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AVIATION FUEL FIRE BEHAVIOR STUDY

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Naval Civil Engineering Laboratory

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Quantitative data obtained consists of the significant spectral emission bands of aviation fuel fires, the fuel burning rates, the thermal radiation field and the temperature profiles downwind of the fires. Results show that the radiation depends strongly on the dimensionless distance from the fires (distance to pan center/pan diameter) and only weakly on the fire size, suggesting the possibility of simple scaling relationship.

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Intensity of heat near pool fires						
Spectral radiation from hydrocarbon flames						
Water spray-effect on pool fires						
Wind effects on pool fires						
Flame geometry of pool fires						
Burning rates for pool fires						
Radiation scaling for pool fires						

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AVIATION FUEL FIRE BEHAVIOR STUDY

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TECHNICAL REPORT
AGFSRS 72-2
February 1972

Aircraft (Ground) Fire Suppression and Rescue
System Program Office (DOD AGFSRS)
Wright-Patterson Air Force Base, Ohio 45433

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FOREWARD

This program was conducted under MIPR FX2826-70-05281 by the U. S. Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California for the Aircraft Ground Fire Suppression and Rescue (AGFSR) SPO in support of System 414N. Mr. Marvin Tyler, ASD/SMF, was program monitor for the AGFSR SPO. This report, No. AGFSRS 72-2, covers research for the period March 1970 to August 1971 under NCEL Work Unit Number 63-016.

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The author wishes to express his thanks to Mr. J. M. Stephenson for his continued interest and assistance during the course of this study, to Mr. R. S. Chapler who helped prepare some of the experimental setup, and to Mr. J. B. Crilly who assisted in the flame emission spectra measurements.

PUBLICATION REVIEW

This document was submitted by the author in February, 1972. It is published to reflect the data obtained and results of fire tests conducted by the author. This report has been reviewed and is approved.

ROBERT B. ARTZ, Lt. Col, USAF
System Program Director
Acft Gnd Fire Suppression and
Rescue SPO

AVIATION FUEL FIRE BEHAVIOR STUDY

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INTRODUCTION

The fire fighting and rescue of crashed aircraft is of ever-increasing concern as new higher speed and larger size aircrafts are developed. In order to improve the present fire fighting techniques and the capability to meet the increasing requirements, adequate knowledge of the behavior of aircraft fires which may occur either on board and/or as a result of a crash landing is clearly important.

For fire fighting and rescue, the understanding of the gross behavior of fires is of primary interest. The types of fires associated with a crashed aircraft are many and the amount of quantitative data on fire behavior directly relatable to the present need of Aircraft Ground Fire Suppression and Rescue Systems (AGFSRS) is insignificant. Of the many aspects of the behavior of a fire, the most needed information for the description of a fire consists of: the fuel burning rate, flame configuration, and the thermal environment. These basic elements are affected by atmosphere conditions such as the ambient wind, temperature humidity, and precipitation.

Among the factors affecting the behavior of a fire, the ambient wind is conceivably the most significant one. A common experience with a windblown fire is the tilting of the flame, consequently, the amount of energy feedback (Reference 1, 2) into the fuel is varied and the burning rate affected.

Flame bending changes the radiation and the temperature level in the neighborhood of a fire. This is an important factor in fire spread either by extending the fire front or by the radiation field and is, therefore, an important factor in deciding the optimum fire fighting strategy, the rescue path, and the design requirements for AGFSRS equipment. A limited amount of data on the effects of wind to flames are available (References 3, 4, 5, 6, and 7). These are primarily results of studies on small size fires of less than three foot diameter. The fuel consisted of natural gas, low boiling liquids, and wooden cribs. Little data are available on the study of the behavior of fires of aviation fuels (References 8 and 9).

A review of the available literature such as mentioned above shows that there is, in general, a lack of information and understanding of the gross behavior of fires of aviation fuels. The work reported here is an initial effort to advance the state of the art and to obtain experimental data applicable to aircraft crash fire fighting.

Small size (up to 8') pool burning fires of selected fuels were studied in an indoor facility. The basic data obtained and analyzed consisted of:

Burning rate

Flame geometry

Radiation field

Temperature field

The effect of wind and water spray on the above items were studied.

PRELIMINARY CONSIDERATIONS

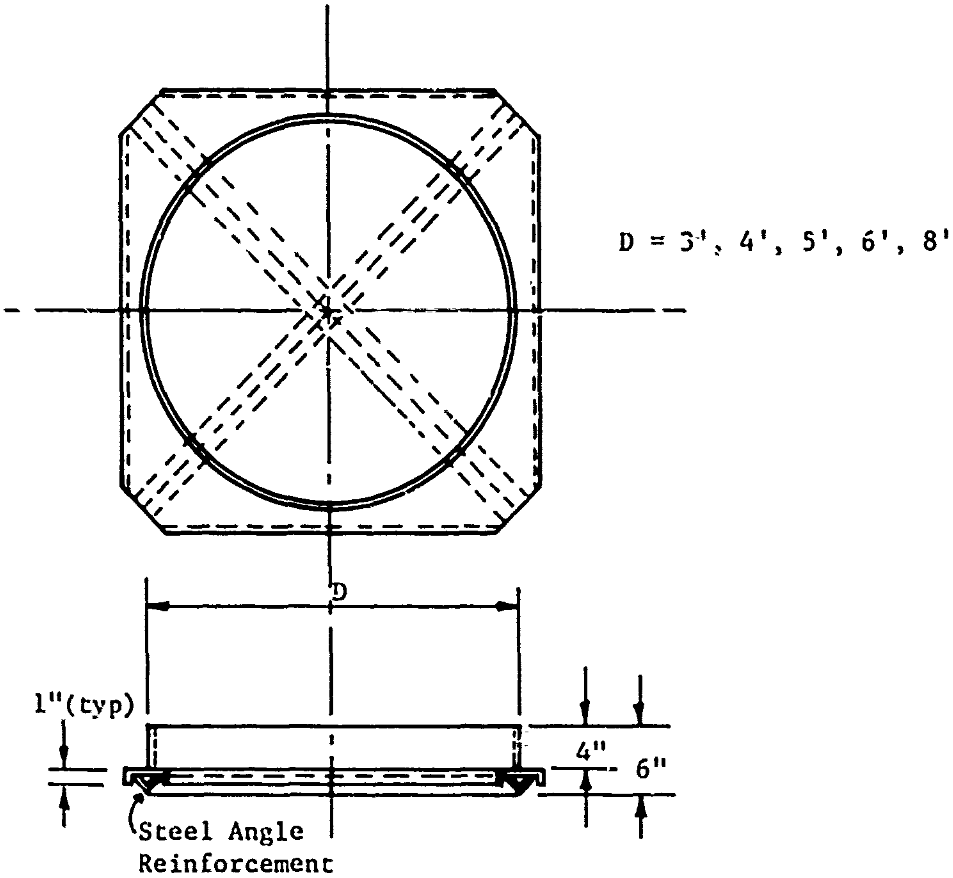
For the study of any physical phenomena, the repeatability of the experimental results is a firm requirement. It has been demonstrated that pool burning fires provide a convenient, well defined, and repeatable experiment (References 1, 10 and 11). Large full size fire tests are usually very costly; furthermore, the associated requirements in instrumentation observation method, personnel coordination, etc., may easily multiply the complexity of the whole task. To avoid excessive cost, the unnecessary confusion which might result from handling of large amounts of data, and the difficulties in isolating the governing parameters, small size fires of circular and rectangular pools of fuel were used in this study. The important considerations for this experimental study are described below in detail.

Pan Design

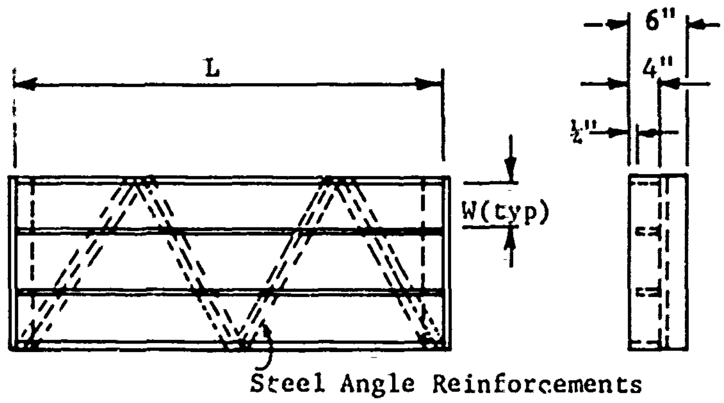
To provide meaningful data for AGFSRS applications, fires in the fully turbulent regime must be used. The data in Reference (1) show that turbulent burning starts at pan diameters as small as one foot and the fully turbulent regime starts at 3-foot diameter. The burning rate becomes nearly constant for fires larger than 3-foot diameter. Fires of sizes larger than three feet were used. For better control all experiments should be conducted indoors, therefore, this limited the maximum size of the fires to an 8-foot significant dimension.

Data of Reference (12) show that the burning rate is insensitive to the fuel depth in the pan for 3-foot diameter fires. For this study, pools of 4-inch depth are considered satisfactory to yield meaningful results. This depth will provide a maximum burning time of about 20 minutes (Reference 1).

The pans for pool burning experiments designed for this study consisted of circular pans of diameters D = 3', 4', 5', 6', 8', and rectangular pans of lengths L = 4', 6', and 8' with length-to-width ratios of 8:1 and 8:3. All these pans were 4" deep and were constructed using 10 gage (0.1345" thick) black steel sheets reinforced at the bottom with angle iron. The major dimensions of these pans are shown in Figure 1. All pans were placed on an 8' x 9' platform (an aluminum structure covered with asbestos board, (see Figure 2) and burning rate measurements were made by a weight loss method.



(a) Circular Pans

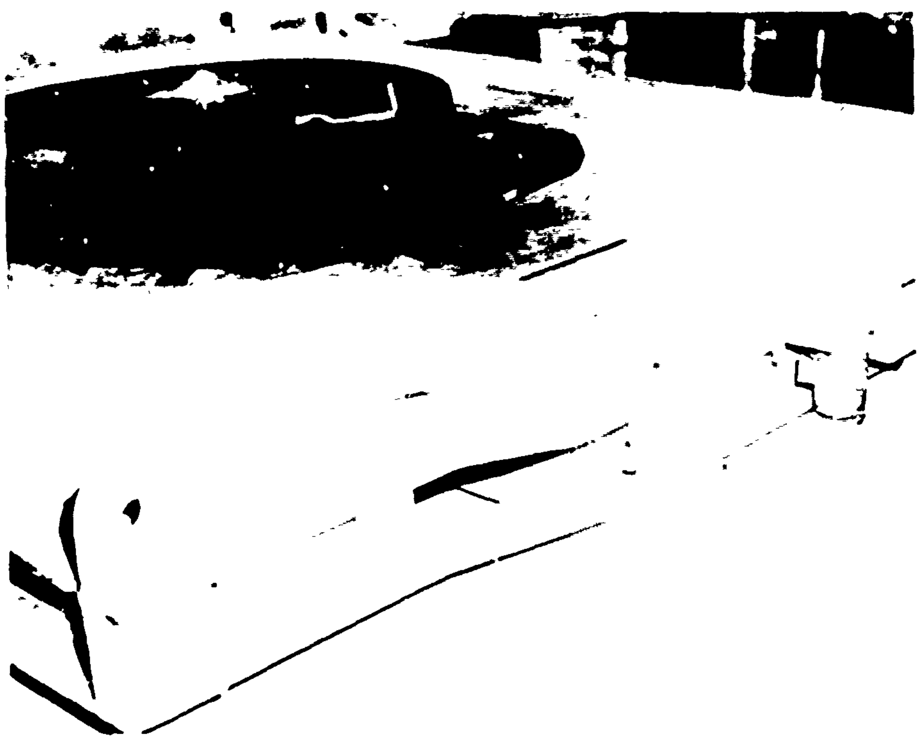


L, in.	48	72	96
W, in.	6	9	12

(b) Rectangular Pans

Figure 1. Pan designs for pool burning experiments.

(a) Platform



(b) Load Cell Installation

Figure 2. Weighing platform for burning rate measurement.

Fuel

For AGFSRS applications, the fires should be made with the commonly used aviation fuels. The use of aviation gasoline (Avgas) is diminishing, especially for military aircrafts. JP-4 is considered best suited for this work because it is the most widely used jet fuel and because it is more difficult to handle than a JP-5 fire (JP-5 is commonly used for naval aircrafts). In the work reported here, roughly the same number of fires were made and studied for each of the three fuels.

Some selected properties of JP-4, JP-5, and Avgas are summarized below:

	JP-4	JP-5	Avgas
Specification	MIL-F-5624G	MIL-F-5624G	MIL-F-5272E
Specific gravity $60^{o}/60^{o}F$	.802-.751	.845-.788	not limited
Maximum freezing point, ^{o}F	-72	-51	-76
Flammability limits at sea level, ^{o}F (Ref. 17)	-20 - 60	140 - 205	-40 - 15
Boiling point (weight average) ^{o}F	313	433	--
Maximum heating value, Btu/lb	18,400	18,300	18,900

Further information concerning these fuels may be found in Reference (13) or from the applicable military specifications.

Burning Rate

The total burning time of a pool of liquid fuel may be divided into three stages: heating, steady state, and burn out. The first two stages are self explanatory and usually do not vary greatly. Most of the fuel in the pool is consumed during these stages. However, during the burn out stage, the fuel layer is thin and the burning may be localized to several low spots in the pan usually resulting in a long burn out time. Therefore, the early method of expressing the burning rate by the fuel regression rate (in cm/min) can be quite misleading. For measuring the burning rate, the weight loss method used in this study is a convenient and precise method.

In order to weigh a high temperature burning pool of fuel and to provide a recordable output, a weighing platform was assembled. This platform was an 8' x 9' aluminum pallet covered with ½ inch thick asbestos boards and was supported on one edge by two self-aligned ball bearings and on the opposite edge by one load cell (Figure 2). This load cell was energized by a 6-volt battery and has an output of approximately 1 mv/100 lbs. To improve the sensitivity, the initial output of the load cell due to the dead weight of the platform itself and the pan was counterbalanced by an adjustable millivolt voltage source. The resulting output, due to the weight of the fuel in the pan, was then amplified before it was connected to the recorder. To avoid unnecessary intermediate calibrations, on-line calibration using a standard weight was performed each day prior to the tests. This method was found very reliable and convenient.

Flame Emission

For this study, the total radiation emitted from the fires is of primary interest. It has been used to specify the ignition threshold of combustible materials (Reference 18) and hence is important for establishing the design criteria for AGFSRS equipment. The spectral emission of fires must be known, however, in order to select the proper instrumentation for total radiation measurements.

The radiation emitted by a free burning fire depends on the combustion products. Aviation fuels are basically hydrocarbons and their combustion products, excepting the carbonaceous particles, are primarily carbon dioxide and water vapor which emit in the infrared region (Reference 8). Beckman Model IR7 and DK2 infrared spectrophotometers were used in this study to determine the prominent emission bands of these fires so that the type of radiometer and its window material could be properly selected. Figure 3 is a typical result of such measurements. It shows that all the significant emission bands fall in the range between 1 and 8 microns.

Radiation

Various methods are available for total radiation measurements from a fire. The desired features are high sensor output, wide viewing angle and large wave length band coverage. Since only averages over a reasonably long period of time (averaging time) are meaningful for the present purposes, fast response of the instrument, though attractive, is not a major consideration.

Figure 3 shows that the radiometer to be used must detect the radiation within the 1-8 micron range. In order for the radiometer to survive the sooty environment near a fire, a protective window was necessary to safeguard the fragile sensing surface. A window can

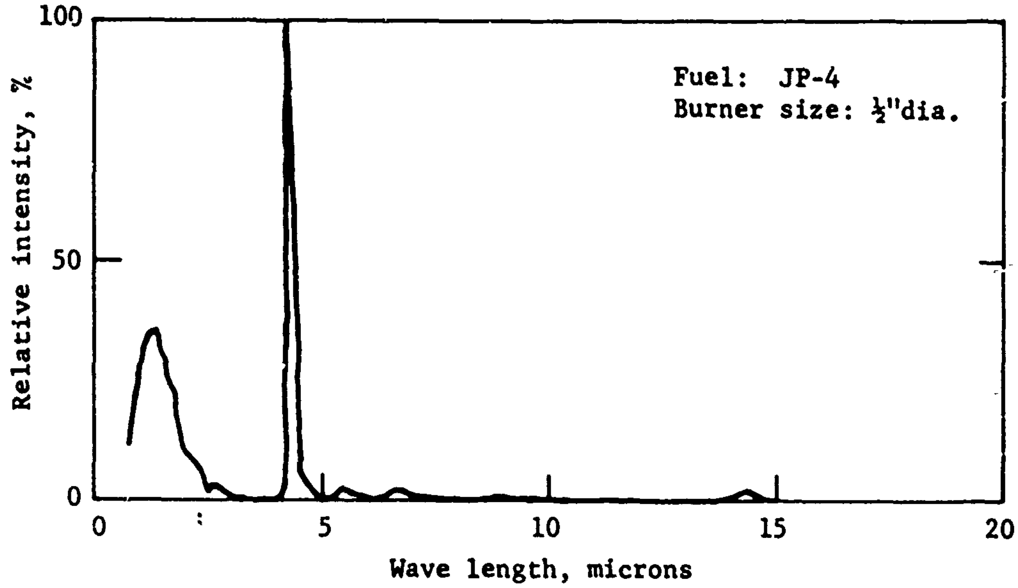


Figure 3. Typical spectral radiation of free burning aviation fuels

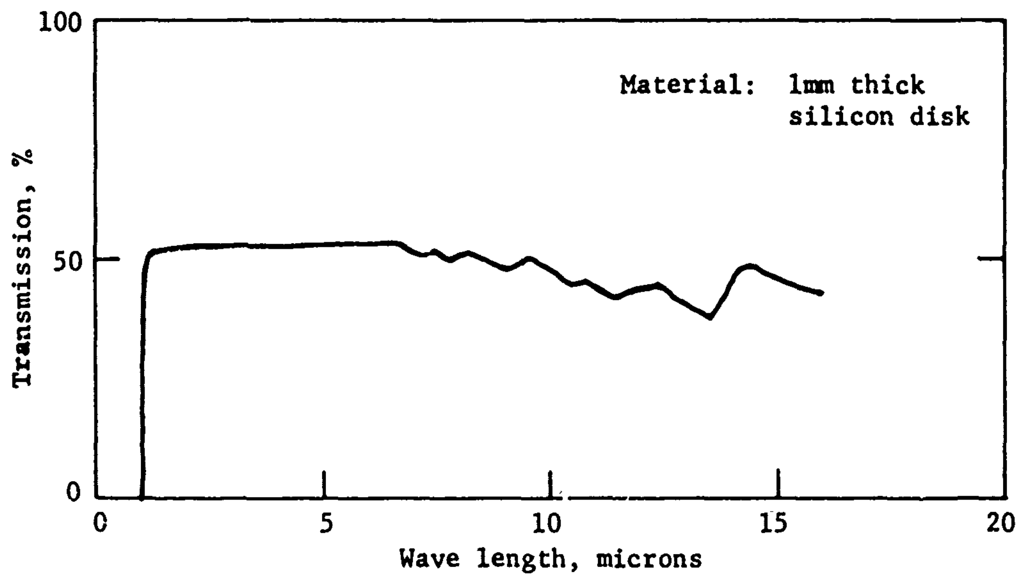


Figure 4. Typical spectral transmission of sil con radiometer windows

air to reduce the convection effects at the sensing surface. A review of the infrared filter materials reported in literature showed that silicon was probably most suited for this experiment in cost, ruggedness, and the flat infrared transmittance desired. It is essentially care free. The spectral transmission of the silicon windows (1 mm thick) used for this experiment were obtained using the Beckman spectrophotometers mentioned above. A typical curve is shown in Figure 4.

Three types of radiometers were used during the preliminary experimentations: thin foil asymptotic (Reference 14), calorimetric (Reference 15), and thermopile (Reference 14). These radiometers are shown in Figure 5. Data taken with these radiometers using 3-foot diameter JP-5 fires showed that the first two types on hand were undesirable due to the magnitude of the outputs and the limited ranges of radiation transmission of their protective window materials (sapphire and quartz, respectively).

The last type of radiometer was a series P-8400-B water-cooled, 150° view angle, pyrheliometer manufactured by Hy-Cal Engineering of Sante Fe Springs, California. With a silicon window, this radiometer has a sensitivity of approximately 24 millivolt per 1 Btu/ft^2-sec and a maximum output of 50 millivolts. This instrument was found most suited for the present work and was used for all the radiation measurements reported here.

Petroleum fires are usually accompanied by heavy, sooty smoke. Figure 6 shows the smoke plume above a 30' x 50' Avgas fire* taken at two different times. This burn was made on a clear day and the wind level was less than 5 mph. It is clear that the smoke height can vary in an indefinite manner, and the height can be very low. The radiation flux in the region of a man's height above the ground is of great importance for crash fire fighting and rescue. Therefore, three radiometers located at 0', 3', and 6' above the fuel pan were used for the early measurements in still ambient air. Radiation flux could have been measured at higher levels but because of the possible smoke blocking effects, the data would be meaningless at times.

Temperature

The temperature field outside an established fire is of considerable interest because of the threat to fire fighters and the potential of spreading the fire by means of convection. For fires in still air, the cold surrounding air moves toward the fuel bed; the air temperature in the neighborhood of the fire is virtually that of its ambient air. For fires under the effect of wind, the hot gas plume is bent in the downwind direction and the temperatures in this region can be quite high.

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*These were taken by the author in 1969 during a demonstration fire by Ansul Company, Marinette, Wisconsin.

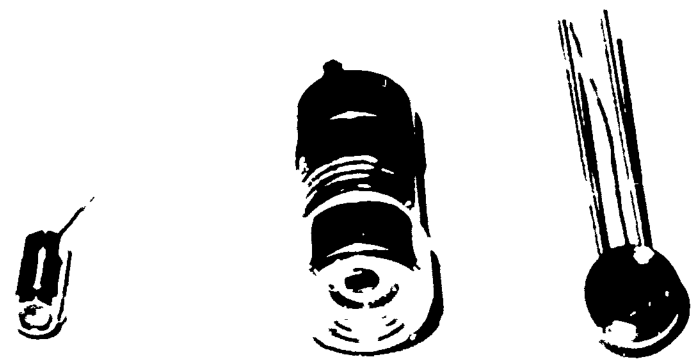


Figure 5. Radiometers investigated.

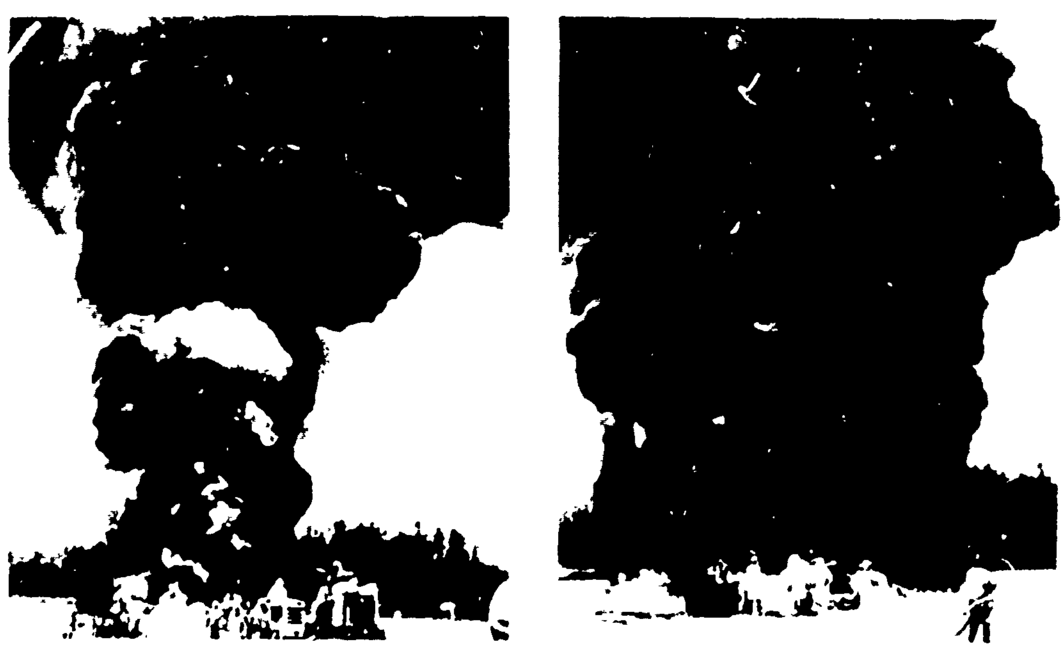


Figure 6. Open burning of aviation gasoline in a 30' x 50' berm.

Clearly, the temperature field downwind of a fire is of importance, therefore, temperature measurements were made in this area.

The maximum temperature inside the plume is about 1600°F (Reference 9). This serves as the upper bound of the temperatures to be measured. Thirty-gage chromel-alumel thermocouples were used for this work. In order to minimize the errors due to radiation effects, these thermocouples were shielded in chrome plated tubes (Figure 7). This design was reported to be very satisfactory for the present type of measurements (Reference 16).

Effects of Water Spray

A notable phenomenon in fire fighting is that the extinguishing agent in order to be effective must be delivered to the fire with sufficient momentum, otherwise, the extinguishing agent will be simply deflected by the convection current generated by the fire leaving the fire completely unaffected. During a rainfall the same argument holds true, i.e., only large rain drops would have any effect on the gross behavior of fires. Therefore, large water sprays were applied to the fires to study their effects.

Two Viking B2-120 nozzles were used to obtain a uniform water spray. This nozzle consists of two parts, the orifice and the body. The orifice is designed to obtain the desired spray cone angle; the body to obtain the flow rate and together they generate water particles. The body has one jet coming out tangentially and one axially; these jets strike each other before they emerge from the orifice and thus produce a solid cone of water spray of coarse water particles. By mounting these nozzles as shown in Figure 8, the spray could cover a 24-foot diameter area on the floor. The water particle size decreases with the increase of nozzle pressure drop, therefore, low pressure drop is desired to obtain large size water particles. The lowest pressure drop which could deliver uniform spray was found to be 10 psi.

The water spray rate in the platform area was checked for uniformity using collecting cans. At 10 psi pressure drop (no fire) the spray coverage was found to be essentially uniform within the accuracy of the measurements and the spray rate was measured to be 9.7 inch/hour. This setting was used for all the fire experiments.

It is to be noted that a precipitation rate greater than 0.3 inch/hour is classified as heavy rainfall. The objective in selecting a high flow rate was based on the assumption that if little effect could be observed in this heavy water spray, the normal rainfall would have no effect on the fire behavior.

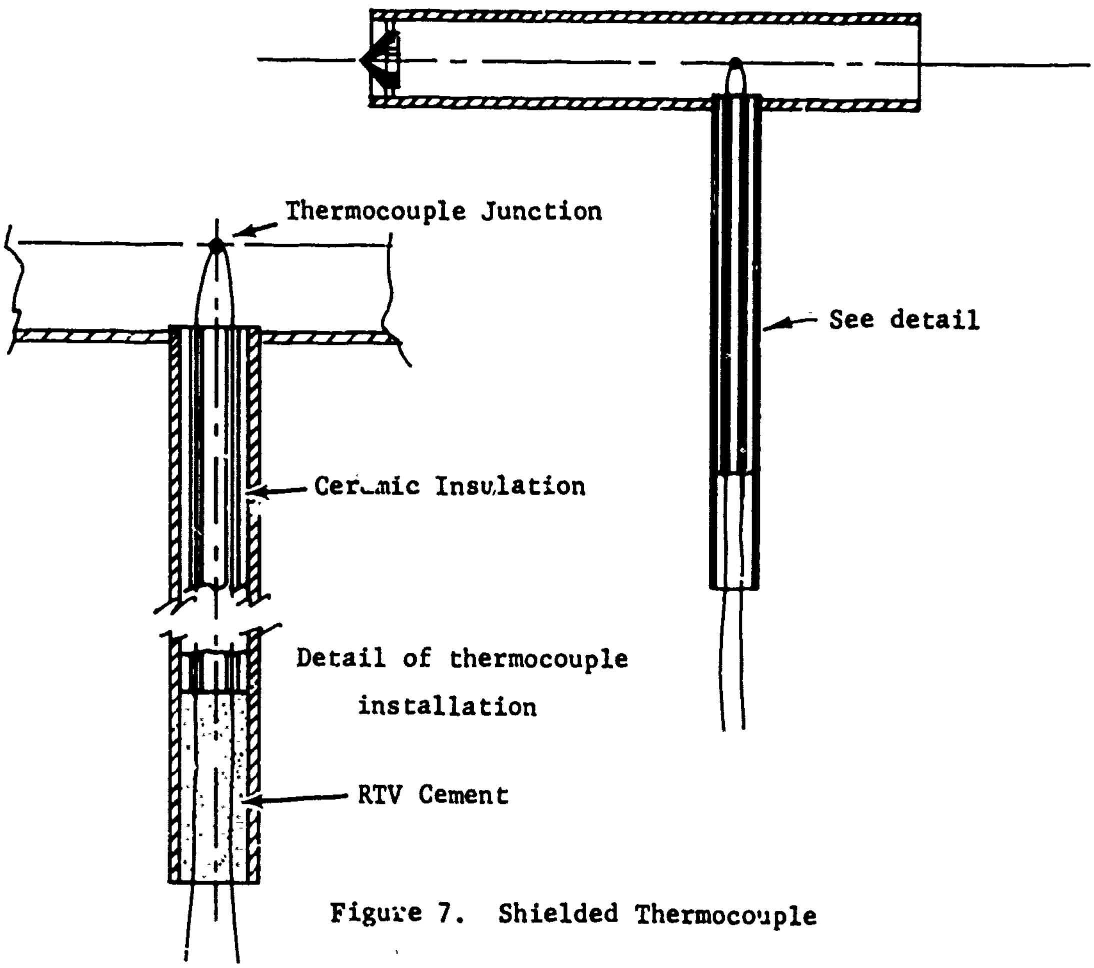


Figure 7. Shielded Thermocouple

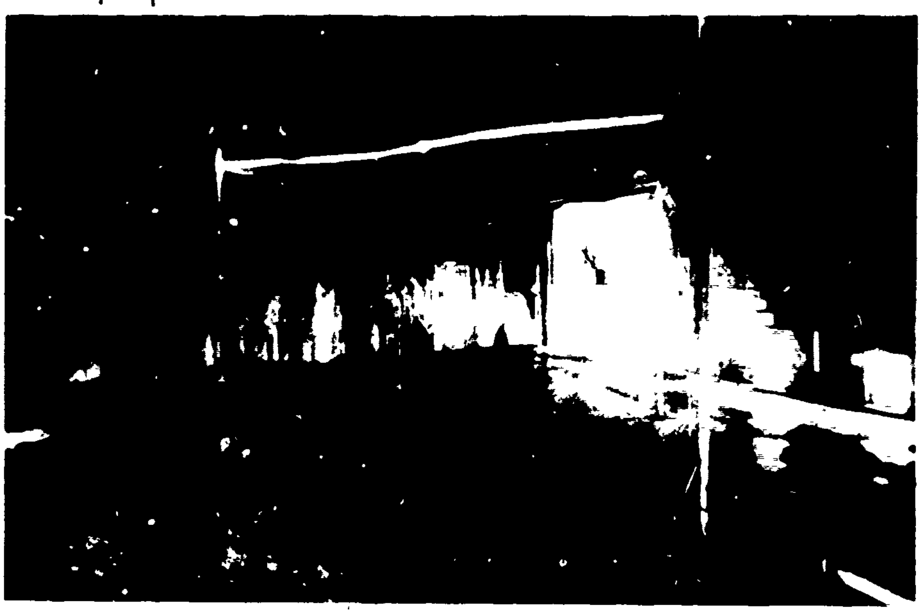


Figure 8. Water spray used during fires.

Effects of Wind

Wind is an important parameter governing the behavior of a fire. It is always desirable to conduct any experimental investigations in controlled environments; however, due to the large heat generation and other reasons, wind tunnel studies have been confined to small size fires. Welker (Reference 16) studied the wind effects in a 8' x 8' low speed tunnel on pool fires of low boiling liquids of up to 2' size for wind speeds up to 5 miles per hour. His data showed that at a distance of 5 pan diameters downwind of the fire, the radiation was essentially unaffected by the wind but at a distance of 15 pan diameters the radiation showed some decrease with wind speed.

For this study, only fires of sizes larger than 3' are considered. Clearly, it is cost prohibitive to conduct such large fire tests in a wind tunnel. An alternate approach was chosen by placing the fire at the entrance of a suction duct. This duct has a 5' wide by 7' high cross section and is driven by a diesel-fan unit. The top wind speed in this duct was 20 mph.

Averaging Time

The measurable quantities associated with an unconfined fire such as thermal radiation, temperature, and wind, can be characterized as low frequency, high amplitude fluctuations. In order to conveniently describe the gross behavior of a fire, averages of these quantities over a suitably chosen time interval, or averaging time, are of primary importance. To determine this averaging time, some preliminary fire tests were made using JP5 in a 3-foot diameter pan. The thermal radiation was taken using a fast response asymptotic type radiometer (Figure 5a). A typical recording of the output of this radiometer is shown in Figure 9. This record shows clearly the characteristic fluctuations of large amplitude and low frequency. The averaging time appears to be on the order of one minute. Based on this, RC filters of approximately one-minute time constant were constructed. These filters were connected between the radiometer and the recorder input which served to remove the large undesirable fluctuations.

As a matter of side interest, a fire whirl was developed during the above mentioned test. This whirl was a vertical column of whirling flame about 1.5' in diameter and 15' high which persisted for about one minute. Because of the relatively stationary configuration of this flame column, the radiometer output showed much less fluctuations during the whirl. This is also shown in Figure 9.

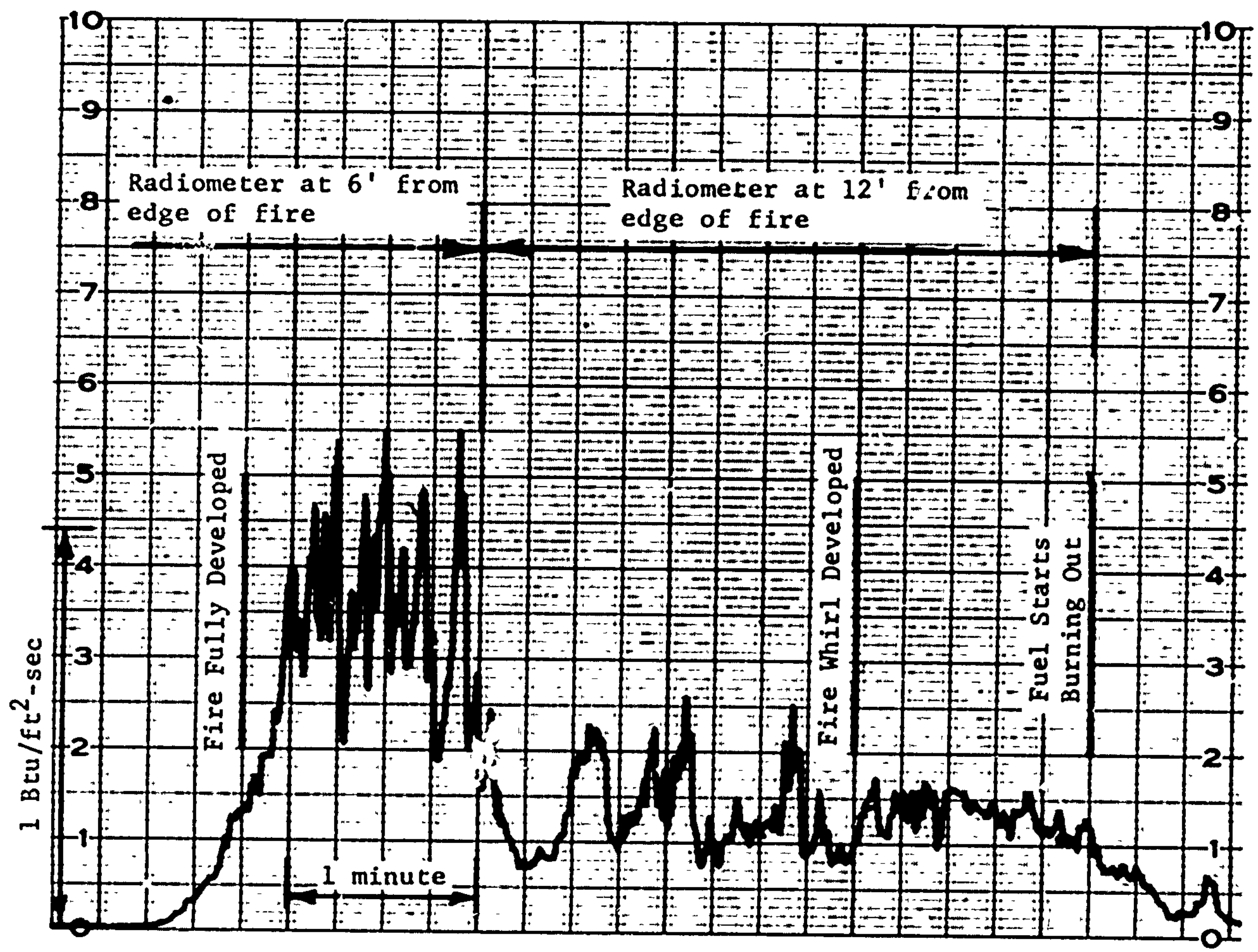


Figure 9. Unifiltered radiometer output (Hy-Cal Series R-2002-B radiometer with a sapphire window, 3' diameter JP5 fire).

Flame Geometry

Flame geometry, or shape, determines the view factor of the flame with respect to a fixed radiometer and hence the radiative heat flux that can be sensed by it. It is also an important parameter related to the fire spread. To describe the gross behavior of a fire, the average shape of the flame is of interest.

Photographic methods are desirable for this type of study. After some experimentations with high and normal speed movie cameras, it was found that full frame 35 mm color pictures would serve the purpose best. In order to have sufficient pictures taken during each fire, a sequence camera of 220 frame capacity was used. An automatic timing device was built to trigger the camera once every 5 seconds. The exposure was set for f/11 and 1/8 second with [illegible]0 film (ASA 100, positive). With a 50 mm lens the camera could be placed outside the southwest door of the building at approximately 24' distance from the center of the fires. This method was found to be very satisfactory for both picture taking and camera protection against heat and smoke.

EXPERIMENTAL SETUP

Test Facility

All the experimental work reported here was conducted at the NCEL fire test facility as shown in Figure 10. This facility is a 40' x 105' isolated test area bordered by two 7' high by 2' thick by 105' long concrete walls. A part of this area is an enclosed test room approximately 38' x 35' x 12' high inside dimensions. This room has two 10' wide sliding metal doors, one 30" wide access door, nine ventilation louvers, and a 5' x 5' exhaust stack connected to a 10' x 10' exhaust hood.

Along the south wall is a 5' x 7' wind duct with induced draft fan which can produce a uniform wind of up to 20 mph. The bellmouth inlet of this duct is connected to the room. Fires can be made near this inlet inside the room for wind effect studies.

A system of water spray nozzles is located inside the room for water spray effect studies. Water is supplied to the nozzles from an outside reservoir through a centrifugal pump of capacity 40 gpm at 38 psi. An 8' x 9' movable weighing platform (see also Figure 2) is used for burning rate measurements by weight loss method. Three fuel storage tanks are located outside of the north wall. Fuel is pumped to the test area by an explosion proof pump at a maximum rate of 15 gpm.

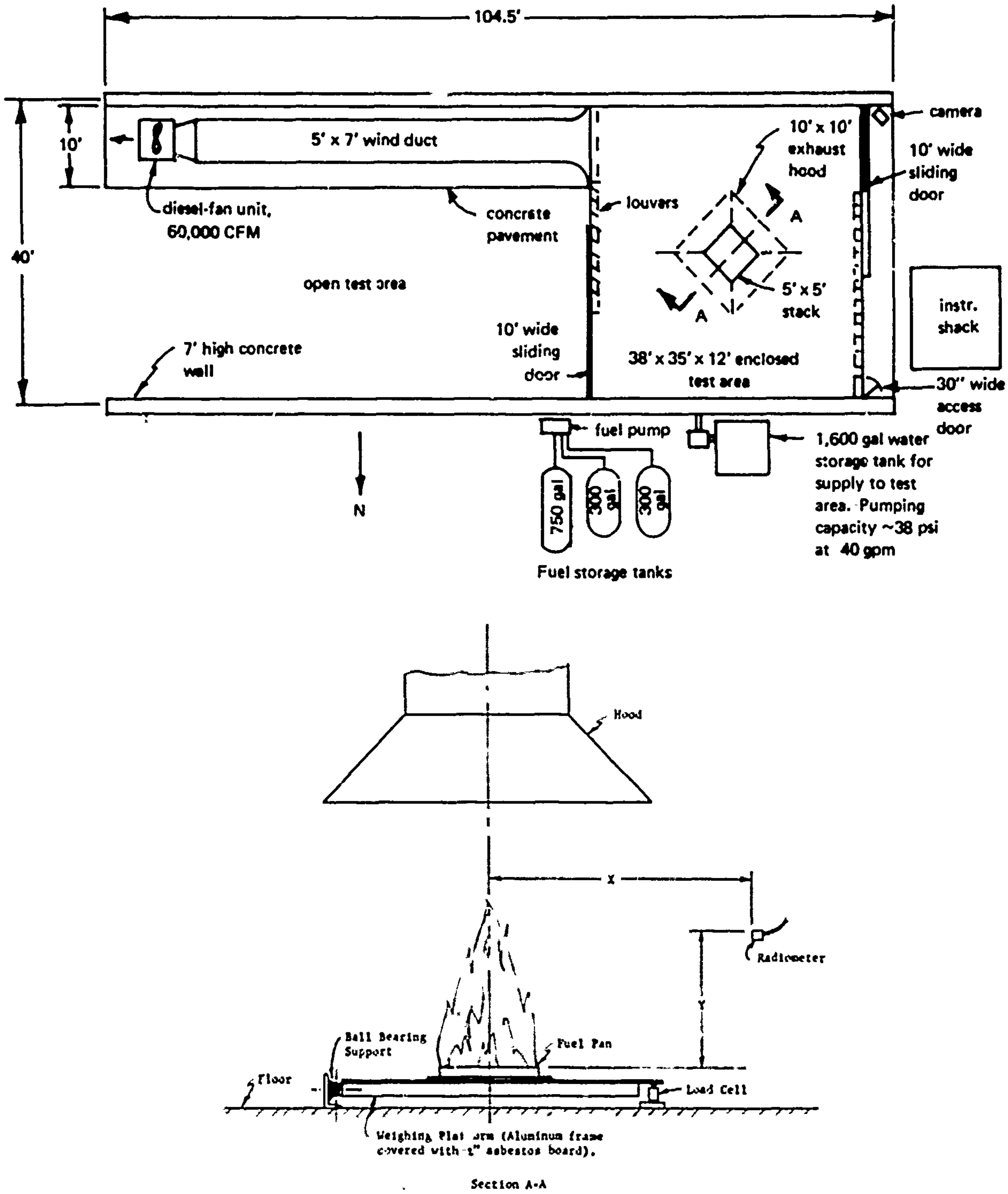


Figure 10. General layout of NCEL fire test facility.

A portable instrumentation room which is equipped with multi-channel recorder, tools, and the necessary instruments for the preparation of the experiments was located near the test room.

Tests in Still Air

For ths series of tests, the weighing platform was placed at the center of the room as shown in Figure 10. The fuel pan was placed at the center of the platform directly below the exhaust hood. Since the air temperature outside the fire is essentially that of the ambient air, no temperature measurements were necessary. Only the radiative heat flux Q (Btu/ft^2-sec) was measured.

The radiations were measured at various distances from the fires in a radial plane for circular fires and in the two principal planes for rectangular fires. The radiations at elevations 0', 3', and 6' above the fuel pans were taken at each of the selected distances from the fire. The radiometers were mounted on a vertical mobile rack with the windows positioned directly facing the fires.

A sequence camera was placed approximately 24' from the fire just outside the southwest door of the test room for photo-recording of the flame geometry.

For each test, the pan was filled 2" to 3" deep and radiations from the fire at several distances (X) were taken first. The water spray at a preset valve setting (10 psi or $\sim$ 10 in/hr for all fires) was then turned on to study its effect. The radiation data were taken at two distances from the fire during the spray. After this, the water was turned off and same data were again taken. This time, the fuel would be floating on the surface of a layer of water in the pan which simulated the condition of a spill fire on wet ground.

A typical set of data as recorded is shown in Figure 11. It is seen that the rate of weight loss, or the burning rate, of the fuel approaches a constant value in a relatively short period of time, say two minutes. But the radiometer outputs, with the high frequency components filtered out by a one-minute time constant RC circuit, still show a fair amount of fluctuations, this being the very nature of free burning fires.

It is interesting to note that these fluctuations decrease as the distance from the fire increases. This result is expected because the details of the flame fluctuations as seen by the radiometer are smeared out as the distance between them is increased. This reasoning is also evidenced from the data at large distances from the fire which approach the inverse square relationship (a relationship which holds only for point sources.).

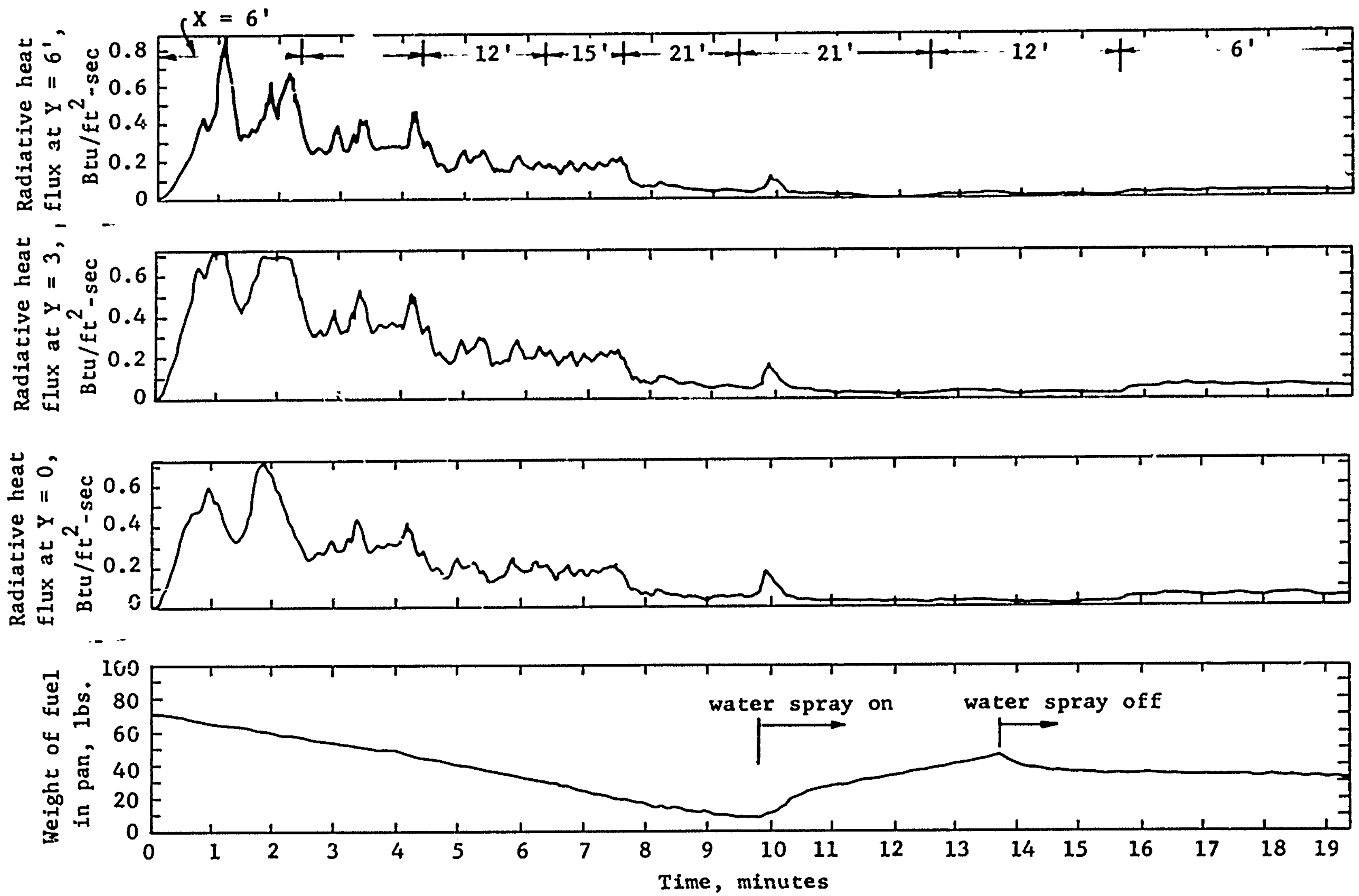


Figure 11. Typical data records (3' dia. JP-5 fire).

Tests Under Wind Conditions

As discussed earlier, the radiation and temperature fields downwind of the fire are of primary interest and the data obtained by Welker (Reference 16) showed that the wind speed did not have significant effects on the radiation measurements downwind of a fire for small values of X/D. For AGFSRS applications, the temperature and radiation fields downwind of fires are important. Therefore, 3-foot circular and 4-foot rectangular fires were made for this series of study and the measurements were made at distances close to the fire.

Results of tests in still air showed that the radiative heat fluxes at 0', 3', and 6' elevations were about the same and the one at 3' elevation was at about the average value. Some measurements were made at this elevation but this method was abandoned shortly afterwards because the bent over smoke plume could both block the view of the radiometer and quickly blacken its window which rendered the measurements inconsistent. In order to avoid the possible blockage by smoke, all the later measurements were made at 18" elevation. The experimental setup for this series of tests is shown in Figure 12.

For the tests reported here, the uniformity of the flow in the wind duct was checked by use of tufts attached to seven horizontal wires stretched at the duct entrance (Figure 13); and the wind speed by measuring the duct static pressure drop in connection with the fan performance data. Figure 13 shows that the flow at the duct entrance was essentially uniform.

QUALITATIVE DESCRIPTION OF THE FIRES

The test results obtained consisted of fires of JP5, JP4, and Avgas fuels. For quick referencing, each of the test fires was identified by the pan size and the fuel used as follows:

3DJP5: JP5 fire using 3-foot diameter pan.

4X1JP4⊥: JP4 fire using 48" x 6" pan (Figure 1), radiometers viewing in the direction along the center line normal to the pan length.

6X3AG||: Avgas fire using 72" x 27" pan (Figure 1), radiometers viewing in the direction along the center line parallel to the pan length.

For safety reasons, the fires of the least flammable fuel, JP5, were studied first. The qualitative (visual) behavior of JP5 fires are, therefore, described here first, JP4 and Avgas fires are then described to compare them with those of JP5.

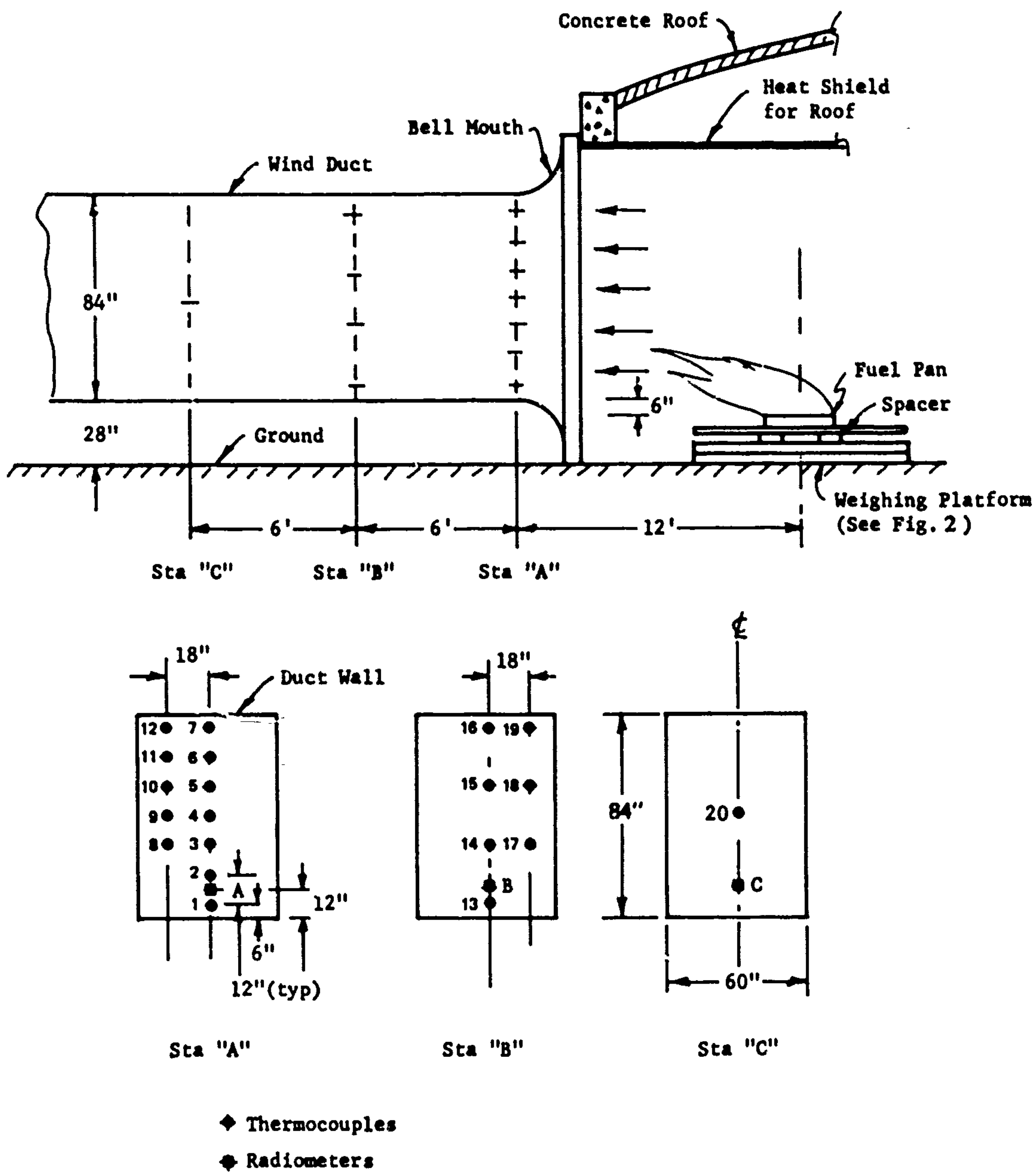
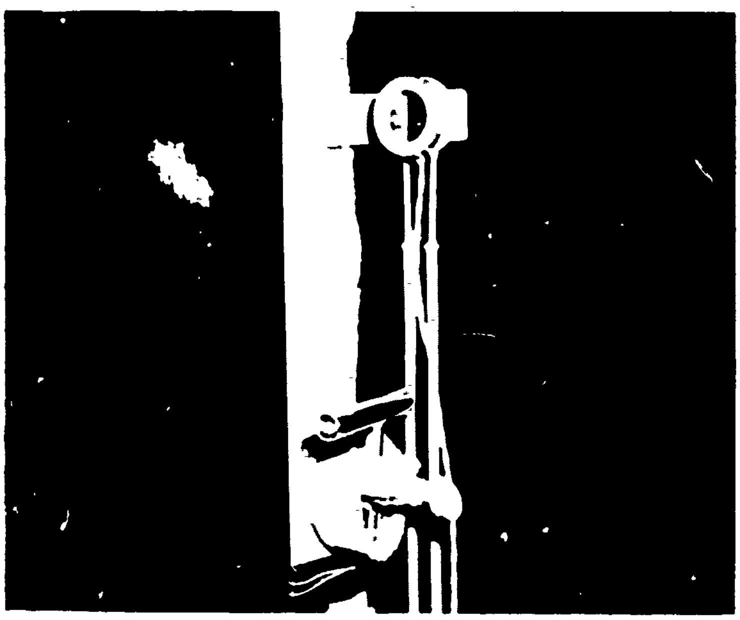


Figure 12. Experimental setup for wir: effect studies.

(a) Flow uniformity check by use of tufts.



(b) Close-up view of shielded thermocouple and radiometer.

Figure 13. Instrumentation at entrance section of wind duct.

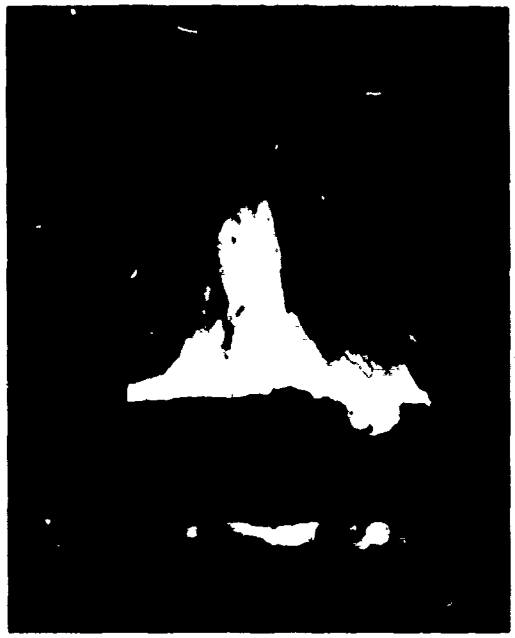
JP5 Fires

The ignition of JP5 is fairly difficult. Flaming wicks made of paper or rag were used to start a fire locally in order to preheat the remaining part of the fuel mass in the pan. The fire was always accompanied by the release of a large volume of dense, black smoke. The color of the flame was dark orange. Because of the smoke released, the flame was frequently shrouded by the smoke, especially at high elevations. For this reason, the radiation fluxes measured at high elevations would not be meaningful due to the radiation attenuation by the smoke in the optical path and by soot deposition on the radiometer window. The fire appeared to be unstable in the sense that the flame often moved or bent from place to place in a relatively unpredictable manner. Flame spilling and detachment from the fuel pan were quite obvious especially for large size fires (Figure 14).

During the burning process, the liquid fuel in the pool receives heat from the fire to vaporize the fuel for sustaining the burn. The fuel vapor usually fills in the space between the base of the flame and the free surface of the liquid fuel. When there is an excess of fuel vapor or an "overly buoyant" plume or both, the flame tends to be pushed or moved away from the pan which allows the heavier-than-air fuel vapor to disperse around the pan. The spilled fuel vapor then ignites and looks like a spilled flame. By this mechanism, when there is a cavity (for example, an empty trough in the rectangular pans used here) adjacent to the fuel pool, flame above the cavity can often be seen. This gives one a false feeling that the burning is also originated from the cavity. The layer of fuel vapor above the fuel free surface is somewhat unstable, this may be attributable to the unpredictable nature of flame spilling.

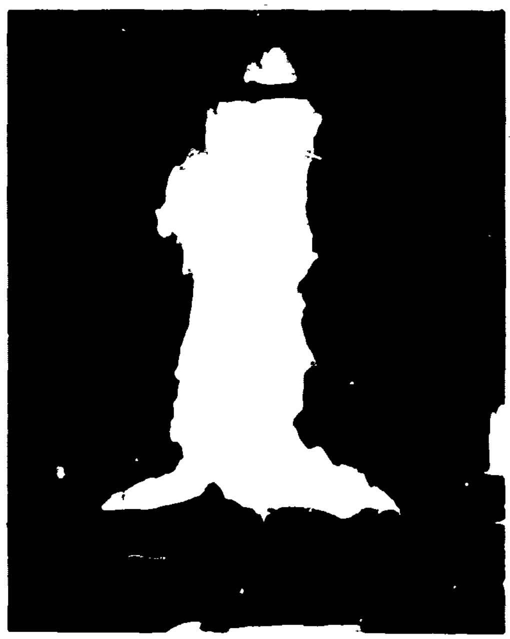
Water spray had a definite effect on the sensible heat radiation. This was due to both the quenching effect of the water and the radiation absorption by the water (in both liquid and vapor form) in the optical path. To express it qualitatively, an observer could feel a sudden relief of the intense heat as soon as the water spray was turned on. When the amount of fuel in the pan was not large, the water spray could sometimes extinguish a 3' or 4' fire. When the amount of fuel in the pan was large (say 1" thick or more), the flame was sometimes lifted a few feet from the base of the pan and was widely spread and the fire appeared to be nearly extinguished (Figure 15). This spectacular phenomenon would last for a few seconds. After this, the burning in the pan would resume and the fire became well behaved, i.e., the flame was more or less straight up and flame was relatively short (Figure 16). The smoke was sometimes essentially gone and the flame appeared to be brighter but the radiation level was considerably reduced.

8DJP5



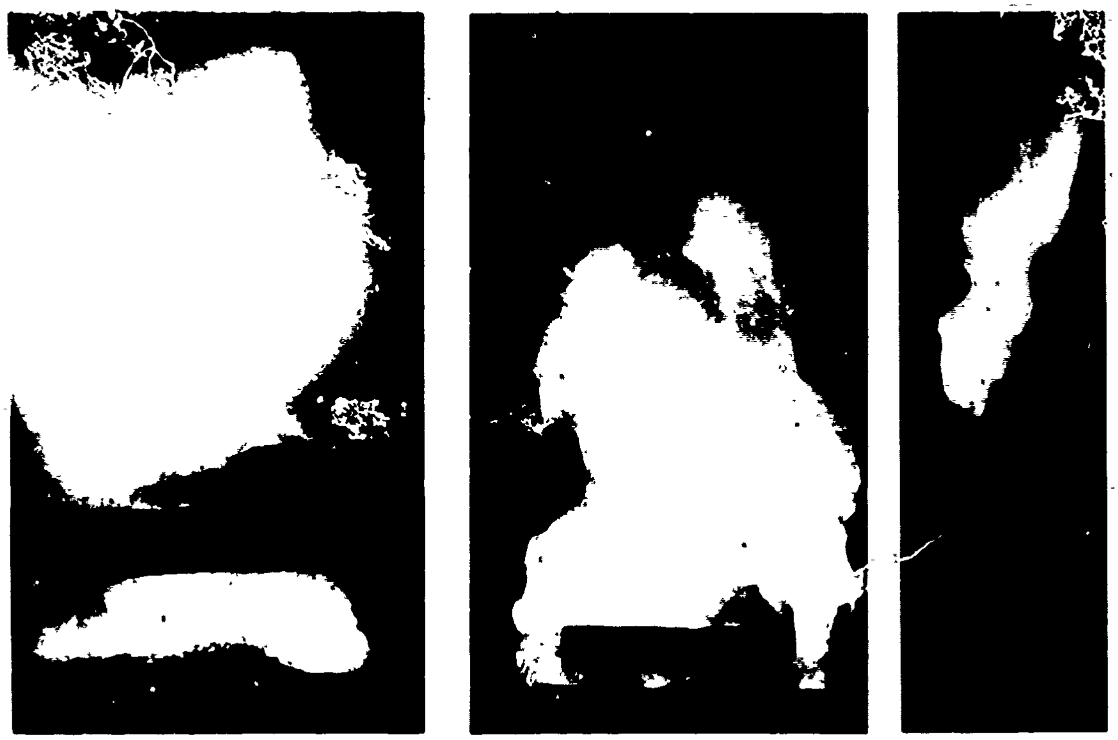
6x3JP5

8DJP4



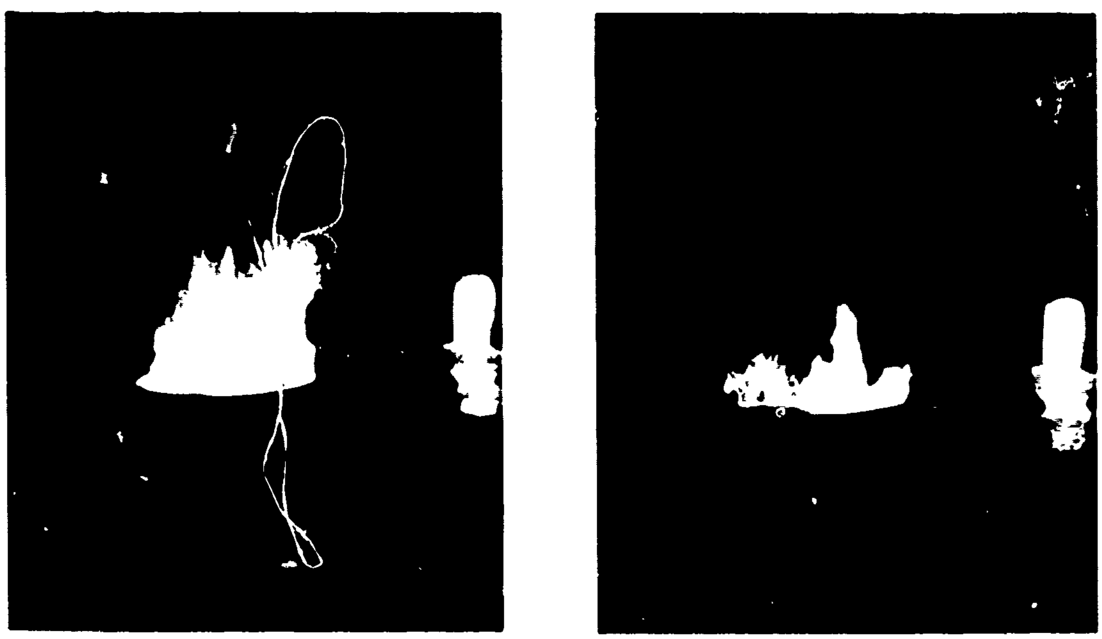
6x3JP4

Figure 14. Flame spilling and detachment.



3DJP5 4x1JP5 4x1JP5

Figure 15. Flame responding to water spray.



(a) During water spray (b) After water spray - burning on surface of water

Figure 16. Burning during and after water spray - 4DJP5 fire.

When water is mixed in the fuel the burning can be continued for a very long time. Boiling of water at the interface can be clearly seen. Only one water spray rate was used during all the fire tests reported here. Thus the rate which appeared to be large to a small fire became relatively insignificant to a large size fire. Consequently, the effects of water spray diminished as the fire size increased. For the 8' diameter fire, except for some chilling effect and driving the smoke out of the room, the water spray did not appreciably affect the fire behavior.

After the water spray was turned off, small size (less than 6-foot) fires would remain about the same as that during the spray. Because of the water accumulated in the pan, the fire sometimes broke into scattered small flames. These small flames tended to move toward the edge of the pan sometimes resulting in small fire whirls. This type of burning was essentially smokeless. For 6-foot or larger fires, due apparently to the insufficient amount of water accumulation in the pan, (Water could not easily penetrate through the fire.) the burning would resume its full extent shortly after the water spray was turned off.

In an established fire, that is, where the burning rate has reached a steady value, noise resulting from boiling of fuel in the pan could be clearly heard. This noise level increased during the water spray and also when there was water in the pan. Small explosions resulting from splashing of water and/or fuel sometimes would occur, but there appeared to be no apparent danger within a short distance (say one pan diameter) from the pan.

Under wind conditions, the flame was bent in the downwind direction preceded by smoke. Because of the larger exposure of the flame in the cross wind direction, the radiation level in this direction was higher than that in the upwind direction. The fire in wind seemed to behave more predictably than in still air, thus the radiometer outputs did not fluctuate as much.

During the 48" x 6" rectangular fires, only one trough of the pan (see Figure 1) was filled and the pan was positioned with the two empty troughs upwind. Flame trailing was observed for all fires in wind conditions but for the rectangular fires, the flame often also spilled in the upwind direction to cover the empty troughs. This created a false feeling that the burning was originated in all three troughs.

JP4 Fires

The qualitative descriptions given above for JP5 fires apply here in general. When compared with JP5 fires, the JP4 fires have the following characteristics:

Ignition	- very easy and care had to be exercised.
Smoke	- dark gray and appeared to be less than that of JP5.
Flame	- brighter.
Burning	- more violent with more obvious flame spilling, detachment, noise, splashing, and explosions.
Water spray	- seemed to have the same effects as those on JP5 fires except that some water remained in the pan after the fire was out.
Wind	- no noticeable difference.

Avgas Fires

The qualitative description given above for JP5 fires apply here in general. When compared with JP5 and JP4 fires, the Avgas fires have the following characteristics:

Ignition	- somewhat easier than JP4. If the fuel is ignited immediately after the filling in the pan, there appeared to be no special danger.
Smoke	- lightest.
Flame	- brightest.
Burning	- most violent. Unlike the fires of JP5 in water, its burnout is much more clear cut.
Water spray	- same effects as JP4 fires. Water can subdue the fire but the burning recovers more readily than JP4 and JP5 fires.
Wind	- no significant difference except that fuel vapor spilling in the upwind direction is clearly visible and extensive.

EXPERIMENTAL DATA AND DISCUSSIONS

The primary objective of this study is to investigate the gross behavior of aviation fuel fires and to obtain experimental data immediately useful for the various AGFSRS applications. A reasonably large amount of data has been obtained during this study and these data are presented here in simple and readily usable forms. The possibility of radiation scaling of such fires is clearly indicated in the form of the presentation.

Because of the complexity involved in the burning processes, any superficial analytical treatment of the problem such as the flame radiation by oversimplified assumptions (for example, references 19 and 20) could be misleading. Therefore, no such attempt is made here.

Flame Geometry

The average flame geometry was determined by photographic method. Approximately 80 pictures were taken during each fire by use of a sequence camera set at 5 second intervals. These pictures were compared and the flame shape most representative of the fire during the steady burning period was then chosen as the average flame shape. Results show that fires of different size have the same average flame shape and appear to differ by a scale factor. For this reason only a set of selected photographs are shown here as Figures 17, 18, and 19.

In view of this similarity it is convenient to express the flame height H in terms of the diameter for circular fires and the hydraulic diameter D_H (D_H = 4x pan area/pan perimeter) for rectangular fires. The results for fires burning in still air are given in Figure 20. It can be seen that the dimensionless flame height H/D and H/D_H decrease with D and D_H, respectively. Since the dimensionless flame height must remain finite, this decreasing trend suggests the existence of an asymptotic value at very large D. That is, when the size of a fire D is larger than some size D_o, the dimensionless flame height is a constant. This is significant in the study of heat radiation from fires.

Radiation

Characteristics of the radiation

During the early stages of experimentation, many JP5 fires were made. All these fires were made with only the building ventilation louvers and the exhaust stack open. It was found later that because of the restricted air supply to the fire, the burning rate was somewhat lower than with the louvers removed. Therefore, this set of data by itself forms a group which serves to show the repeatability of the data. Only eight fires were recorded and they are shown in Figure 21.

Figure 21 shows that:

1. The inverse-square relationship is approached for $X/D > 2$.

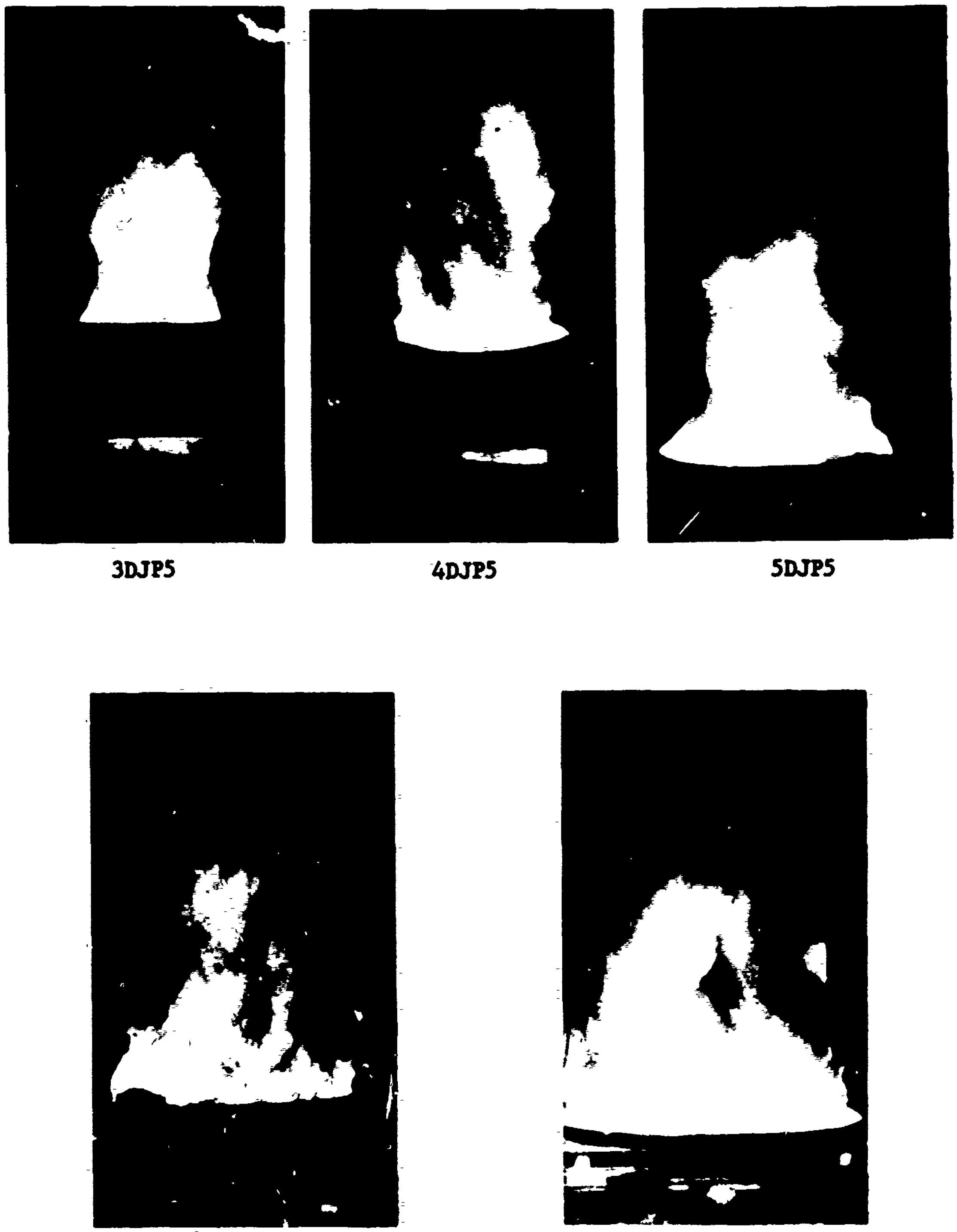


Figure 17. Average flame shape - circular fires in still air.

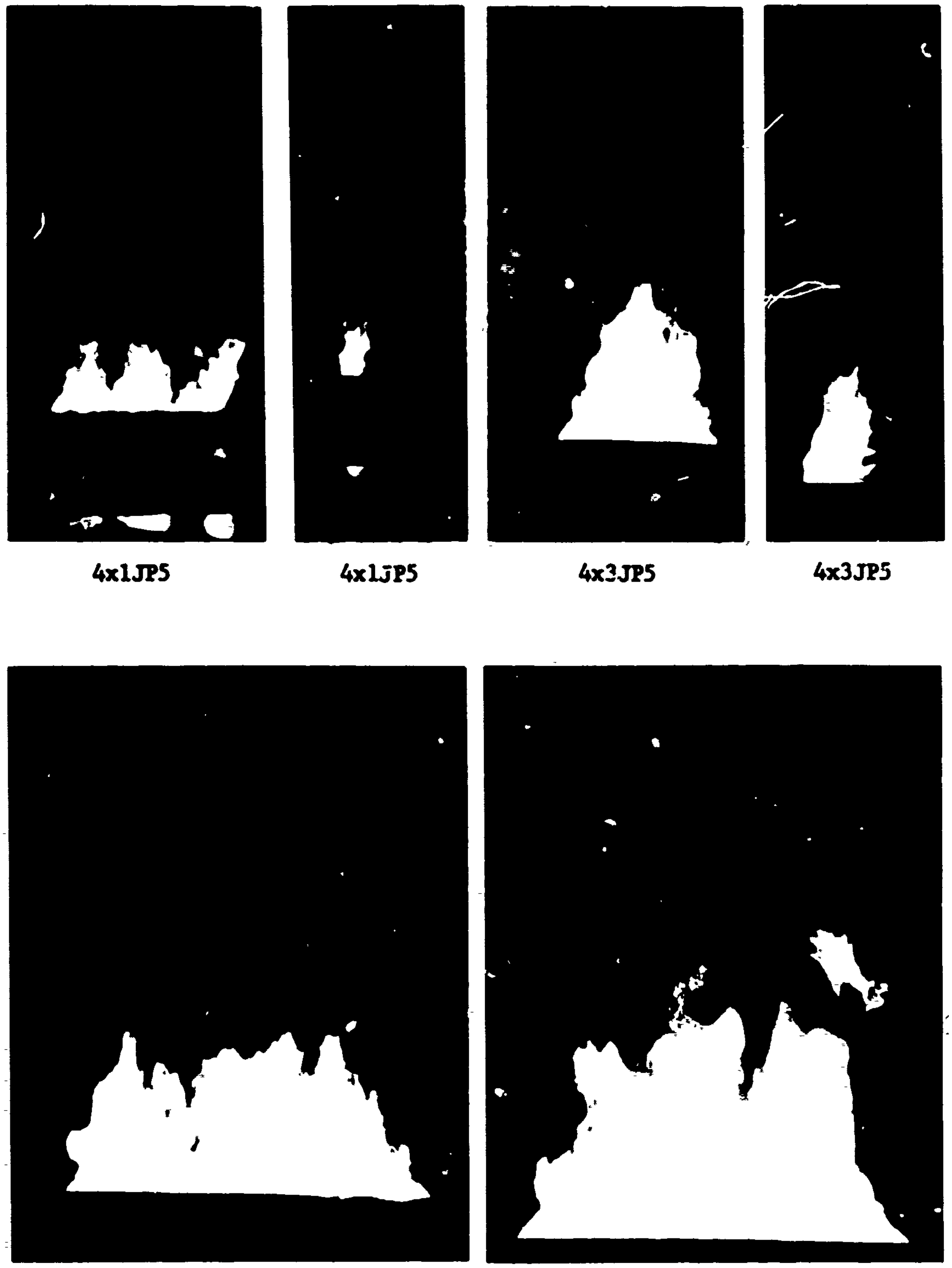
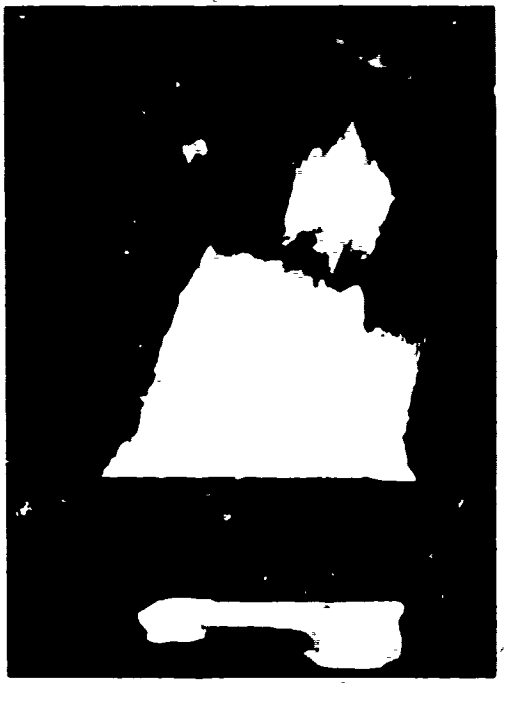


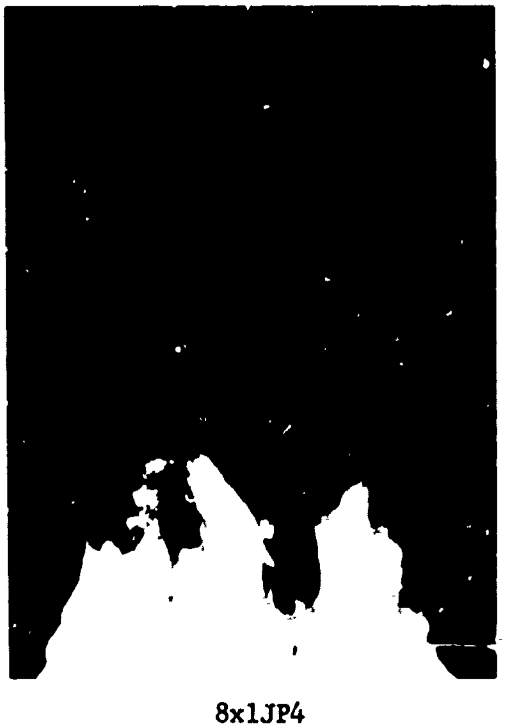
Figure 18. Average flame shape - rectangular fires in still air.

6x3JP5

6x1JP4

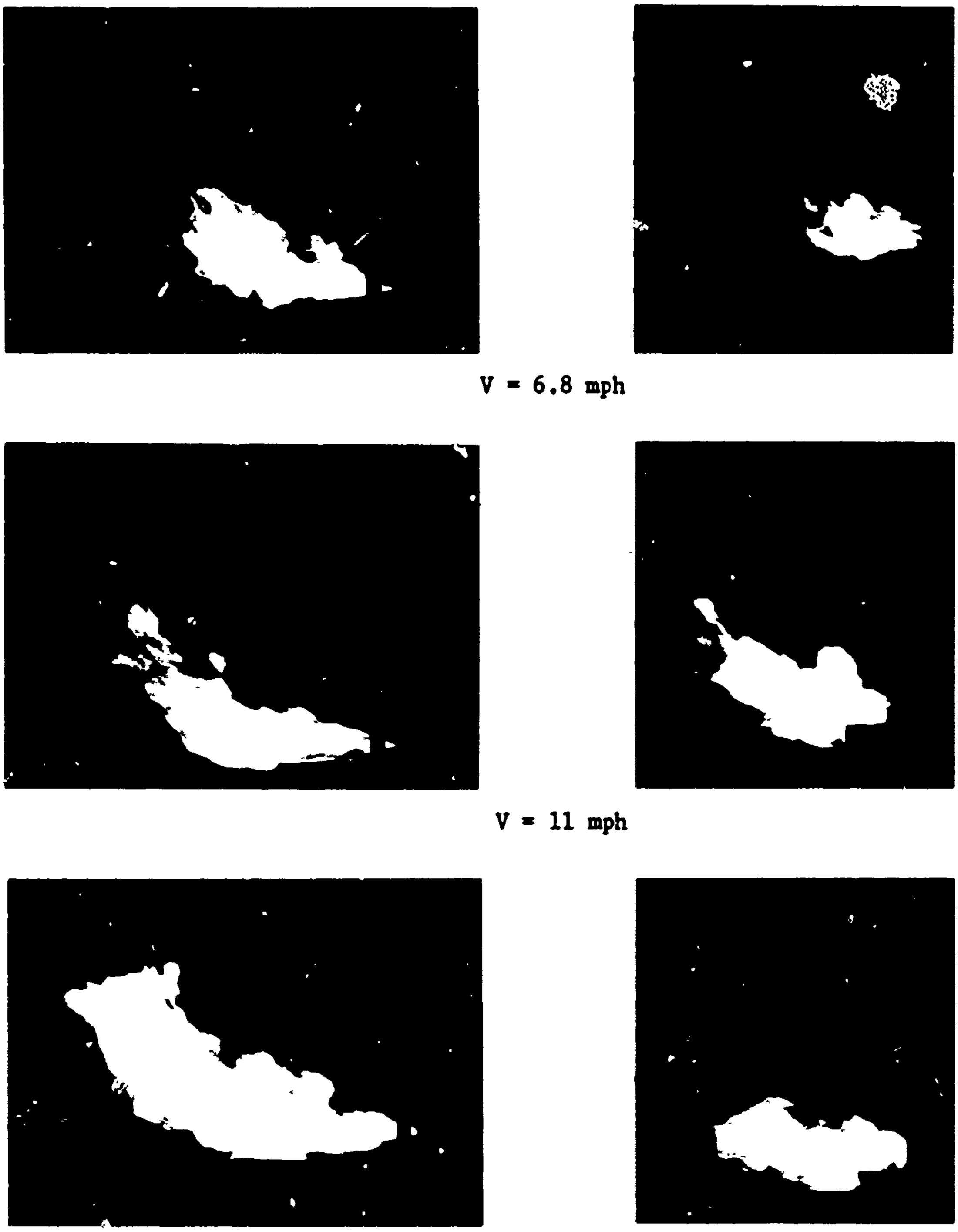


6x3JP4



8x1JP4

Figure 18. (Cont'd)



(a) 3DJP4 fires (b) 4x1JP4 fires

Figure 19. Average flame shape - in wind.

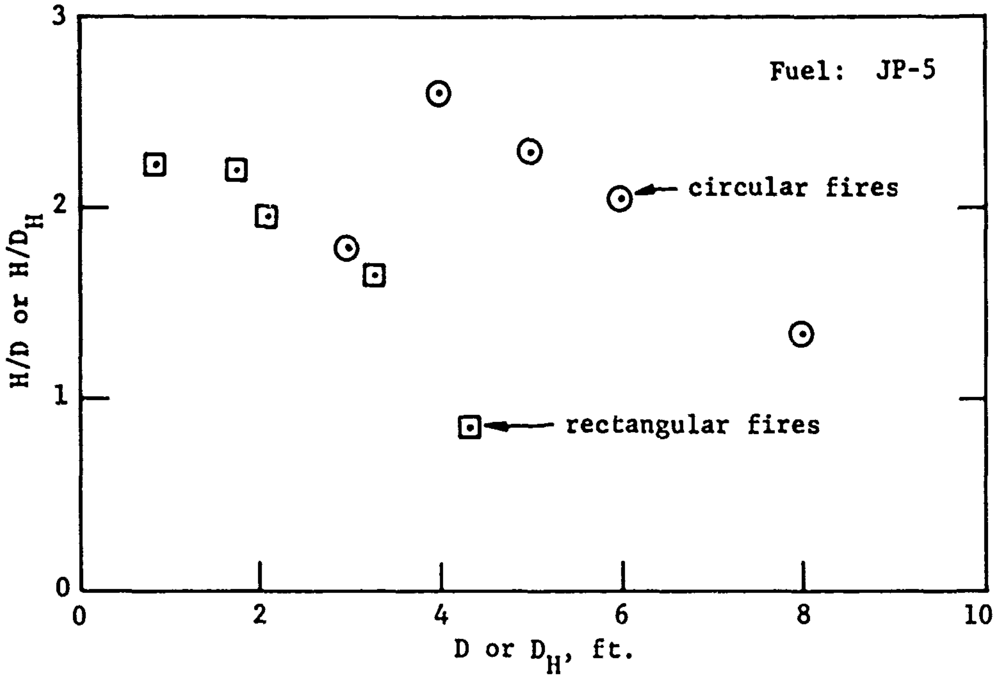


Figure 20. Flame heights of fires in still air.

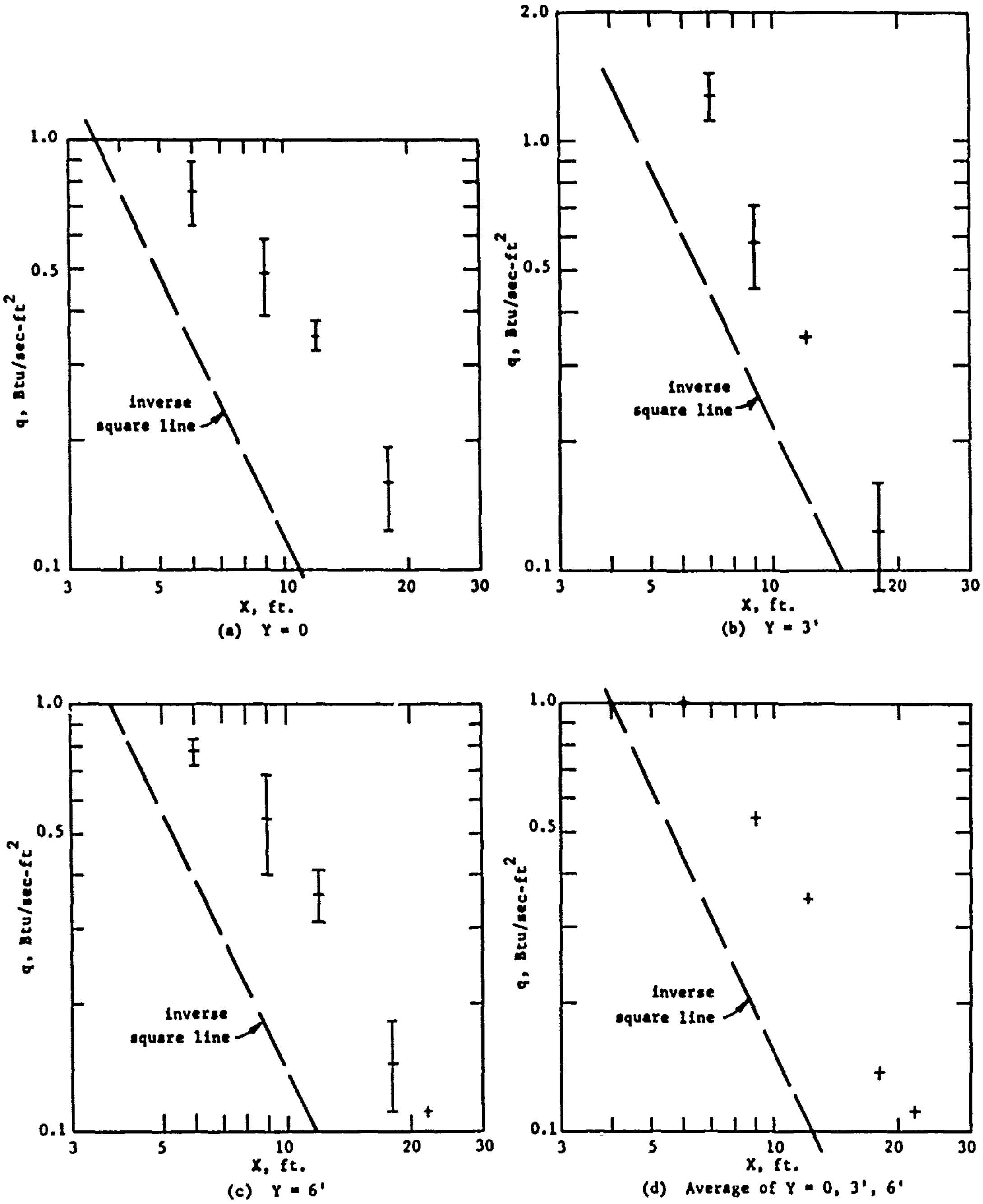


Figure 21. Average heat radiation from 3DJP5 fires.
(Vertical bars indicate ± one standard deviation).

2. The standard deviation is around 20%. This small value is mainly attributable to the large averaging time used during data taking.

The same data as described above were taken for many fires in still air (with the building ventilation louvers removed). Two typical sets of these data are shown in Figures 22 and 23. In addition to the inverse-square relationship as described above, these data show that:

1. The elevation Y does not greatly affect the radiation level (within scatter).

2. The radiation level appeared to be the highest at Y = 3'.

3. The average of the values at Y = 0', 3', and 6' may be representative (within scatter) of the actual situation.

4. The radiation level during the water spray is about one order of magnitude smaller than that before the spray.

5. The radiation measured in the direction parallel to the length L of a rectangular fire was not significantly smaller than that perpendicular to the fire.

6. The radiation level for fires of large L/W (length-to-width ratio) is noticeably smaller than that of small L/W.

To determine the variation of heat radiative flux Q with respect to the elevation Y, 8DJP4 fires were made. The values of Q were measured at Y= 0', 2', 4', 6', and 8' for X/D = 2.9 and 3.5. The data show (Figure 24) insignificant variations of Q within one pan diameter height. Since radiometer windows were often contaminated by smoke deposition at high elevations (Y > 6'), the mounting of radiometers at suitably low elevation is always desirable. Therefore, for all production runs, the radiometers were mounted at approximately 3' above the pan rim The data in Figure 24 show that the radiation measured in this manner can properly describe the fire. For showing the upper bound of radiation from rectangular fires, Q along the centerline perpendicular to the pan length was measured.

Data Summary

1. Fire burning in still air. The data for circular fires are shown in Figure 25 and those for rectangular fires in Figure 26. These data show clearly the inverse-square relationship between Q and X/D or X/L. The data show also that Q is the largest, on the average, for Avgas fires and decreases in the order of JP4, JP5.

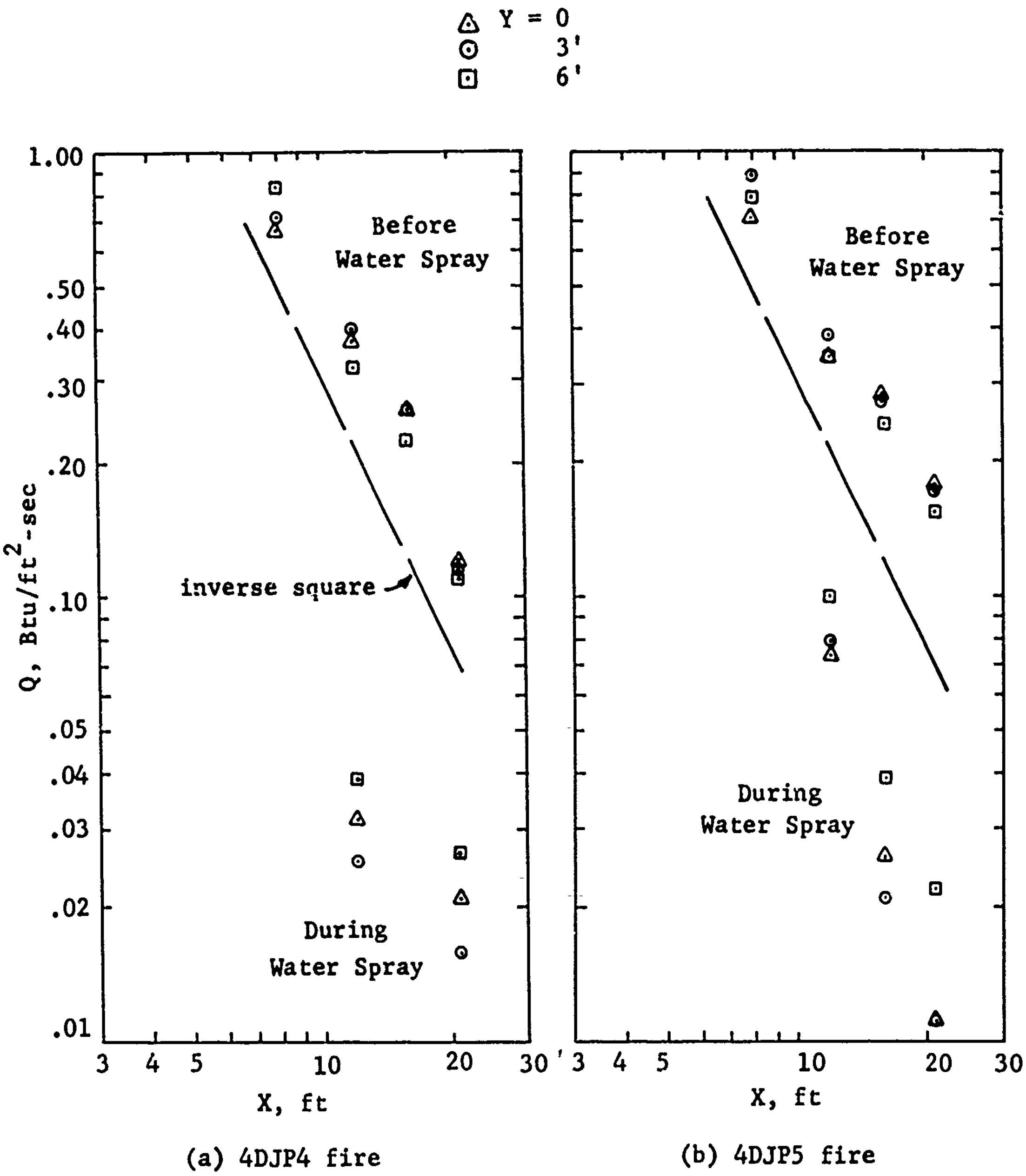


Figure 22. Typical radiation data - circular fires.

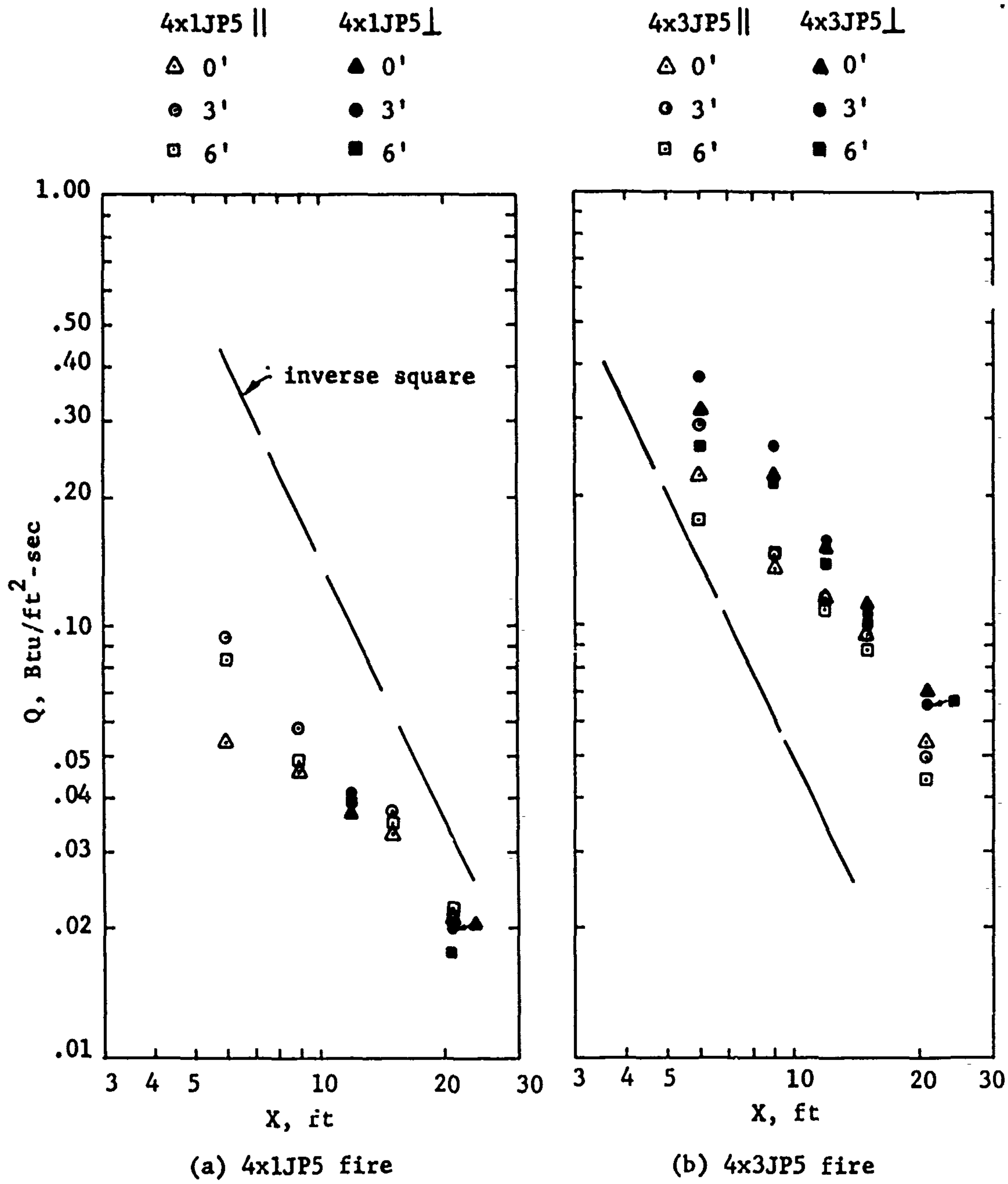


Figure 23. Typical radiation data - rectangular fires.

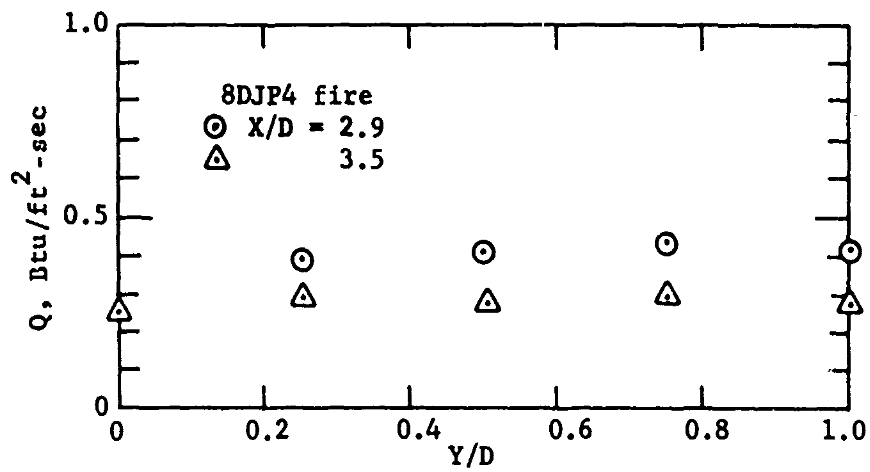


Figure 24. Vertical variation of Q

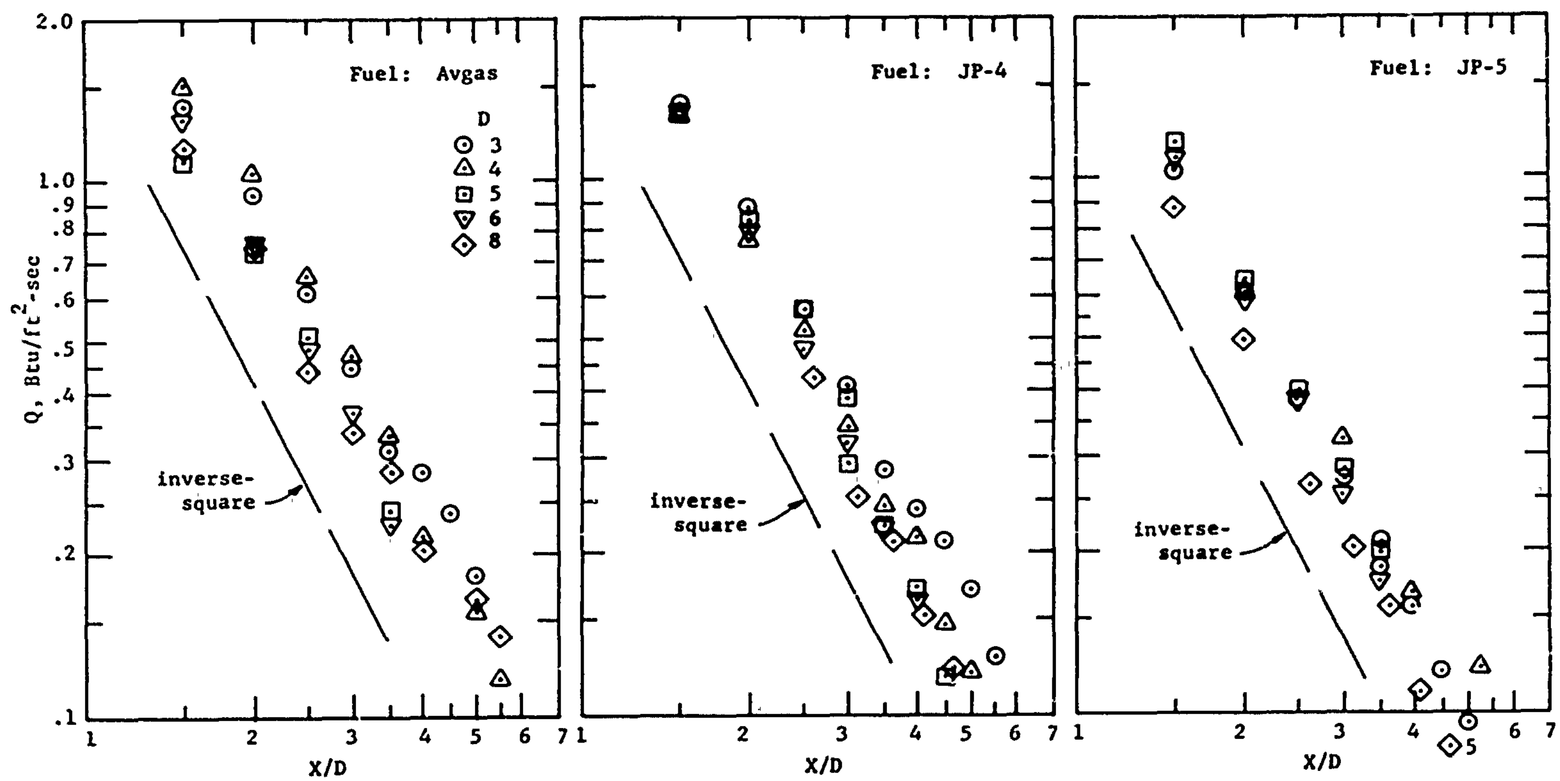


Figure 25. Heat radiation from circular fires - Q vs X/D

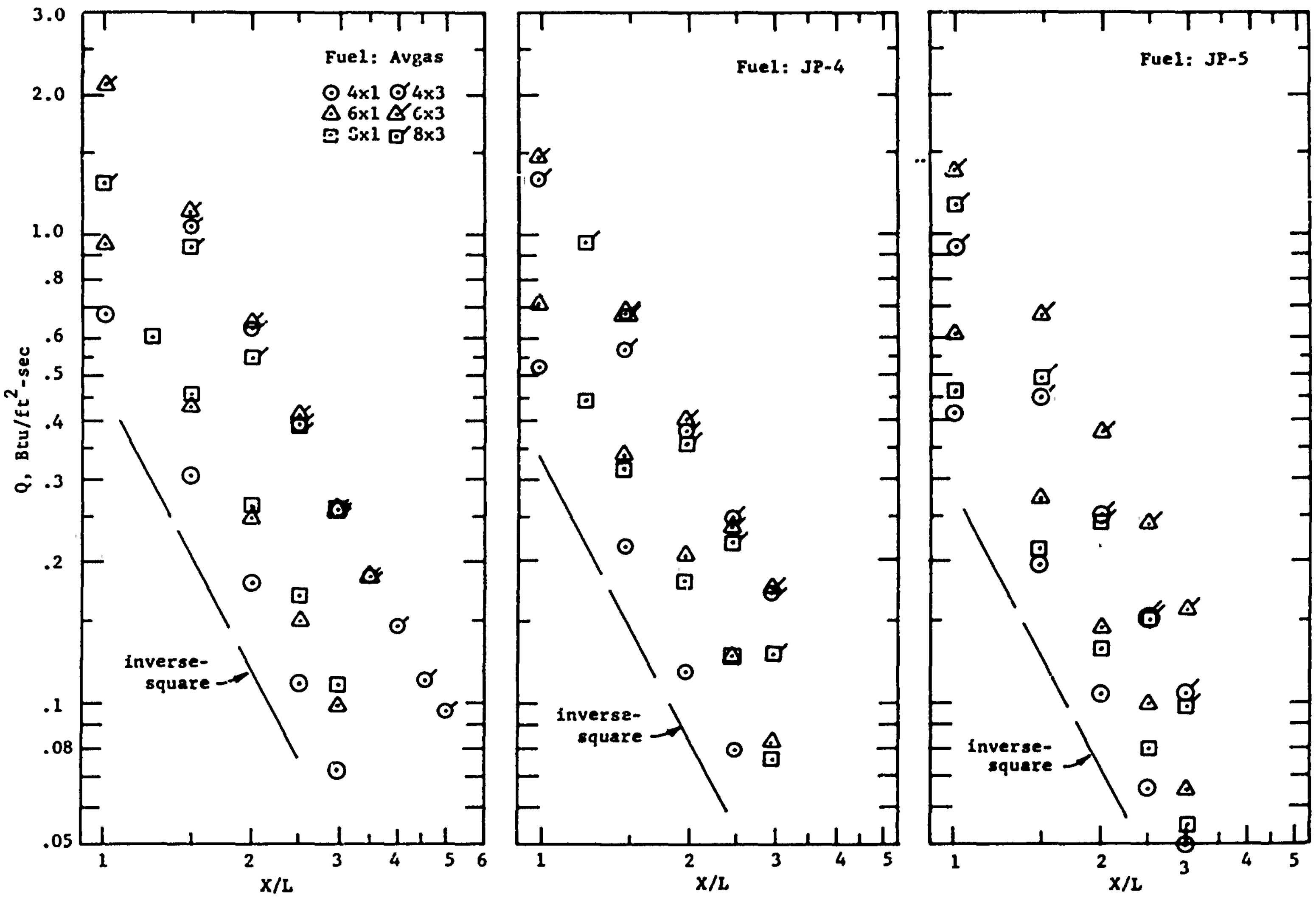


Figure 26. Heat radiation from rectangular fires - Q vs X/L

Figure 26 shows that fires of the same L/W value group together and thin fires (large value of L/W) radiate appreciably less than thick fires. This is largely due to the relatively small size and the openness of the flames (see Figure 18). When the fire thickness W is less than some value, this effect is more pronounced (see data for 4x1 fires in Figure 26).

For the case D = L, circular fires radiate more than rectangular fires but the difference decreases with L/W. This result appears to be due to the flame thickness of the fires. Thus, we expect a square fire (a limiting case where L/W = 1) to radiate the same as a circular fire of the same size. The data in Figure 26 suggests that a L/W = 8/3 rectangular fire may already radiate much the same as a circular fire. It appears safe to assume that rectangular fires of L/W < 2.0 radiate the same as circular fires of size D = L. To establish the criteria for AGFSRS applications, the upper bound of Q should be used. Unless for special reasons, circular fire data should be considered for this purpose.

A replot of data in Figure 25 using D as the abscissa and X/D as parameter is given in Figure 27. It shows that Q decreases gradually with D for fixed X/D. Since Q must remain finite for large D, we expect that it approaches an asymptotic value Q_0 at some sufficiently large diameter D_0. Since Q depends largely on the flame size, Figure 27 suggests that a fixed dimensionless flame height H/D will be reached at D_0. This discussion is qualitatively supported by Figure 20 and the data reported in Reference 1.

2. Fire Burning in Wind. The radiation from a fire is significantly affected by the presence of wind. Because of asymmetry of the fire configuration, the radiations downwind, crosswind, and upwind of the fire were all measured. The results are shown in Figures 28 and 29. As expected, Q-downwind is affected by wind the most but this effect diminishes as the distance increases.

The data show, in general, that Q-downwind increases with the wind speed but reaches a maximum between 15 and 20 mph. Q decreases at higher wind speeds because of the excessive flame bending which makes the flame appear smaller to the radiometer. The same behavior is seen for Q-crosswind and Q-upwind, although their variations are relatively smaller than Q-downwind.

At X/D = 3, radiometer A (see Figure 12) was occasionally touched by the flame tip. The maximum Q recorded was about 1.5 Btu/ft^2-sec, about 10% that of the extrapolated maximum value described below. As expected, the values of Q for 48" x 6" fires were smaller than those for 48" diameter circular fires.

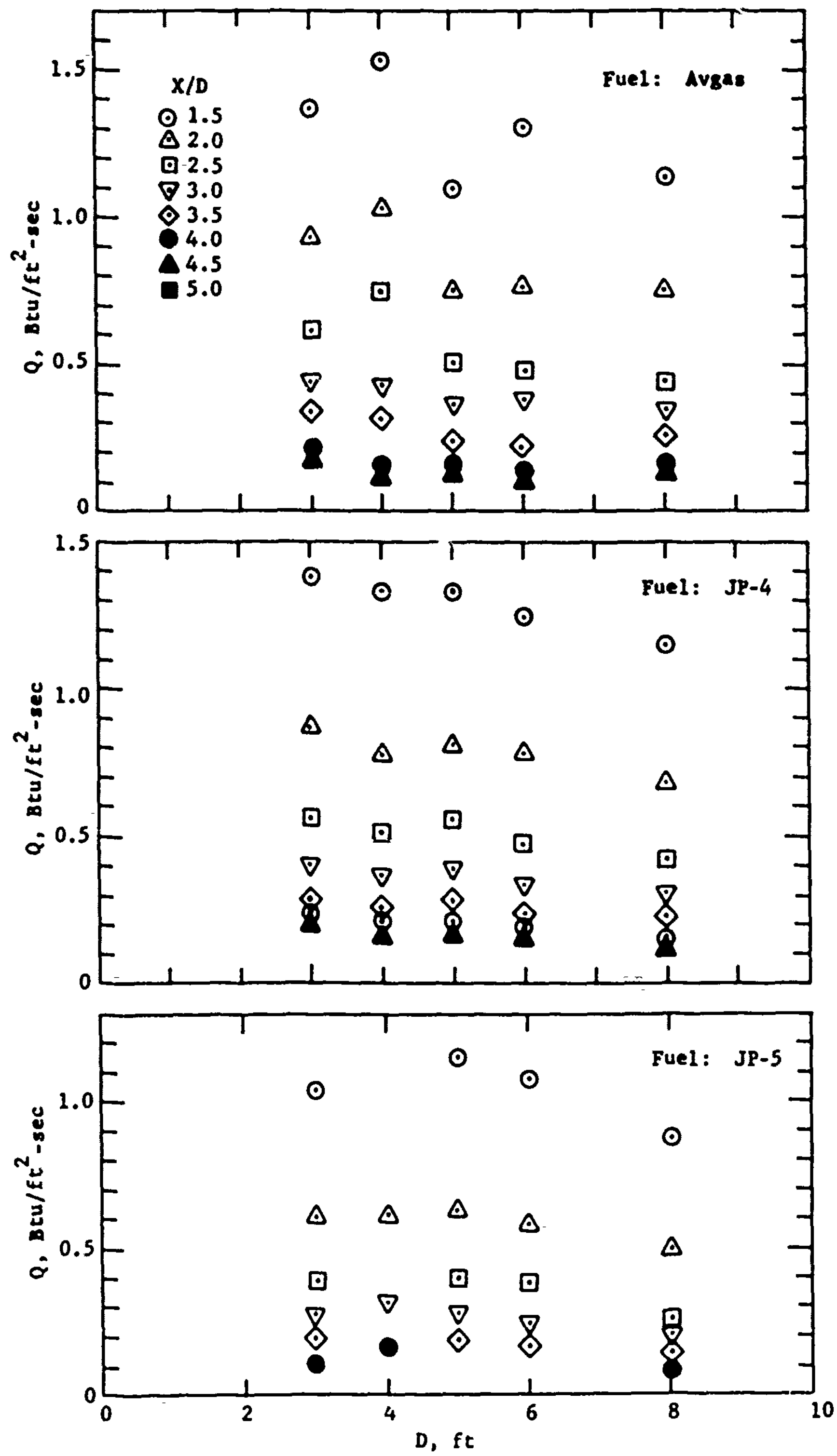
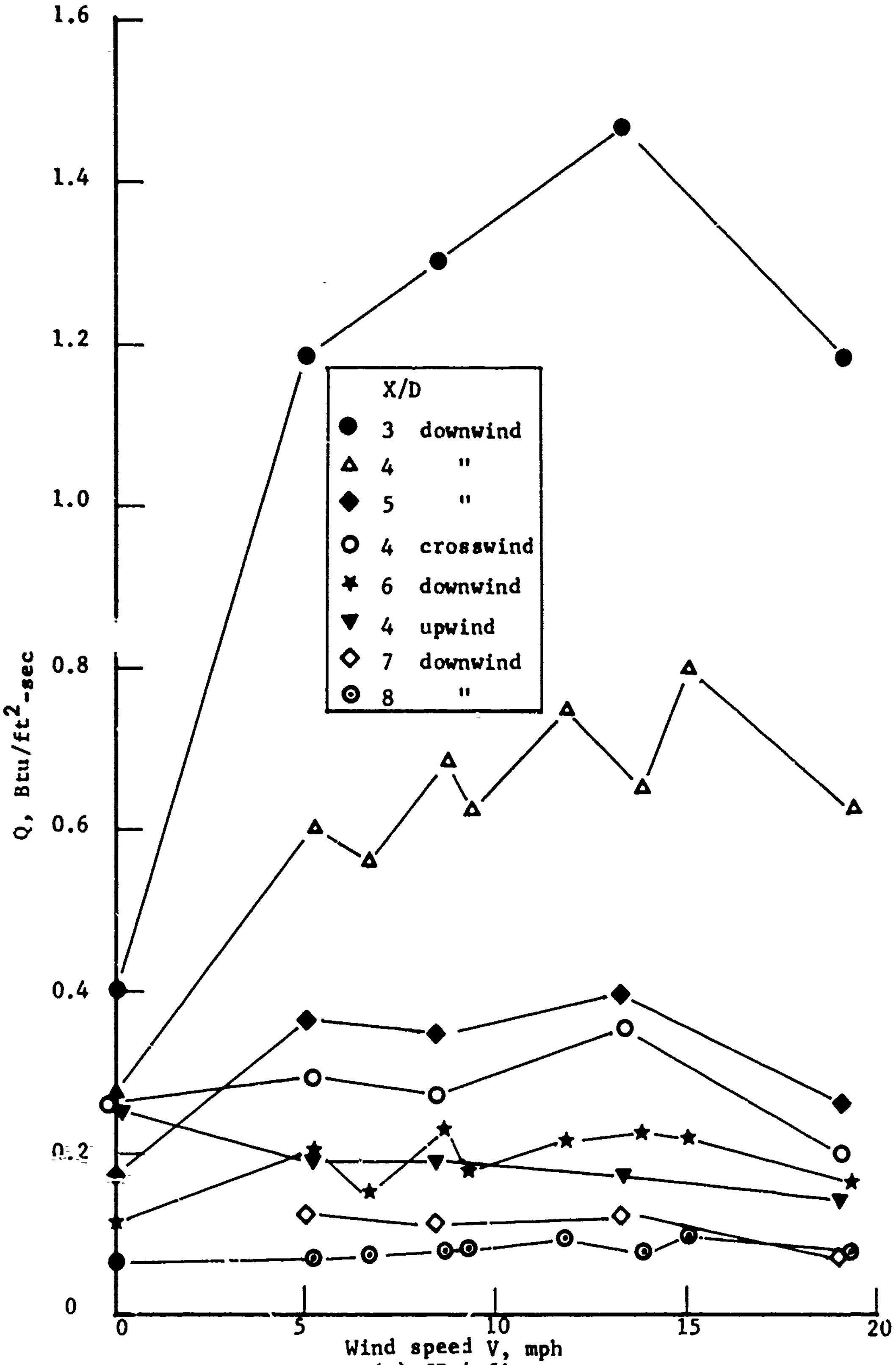
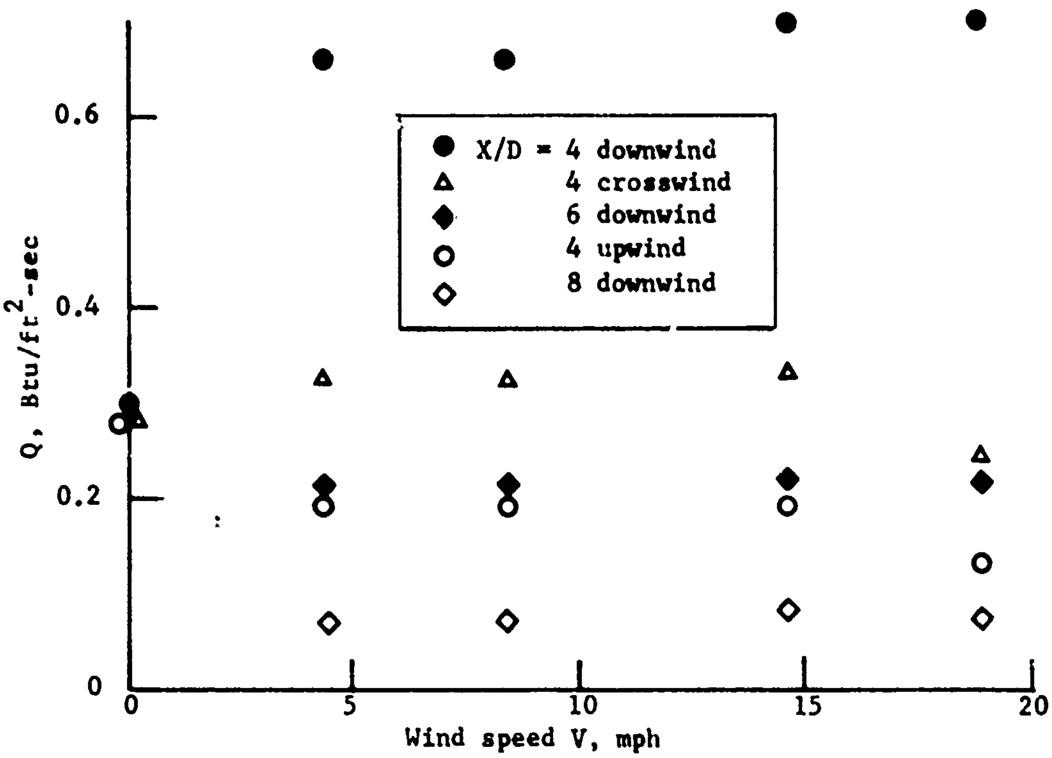


Figure 27. Heat radiation from circular fires - Q vs D

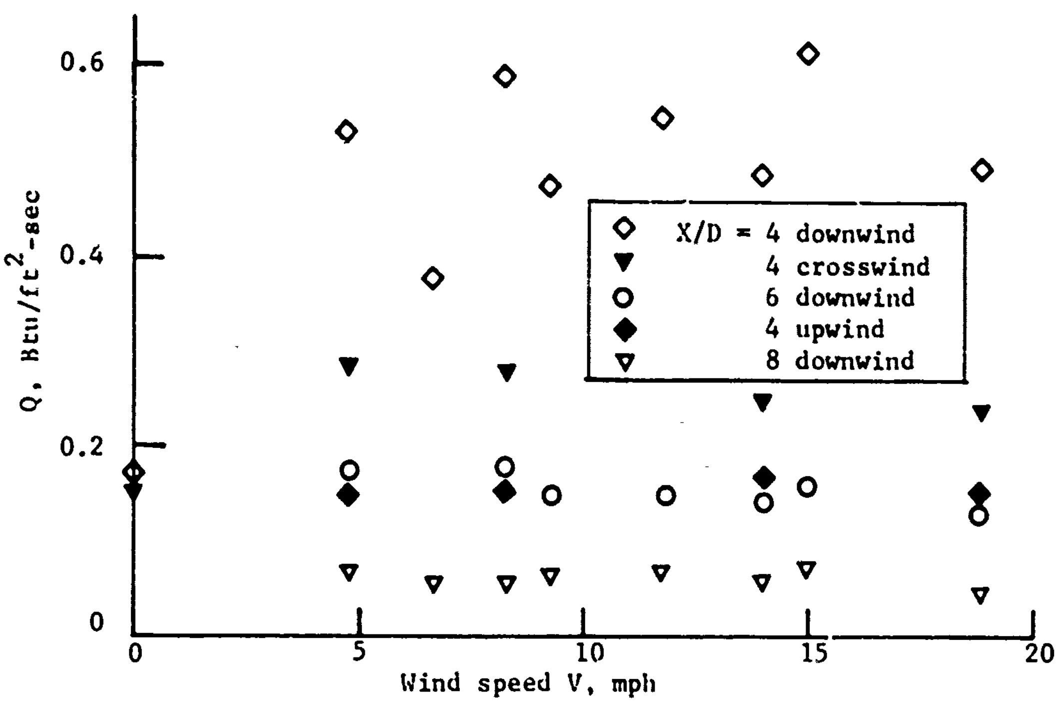


(a) JP-4 fire

Figure 28. Wind effects on radiation from 3' diameter pool fires.



(b) Aviation gasoline fire



(c) JP-5 fire

Figure 28. (Cont'd)

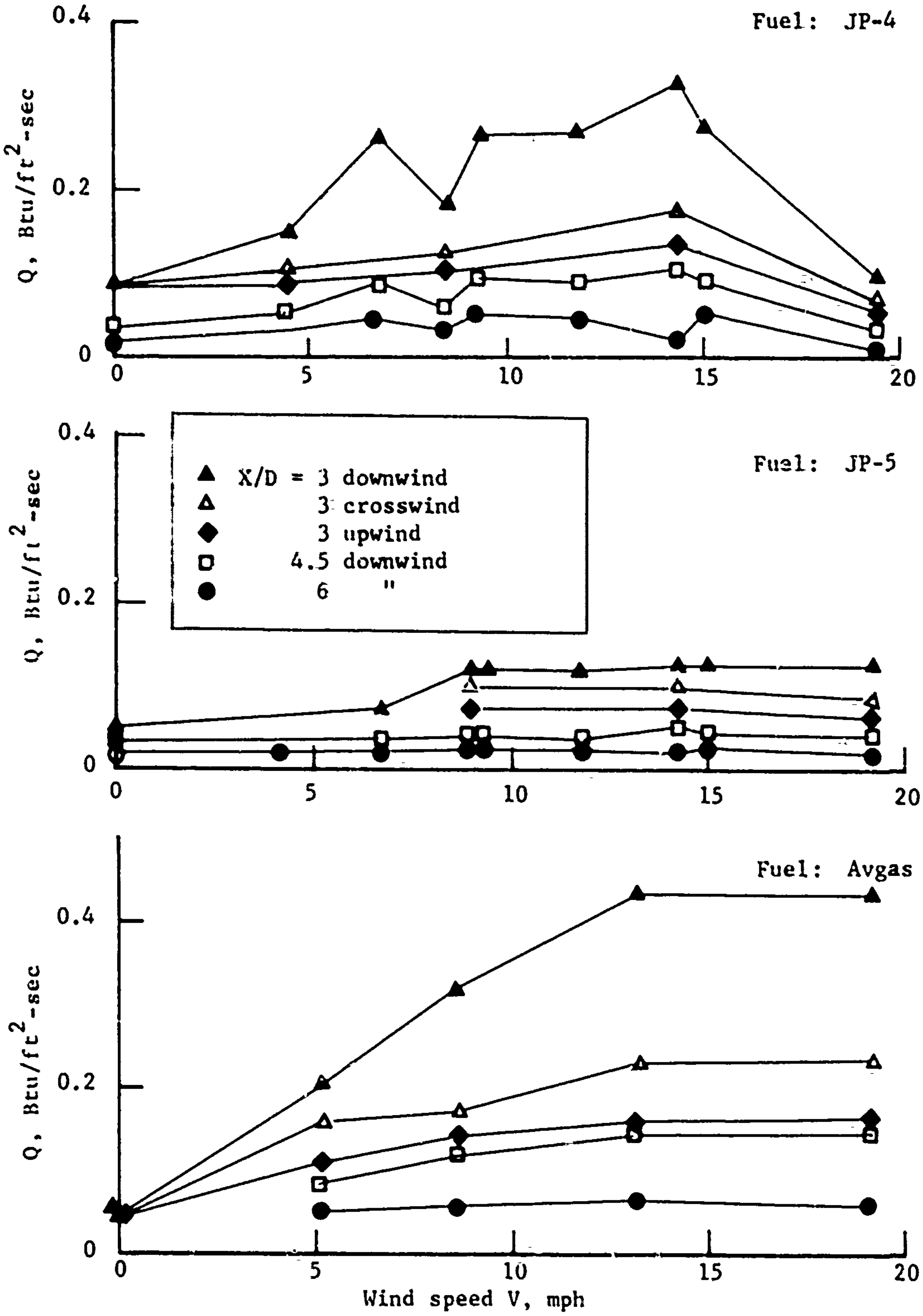


Figure 29. Wind effects on radiation from 48" x 6" rectangular fires.

Some Implications

1. To avoid possible damage due to direct contact with the fire during the measurements, the radiometers were placed at a safe distance from the fires. The inverse-square relationship between Q and X/D (or X/L) suggests that we need not measure the radiation very closely to the fire in order to obtain the maximum value of Q. Instead, we may make a reasonable estimate by extrapolating from the data at $X/D > 2$. For example, the maximum value of Q for Avgas at $X/D = 2.5$ is 0.65 Btu/ft^2-sec. Based on this figure, the maximum radiation Q_{max} at the surface of the fire ($X/D = 0.5$) would be

$$Q_{max} = 0.65 \left(\frac{2.5}{0.5}\right)^2 = 16.3 \text{ Btu/ft}^2\text{-sec } *$$
$$= 4.4 \text{ cal/cm}^2\text{-sec}$$

2. The fraction of the total heat from a fire transmitted to the surroundings by means of radiation is often of practical interest. Consider a cylindrical envelope centered at a fire with radius X and height D, the total radiation passing through this envelope is (assuming Q is uniform in Y for $0 \leq Y \leq D$)

$$2\pi XDQ = 2\pi\left(\frac{X}{D}\right) D^2 Q.$$

The total heat released from the fire is approximately

$$\left(\frac{\pi}{4} D^2\right) Wh$$

where W is the specific burning rate and h the lower heating value of the fuel. The fraction is, therefore,

$$F = \frac{2\pi \left(\frac{X}{D}\right) D^2 Q}{\left(\frac{\pi}{4} D^2\right) Wh} = 8 \left(\frac{X}{D}\right) \frac{Q}{Wh}$$

For Avgas,

$$Q_{max} = 0.65 \text{ Btu/ft}^2\text{-sec} \quad \text{at} \quad X/D = 2.5$$
$$h = 18{,}900 \text{ Btu/lb.}$$
$$W = 1.16 \text{ lb/ft}^2\text{-min}$$

* 1 Btu/ft^2-sec = 0.272 cal/cm^2-sec

we get

$$F = 3.6\%$$

Temperature

As discussed earlier, the air temperature in the downwind direction only would be significantly affected by the fire. To describe this phenomenon, the temperatures in the plane containing the centerline of the fire were measured. This choice was made because these are the maximum temperatures and, thus, directly related to AGFSRS applications to determine the convective boundary conditions. The locations of the thermocouples for these measurements are shown in Figure 12.

At a given distance downwind of the fire, our data showed that the elevation where the maximum air temperature occurs decreases with the increase of wind speed and this effect diminishes farther downwind of the fire. This description is typical for all fires measured. Therefore, only data for 3DJP4 fires are presented here (Figure 30).

Figure 31 shows the temperature decay at $Y/D = 1$ in the downwind direction. We see that the wind speed did not have significant effect except very near the fire. In general, Avgas fires appear to be the hottest, decreasing in the order of JP4 and JP5 fires.

At $X/D = 3$, the fire was occasionally touching the thermocouple shielding tubes. The maximum temperature rise recorded was about 650°F in a 20 mph wind. This temperature and the maximum temperature in the fire (1600°F) may be considered the bounds for specifying the convective boundary conditions for exposure studies.

Burning Rate

The specific burning rate, W, of JP5, JP4, and Avgas in still air are shown in Figure 32. The data show that W is essentially constant for each fuel. On the average, W is largest for Avgas fires and decreases in the order of JP4, JP5 fires. This may be more clearly seen in the composite plot of W vs D_H in Figure 32(c).

The burning rate data were fit into straight lines by the least square method. The results for the range of experimentation ($1.87' < D_H < 8'$) are shown below:

Fuel	W = , lb/ft^2-min	Standard deviation, lb/ft^2-min
JP5	$1.009 - 0.0251D_H$	0.064
JP4	$1.090 + 0.0217D_H$	0.123
Avgas	$1.158 + 0.0419D_H$	0.146

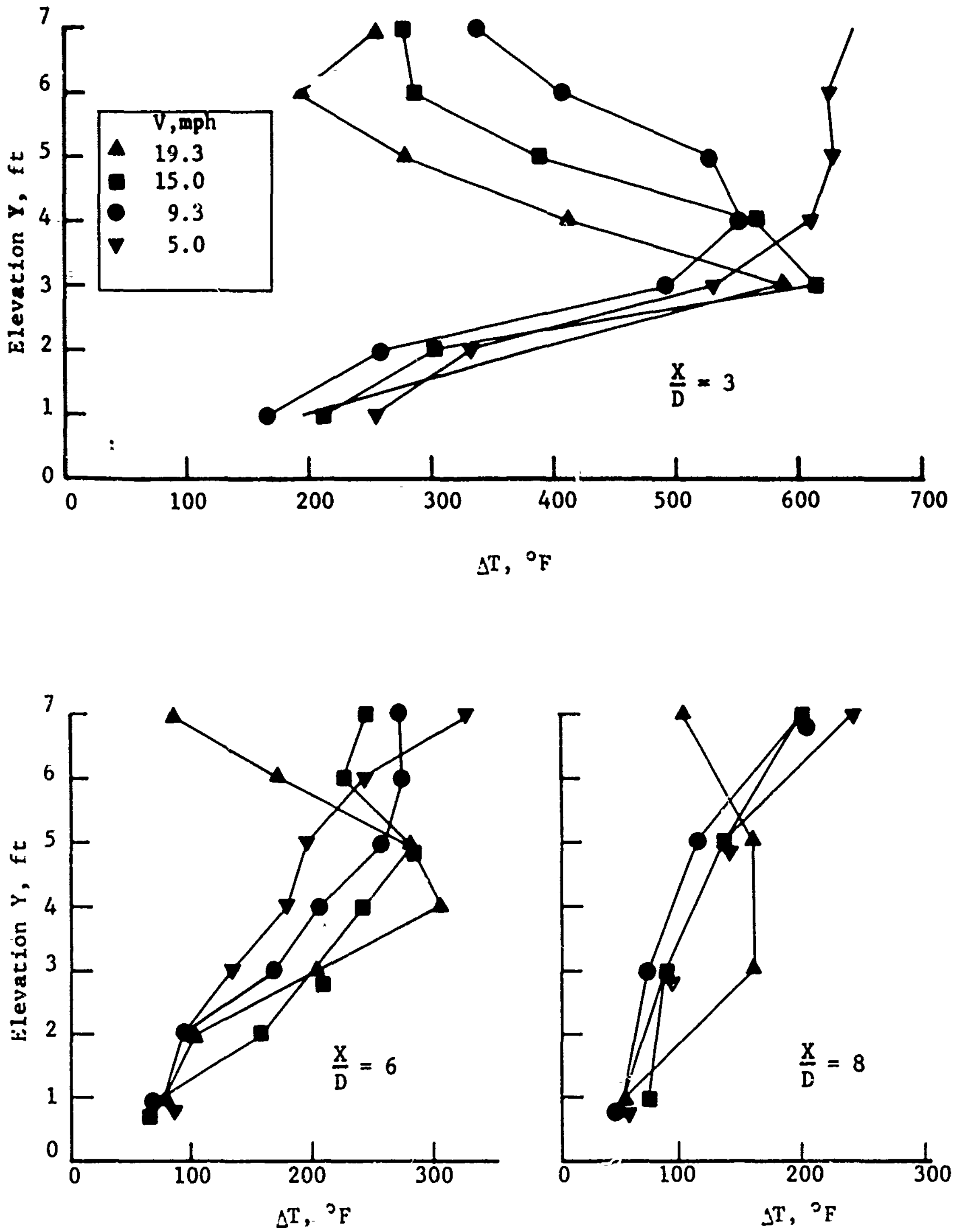


Figure 30. Typical temperature rise ($\Delta T = T - T_{ambient}$) in the centerline plane downwind of 3' diameter fires (data shown are for 3DJP4 fires).

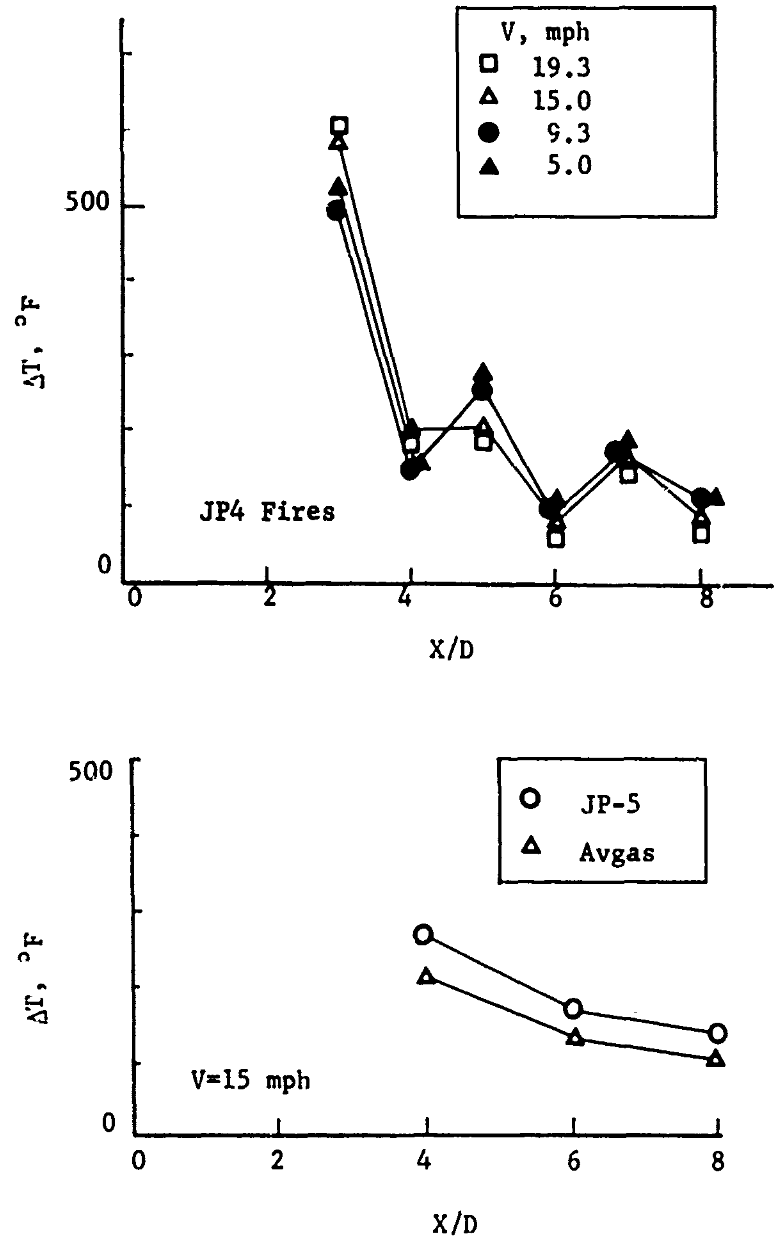
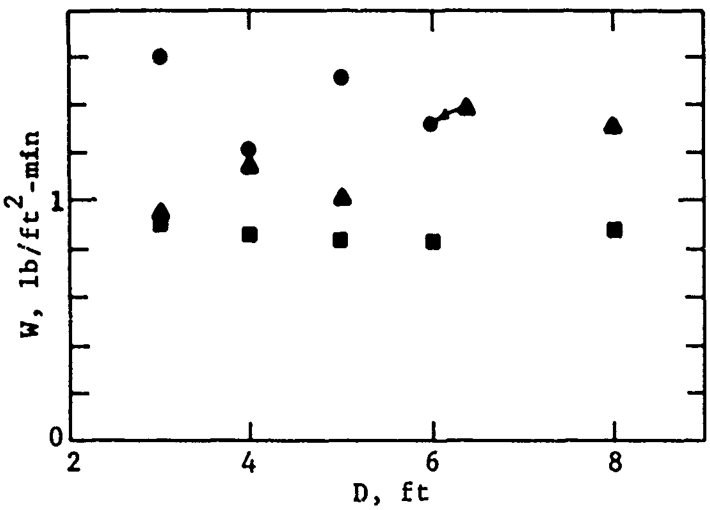
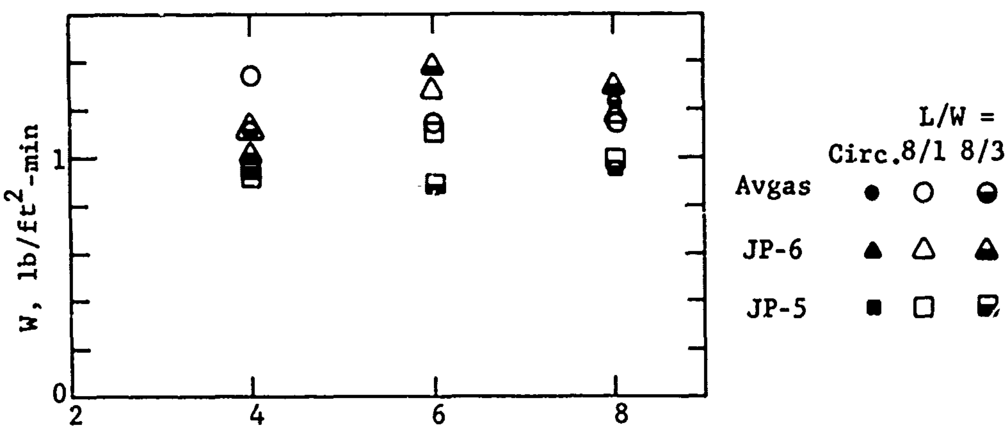


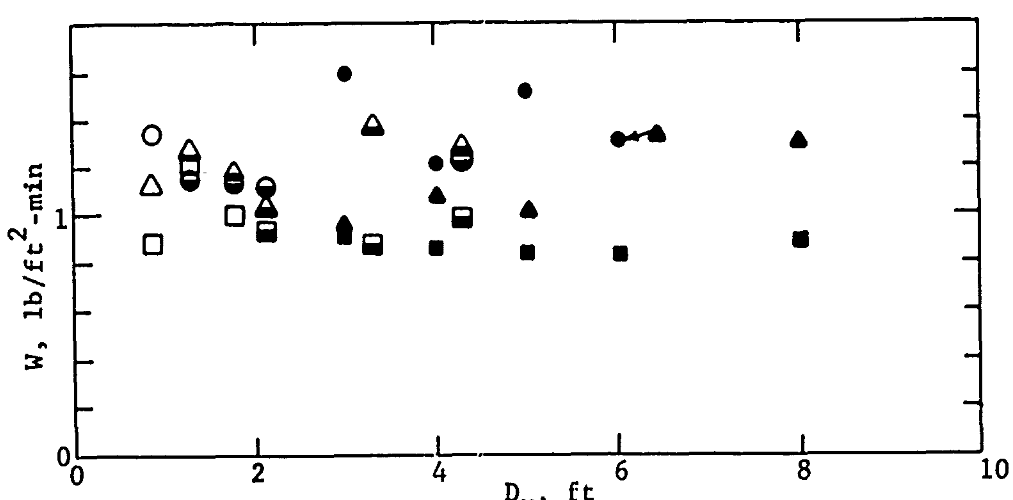
Figure 31. Temperature rise in the centerline plane downwind of 3' diameter fires (Y/D = 1).



(a) Circular fires



(b) Rectangular fires



(c) Composite plot based on hydraulic diameter

Figure 32. Burning rate in still air.

If only the first terms are considered, we have the burning rates 1.0, 1.1, and 1.16 lb/ft^2-min for JP5, JP4, and Avgas, respectively.

Under wind conditions, the weight loss method described earlier for measurements in still air was found too insensitive to be satisfactory for the small weight loss involved in these measurements. Therefore, improvements were made by placing a very sensitive load cell inside a large coil spring. Under static conditions the total weight of the platform was supported by the spring and the bearing-shaft arrangement. The load cell was then loaded with a screw jack mounted on the platform, and this screw jack was turned so that the load cell output corresponded approximately to the weight of the fuel This system had a sensitivity the same as the old one, approximately 100 lb/mv, but it has a much better resolution, approximately 4 ounces. Calibrations were made by siphoning a can of water on the platform and the result was very satisfactory. It was soon found, during actual fire tests under wind conditions, that this method was also unsatisfactory. The reasons may be: (1) aerodynamic forces on platform, and/or (2) warping action of platform due to the heating by the trailing flame (direct contact of flame with platform). Therefore, no burning rate data were obtained.

Some data on the wind effects on burning rates of simple fuels were obtained by Welker (Reference 16). In the limited range of velocities (< 7 mph) studied, his data showed no apparent change of burning rate due to wind for most fires and some decrease for several cases. Burning rate decrease may be explained by the decrease of back radiation to the fuel source due to flame bending. Our observations showed significant flame detachment from the leading edge of the pan, and as a result, fuel vapor spilling increased with the wind speed. This behavior was responsible for the flame propagation in the upwind direction, and perhaps, it may also have caused the burning rate to increase. However, when the wind speed is sufficiently large, the flame may be completely blown off and be extinguished, this being a limiting case. In view of the insufficient amount of information available, some refined experimental studies in this respect would seem necessary.

CONCLUSIONS

1. The flames of Avgas, JP4 and JP5 fires tend to spill and to detach themselves from the fuel pan. These phenomena are more obvious for large fires and decrease for the fuels in the order listed.

2. The burning activity is most violent for Avgas and less violent for JP4 and JP5 fires, in that order. The smoke color is lightest for the Avgas fires and is darker for JP4 and JP5 fires, in that order.

3. Heavy water spray can sometimes extinguish a 3-foot fire. At a given spray rate, the effect decreases with the increase of fire size, but the beneficial effects of heat shielding and smoke reduction due to the water spray should be of practical interest to the fire fighters.

4. The spectral radiation emitted by aviation fuel fires are in the infrared region. The prominent emission wavelength bands lie between 1 to 5 microns.

5. The radiative heat flux, Q, and the specific burning rate, W, are highest for Avgas fires and decrease in the order of JP4 and JP5. At one fire size distance (X/D or X/L = 1) from the fire, the value of Q ranges from 2 to 3 Btu/ft^2-sec.

6. At a distance greater than 2D away from the center of the fire, Q is practically constant for heights below one fire diameter. This permitted meaningful measurement of radiation by placing the radiometers at a convenient height without regard to the exact location relative to the fire.

7. Q correlates well with the dimensionless distance X/D or X/L. That is:

$$Q \propto \left(\frac{X}{D}\right)^{-2} \text{ or } \left(\frac{X}{L}\right)^{-2} \text{ when } \frac{X}{D} > 1.5 \text{ or } \frac{X}{L} > 1.$$

For the range of fire sizes studied (3' - 8'), Q depends only weakly on the fire sizes D or L.

8. Conclusions 6 and 7 suggest the possibility of measuring radiation by placing only one radiometer at a convenient height and at a far enough distance from the fire (X/D > 2, for example). The radiation at other locations may be extrapolated from this single point measurement.

9. At a fixed X/D, Q decreased gradually with the increase of D. This suggests the existence of an asymptotic value Q_o when D is larger than some diameter D_o. Data show that $Q_o \approx$ Btu/ft^2-sec at X/D = 1.5. By inverse-square relationship $Q_o \approx 9$ Btu/ft^2-sec (2.5 cal/cm^2-sec) at the edge of the fire (X/D = 0.5). The maximum extrapolated value of Q at X/D = 0.5 is approximately 16 Btu/ft^2-sec (4.4 cal/cm^2-sec), whereas the peak recorded value by a radiometer at X/D = 3 that was occasionally touched by the flame was only 1.5 Btu/ft^2-sec.

10. Hydraulic diameter appears to be a useful parameter for presenting the burning rate data of rectangular fires.

11. Dimensionless flame height H/D (or H/L) decreases with the fire size, and it appears to approach to an asymptotic value as does Q.

12. Due to the unstable flame configuration, the radiation measured in the direction parallel to the length of a rectangular pan is not significantly smaller than that in the perpendicular direction.

13. As the length-to-width ratio of a rectangular fire decreases, the openness of the flame decreases, consequently, radiation in the direction perpendicular to the length increases. For $L/W < 2.0$, data suggest that the rectangular fire radiates about the same as a circular fire of diameter $D = L$.

14. Effects of wind on burning rate require a refined measuring technique. Data available are insufficient to support either the increase or the decrease argument of burning rate with the increase of wind speed.

15. The location of the maximum air temperature downwind of a fire moves closer to the ground as the wind speed increases. The bounds of the temperatures near a fire may be between 650° to 1600°F above the ambient temperature. Among the fires, Avgas fire appears to be the hottest followed, in order, by JP4 and JP5 fires.

16. Downwind of a fire, the radiation increases with the wind speed and reaches a maximum between 15 and 20 mph and decreases as the wind speed is further increased. Q in the upwind and crosswind directions are only slightly affected by the wind.

17. The upper bound of heat radiation from a fire through an envelope between $Y/D = 0$ and 1 calculated from the experimental data was 3.6% of the total heat released from the fire.

RECOMMENDATIONS

1. The radiation data presented here show that Q correlates strongly with the dimensionless distance X/D but weakly with the fire size D itself. Radiation scaling appears readily accessible. Data from large size fires would be needed for substantiation. Since burning large size fires for this reason only is difficult to justify, especially from the air pollution standpoint, we recommend that such measurements be made by use of portable instrumentation package and be ready to take the data by joining any large fire experiments in the nation as available. Since only the travel plus one man labor for a short period each time are involved, the return in terms of the investment is attractive.

2. The data presented here provide a realistic range of thermal boundary conditions for exposure studies. The thermal responses of various materials such as: the fabric for fire fighter's protective clothing, aircraft skins and structural members, ordnances, etc., may

be objectively studied both by analytical methods and by use of small scale experiments during the initial screening processes. Criteria for fabric selection, ordnance cooking time, etc., could then be established.

3. Wind effect on the thermal environment of a fire is critically important in aircraft fire fighting and rescue operations. More work should be conducted in this area. Since no satisfactory method for studying the effects of wind on large fires has been available, new concepts should be developed.

4. Brief observations show that the burning of thin layers of fuels could be quite different than the steady state burning behavior as described here. This is because of the presence of a large heat sink and the limited fuel supply. Spilling of fuel on concrete, water, and metal surfaces, and on or near fire fighting foams are all realistic situations which may occur during an emergency landing. Information in this respect is nil and should be carefully studied to improve the present fire fighting technology.

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