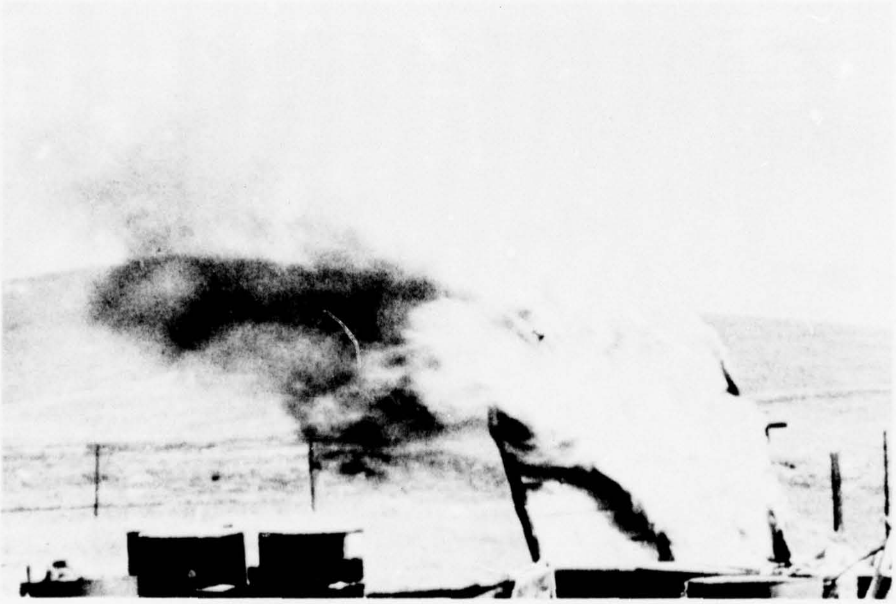
FIGURE 5 PHOTOGRAPHS OF JP-4 TWO-MODULE CASCADE FIRES

(a)
Fuel flow rate is 2.1 gpm



(b)
Fuel flow rate is 3.95 gpm

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FIGURE 6 PHOTOGRAPHS OF JP-4 FIRES USING THE AIR INJECTION NOZZLE air to the nozzle at 58 psi, the maximum airflow capacity of our system. The visible smoke continually increased with the flow rate at rates greater 3.5 gpm, e.g., Figure 6(b) shows some smoke at 3.95 gpm. Flow rates of up to 6.0 gpm were used.

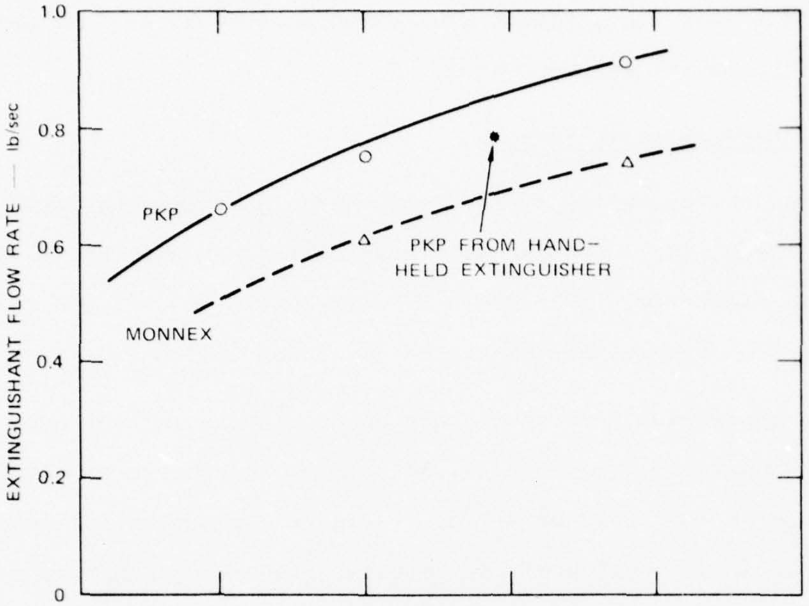
3.3 The Extinguishing Systems

Three extinguishing systems were used in experiments with the cascade fires; (1) a continuously pressurized dry chemical extinguisher (shown in Figure 1), (2) a 20-lb PKP fire extinguisher, and (3) a CB-10 wheeled fire extinguisher converted for Halon 1211 use.

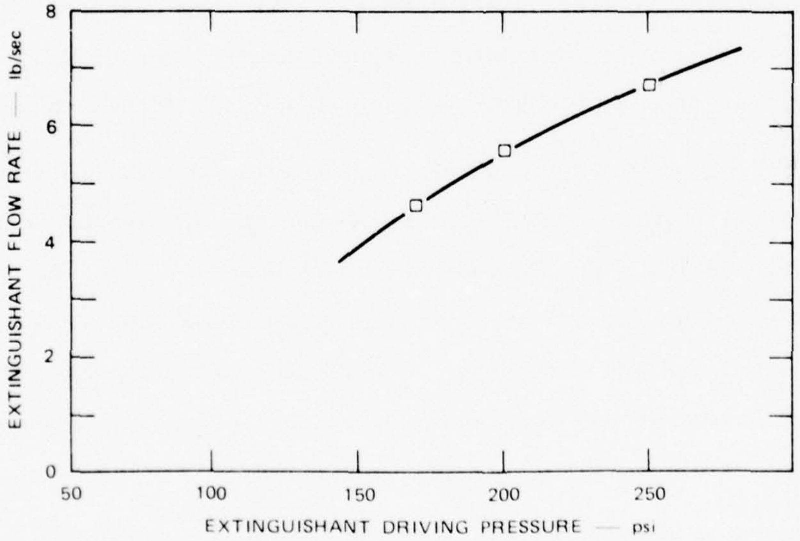
The continuously pressured dry chemical extinguisher used with both PKP and Monnex had a capacity of 50 pounds. Discharge pressure was maintained at 100, 150, or 240 psi. Figure 7 gives extinguishant agent flow rates as a function of the driving pressure. As can be seen in Figure 7(a), for a given driving pressure, the PKP mass flow rate is about 25 percent greater than the Monnex flow rate. All extinguishing effectiveness data is for manual extinguishment. For example, Figure 8 shows typical fire suppression tests with PKP and Monnex powders.

An attempt was made to eliminate the human element in evaluating agent effectiveness by supplying the powder through two or three stationary nozzles supplied from the 50-lb bottle. However, no data were collected as the effective stationary jet positioning was extremely sensitive to wind and fire size. A person handling the one nozzle was much more effective and consistent in extinguishing fires than any combination of stationary nozzles that was tried.

A portable commercial PKP fire extinguisher was used to apply dry chemical agents to the cascade fires. This unit was filled with the recommended charge of approximately 20 pounds of PKP and pressurized to 195 psi with N_2. The average PKP flow rate of about 0.75 lb/sec did not appear to decrease appreciably during the first 15 seconds of



(a) DRY CHEMICAL POWDERS



(b) HALON 1211

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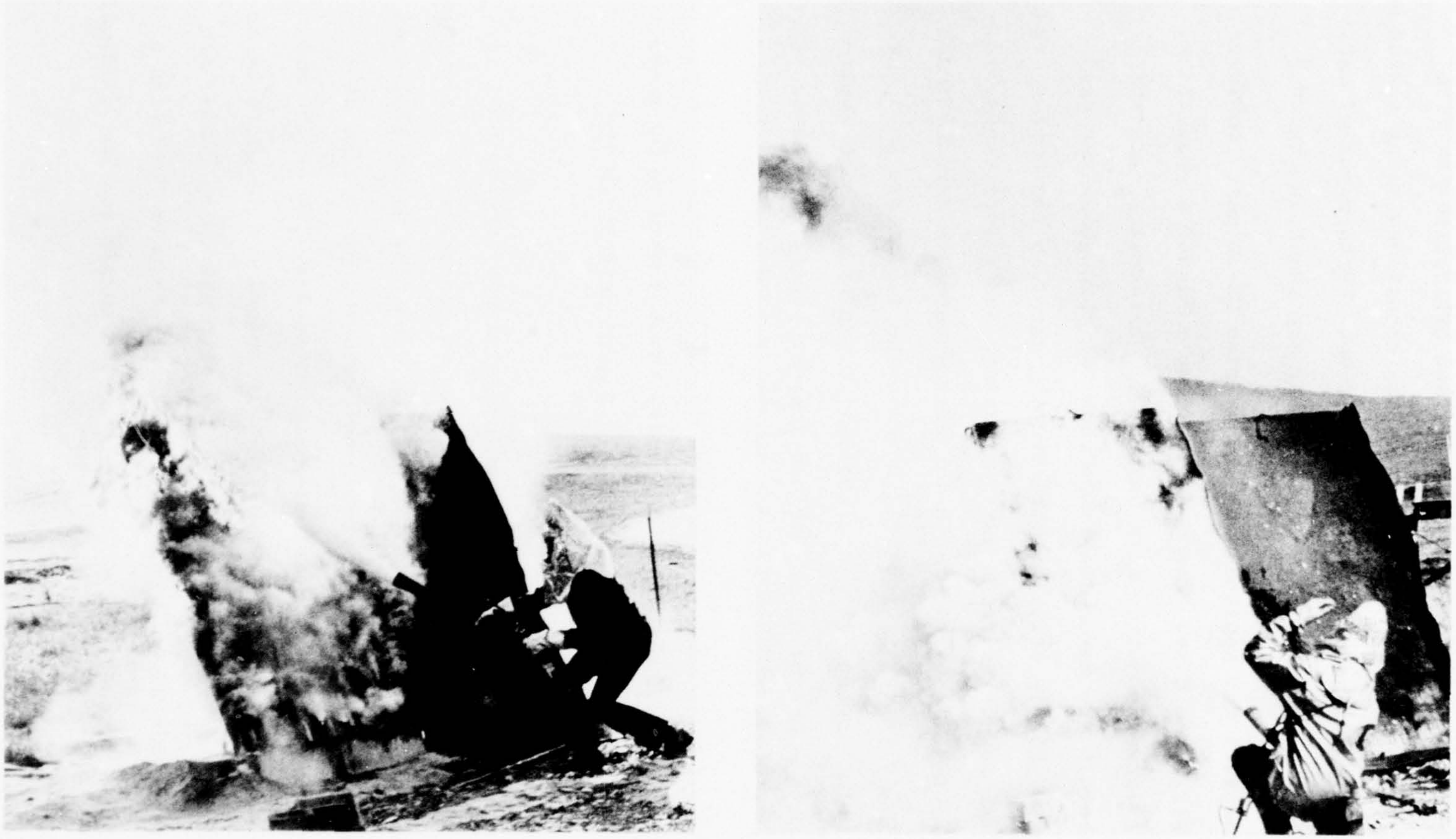
FIGURE 7 EXTINGUISHANT FLOW RATE AS A FUNCTION OF THE DRIVING PRESSURE



(a)
PKP flow rate is 0.91 lb/sec

(b)
Monnex flow rate is 0.61 lb/sec

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FIGURE 8 EXTINGUISHMENT WITH CONSTANT PRESSURE DRY CHEMICAL EXTINGUISHER discharge, which was sufficient time to either extinguish the fire or determine that the fire resulting from the conditions being tested could not be extinguished in any length of time. Photographs of extinguishment with the hand-held PKP extinguisher are shown in Figure 9.

The Halon 1211 was applied with a converted CB-10 unit[2] borrowed from Travis Air Force Base. The modifications included a pressurized system for filling the bottle with Halon 1211, external N_2 pressurization to maintain the Halon flow rate constant throughout the agent discharge, a weighing platform to measure the agent in the bottle, and an experimental nozzle selected for its pattern and effectiveness in delivering Halon 1211. Since the Halon extinguishments were designed for comparison to tests at Tyndall AFB where the fuel flows down sheets of expanded metal screen, it was essential to employ the same application systems and operating conditions for both tests. Consequently, this part of the test program was coordinated with Major Glen Chambers of Tyndall AFB who arranged for the loan of the CB-10 unit and the Ansul CB nozzle with the 0.422-inch throat, which proved to be quite effective in dispensing the Halon 1211 in a good pattern in the Tyndall AFB tests.

Figure 10 shows photographs of the extinguisher and its use. As can be seen in Figure 10(a), the agent tank was removed from its wheels and placed on the platform scale so that the amount of Halon 1211 used could be easily determined. In accordance with the procedures at Tyndall AFB, the tank was continuously pressurized to 150 or 120 psi. An operator position of 20 feet from the fire panel was found to be an effective operating distance; therefore, after preliminary tests, the 20-feet distance was used. A few preliminary tests were done with a tank pressure of 200 psi. At this pressure the nozzle was too difficult

(a) **BEFORE EXTINGUISHMENT**
JP-4 flow rate is 4.7 gpm

(b) **DURING EXTINGUISHMENT**
PKP flow rate is 0.78 lb/sec

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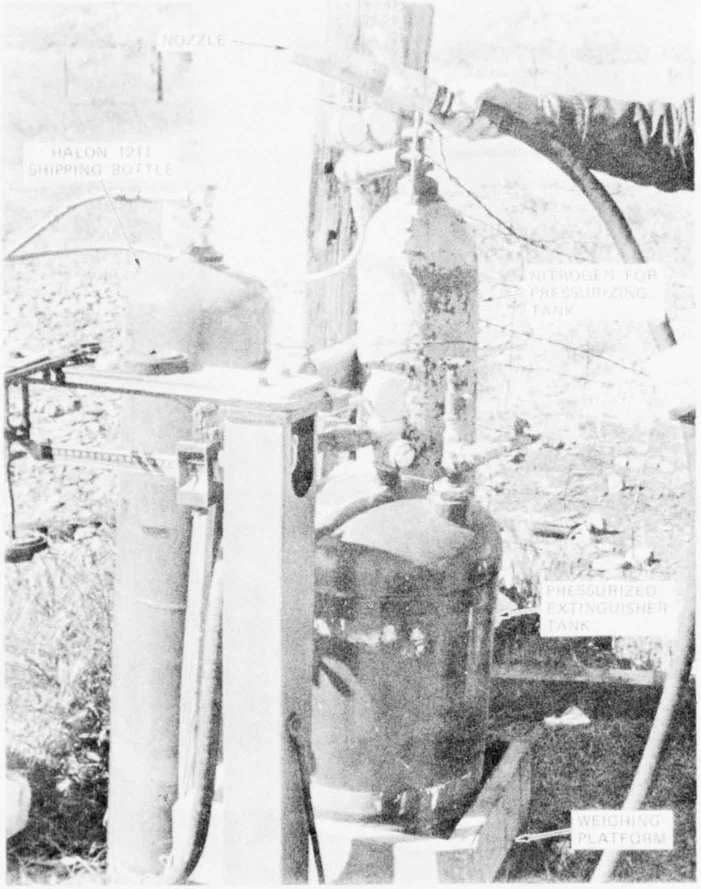
FIGURE 9 EXTINGUISHMENT WITH PKP HAND EXTINGUISHER



(a) HALON 1211 EXTINGUISHER UNIT

(b) HALON 1211 FLOW RATE IS 5.5 lb/sec

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FIGURE 10 EXTINGUISHMENT WITH HALON 1211 to hold and control; therefore, only the 150 and 120 psi pressures were used in subsequent tests. Halon 1211 flow rates as a function of driving pressure are shown in Figure 7(b).

4.0 EXPERIMENTAL RESULTS

4.1 Fire Characteristics

The observed or controlled fire characteristics were burning rate (which was the fuel flow rate when no excess fuel flowed to the sump), flame temperature, flame shape, smoke production, and thermal radiation. These parameters were examined as a function of fuel type and wind conditions. Flame shapes, smoke production and wind effects were recorded with super 8 time-lapse and 35mm still photographs.

Average flame temperatures for the various fuel and nozzle conditions as measured with a telescopic radiometer focused on the center of the fire panel were:

Fuel	Nozzle Type	Average Flame Temperature
JP-4	fan spray	1,590°F
JP-5	fan spray	1,670°F
methanol	fan spray	< 1,400°F
JP-4	air injection	1,780°F

The measured flame temperatures varied several hundred degrees between tests using the same fuel and nozzle type, but the variation was random and did not appear to depend on burning rate or wind conditions. Flame temperatures for methanol were less than 1,400°F, which was the minimum temperature that we could measure.

Thermal radiation levels were measured at a location 10 feet directly in front of the fire panel. Figure 11 shows radiation levels as a function of burning rate for fan spray nozzle JP-4 fires on the one-module panel. These data were separated into three wind speed categories, which in turn were fitted by least squares linear

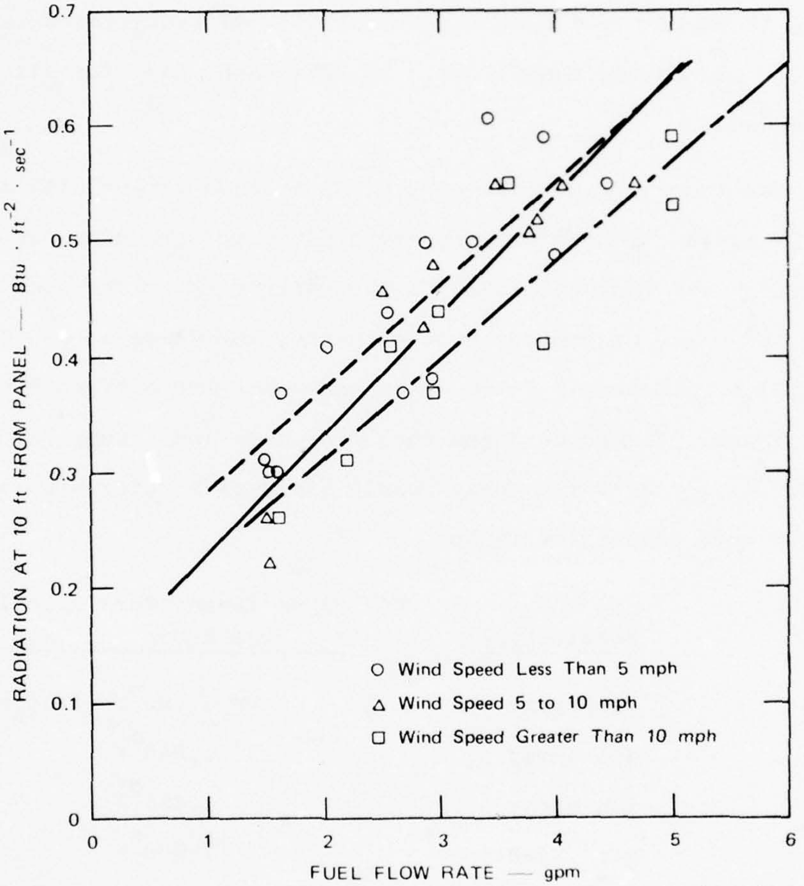

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FIGURE 11 THERMAL RADIATION DATA FOR JP-4 ONE-MODULE FIRES USING FAN SPRAY NOZZLES regressions (straight lines in Figure 11). The wind direction was within 45 degrees of normal to the panel for all recorded tests. As can be seen, increasing wind speeds decrease the radiation slightly. This reduction is probably due to an increase in the distance from the radiometer to the flames, the higher winds tending to hold the flames closer to the panel.

Figure 12 shows the linear regression fits of radiation data for the various fuels and nozzle conditions. In this case, data for all wind speeds were used.

Since the thermal radiation emitted by a flame varies with the fourth power of the temperature, relative flame temperatures can be calculated from the radiation data if the emissivity is the same in all cases. On the basis of photographic evidence, the flame areas for a given fuel flow rate were assumed to be equal for the different fuels and nozzle types. Using the 3 gpm fuel flow data and a temperature of $1590^{o}F$ ($2050^{o}R$) for JP-4 fan spray nozzle fires as a reference, other temperatures were calculated to be:

Fuel	Nozzle Type	Flame Temperature Calculated from Radiation Data
JP-4	fan spray	$1,590^{o}F$ (reference)
JP-5	fan spray	$1,640^{o}F$
methanol	fan spray	$1,450^{o}F$
JP-4	air injection	$1,800^{o}F$

These calculated flame temperatures compare quite well with the average flame temperatures measured with the telescopic radiometer except for methanol, where the calculated temperature is at least $50^{o}F$ above the measured value.

JP-4 fire areas for several different wind and nozzle conditions can be seen in the photographs of Figures 4-6. Although flame areas were not measured, several qualitative observations can be made.

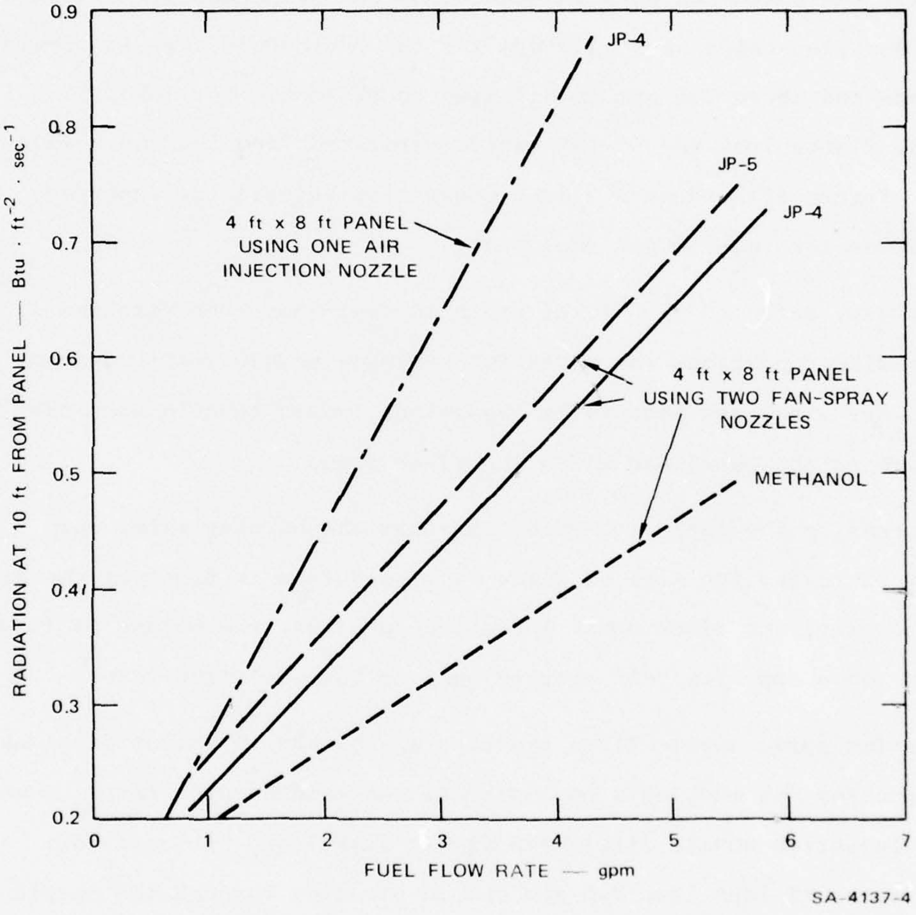


FIGURE 12 THERMAL RADIATION AS A FUNCTION OF BURNING RATE

JP-4 and JP-5 flame shapes appeared to be the same for equivalent fuel flow rates. The JP-5 flames were a darker yellow than the JP-4 flames. flames. Methanol flames are virtually invisible in bright sunlight; consequently, flame shape or spectra are not known.

With the fan spray nozzles, the flames covered the entire plate except for the bottom corners and exhibited an approximately uniform density for flow rates above 1.5 gpm for the one-module case in no wind conditions and above 2.5 gpm in all wind conditions. For lower flow rates the flames from the bottom nozzle separated from the top nozzle flames. Figure 4(a) shows a slight separation between the upper and lower flames for the 1.6 gpm fuel flow.

Buoyancy extended the flames up to 10 feet above the fire panel, but under no-wind conditions the width for a single module remained about 4 feet. Any wind, and especially crosswinds, would tend to wrap the flames around the panel and widen the flame areas.

Increasing the fuel flow rate, and thus the burning rate, only slightly increased the area of flame as viewed from in front of the fire panel; however, the flame depth increased such that the volume of flames appeared to be approximately proportional to the fuel flow rate.

The fan spray nozzle fires produced a substantial amount of black smoke, probably as much as a pool fire of the same burning rate. However, the air injection nozzle fires were almost smokeless, at least for burning rates of less than 3.5 gpm and an air flow through the nozzle of about 2 lb/sec. Some smoke appears at higher burning rates, as shown in Figure 6(b) for a fuel flow rate of 3.95 gpm.

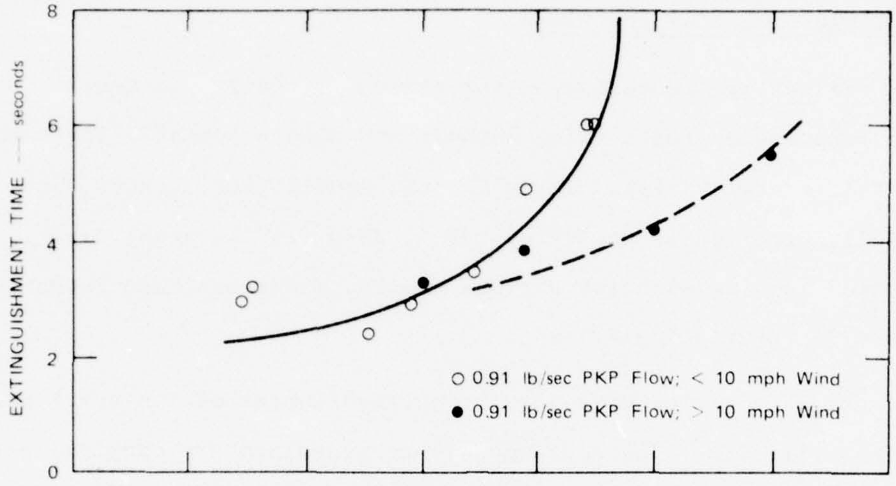
The air injection nozzle fires were more conical in shape than the fan spray nozzle fires and had an almost white flame. The area of flame as viewed from in front of the fire panel appeared to increase in proportion to the burning rate. The wind did not effect the flame geometry appreciably.

4.2 Extinguishment of the Fires

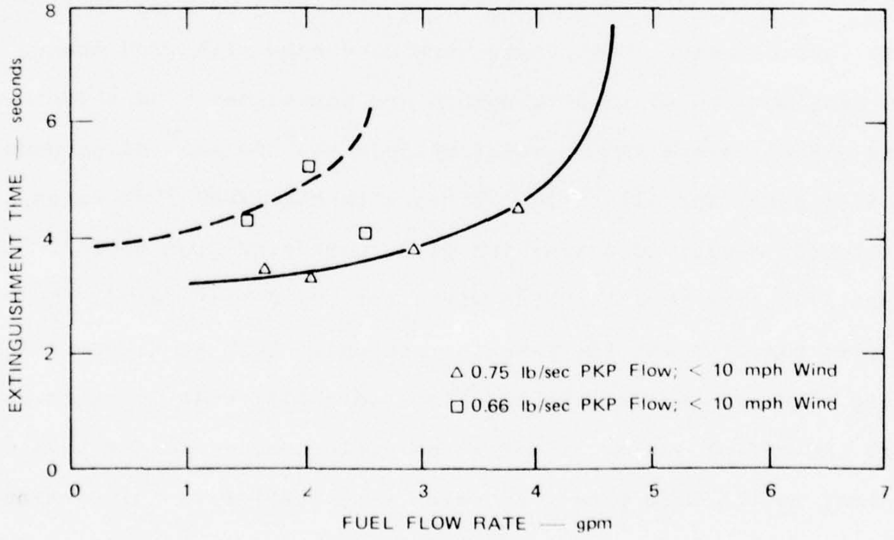
In evaluating the design of the cascade fires it was necessary to do some suppression tests using methods and agents suitable for combatting accidental aircraft fires. Three agents, namely, PKP, Monnex, and Halon 1211, were tested on various JP-4, JP-5, and methanol fires. Typical suppression results with the various agents, apparatus, and techniques are shown in Figures 13-18.

Figure 13 contains data for the extinguishment of fan spray nozzle JP-4 fires with PKP. The continuously pressureized dry chemical extinguisher was used. Data are shown for PKP flow rates of 0.65, 0.75, and 0.91 lb/sec, which correspond to driving pressures of 100, 150, and 240 psi, respectively. Most tests were conducted with wind speeds less than 10 mph, but the solid data points are for higher wind velocities. The wind direction was in the quadrant from -45^{o} to $+45^{o}$ of perpendicular to the fire panel for all tests. Fires with high fuel flow rates appeared to be slightly easier to extinguish with increasing wind speeds. This was especially true when the wind direction was nearly normal (head on) to the fire panel as was the case for the data shown in Figure 13(a). Cornering winds seemed to make the fires more difficult to extinguish, although the effect was minor until the angle became greater than 45^{o} from normal to the fire panel, at which time testing was discontinued. The minimum powder application time or extinguishment time was 2.5 seconds.

Figure 14 shows data for PKP extinguishment of JP-5 and methanol fires. Only PKP flow rates of 0.75 and 0.91 lb/sec were tested with these fires.



(a) JP-4 FUEL



(b) JP-4 FUEL

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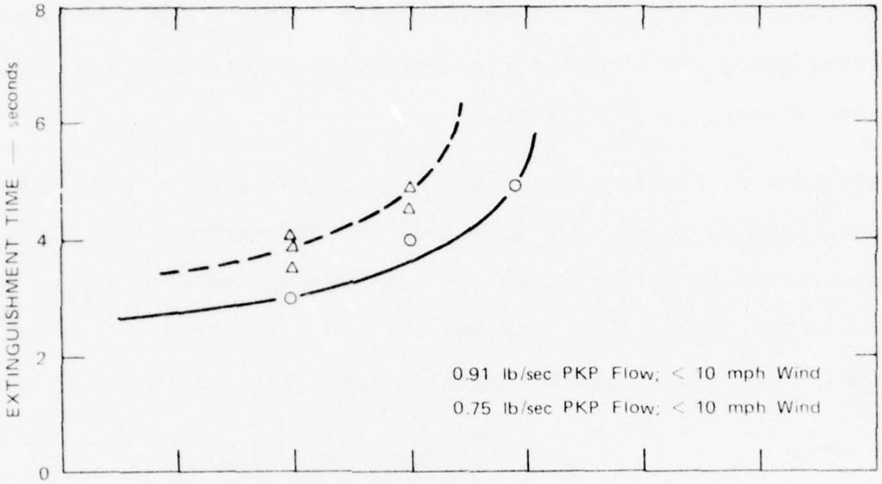
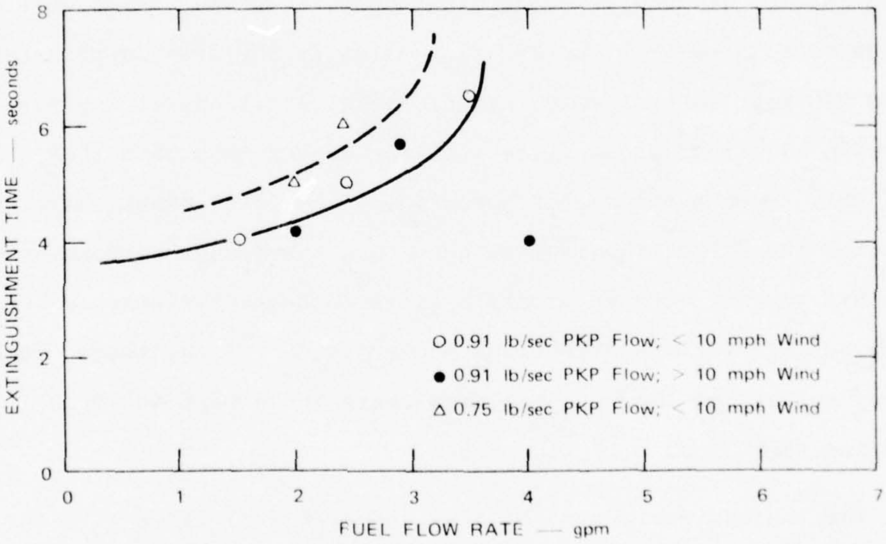
FIGURE 13 PKP CONSTANT FLOW EXTINGUISHMENT OF JP-4 FIRES



(a) METHANOL FUEL



(b) JP-5 FUEL

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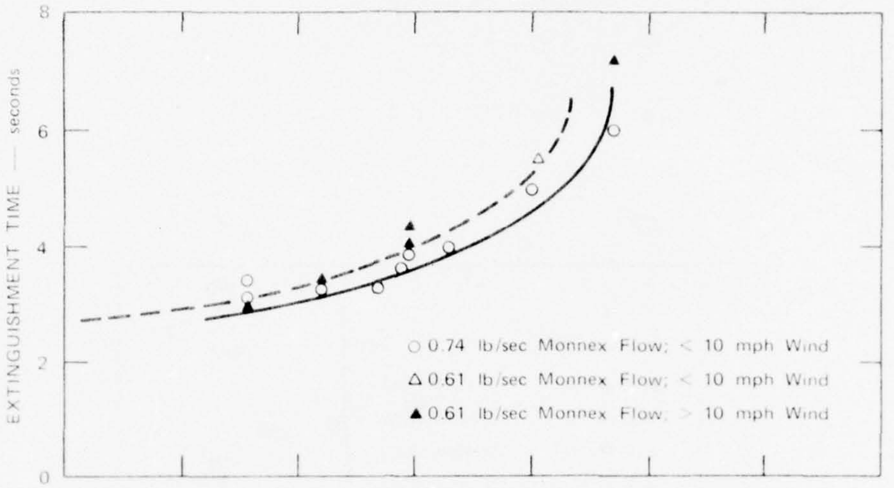
FIGURE 14 PKP CONSTANT FLOW EXTINGUISHMENT OF JP-5 AND METHANOL FIRES

One data point for JP-5 tests, namely, a 4-second extinguishment of a 4-gpm fire, appears out of place and warrants a comment. In this test, a 17.5-mph wind blowing directly toward the fire panel appeared to confine the fire to a smaller volume than with either a low wind speed or a cornering wind, and the fire was extinguished more easily than expected from results of other tests.

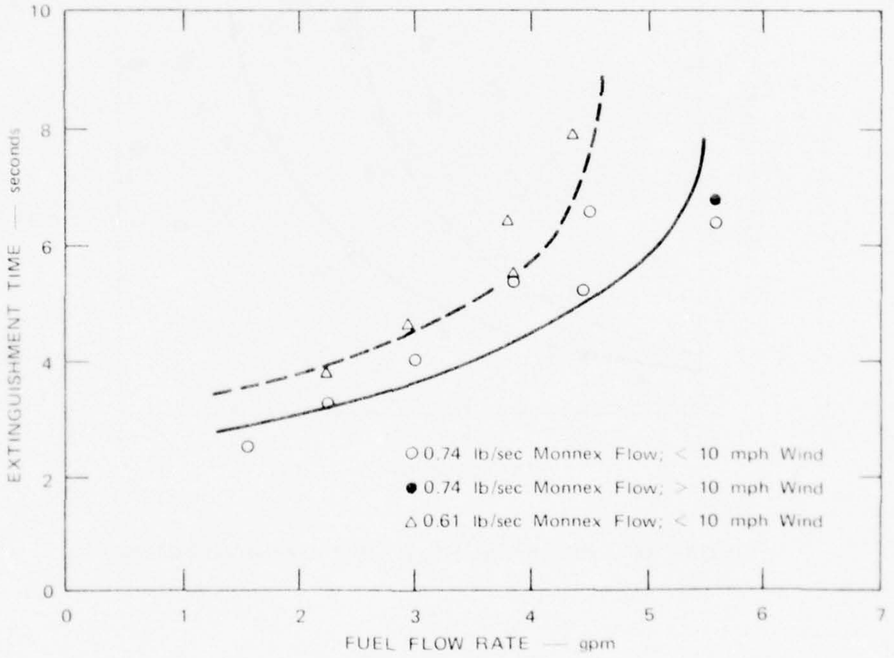
A comparison of Figures 13 and 14 shows that higher burning rates could be extinguished for JP-4 than for JP-5. The maximum fuel flow of methanol that could be extinguished was between that of JP-4 and JP-5. However, the extinguishment of methanol fires was impaired by the difficulty in seeing the flames and determining where more extinuishant was necessary.

Figure 15 shows data for Monnex extinguishment of JP-4 and JP-5 fires. Monnex was applied at flow rates of 0.61 and 0.74 lb/sec, which were about 25 percent lower than the PKP flow rates at the driving pressures of 150 and 240 psi, respectively. Under these conditions it was possible to extinguish slightly larger fires with the Monnex than with that same weight of PKP. A comparison of Figures 13(a) and 15(a) shows that the wind effected the PKP extinguishment more than the Monnex extinguishment. However, this was not because of differences in characteristics of PKP and Monnex but due to wind directions occurring during the tests, which were nearly normal for the PKP high wind tests and almost 45^o from normal during the Monnex high wind tests.

Data for the exginguishment of JP-4 and JP-5 fuel fires with the hand-held PKP extinguisher are shown in Figure 16. Most of the data for the JP-4 fires are for winds greater than 10 mph, while those for JP-5 fires are for winds less than 10 mph.



(a) JP-4 FUEL



(b) JP-5 FUEL

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FIGURE 15 MONNEX CONSTANT FLOW EXTINGUISHMENT

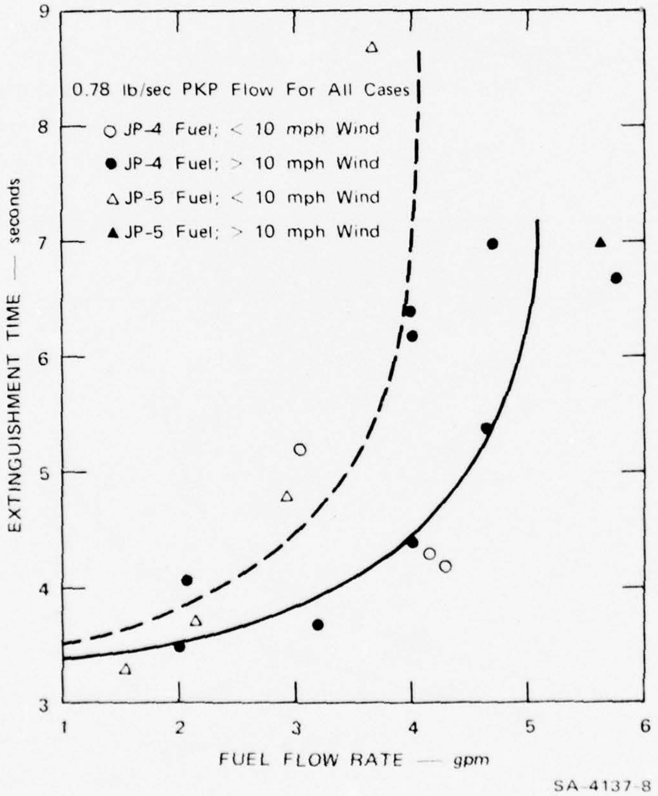

FIGURE 16 PKP HAND-HELD UNIT EXTINGUISHMENT

Figure 17 shows data for the extinguishment of JP-4 and JP-5 fuel fires with Halon 1211. The data shown are for a two-module fire panel (8 feet wide by 8 feet high with four fan spray nozzles). A few tests were done on the single panel employed in the powder tests, but in all such cases, the extinguishment was very rapid, occurring in less than three seconds even with the maximum fuel flow rate of 6 gpm. When discharged at a distance of 20 feet from the panel, the Halon 1211 appeared to be mostly gaseous by the time it reached the fire, as can be seen in Figure 10(b). Again, the wind did not affect the extinguishment times. However, in all cases the wind was almost normal to the fire panel. A crosswind probably would disperse the Halon 1211 stream more rapidly, making extinguishment more difficult.

Extinguishment of two-module (8 foot by 8 foot) fires with PKP, using the continuously pressurized extinguisher, was also attempted. However, we were unable to extinguish any of these fires even with the maximum flow of 0.91 lb/sec and the minimum JP-4 fuel flow of 3 gpm (0.75 gpm per nozzle). As can be seen in Figure 13, we extinguished JP-4 fires of 4.5 gpm on the one-module panel in low wind conditions and up to 6 gpm in high wind conditions. Therefore, the ease of extinguishment must depend on the fire panel area as well as the fuel flow rate.

Figure 18 shows data for the PKP extinguishment of JP-4 fires produced with the air injection nozzle. With these fires there is a narrow transition fuel flow region below which the flames are extinguished rapidly and above which extinguishment is impossible for the given PKP flow.

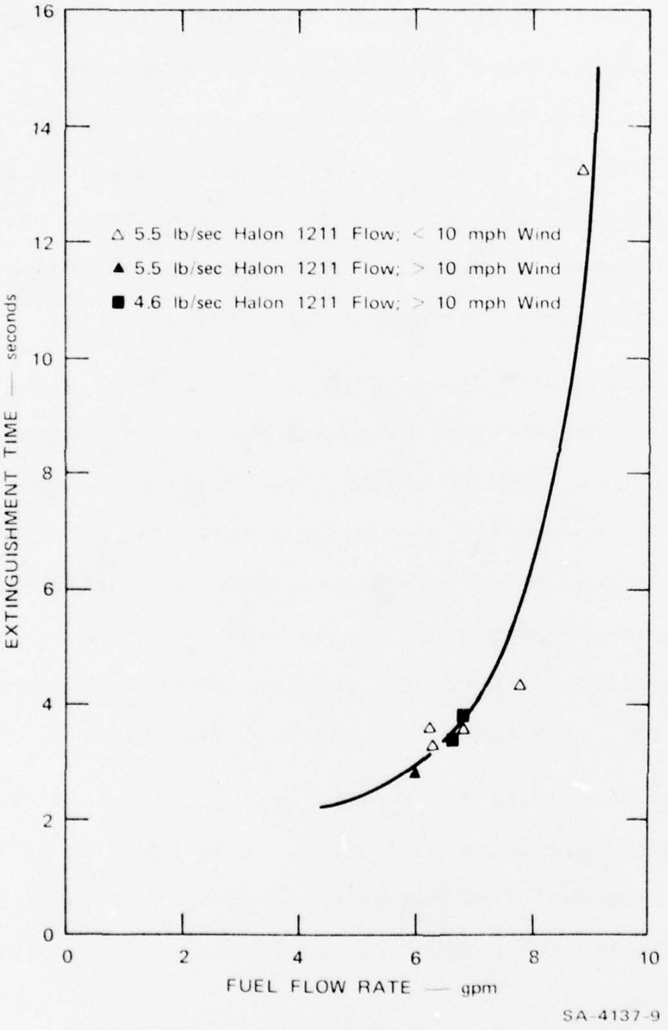

FIGURE 17 HALON 1211 EXTINGUISHMENT

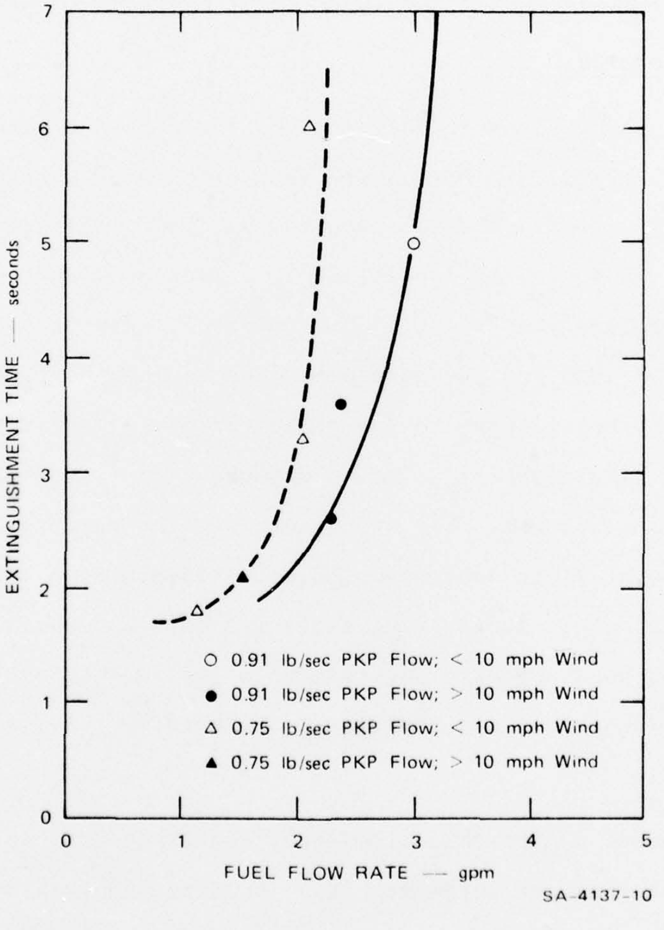

FIGURE 18 EXTINGUISHMENT BY PKP OF JP-4 FIRES USING THE AIR INJECTION NOZZLE FOR THE FUEL

5.0 DISCUSSION

The cascade fire as designed is a well-defined kinematic fuel fire and appears to be suitable for testing countermeasures for the spraying and pouring fuel fires that often occur in aircraft accidents.

5.1 The Fuel Burning Rate

The fuel burning rate is controlled by the spraying rate. The burning rate of 0.2 in^3/min per square inch of burning surface (0.125 gpm/ft^2), given in the introduction as typical of severe fires with JP-4 and JP-5 fuels, is approximately a flow of 4 gpm over the 4-foot by 8-foot fire panel. With our apparatus, burning rates of approximately 1.5 to 6 gpm are possible. The minimum burning rate, determined by the point at which the flames involving the fuel from the upper and lower nozzle sprays merge to produce a continuous fire, occurs at rates of 1.5 to 2.5 gpm. The wind increases the spraying rate required to prevent flame separation; e.g., a 15-mph wind requires the 2.5-gpm spraying rate. At spraying rates greater than about 6.0 gpm, some of the fuel does not burn and runs into the collection trough at the bottom of fire panel, and therefore, the burning rate is less than the spraying rate.

Two fire panel design characteristics contribute to the wide range of burning rates that are possible: (1) the fine atomization nozzles and (2) the ability to heat the front surface of the plate.

To get the fine atomization of fuel, it was necessary to change the nozzles for different flow rates and apply at least 30 psi pressure at the nozzles, as previously explained. Nozzles producing larger drops were used in preliminary experiments and found to permit some of the fuel to escape unburned.

The shingle design permitted the front surface to become hot and still not warp the structure. As can be seen in Figures 4(b) and (c), the shingles warp but the structure remains rigid because the frame and back surface are water cooled. The shingle design also permits easy replacement of shingles that become badly warped. However, we did not find replacement necessary in all of our testing. The shingles characteristically reached temperatures of 750 to 1000°F when burning JP-4 or JP-5 and 500 to 600°F when burning methanol, while the back plate was usually maintained at less than 200°F.

5.2 Wind Effects on Flame Extinguishment

As previously mentioned, only wind directions that were within the quadrant of -45° to $+45^{\circ}$ from normal to the fire panel were permitted in the data of extinguishment results. As long as the wind direction was within this quadrant, and below 18 mph, the maximum velocity examined, the times to extinguish were within about ± 50 percent of the average time. High wind speeds and close to the normal direction made extinguishment slightly easier. The solid fire panel, as contrasted to a fire on a screen, which has been used in previous kinematic fuel fire tests,[3] appears to make the dependence of extinguishment results on wind variations manageable.

Crosswinds of a direction greater than 45° from the normal direction, and especially those of a direction greater than 90°, greatly impaired extinguishment. With these winds, much of the fuel spray would be carried away from the panel before burning, and the fire area would be increased and not well-defined. The person trying to extinguish the fire would therefore not be able to approach the fire as closely as when the wind direction was closer to normal.

For a cascade fire test facility, it may be worthwhile to design an apparatus that could be rotated so that test operation would not depend on wind direction. In our case, the prevailing winds at the test site are such that the direction is usually within the proper quadrant.

5.3 Adjustable Fire Panel Size

An adjustable fire size for testing various types and sizes of extinguishing systems was identified as a desirable feature of the apparatus. The fire panel is designed so that each 4-foot by 8-foot section is a module, and modules can be added as desired. Most of our tests were done with just the one module; however, a second module was added for a few tests, particularly the Halon 1211 extinguishment tests. As was stated in the Phase I report,[1] to evaluate extinguishment, it is important that the fire is not overwhelmed by the extinguishing action and that the fire challenge the extinguisher ability.

A one-module fire panel sufficiently challenged the dry chemical extinguishing systems that were used. The fire size (fuel flow rate) could be adjusted from easily extinguishable to impossible to extinguish. However, a two-module panel gave a fire that could not extinguished by our dry chemical extinguishing systems.

For the Halon 1211 system, the two-module fire panel appeared to be a good size.

There appear to be no fundamental problems in adding fire panel modules except that the fuel and water requirements increase directly with fire panel area and may become cumbersome after two or three modules.

It appears that difficulty of extinguishment is not directly proportional to fire panel size. Two examples support this conclusion. First, it can be seen in Figure 13(b) that a 3-gpm JP-4 fire on the one fire panel can be extinguished quite easily, usually within 4 seconds at a 0.75 lb/sec PKP flow. Yet, a 6-gpm fire on a two-module fire panel could not be extinguished by two extinguisher operators acting simultaneously using PKP extinguishers with 0.78 and 0.91 lb/sec flows.

In a second example, using the Halon 1211 extinguishing system, a 6-gpm fire on a one-module panel required only a short burst of extinguishant, 20 pounds, while a 9-gpm fire on a two-module panel required 82 pounds of Halon 1211 and a 10-gpm fire could not be extinguished.

Although a quantitative basis for difficulty of extinguishment has not been well-defined and is, in fact, based on different criteria for the two examples above, the examples suggest that the difficulty of extinguishment increases more rapidly than fire panel size as the number of modules is increased.

We had hoped to compare the relative merits of the dry chemical extinguishants with the Halon 1211, but this was not possible because of the application rates and patterns available and the different-sized fires required to challenge the two extinguishing systems.

5.4 The Relative Merits of Using the Air Injection Nozzle Versus The Fan Spray Nozzles

The advantage of using the air injection nozzle is the less smokey fires. However, the fan spray nozzles give other fire characteristics that are better for fire countermeasure tests.

The smokeless feature of the air injection nozzle is a result of (1) the fine atomization of the fuel that results from the air injection and (2) the mixing of some of the oxygen required for burning with the fuel to give a partially premixed flame. The fine atomization of the fuel is probably the dominant factor in producing the smokeless fires as a 3.5-gpm fire requires about 300 lb/min of air and only 2 lb/min is supplied through the nozzle; i.e., less than 1 percent of the combustion air requirement. However, when nitrogen was used in place of air, the maximum burning rate for smokeless fires was about 3.0 gpm.

The fire characteristics and required extinguishment techniques are considerably different with the two nozzle options. The fires produced with the single air injection nozzle were easily extinguished with PKP at the fuel flow rates at which extinguishment was possible. The dry chemical powder stream was aimed at the nozzle outlet and the powder was carried with the fuel stream. Little skill by the extinguisher operator was required. With the fan spray nozzle fires, the extinguishing technique was to begin extinguishment at the bottom of the fire panel and continue up the fire panel, finally "pushing the flames off the top" while preventing flashback to the bottom of the fire panel. Therefore, extinguishment of the fires generated with the fan spray nozzle required a skilled operator. The required extinguishment technique is probably characteristic of that needed for many accidental kinematic fires. While the present design with the one air injection nozzle may be satisfactory for use in testing fire suppression agents, the multiple fan spray nozzle option is much better for testing extinguishment techniques and training firemen. The appendix describes fireman training exercises conducted with the cascade fire apparatus.

The difference in fire and extinguishment characteristics between the two nozzle options is a function of (1) the single spray pattern of the air injection nozzle versus the interacting spray pattern from the upward and downward pointing fan spray nozzles and (2) the air injection versus no air injection. The use of two or more nozzles to give an interacting spray pattern instead of a single source of fuel is necessary to simulate the accidental fires.

If it were possible to construct an air injection nozzle that gives a spray pattern similar to the fan spray nozzles, air injection nozzles would be satisfactory and air pollution problems diminished. However, no such commercially available nozzles were found. The design problem in constructing such a nozzle is to provide air injection at a high enough pressure at the nozzle exit to finely atomize the fuel and yet minimize the induced fuel droplet velocity after exit from the nozzle. The design and construction of such a nozzle could not be done within the funds of this project.

6.0 CONCLUSIONS

In Phase I of this program the cascade fire was selected from the various kinematic fuel fires to characterize and simulate in a test facility. The apparatus for simulating such a fire was designed and tested for its suitability in testing fire suppression agents, application apparatus, and techniques. Conclusions about the cascade fire apparatus and also about suppression effectiveness of the agents used in experiments follow.

6.1 The Cascade Fire Apparatus

The cascade fire apparatus provides for:

- A kinematic fuel fire with a controllable burning rate of from 0.7 to 0.3 in^3/min per square inch of burning surface (0.04 to 0.2 gal/min/ft^2) when using JP-4 or JP-5 aircraft fuels. The controllable burning rate is made possible by the fact that all the sprayed fuel is burned. The controllable burning rate makes it possible to vary the degree of difficulty of extinguishment.
- A reproducible fire; that is, a fire for which the difficulty of extinguishment from fire to fire is the same.
- A flame geometry that minimizes wind effects. The solid back plate behind the fire provides for a minimization of wind effects on extinguishment as long as the wind direction is within the quadrant of -45° to $+45^\circ$ from the normal. Maximum tolerable wind speed is 15-20 mph, above which the spraying fuel, particularly the unburned fuel before ignition and after extinguishment, is dangerously scattered in the surrounding area.
- An adjustable fire size by virtue of the modular nature of the fire panels. Our experiments included one- and two-module panels, which resulted in a 4-foot-wide by 8-foot-high burning area or an 8 foot by 8 foot area.

Two different nozzle options were used. The air injection nozzle produced smokeless fires but did not, in its present single nozzle arrangement, yield a fire suitable for many of the countermeasure testing applications. In contrast, the fan spray nozzle option provides a fire that is well-suited for many countermeasure testing applications, including testing agents, testing techniques, and training firemen in countermeasure techniques. However, the fires were quite smokey.

6.2 Evaluation of Extinguishing Agents

The two dry chemical extinguishing agents, Monnex and PKP, required approximately the same amounts at similar flow rates to extinguish the JP-4 fuel fires. The Monnex was more effective in extinguishing the JP-5 fuel fires, requiring about 75 percent of the amount of PKP to extinguish the fires. With Monnex, several 5.5-gpm JP-5 fires were extinguished, while the largest JP-5 fire extinguished by PKP was 4 gpm.

JP-5 fires proved to be considerably more difficult to extinguish than JP-4 fires with the dry chemical powders. Maximum fuel flow rates that were possible to extinguish were 20-40 percent higher for JP-4.

It was not possible to compare the extinguishment effectiveness of the Halon 1211 with the dry chemical powder either on a weight effectiveness or a cost effectiveness basis because of the different capacity extinguishers used. This was because the Halon 1211 extinguisher system had a mass per second output more than five times that of the dry chemical extinguishing systems, and two modules of fire panel had to be used to challenge its capability.

Appendix

FIREMAN TRAINING EXERCISES USING THE CASCADE FIRE APPARATUS

Four firemen from the Camp Parks, California Fire Department participated in experimental firefighting training exercises using the cascade fire apparatus. Two fire extinguishment situations were used: (1) a 6-gpm JP-4 fire on the 8 foot by 8 foot fire panel with Halon 1211 at a flow rate of 5.5 lb/sec and (2) a 4-gpm JP-4 fire on the 4 foot by 8 foot fire panel with the hand-held 20-lb PKP extinguisher.

Our two staff members who operated the extinguishers and had con-considerable practice by this time were quite consistent in extinguishing these two fires, the first one requiring them three to four seconds, or about 20 pounds of Halon 1211, and the second requiring four to six seconds, or less than 5 pounds of PKP. Previous experience by the firemen had been almost entirely with water. Almost all training in the use of dry chemical powder extingishers had been by demonstrations.

Each of the four firemen was given one attempt with the Halon 1211. They extinguished the fires with 18, 73, 35, and 32 pounds of agent. It is interesting that the fireman who used only 18 pounds of agent had received some training in the use of CB extinguishers while in the Air Force Reserves. The next fireman, who used 73 pounds of agent, let the fire flash back to the bottom of the fire panel several times before mastering the technique of sweeping the fire from the panel. The next two participants appeared to have learned how to prevent the fire from flashing back to the bottom of the panel from watching the second fireman. However, they were very cautious in doing so, and therefore used more agent than required for the most efficient extinguishment.

Each fireman had two or three attempts at extinguishment with the hand-held PKP extinguisher. In the initial attempts only one of the firemen was able to extinguish the fire. The main problem was preventing flashback to the bottom of the panel after beginning to sweep upward. The second problem was failing to step closer to the panel after the bottom half had been extinguished so that sufficient powder would reach the top of the panel. In the second attempts one more fireman was able to extinguish the fire. For the third attempt, the fuel flow rate was decreased from 4 to about 3 gpm. One more fireman was then successful in extinguishment, however, one was still unsuccessful.

The use of the cascade fire apparatus appeared to be suitable as a training facility. In training firemen there is the danger of having practice fires that require an extinguishing technique that is not characteristic of that required in actual fires. However, the cascade fire apparatus appears to provide a test of the ability to sweep a fire from a flowing or spraying fuel while preventing flashback to that part of the fire already extinguished, which is the important criteria in extinguishing actual accidental fuel leak fires.

Two characteristics of the facility were particularly appealing to the firemen: (1) the ability to rate the effectiveness of the fireman in extinguishing the fire and (2) the ability to vary the difficulty of extinguishment so each extinguishing system can be challenged.

For each fire extinguishing system situation, a minimum extinguishing time or a minimum required agent can be established. The fireman can then evaluate his effectiveness against that standard.

The difficulty of extinguishment can be varied by varying the fuel flow rate and also the number of fire panel modules used. Therefore, each extinguisher can be challenged. Also, after a fireman masters the extinguishment of relatively easy fires, the difficulty of extinguishment can be increased to still provide a challenge.

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