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CRASH FIRE HAZARD EVALUATION OF JET FUELS

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FINAL REPORT

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16. Abstract

An investigation was conducted to determine the relative crash fire hazards of jet fuels under survivable crash conditions. Kerosene, JP-4, and mixtures of both were evaluated under various release modes (pools, drips, streams and sprays) and in the presence of possible ignition sources (electrical sparks, friction sparks, open flames, and hot surfaces). Wind speed, wind air temperature and fuel temperatures were also varied. The results of this evaluation and the conclusions reached are discussed in the report.

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PREFACE

This report was prepared by the Naval Air Propulsion Test Center, Aeronautical Engine Department, Naval Base, Philadelphia, Pennsylvania, for the Federal Aviation Administration. The work was part of a program of the Aircraft Division, Systems Research and Development Service, Washington, D.C. The work was administered under the direction of Mr. Samuel V. Zinn, Jr., who served as Project Manager for the Instruments and Flight Test Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

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INTRODUCTION

The analyses of survivable aircraft crashes (where the impact force is not of a fatal level) indicate that post-crash fires can and do seriously increase fatality rates (1). In an effort to define, eliminate, or mitigate the causes of this hazard various investigations have been conducted. Pinkel, et al.(2, 3) have reported that a major cause of post-crash fire is the ignition of fuel sprays by hot surfaces with both piston engine and jet engine aircraft. Scull (4) has made a literature search on the flammability of hydrocarbons under various conditions, but the majority of the data were not obtained with actual jet fuels. In an attempt to eliminate the fire hazard, various approaches have been studied; these include the modification of fuel tanks, the elimination of ignition sources, and the alteration of fuel characteristics (5). There has not, however, been any systematic test program conducted to specifically evaluate the relative safety hazards of JP-4 and aviation kerosene.

The Federal Aviation Administration initiated this program to conduct such an evaluation. The purpose was to determine the relative safety hazards of JP-4, aviation kerosene, and mixtures of both under typical environmental conditions. The aviation kerosene used in this program was the Navy fuel, JP-5. The civilian counterpart for this fuel is Jet A, also an aviation kerosene. Since the flash point and specific gravity of Jet A are lower than those of JP-5, the data curves for Jet A where volatility is a factor would show slightly less difference between kerosene and JP-4 than is shown in this report. The fuels were evaluated under various release modes (pools, drips, streams, and sprays) in the presence of possible ignition sources (electric sparks, friction sparks, open flames, and hot surfaces) and with variations in wind speed, wind air temperature, and fuel temperature. The project was divided into two phases. In the first phase a literature search was conducted in order to avoid duplicating valid and applicable work done by others. The second phase focused on determining the effect of those parameters influencing fuel flammability not covered or inadequately covered in the surveyed literature, and designing suitable test apparatus to achieve this end.

This report presents the details of the work performed, the data obtained, and the conclusions established.

TEST PROGRAM

The test program was established to conduct a hazard evaluation of aviation fuels under the various release modes likely in an aircraft crash (drips, streams, pools, and sprays), each in the presence of possible ignition sources (open flames, hot surfaces, electrical sparks, and friction sparks). Also included in the program were variations in wind velocity, wind air temperature, and fuel temperature. Details of the test procedures will be given in the discussion section of the report.

DISCUSSION

Dripping Mode

Testing was initiated with the open flame ignition of fuel drops. The investigation was aimed at finding those conditions under which a flame would climb a column of dripping fuel. The evaluation of this phenomenon is important since it determines the ability of a flame to propagate to the fuel source and potentially cause a catastrophe. The test consisted of dripping fuel from a needle tip, at a predetermined rate, into a pan of burning fuel. This pan was positioned approximately twenty inches below the fuel source. Twenty inches was the maximum distance the fuel source could be placed above the open flame. The maximum distance was chosen for the test, since at that position the open flame exerts the least aerodynamic and heating effect on the flow field immediately around the fuel source. The temperature of the fuel was increased until the flame propagated up the column of dripping fuel to the fuel source. Drop size was varied from 0.20 to 0.25 centimeters and fuel flow rate ranged from zero to that rate which produced a solid stream. With the use of needle tips each drop size remained constant over the entire fuel flow range. At each drop size and flow rate condition, fuel temperature was increased from ambient (65°F) to 175°F for JP-4 and 250°F for kerosene. Flame climbing was not observed with either JP-4 or aviation kerosene under the range of conditions tested. The climbing phenomenon was observed only with a steady stream of fuel.

As two consecutive drops fall from the fuel source, the distance between them increases with time. There is obviously some minimum distance at which a burning drop can ignite the drop immediately above it. This minimum distance is dependent on the drop size, the flame height to drop diameter ratio, the ignition lag time, and the environmental conditions. In addition to the testing discussed, a theoretical study was conducted assuming the more favorable ignition conditions. Consecutive drops were assumed to be touching as they left the fuel source, a flame height to drop diameter ratio of 10 was employed in the calculations (6, 7), and ignition delay time of 0 sec. was assumed. Calculations were done for drop diameters of 0.20 cm and 0.60 cm. These calculations indicate flame climbing will not occur unless the ignition source is approximately 4 inches from the fuel source. Since deviations from these ideal conditions are a certainty, it is considered that the occurrence of a flame climbing a dripping column of fuel is extremely remote.

Stream Mode

This investigation, as with the dripping mode evaluation, was centered on finding those conditions under which a flame would climb up a column of fuel to the fuel source. The initial tests consisted of ejecting fuel from a needle tip, at a predetermined rate, into a pan of burning fuel and determining the minimum fuel temperature for flame climbing. The distance from the fuel source to the ignition source was twenty inches. The stream was ejected from a 0.03 inch diameter needle tip. This diameter was chosen since it was the minimum diameter at which the stream remained intact; that is, no misting or breakup was observed. For each test, fuel flow rate (100 cc/min and 200 cc/min) and wind air temperature (0^{O}F, 85^{O}F and 125^{O}F) were fixed. Wind velocity was varied in increments from 0 to 1.5 mph and the minimum fuel temperature for flame climbing was noted. (Since stream breakup occurred at wind velocities above 1.5 mph, this velocity was not exceeded.) The data obtained are plotted on figure 1 and illustrate the effect of wind velocity on the minimum fuel temperature for flame climbing for both kerosene and JP-4. Since the wind air temperature variation produced no discernible effect on the JP-4 fuel temperature necessary for flame climbing, this variable was omitted in the kerosene tests. The results of these tests indicate that: (1) as wind velocity increases the minimum fuel temperature for flame climbing increases; (2) there is no significant effect of fuel flow rate or wind temperature on the fuel temperature necessary for flame climbing; and (3) the minimum temperature for flame climbing is significantly higher for kerosene than for JP-4 under all conditions.

The second series of tests conducted with fuel streams utilized a 10 joule DC spark as the ignition source. The spark was placed at various radial locations relative to the fuel stream and at incremental vertical distances from the stream source. The fuel temperature was varied and the minimum fuel temperature for flame climbing was noted. The data obtained are illustrated in figure 2. As the ignitor is moved away from the stream in a radial direction, the minimum temperature required for flame climbing increases significantly. At any one radial location, as the spark ignitor is moved vertically away from the fuel source, the temperature required for flame climbing decreases. For temperatures below 225^{O}F for kerosene and below 50^{O}F for JP-4, the flame travelled downward from the ignition point but flame climbing did not occur. In the open flame ignition tests, flame climbing to the source was also limited by these same respective temperature values.

At all ignitor positions, the minimum fuel temperatures for both ignition and ignition with flame climbing were significantly higher for kerosene than for JP-4. For any one fuel temperature, the spatial ignition envelope for JP-4 is wider than that for kerosene. Figure 3 shows this comparison for a fuel temperature of 250^{O}F, in which flame climbing occurs within the ignition envelope. For kerosene the spatial ignition envelope ceases to exist at fuel temperatures below 155^{O}F; for JP-4 this limitation decreases to -30^{O}F.

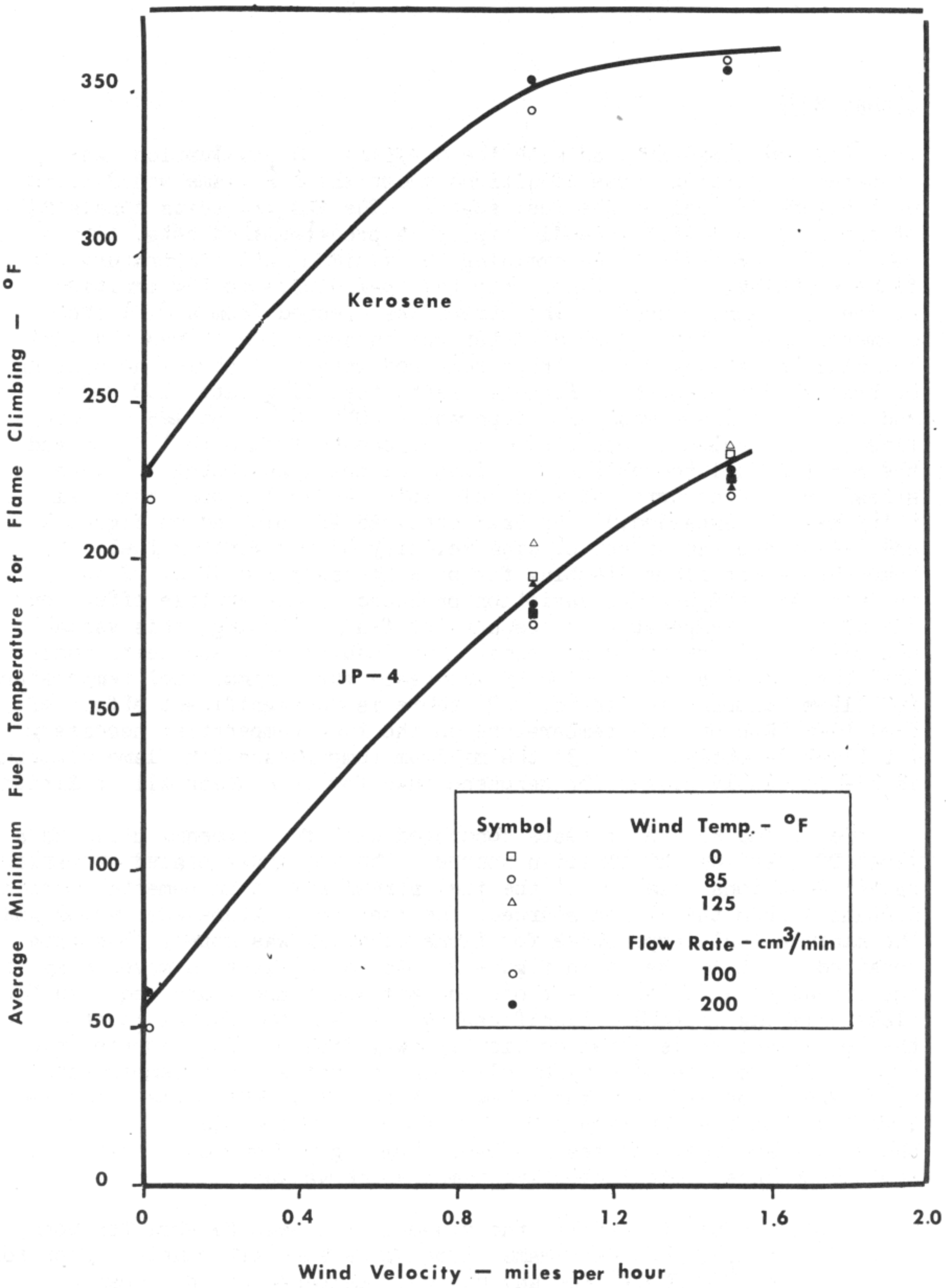


FIGURE 1

The Effect of Wind Velocity on the Minimum Fuel Temperature Required for Flame Climbing up a Fuel Stream

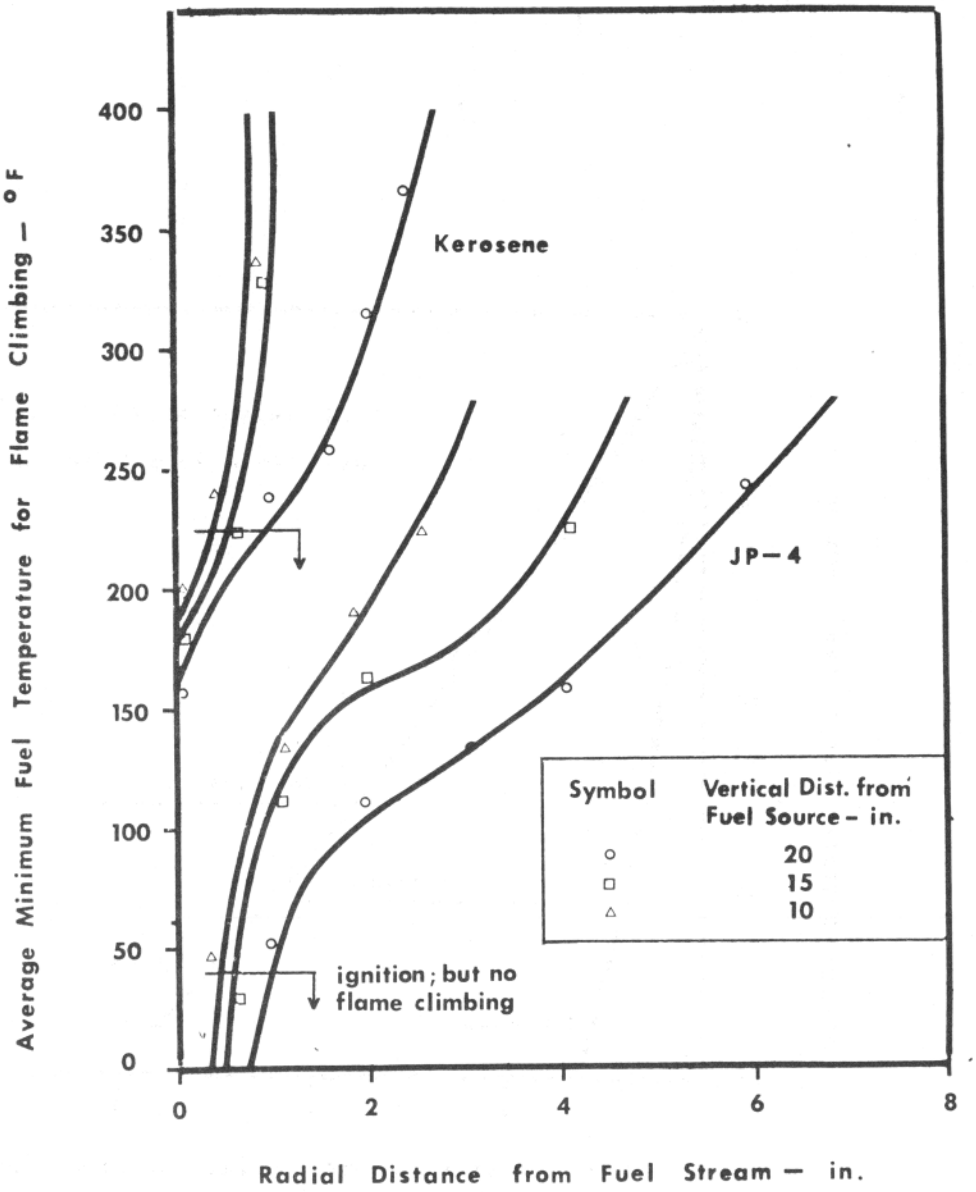


FIGURE 2

The Effect of the Spark Ignitor Location on the Minimum Fuel Temperature Required for Ignition and for Flame Climbing up a Fuel Stream

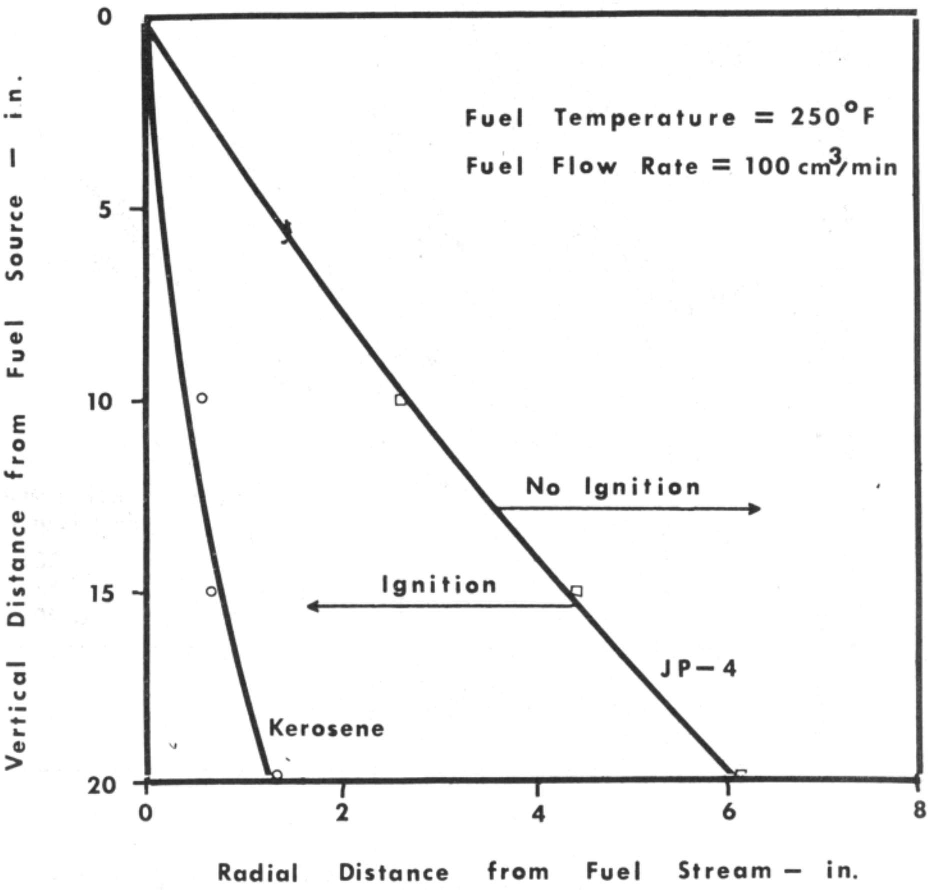


FIGURE 3

The Spatial Ignition Envelope with Flame Climbing at a Fuel Temperature of 250°F

In the final series of stream tests, the hot surface ignition characteristics of JP-4 and kerosene were investigated. 4.5 cm^3 of liquid fuel were ejected onto a hot stainless steel plate 2.5 inches below the fuel source. Wind velocity across the plate was varied and the minimum surface ignition temperature was noted. The plate dimensions were 19 inches x 26 inches with a directly heated area 9 inches x 16 inches. The fuel was ejected 6.25 inches downstream of the leading edge of the plate (2.5 inches downstream into the directly heated area). The plate temperatures reported are the averages of four surface thermocouple measurements located in the vicinity of the fuel stream impingement point. In this vicinity, the maximum temperature difference between thermocouples was approximately 80°F.

The data obtained, as illustrated in figure 4, show that as wind velocity increases there is a corresponding increase in the surface temperature required for ignition with both JP-4 and kerosene. For ignition to occur, both time and sufficient thermal energy (surface temperature) are required. The higher the surface temperature, the shorter the ignition delay time (the time necessary for ignition). By controlling the wind velocity, the fuel vapor residence time in the vicinity of the hot surface is also controlled. If residence time equals or exceeds ignition delay time for the test temperature, ignition will occur. As wind velocity is increased there is a decrease in residence time and therefore a higher surface ignition temperature is required.

Goodall and Ingle (8), in their tests with kerosene, also have shown the effect of wind velocity on surface ignition temperature. For wind velocities of 2 ft/sec and above, their data display the same general linear relationship between wind velocity and surface ignition temperature as the data obtained in this program. However, their surface ignition temperatures were, for any one wind velocity, 100°F lower than those obtained in this test program. A feasible explanation for this difference is that their heated surface was longer than that used in this program, thereby producing a greater residence time which caused ignition to occur at a lower surface temperature.

Goodall and Ingle have also reported that at 2 ft/sec and below, wind velocity has a much more pronounced effect on surface ignition temperature requirements. At near static conditions, their reported surface ignition temperature is approximately 650°F and it rises to 1150°F at 2 ft/sec. This static ignition temperature (650°F) has also been reported by MacDonald (9). MacDonald's work, in this area, consisted of dropping liquid kerosene onto a heated 6 inch pipe enclosed in an 18 inch sphere - this enclosure confines the vapor to the vicinity of the heated surface. With the test facility used by Goodall and Ingle the fuel vapors at the near static conditions were essentially confined since they could not diffuse or convect more than 4 inches above the hot

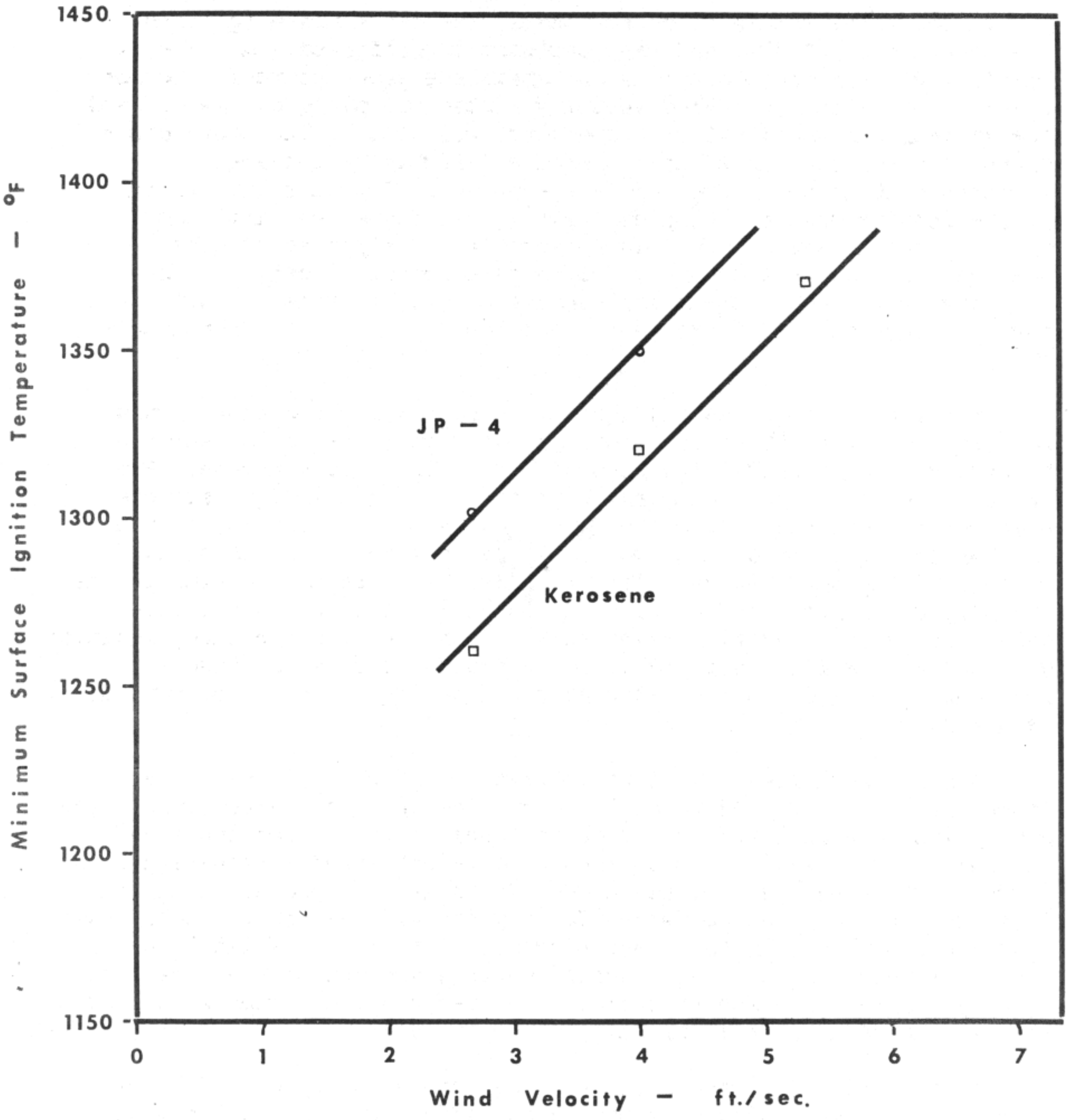


FIGURE 4

The Effect of Wind Velocity on the Minimum Surface Ignition Temperature for Fuel Streams surface. On the other hand, at the higher velocities (> 2 ft/sec) the system approaches that of an open plate, since the vapors were more readily carried away. The degree of confinement is very important.

The use of a 42 inch duct in this program permitted fuel vapors to readily escape the heated region above the plate for all wind velocities. Therefore, the time allowed for ignition is decreased. Due to this decrease in allowable ignition time, the surface temperature required for ignition is substantially increased, and the projected static ignition temperatures obtained are higher than the 650°F reported by other investigators. Scull (4) has reported on the ignition of fuels dropped on heated metal plates in open air. The data indicate that the ignition temperature of kerosene is much higher when dropped on a heated open plate than when dropped onto a heated metal tube that confines the mixture to a high temperature region. A comparison of these two environments for kerosene shows a surface ignition temperature of 417°F with the confined system and 1202°F with an open steel plate. This latter value agrees quite well with the projected static surface ignition temperature obtained in this program.

The data obtained also indicate that the surface ignition temperature at any one wind velocity is 50°F higher for JP-4 than for kerosene. MacDonald (10) found the same magnitude of difference between these fuels in his static test, in which the sphere temperature enclosing the hot surface was varied from 70°F to 400°F. In the ASTM 2155-66 autoignition temperature test for liquid petroleum products, the ignition temperature of kerosene is again approximately 50°F higher for JP-4. For the ASTM test, the entire environment is maintained approximately at constant temperature.

In reviewing all of the efforts conducted, combined with the wind velocity experiments in this program, the indication is that the ASTM autoignition test provides a good reliable guide in determining the difference in surface ignition requirements between fuels. The absolute temperature requirement for each fuel will depend on wind velocity, ignition surface area, surface composition and condition (4), fuel injection rate (9), and the degree to which the fuel vapors are confined to the heated region.

Pool Mode

One of the more comprehensive reports on the combustion process associated with pools has been written by Glassman and Hansel (11). Their work includes a critical literature review and remarks on such aspects as flame spreading and steady burning of pools of flammable liquids, but contains limited comment on ignitability. Their report and their references were a prime source of information related to pool fires.

It has been concluded that for conventional fuels the most important parameter governing the mechanisms of flame spread across a fuel surface is the flash point of the fuel-- or to be more precise the fire point. Since the flash point is only a few degrees lower than the fire point, and since it is more commonly used as the limiting temperature in safety applications, the flash point is used as the reference temperature in this discussion. The flame propagation rate across a pool will be governed by gas phase phenomena when the pool fuel temperature is above the flash point, and by liquid phase phenomena when the pool fuel temperature is below the flash point. The reported (12) rates of flame spread as a function of fuel temperature, for both JP-4 and aviation kerosene, are illustrated in figure 5. The rate of flame spread increases rapidly at temperatures immediately above the flash point for each fuel, and then levels out to a common rate. The flame spread rate for JP-4 is higher than that for kerosene at all temperatures below 200°F, and it is much higher at the more common ambient temperatures.

Blinov and Khudiahov (13) have reported on the linear burning velocity or regression rate (the depth of fuel consumed per unit time) as a function of pan diameter for various fuels. In addition, the Bureau of Mines (14) has conducted tests which have provided the regression rates for JP-4 and kerosene in an 8 inch diameter pan. A review of the combined data indicates that there is no significant difference in the JP-4 and kerosene linear burning rates for pan diameters below 50 inches and for pan diameters above 50 inches they are identical.

Welker (15) has published data showing the effect of wind velocity on the angle of flame tilt for a wind blown pool fire. Various pure compounds such as acetone, benzene, cyclohexane, n-hexane, and methanol were used as fuels in his experiments. A derived formula and experimentation demonstrate that the important parameters governing flame tilt angle are the flame drag coefficient, the pan diameter, the flame density and the ambient air density. A review of the foregoing work leads to the conclusions that, for a particular set of wind and temperature conditions, the tilt angles for JP-4 and kerosene will not differ significantly.

Tests in this program were focused on determining wind extinction velocities for pool fires and the comparable ignitability of pools of JP-4, kerosene, and blends of these fuels. These areas are of obvious interest from a fire hazard standpoint, and only limited information could be found in the literature. Initial tests were conducted to ascertain the wind velocity required to blow out a pool of burning fuel. Pool diameter was varied from 6 inches to 10 inches. The range of initial fuel temperatures tested was dependent on the fuel type. All tests were conducted at atmospheric pressure and the wind air temperature was approximately 60°F. Figure 6 shows the data obtained with an 8 inch pool, in which the effect of fuel type and initial fuel temperature on

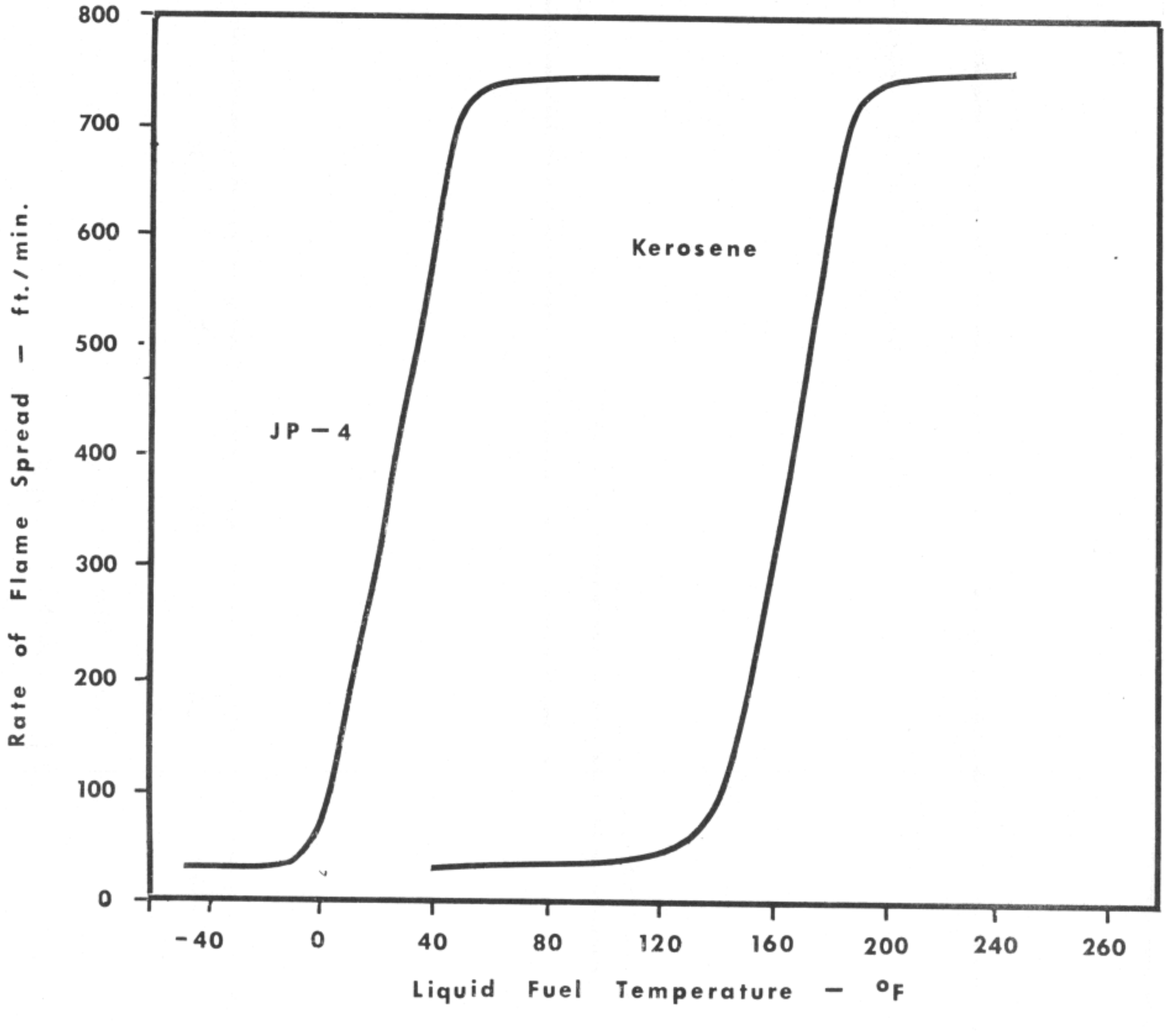


FIGURE 5

The Effect of Liquid Fuel Temperature on the
Rate of Flame Spread Across a Fuel Pool (Reference 12)

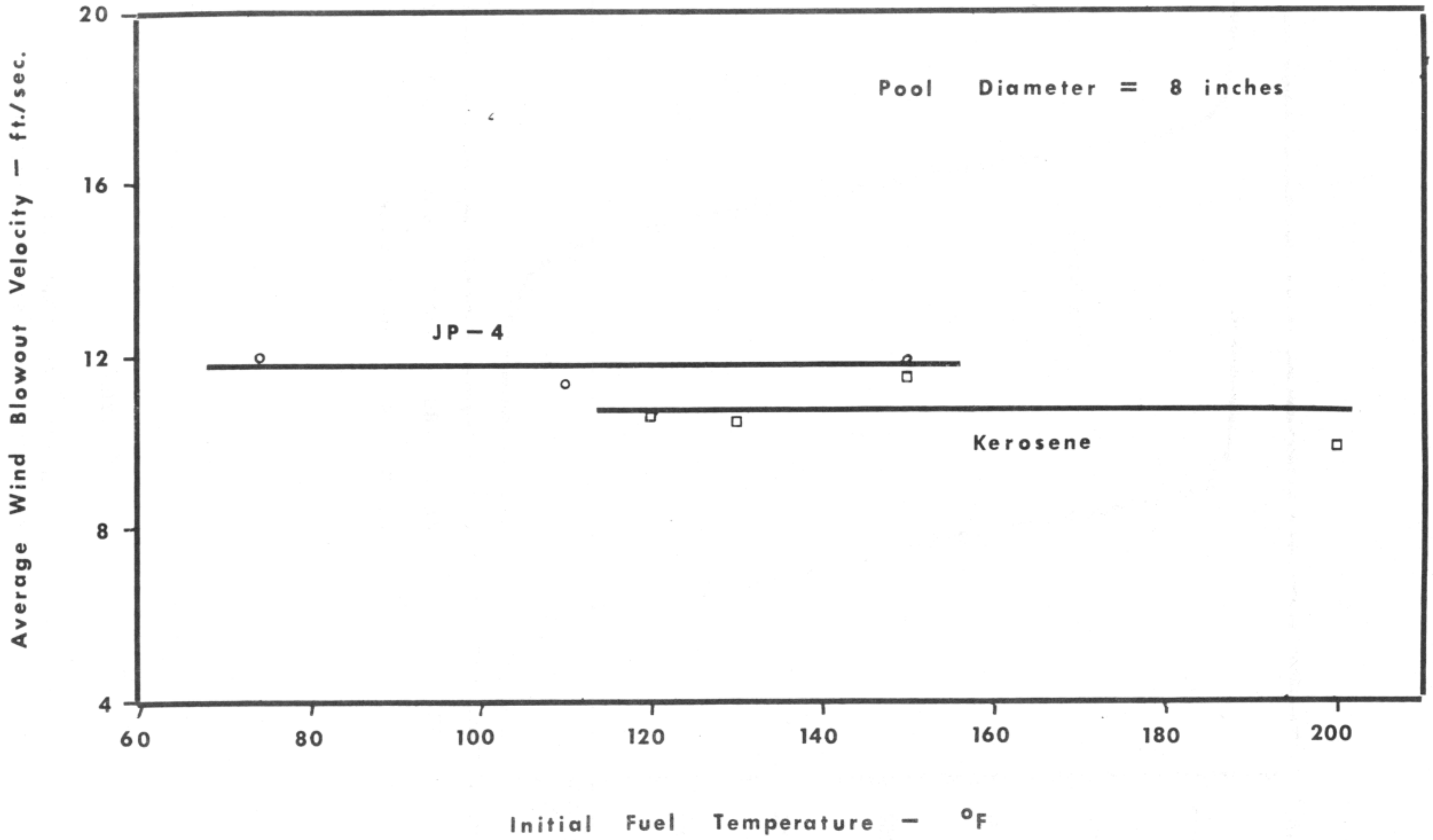


FIGURE 6

The Effect of Initial Fuel Temperature on the Average Wind Blowout Velocity of Burning Fuel Pools wind blowout velocity can be noted. Initial fuel temperature did not affect the average wind blowout velocity, and the difference measured between fuel types is considered insignificant. Hirst and Sutton (16) have also reported that extinction velocity was not affected by initial fuel temperature in their experiments with kerosene at atmospheric pressure. However, they found that there was a temperature effect at pressures below 0.4 atmospheres. At these lower pressures, increases in fuel temperature effect an increase in the extinction velocity required. Figure 7 illustrates the effect of pool diameter. As the diameter of the pool increases there is a corresponding increase in the wind blowout velocity. The difference in values obtained with JP-4 and kerosene is not considered significant. From the blowout velocity tests conducted, and from the review of all applicable work, it is expected that the extinction velocities for JP-4 and kerosene will be approximately the same for all pool diameters.

Upon completion of the wind blowout velocity testing, experimentation was aimed at determining the ignition characteristics of fuel pools with various ignition sources. In the initial test a 10 joule DC spark was placed at various heights above the center of a 10 inch pool of JP-4 and the minimum fuel temperature for ignition was measured. It was observed, however, that ignition occurred (even at elevated temperatures) only when the ignition source was placed extremely close to the pool surface. Since the fuel vapors were not diffusing more than 1 inch vertically and therefore relative data would be difficult to obtain (it was assumed that the kerosene height range would be even smaller), a 12 inch high shroud was placed around the pool to circumvent this problem. A two inch wide opening at the downstream end of the shroud allowed ignition source placement and also allowed some fuel vapor to escape. The partially shrouded pool simulates a spatial position internal to a much larger pool, in which fuel vapor would more readily diffuse upward. The plotted results of these tests are shown on figure 8. As the height of the ignitor above the pool was increased, the minimum fuel temperature for ignition also increased; and for all ignitor heights the minimum fuel temperature for ignition was higher for kerosene than for JP-4.

An open flame was the second ignition source used in the pool ignition experiments. These tests were conducted using the same pool shroud employed in the previous electrical spark tests. The data obtained are illustrated by the solid lines on figure 9. As the height of the flame above the pool was increased, the minimum fuel temperature required for ignition increased correspondingly. For all ignitor heights above the pool surface, the minimum fuel temperature required for ignition was again higher for kerosene than for JP-4. Also plotted on figure 9 are the electrical spark data. Minimum fuel ignition temperatures for both fuels are lower with open flame ignition than with electrical spark ignition for all ignitor heights. Since the continuous flame ignition source creates air convection currents, which can sweep the fuel pool and carry fuel vapors to the flame, ignition is enhanced. Convection, then, can play an important role in the ignition of these fuels.

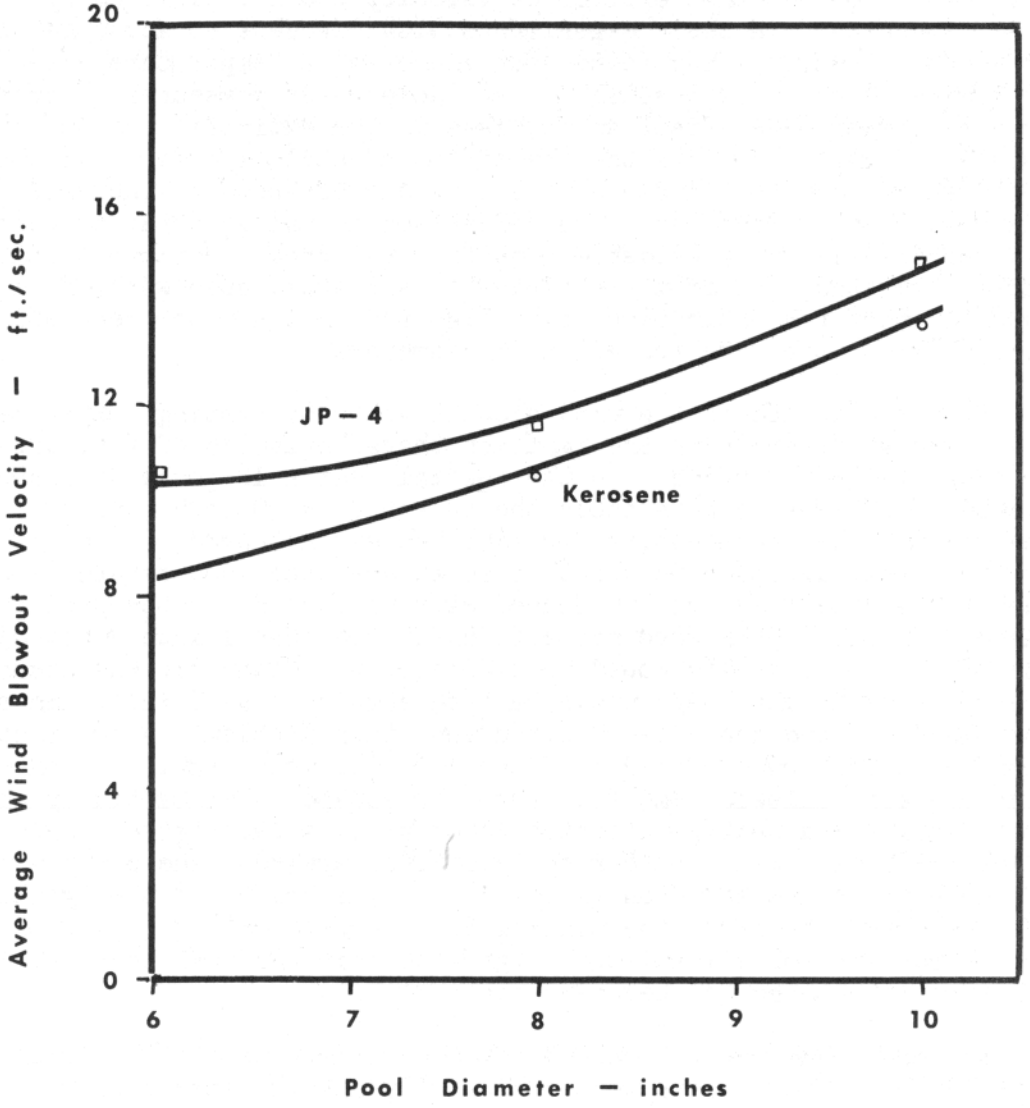


FIGURE 7

The Effect of Pool Diameter on the Average
Wind Blowout Velocity of Burning Fuel Pools

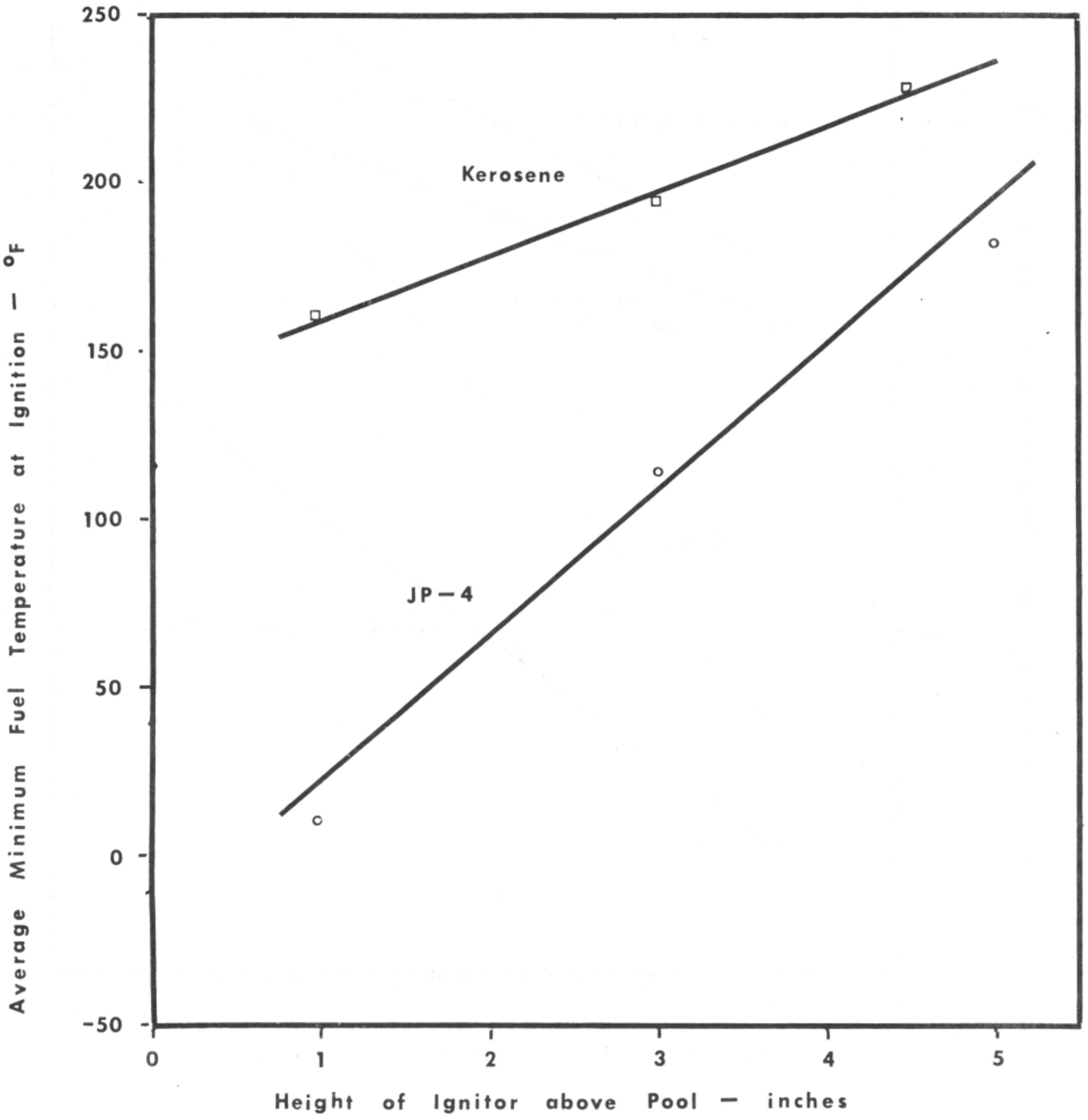


FIGURE 8

The Effect of Spark Ignitor Height on the Minimum
Fuel Temperature Required for Ignition of Shrouded Fuel Pools

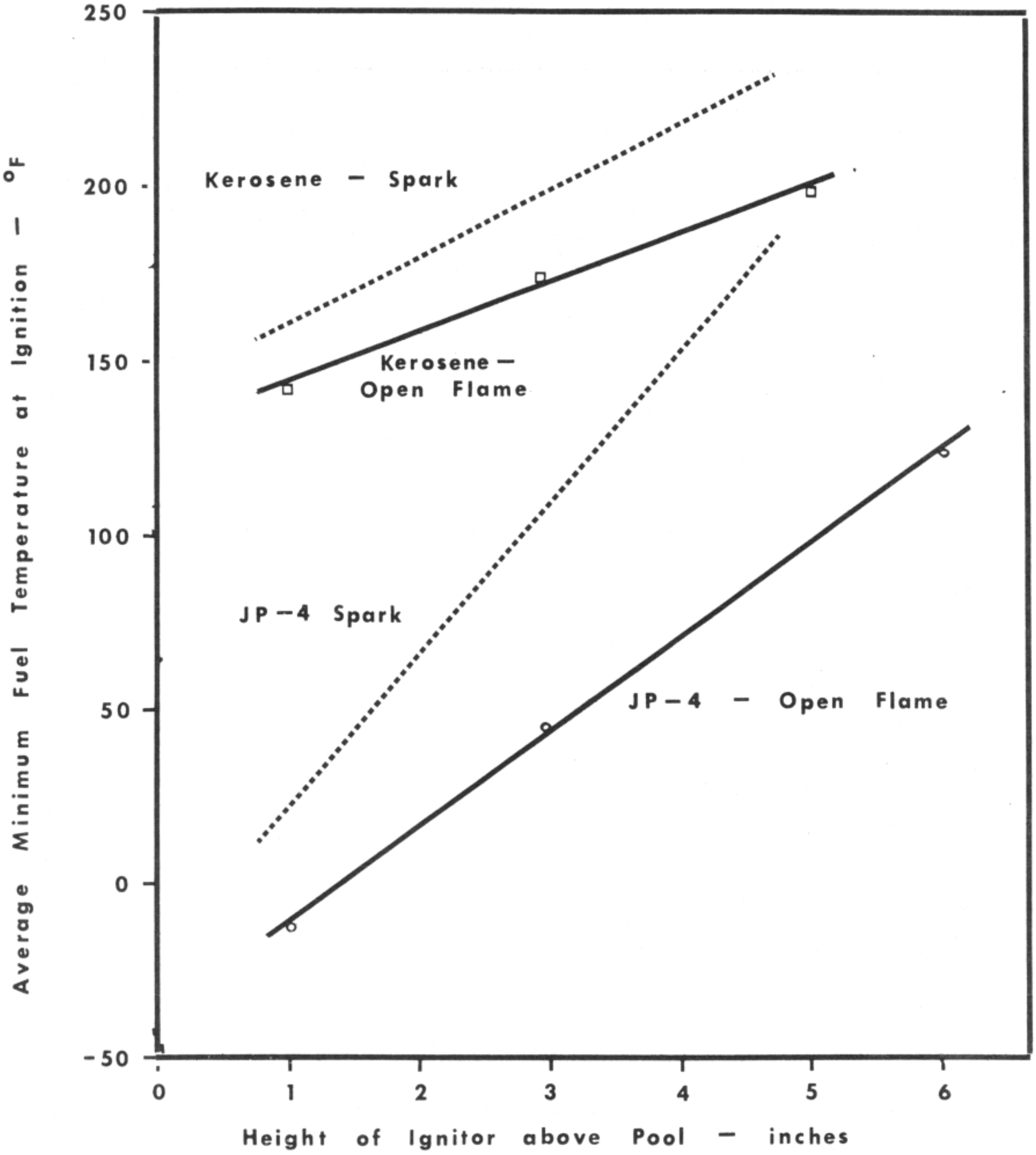


FIGURE 9

The Effect of Open Flame Ignitor Height on the Minimum Fuel Temperature Required for Ignition of Shrouded Fuel Pools

Since ignition with the open flame occurred at lower fuel temperatures, it was decided to experiment with unshrouded pools employing the open flame as an ignition source. Due to the forced convection provided by the open flame, unshrouded fuel pools were able to be ignited at various ignition heights. The data obtained, which are illustrated in figure 10, are similar to those obtained in other ignition experiments. That is, the minimum fuel temperature for ignition increased as the height of the ignition source was increased, and the fuel ignition temperatures were higher for kerosene than for JP-4 for all ignitor heights investigated.

In order to gain a better understanding of the ignition phenomena involved, a more thorough investigation of the ignition characteristics of unshrouded pools was pursued with the electrical spark as the ignition source. The results of these tests are illustrated in figure 11 along with the open flame data. For kerosene the minimum fuel temperature for ignition was higher when using electrical sparks than when using the open flame; and as the ignition height increased, there was a more pronounced increase in the fuel temperature required for ignition. In concert with the earlier unshrouded pool tests, experiments conducted with pools of JP-4 using the electrical spark as the ignition source yielded limited data. At an ignitor height of one inch, ignition occurred at -15°F and repeatability was good. At ignitor heights above one inch but below two inches, ignition occurred, but at such erratic temperature levels that no reliable data point could be reported. With a spark ignitor height of two inches ignition did not occur even with the JP-4 fuel temperature as high as 190°F.

Visual observation of the JP-4 vapors indicate they rise to a height of approximately one inch and then move horizontally along the test tunnel floor. Slight, but unavoidable, drafts influence the flow of these vapors to such an extent that they can cause random vapor flow upward to the ignition source, and hence ignition occurs. The irregularity of these drafts causes irregular flow and hence large scatter in the minimum fuel temperature at ignition. In contrast to the vapor flow behavior observed with JP-4, visual observation of the tests with kerosene clearly shows a convection effect in which the fuel vapor-air mixture rises to the spark ignition source (as opposed to pure diffusion). Due to the predominant convection effect with kerosene, its ignition characteristics could be consistently established.

The question naturally arises as to why, in the spark ignition tests, kerosene vapors are convected upward with heated air while JP-4 vapors are not. Convective air flow in the pool ignition experiments can be caused in two ways in a quiescent atmosphere. First, as the fuel is heated above ambient temperature, it can heat the air immediately above the fuel pool surface causing it to convect upward. Second, an ignition source such as an open flame can create convection flow around itself which causes the air below to flow over the fuel pool and rise. In the electrical spark tests, convection can occur only through heat transfer from the hot fuel surface to the air above.

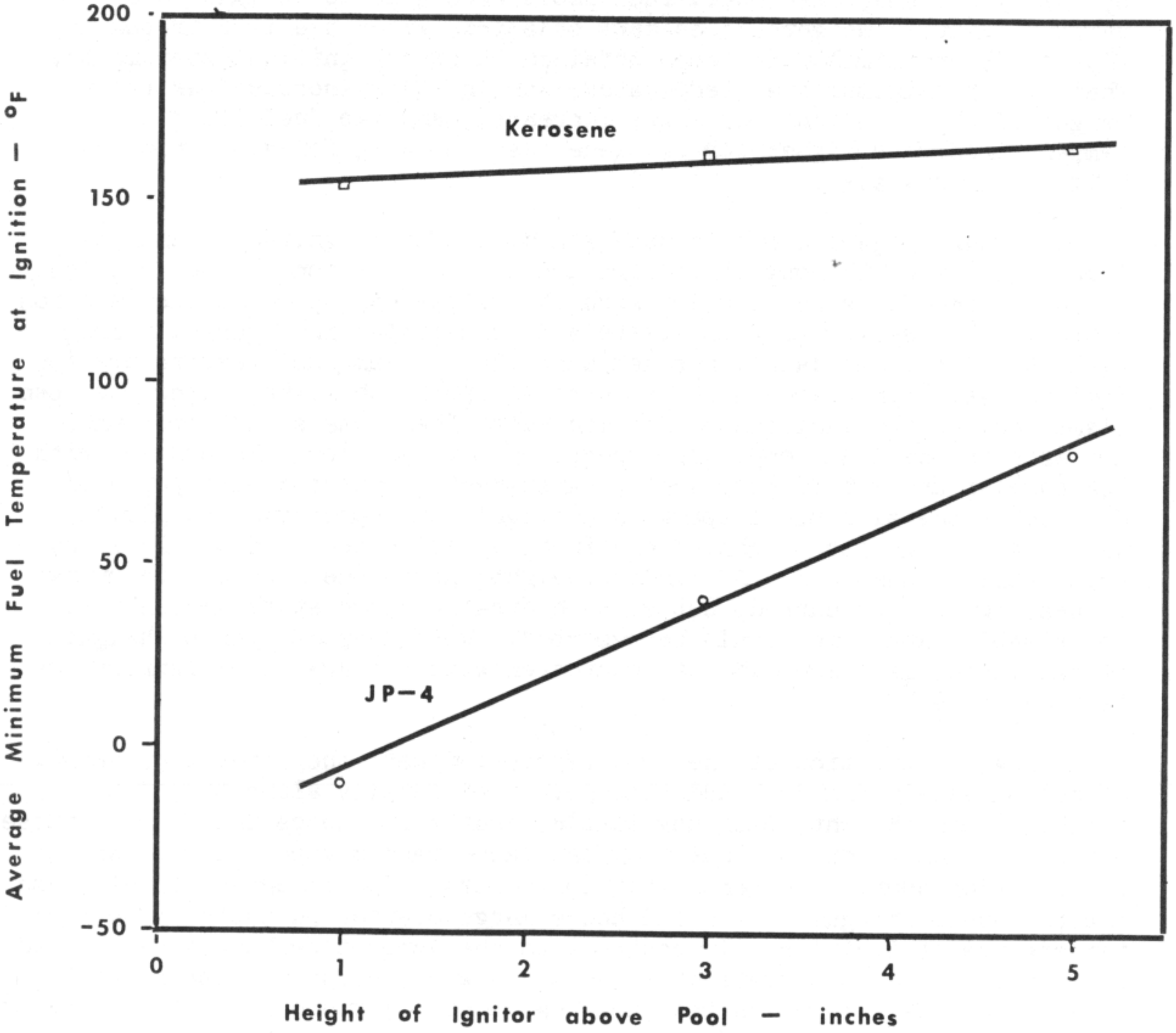


FIGURE 10

The Effect of Open Flame Ignitor Height on the Minimum Fuel Temperature Required for Ignition of Unshrouded Fuel Pools

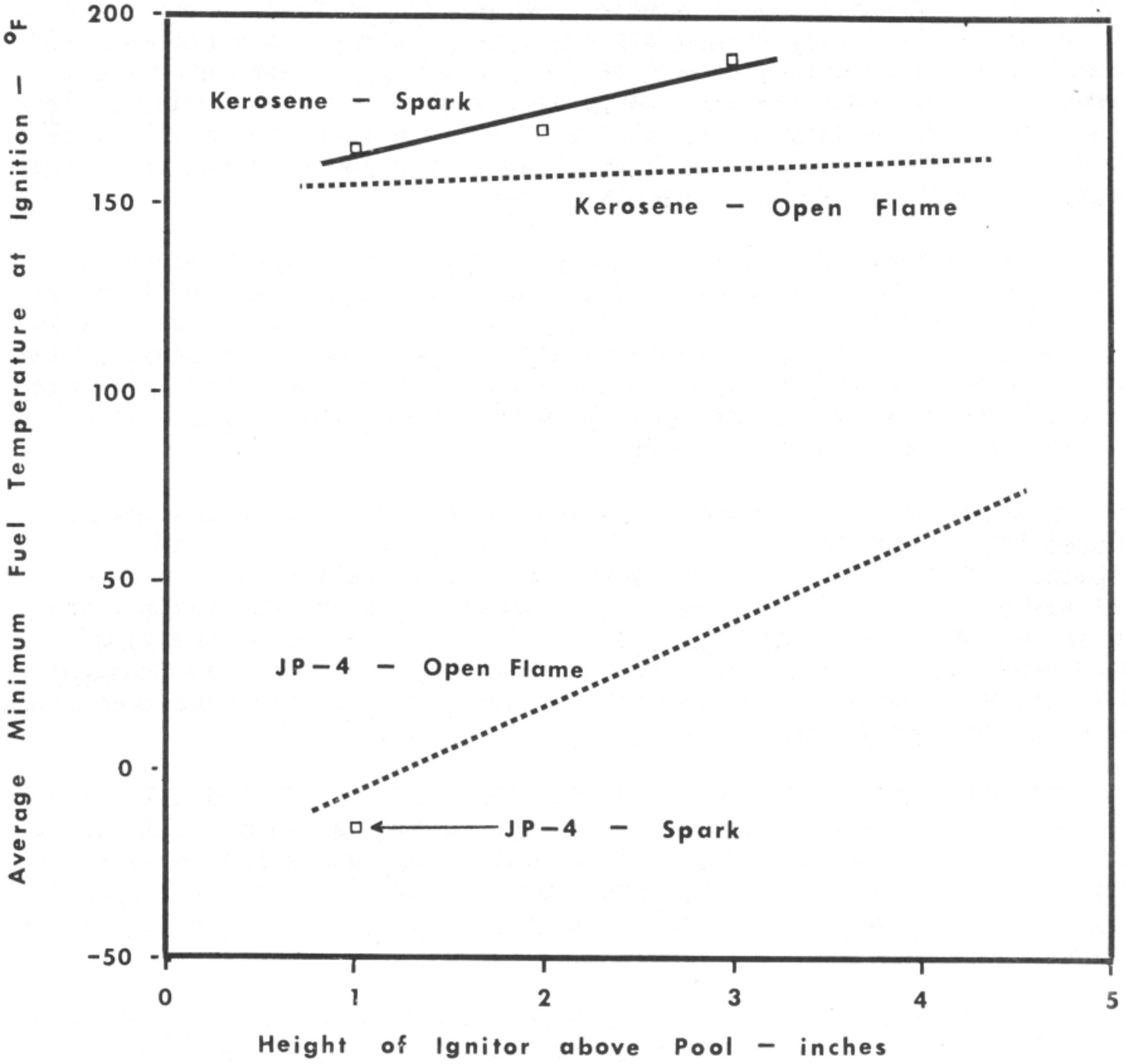


FIGURE 11

The Effect of Spark Ignitor Height on the Minimum Fuel Temperature Required for Ignition of Unshrouded Fuel Pools

There is a high concentration of JP-4 fuel vapors above the fuel pool, at ambient temperatures and above, which rise to approximately one inch above the pool surface. This layer of vapor, in effect, insulates the hot fuel surface from the surrounding ambient air. Therefore, since efficient heat transfer from the liquid fuel to the air does not occur, sufficiently strong air convection currents are not realized. In addition, calculations show that for ambient fuel temperatures and above, the JP-4 vapor-air mixture is denser than the surrounding ambient air. Therefore, natural convection will not occur and hence the vapor-air mixture will not rise. Without these convection currents the possibility of ignition is significantly mitigated.

Kerosene has a much lower vapor pressure than JP-4, and there is almost no vapor buildup above the pool surface. Heat transfer from the hot pool surface to the surrounding ambient air is therefore reasonably efficient, and convection currents do occur. In addition, because of the low vapor pressure of kerosene at the fuel temperatures tested, the vapor-air mixtures were less dense than the 60°F - 80°F ambient air. This mixture then, will convect upward.

In these tests, the lack of convection air currents significantly reduced the chance for ignition of JP-4 fuel pools. It should be realized however that in a real environmental situation air currents will always exist. Consequently, JP-4 ignition at ambient temperature can occur, while the limiting height will be determined by the flow characteristics of these air currents. In a non-quiescent environment then, the difference in ignitability between JP-4 and kerosene fuel pools can be attributed primarily to flash point differences.

The next series of unshrouded pool tests was conducted using a hot nichrome wire as the ignition source. The data obtained are illustrated in figure 12. Again, minimum fuel ignition temperature increased as the height of the ignitor above the pool was increased, and for all ignitor heights the average minimum fuel temperature for ignition was higher for kerosene than for JP-4.

Pool testing with friction sparks as the ignition source also indicated that higher fuel temperatures are required for the ignition of kerosene as compared to JP-4. The sparks were produced through friction contact between a six inch diameter Simonds aluminum oxide abrasive wheel and a titanium alloy block. The sparks were thrown toward the surface of the pool. Because of the dynamic nature of the test, determination of the effects of variation in ignition source height was impractical. The results of these tests are given in the table below.

Table 1

Fuel	Average Minimum Fuel Temperature for Ignition
JP-4	-18°F
Kerosene	141°F

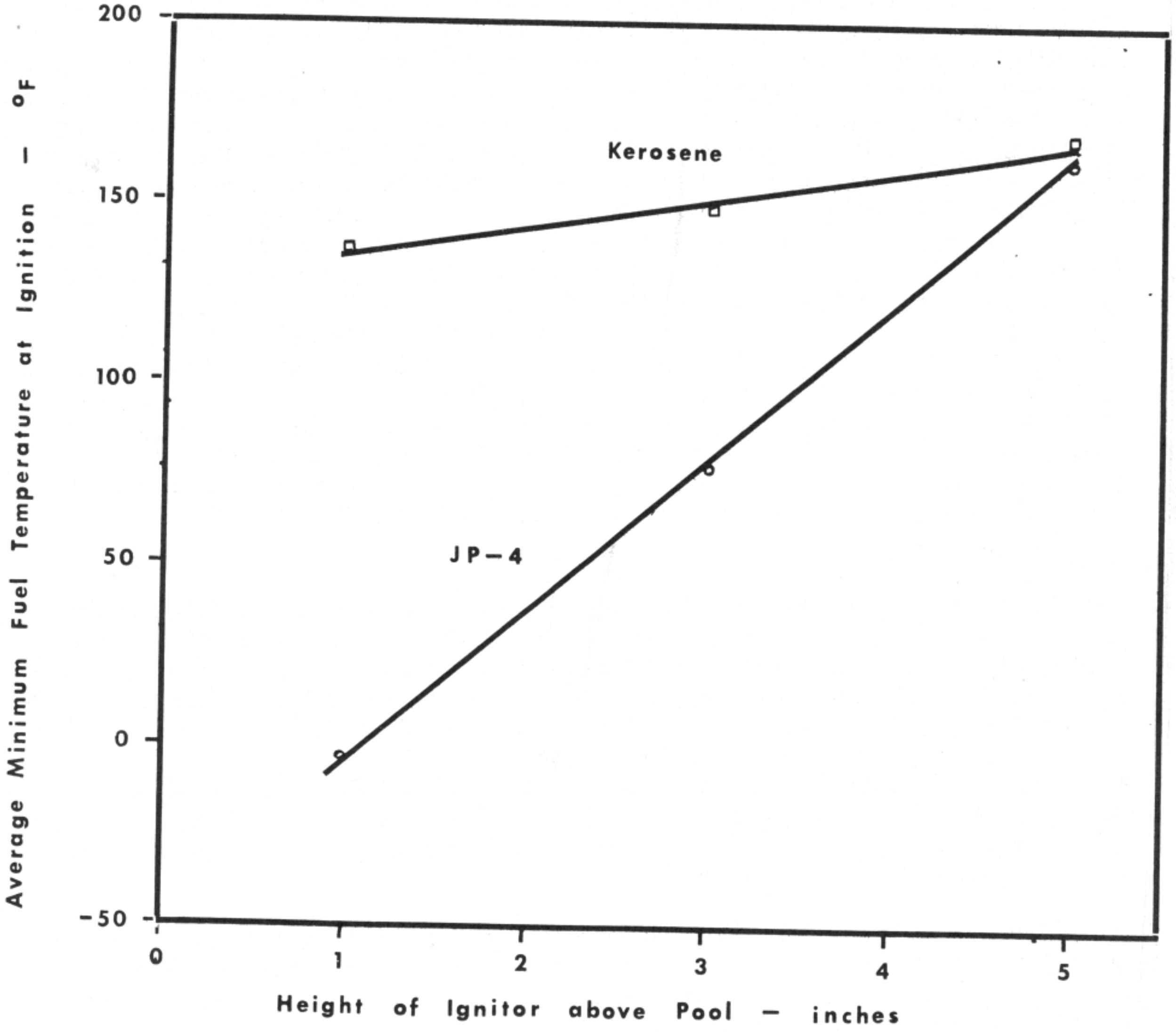


FIGURE 12

The Effect of Hot Wire Ignitor Height on the Minimum Fuel Temperature Required for Ignition of Unshrouded Fuel Pools

The next sequence of experiments centered on determining the effect of wind velocity on the minimum fuel temperature for ignition. The ignition sources were placed at the downstream edge of the pool, close to the pool surface. Fuel temperature and air temperature were maintained approximately equal and were increased at each wind velocity until ignition occurred. The data obtained from these experiments are plotted on figure 13. The open flame ignition tests indicate that for any wind velocity the kerosene ignition temperature is significantly higher than that for JP-4. For both kerosene and JP-4, the minimum fuel ignition temperature increases with higher wind velocities. The JP-4 spark ignition experiments indicate that the effect of wind remains characteristically the same regardless of the type of ignition source. The difference in the JP-4 ignition temperatures with the open flame and the electrical spark is not attributed to convection (because of the wind velocities) but rather to the difference in wind and fuel vapor flow patterns over the two geometrically different ignition sources. The ignition of kerosene with electrical sparks was attempted; however, a facility limitation precluded these tests. To achieve high fuel temperatures in a wind environment, high air temperatures were also necessary. The wind temperature requirements needed in the kerosene tests were beyond the limit of the air heating facility.

The final series of pool ignition tests were conducted with blends of JP-4 and kerosene using an open flame as an ignition source. A ten inch diameter pool was used, with a propane flame held one inch above the pool center. The average minimum temperatures for ignition together with measured flash points (17) are plotted against blend composition in figure 14. These data show that the flash point of a fuel or a fuel blend is a reliable indicator of the ignitability of fuel pools. Furthermore, it is apparent that small additions of JP-4 to kerosene significantly change the flammability, while small additions of kerosene to JP-4 have a negligible effect on flammability.

In summary, the fuel pool ignition data indicate that ignition source position, ignition source type, and environmental conditions all affect the minimum temperature required for the ignition of each fuel. The difference noted between fuel types, however, is primarily a function of the flash point of the respective fuel.

Spray Mode

Various investigations have been conducted on the flammability characteristics of sprays. Burgoyne (18) has shown that a mist with droplet size below 10 microns behaves like a vapor; it will have the same lean flammability limit as a vapor and the same flame speeds for equal fuel-air ratios. For mists with droplet size above 10 microns the lean flammability limit decreases with increasing droplet size until a size of 60 microns is approached. Anson (19) has demonstrated that the lean flammability limit for a mist of 60 micron droplets is below that for a vapor, and has shown that for mists with droplet size above 60 microns the lean flammability limit increases with increasing drop size.

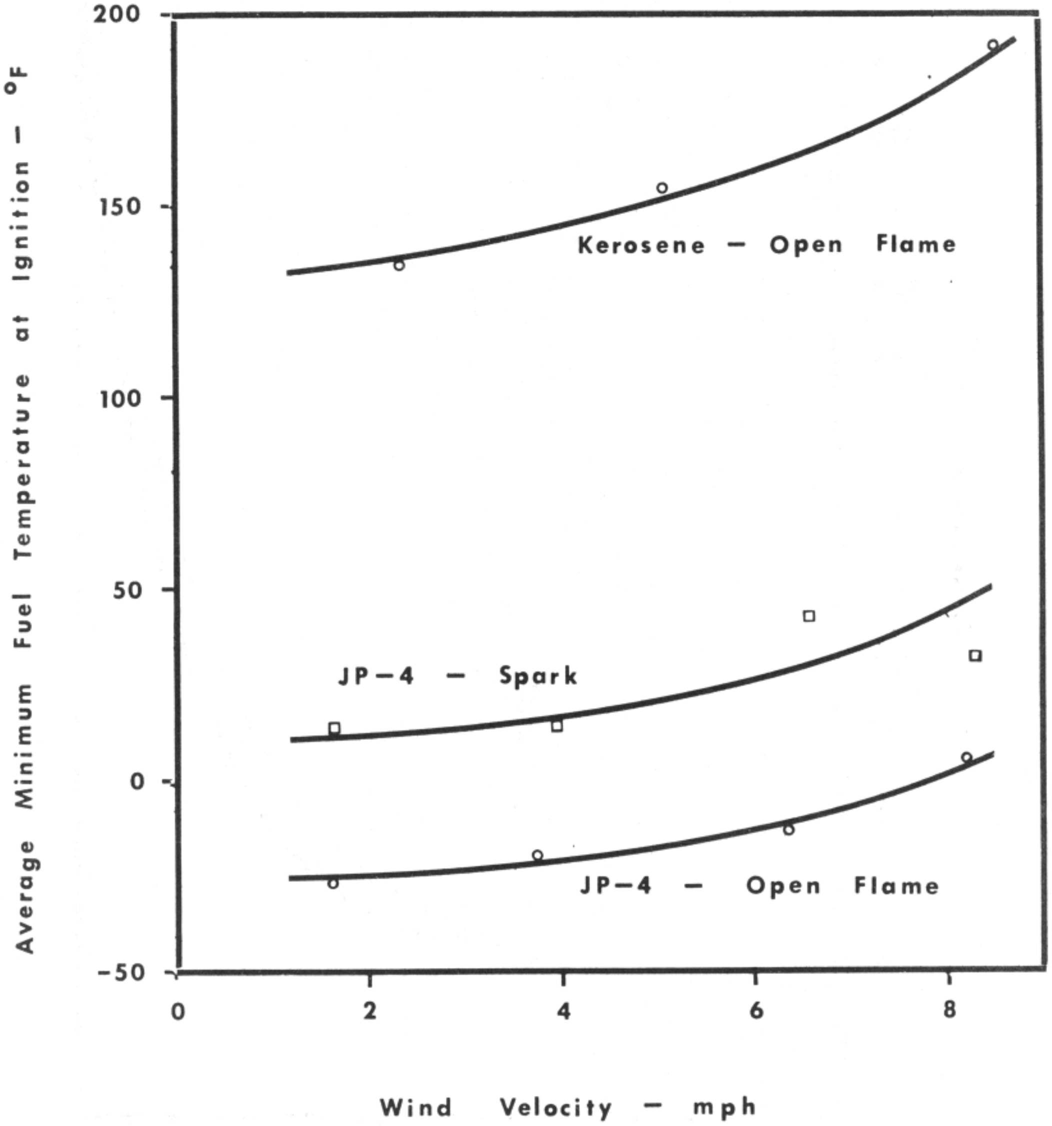


FIGURE 13

The Effect of Wind Velocity on the Minimum Fuel Temperature Required to Ignite a Fuel Pool

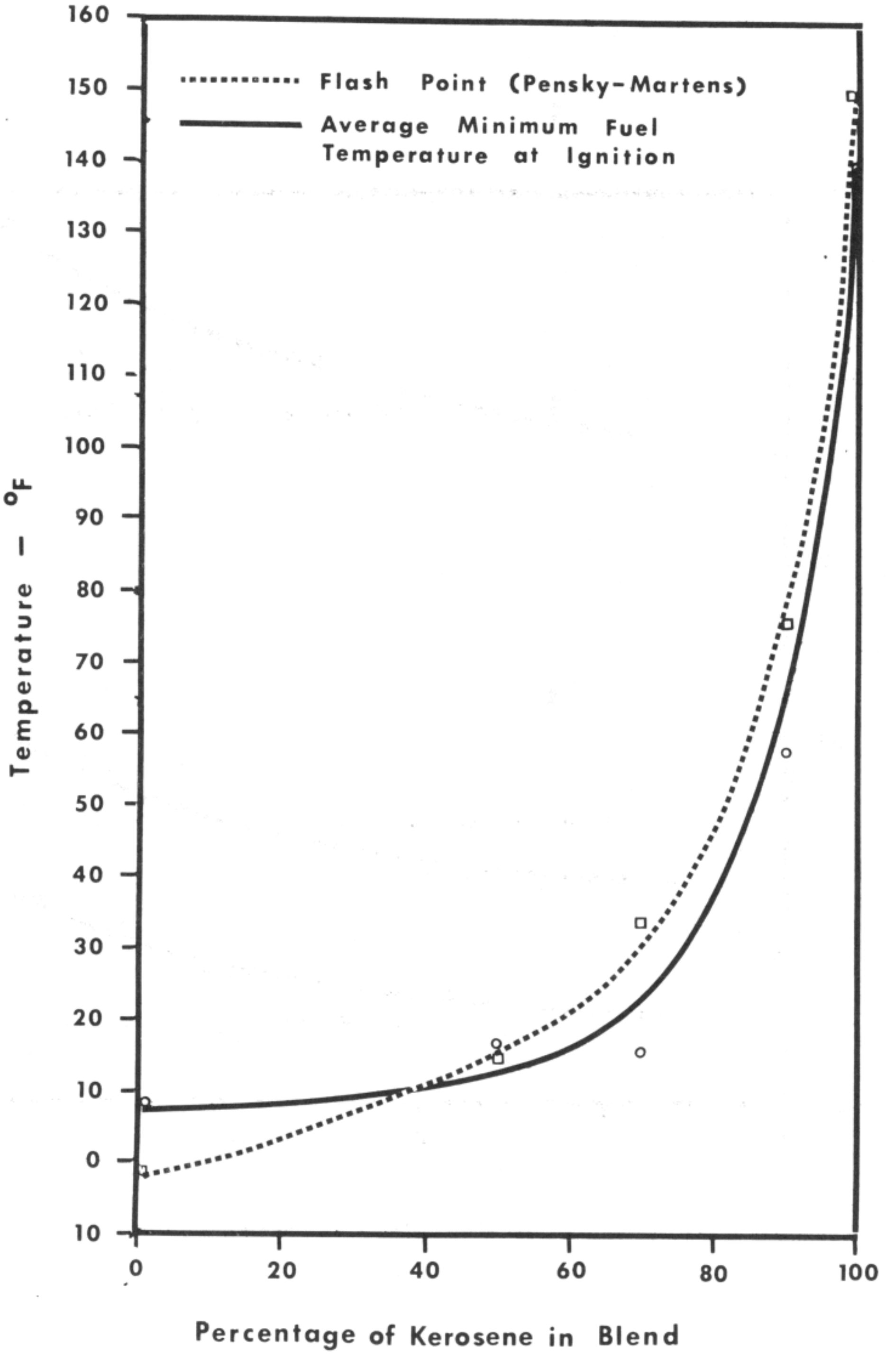


FIGURE 14

The Effect of Fuel Blend Composition on Flash Point
and the Average Minimum Temperature at Ignition
(Open Flame Ignition Source Placed 1 Inch Above Pool Center)

Burgoyne, in his experiments with tetralin, shows that, for mists with droplet size about 10 microns, flame speed increases with droplet size up to approximately 20 microns and then tends to level off (there are no data reported for droplet sizes above 38 microns). Eventually, as reported by Williams (20), flame speed should decrease with drop size when heterogeneous combustion becomes the controlling mechanism.

Liebman (21) has reported data indicating that the energy required to ignite a mist is about 25 times greater than that required to ignite the vapors of the same material. The spark energy required to ignite a mist varies with temperature and fuel type. Liebman's data for JP-4 and kerosene are shown in figure 15, and indicate through extrapolation that a constant ignition energy requirement of approximately 5 millijoules exists at the respective flash point temperatures of the fuels.

Campbell (22) has investigated the ignition characteristics of JP-4, kerosene and avgas sprays using friction sparks. Bearing loads of 20 to 1455 psi with sliding speeds of 5 to 40 miles per hour were obtained with five different metals. The effect of bearing surface was studied by using both concrete and asphalt runways.

The results indicate that aluminum will not produce friction sparks that will ignite the fuel sprays under the test conditions mentioned above. The titanium alloy (Ti 100A) ignited fuel sprays readily even at low bearing pressures (20 psi) and slow sliding speeds (5 mph). However, the other three metals tested, magnesium alloy (FS 1), chrome-molybdenum (SAE 4130) steel and AlSl 347 stainless steel, ignited the fuel mist at slide speeds and bearing pressures less than those expected in an actual aircraft crash.

Campbell states that kerosene fuel appears to be slightly less susceptible to ignition under the test conditions than JP-4 or avgas. The difference was in the number of times the spray would ignite; however, this difference was slight. The kerosene did not ignite as often as JP-4 at low bearing pressures, though both fuels gave inconsistent results at these conditions. It is expected that at fuel temperatures higher than that tested (ambient) the kerosene and JP-4 would be equally susceptible to ignition.

The type of surface (asphalt or concrete) had no effect on the titanium alloy, but the asphalt surface required higher bearing pressures and sliding speed with the chrome-molybdenum alloy. It was assumed that the magnesium and stainless steel would give approximately the same results as the chrome-molybdenum alloy.

Since the more relevant data have been reported on the static ignition characteristics of JP-4 and kerosene mists, tests in this program were aimed at determining the relative flame speeds of these fuels and their ignition characteristics under dynamic conditions. The apparatus

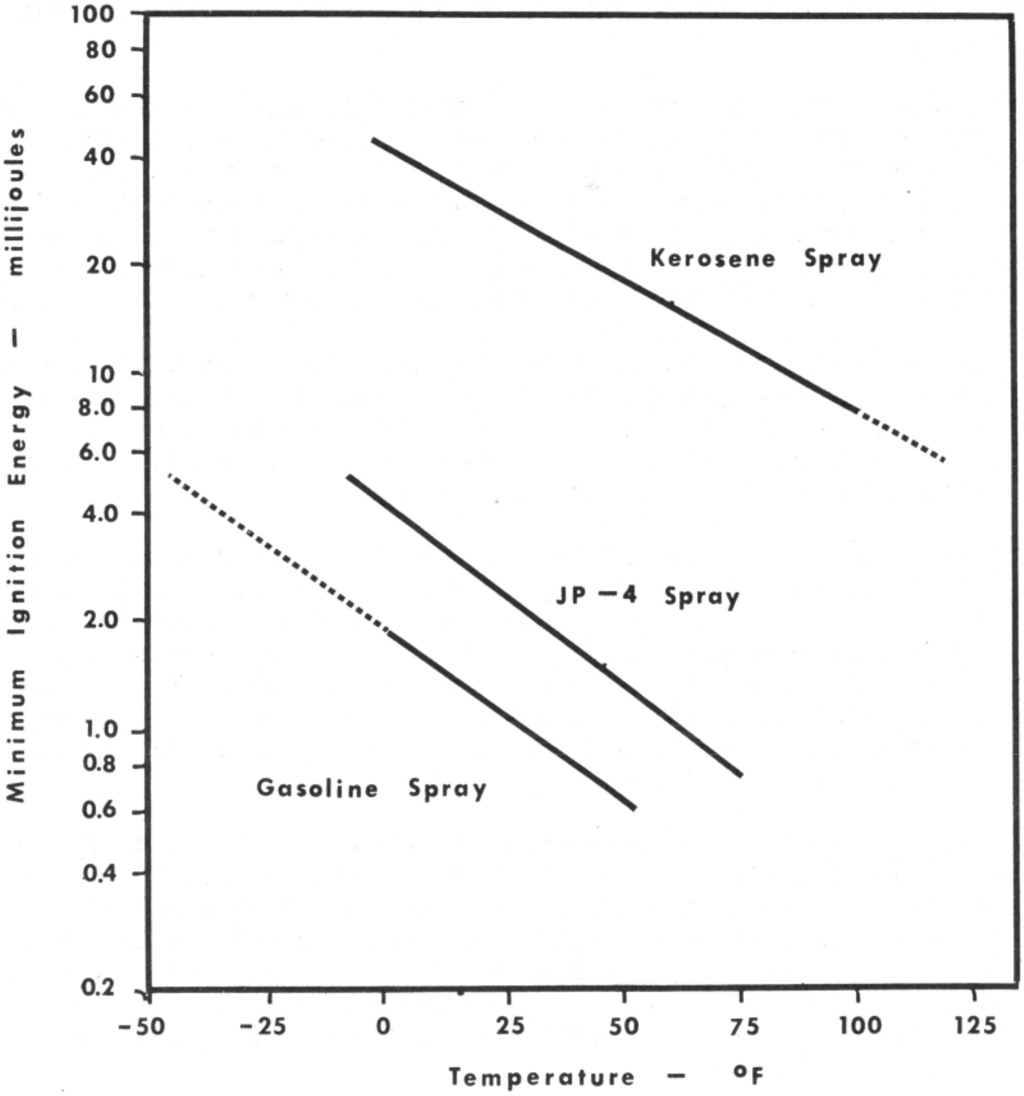
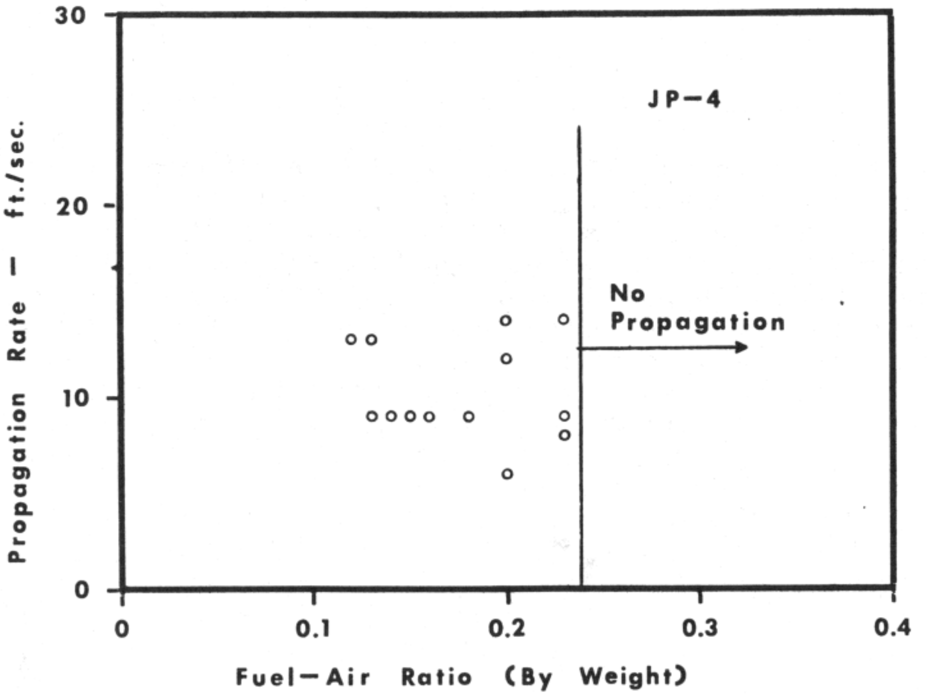


FIGURE 15

The Effect of Fuel Spray Temperature on the Minimum Ignition Energy Requirements (Reference 21) constructed for, and employed in, the flame speed tests is shown schematically in Appendix I. Basically, a fuel mist, produced by a pneumatic atomizing nozzle, is injected into the top of a four foot long tube, and ignition is provided at the bottom of the tube by means of a heated nichrome wire assembly. Airflow through the nozzle is regulated by varying the air pressure, and fuel flow is controlled by changing the total head pressure of an external fuel reservoir. Ionization probes, separated by a one foot interval, record the passage of the flame. The upward flame speed is calculated by dividing the probe separation distance by the time required for the flame to pass from the first probe to the second (as recorded on an oscilloscope). The ionization probes register flame passage by detection of a small amount of ionization associated with the passing flame front. This technique is especially suitable for flame propagation measurements because of its extremely short response time. Based on information contributed by the nozzle manufacturer (23) and other available information (24), mean drop size was calculated to be between 20 and 40 microns. Mixture flow velocity in the tube was between 0.4 and 0.6 ft/sec. in all tests. It is realized that in any attempt to obtain absolute propagation rates, apparatus effects must be considered; nevertheless, these experiments can be used to determine the relative flame speeds of fuels. In these tests a large percentage of the fuel collects on the flame tube walls and drips down the walls to the bottom of the tube. For an accurate determination of mist fuel-air ratio, the wall drippings are measured and subtracted from the total fuel flow rate. Since the air flow is known, the mist fuel-air ratio is then determined. Figure 16 illustrates the flame propagation rates for a range of fuel-air ratios, where the fuel temperature range is between 50°F and 60°F. Due to the random variables associated with flame propagation in tubes there is a certain amount of scatter apparent in the data - especially with the kerosene fuel. It can be noted that there is no apparent relationship of propagation rate to mist fuel-air ratio in these tests; nevertheless, the bulk of the observed rates lie in a certain range. This range, therefore, can be used as a basis of comparison between fuels, and for these tests the results indicate that kerosene has a higher range of flame speeds than does JP-4.

Experiments to determine the effect of mist temperature on the flame propagation through fuel mists were also conducted. Modification of the flame tube apparatus provided for fuel mist temperature variation by routing the fuel and air lines through a heat exchanger. The flame tube is enclosed in a metal box, hence, the tube temperature was controlled by passing air of the desired temperature through the box around the flame tube. Since the insulated box was sealed and wall drippings could not be measured, an accurate determination of mist fuel-air ratio could not be determined. Although fuel-air ratio values of the non-ambient test are not specifically known, tests were run within the same range of total fuel-air ratios as the ambient fuel temperature tests.



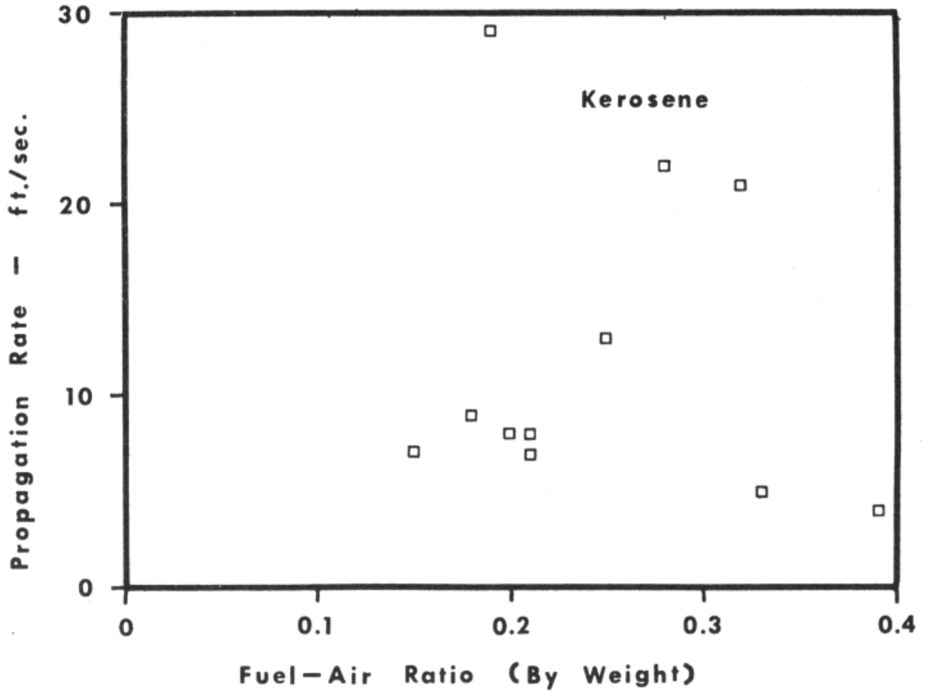


FIGURE 16

The Effect of Fuel-Air Ratio on the
Flame Propagation Rate Through Fuel Sprays

The data obtained at fuel temperatures of 0°F, 55°F and 85°F are plotted on figure 17 in bar graph form. These data indicate that flame speeds through rich JP-4 mists do not change appreciably with temperature; however, flame speeds through corresponding kerosene mists increase significantly with temperature. This phenomenon can be explained in terms of the relative volatility of the two fuels. As a flame front passes through a fuel mist, the fuel droplets are preheated by the flame front. The individual droplets experience an increase in temperature before the flame front reaction zone reaches the droplets. Because JP-4 and kerosene have similar heats of reaction, their average flame front temperature profiles will be the same. JP-4 has a distillation curve approximately 200°F lower than kerosene however, and a significantly greater portion of a JP-4 droplet will vaporize and diffuse during the preheating time as compared to a kerosene droplet. Thus, for an equivalent mist fuel-air ratio, the effective vapor fuel-air ratio in the preheat zone will be richer for JP-4 than for kerosene.

For the rich mist fuel-air ratios reported here, the effective-vapor fuel-air ratio for the JP-4 mist would also be rich. Thus, increasing the temperature does not increase the flame speed. For kerosene, increasing the temperature will bring the effective vapor space fuel-air ratio from a lean value towards stoichiometric fuel-air ratio. Thus, the kerosene flame speed would be expected to increase with temperature, as it does. Eventually, a mist temperature will be reached where preheating would make the kerosene mist vapor space rich, but these tests indicate that, for 30-micron particles, this occurs at a temperature greater than 100°F.

For lean mist fuel-air ratios, temperature increases have a different effect on JP-4 flame speeds. A significant study of prevaporization on mists of lower overall fuel-air ratios has recently been reported (25,26). This investigation indicates that at lean overall fuel-air ratios, the flame speed through the more volatile mist will be somewhat higher. Thus, for lean overall fuel-air ratios, flame speeds would be greater through JP-4 mists than through kerosene mists. In addition, at lean overall fuel-air ratios, an increase in temperature will effect an increase in flame speed for both JP-4 and kerosene mists. Furthermore, for both fuels, flame speeds should be equivalent for mists of particle size below 10 microns. For such fine mists, droplets are completely vaporized in the preheat zone and have been reported by others to behave as a vapor.

In summary, for rich mists kerosene has the greater flame speed; for lean mists JP-4 has the greater flame speed. Overall, neither seems to offer a substantial safety advantage considering flame propagation through mists.

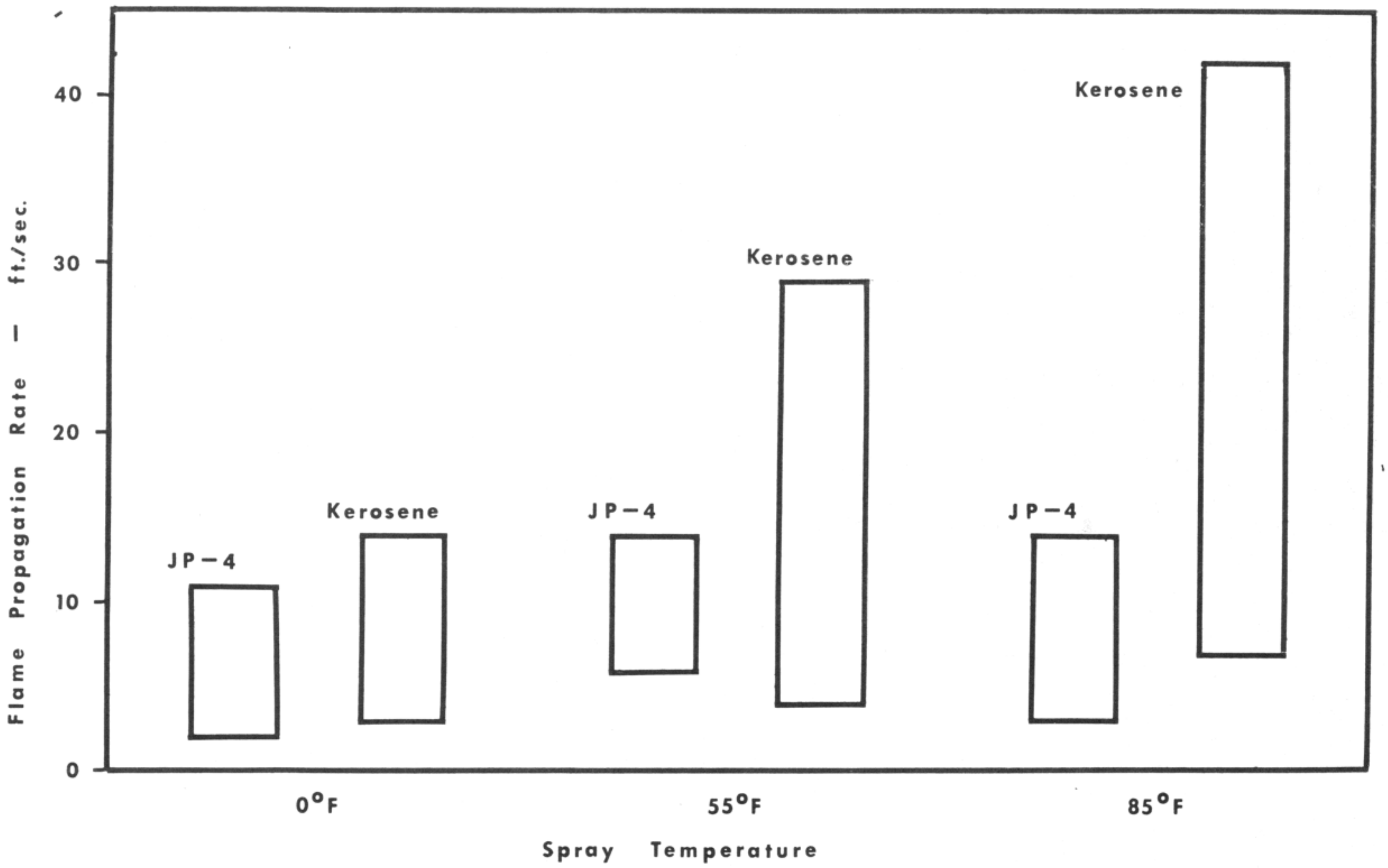


FIGURE 17

The Effect of Fuel Temperature on the Flame Propagation Rate Through Fuel Sprays

It was noted in the ambient mist temperature tests that a rich flammability limit existed for JP-4 at a fuel-air ratio of .024. With kerosene mists, no rich limit was observed. This can be explained when one considers the effective vapor fuel-air ratio mentioned in the discussion above. Furthermore, it was observed visually that the flame front propagating through the kerosene-air mixtures was substantially thicker than that propagating through JP-4 air mixtures. This indicates that the kerosene droplets are not pre-vaporized as readily by the approaching flame front, and in fact are actually post-vaporizing and burning behind the flame front. Without this pre-vaporization the effective vapor-air mixture is lean and explains why a rich limit was not achieved.

An attempt was made to find a lower temperature limit for the ignition of fuel mists. At the lowest temperature attained (-40°F), the hot wire ignited both JP-4 and kerosene. Zabetakis (27) has reported tests in which sprays of both kerosene fuel and a "wide cut" fuel were ignited at -100°F with a high energy spark. It can be concluded that mists of JP-4 and kerosene can be ignited in any temperature environment encountered in an actual crash.

In the final series of tests the hot surface ignition characteristics of kerosene and JP-4 sprays were investigated. The test apparatus used was the same as that used in the stream tests, and a limited quantity of fuel (5.9 cm^3) was sprayed onto the hot plate. The only difference between these two series of tests was that a low flow nozzle tip was used to atomize the fuel for the spray tests whereas an orifice was used to produce the stream. The data obtained are plotted on figure 18 along with the stream data and indicate, as in the tests with fuel streams, that for higher wind velocities there is a corresponding increase in the surface temperature required for ignition. Surface temperature ignition requirements, for both fuels, are higher for sprays than for streams at all wind velocities. This is apparently due to the fact that the wind can carry the spray away from the heated region above the plate. The sprays then have a lower residence time than the streams and therefore the time allowed for ignition is decreased. This decrease in allowable ignition delay time increases the thermal energy requirement for ignition, and therefore a higher surface ignition temperature is needed. These effects are explained in more detail in the stream discussion section of this report.

Although there is a difference in the minimum surface ignition temperature between JP-4 and kerosene, the magnitude of this difference is not considered significant.

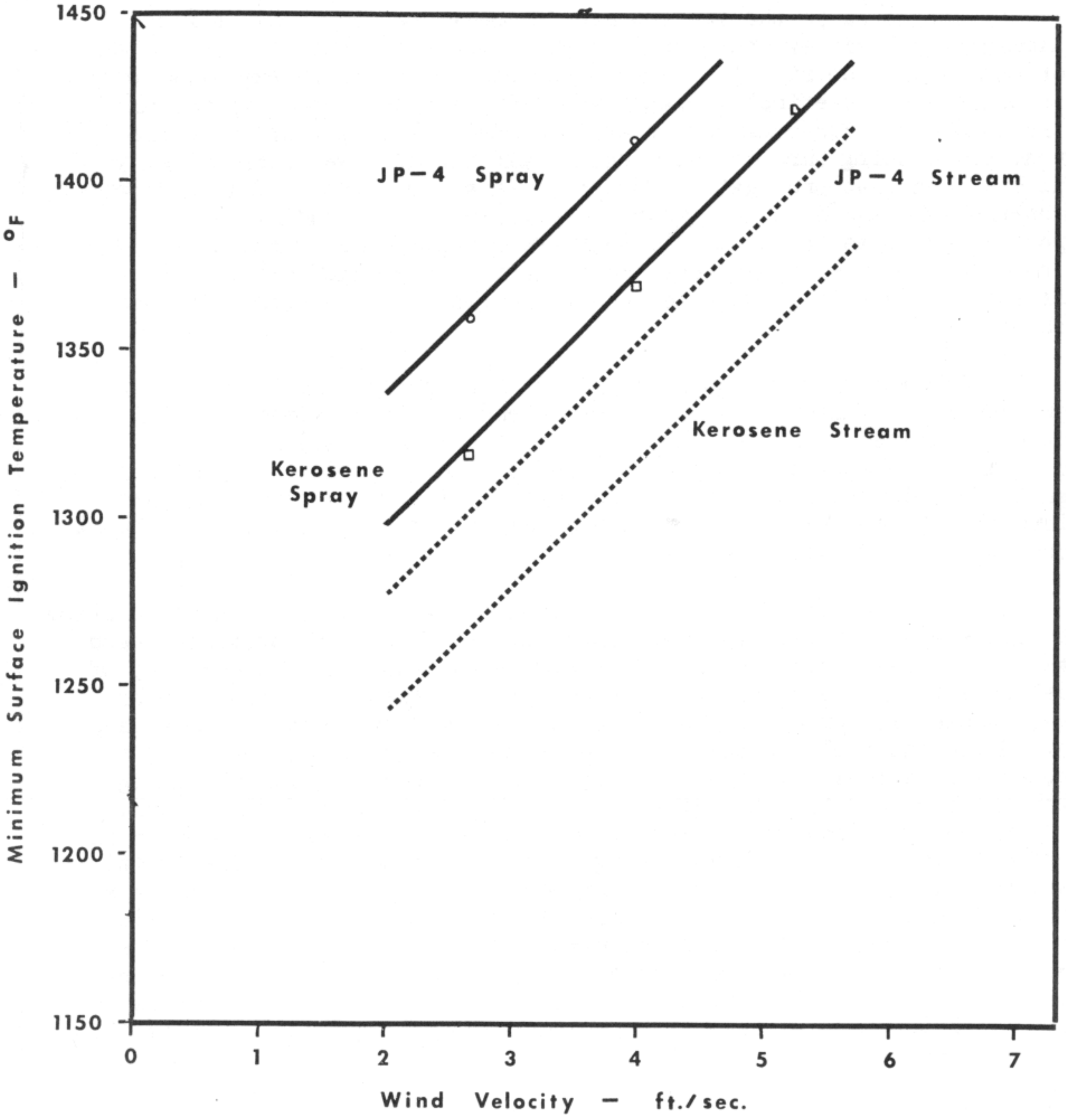


FIGURE 18

The Effect of Wind Velocity on the Minimum Surface Ignition Temperature for Fuel Sprays

CONCLUSIONS

This investigation has provided information on the crash fire hazards of aviation kerosene and JP-4 which substantiates the following conclusions:

(1) The possibility of a flame climbing a column of dripping fuel (JP-4 or kerosene) is extremely remote.

(2) The minimum fuel temperature for flame climbing up a stream of fuel is significantly lower for JP-4 than for kerosene.

(3) The spatial ignition envelope, for fuel streams, ceases to exist when the fuel temperature falls below the respective flash points.

(4) The fuel pool ignition characteristics are affected by the ignition source placement, the ignition source type, and environmental conditions; however, the difference noted between fuel types is primarily a function of flash point.

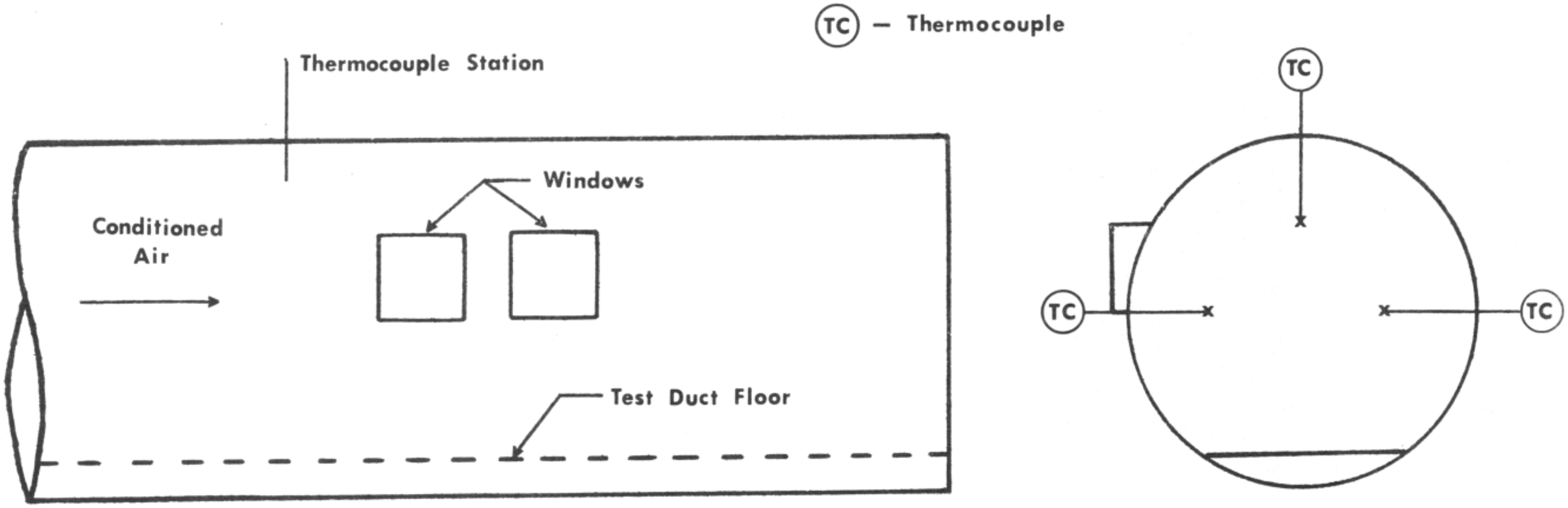
(5) There is no significant difference in the wind velocities necessary to blow out pools of burning JP-4 and kerosene.

(6) Neither JP-4 nor kerosene offers a substantial safety advantage when considering the flame propagation rate through mists and mist ignitability.

(7) The surface temperature required for the ignition of both mists and streams was not significantly different for JP-4 and kerosene.

APPENDIX A

The test apparatus and apparatus configurations employed in this test program are illustrated in figures 1.1 through 1.10. All drop, pool, and stream experiments as well as the fuel spray hot surface ignition tests were conducted in the wind tunnel shown in figures 1.1 and 1.2. The wind tunnel configurations used for the stream, pool, and hot surface ignition tests are schematically and photographically illustrated in figures 1.3 through 1.8. A flame tube, designed to measure the flame propagation rates through fuel sprays is shown in figures 1.9 and 1.10.



Duct Length — 15 feet
Duct Diameter — 43 inches

Air Velocity Range — 0 to 20 mph
Air Temperature Range — -40°F to 130°F
Duct Pressure — Ambient

FIGURE 1-1

Schematic of Wind Tunnel Test Section

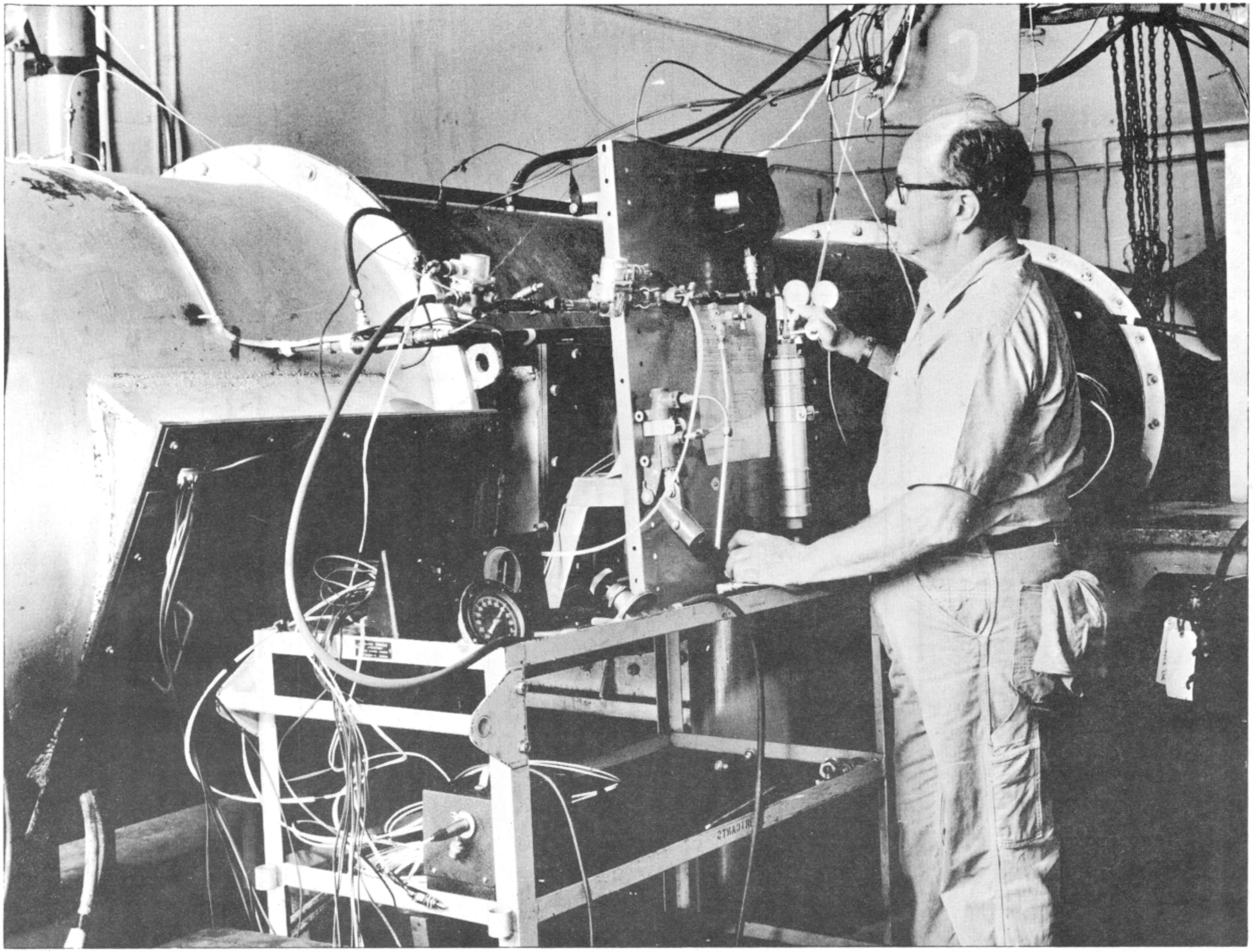
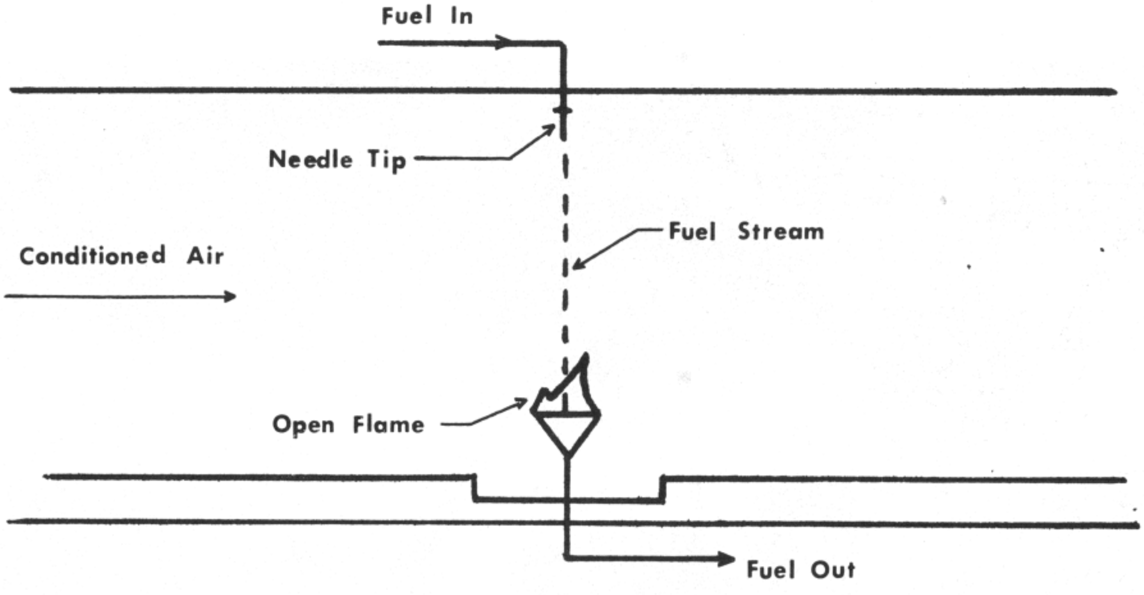
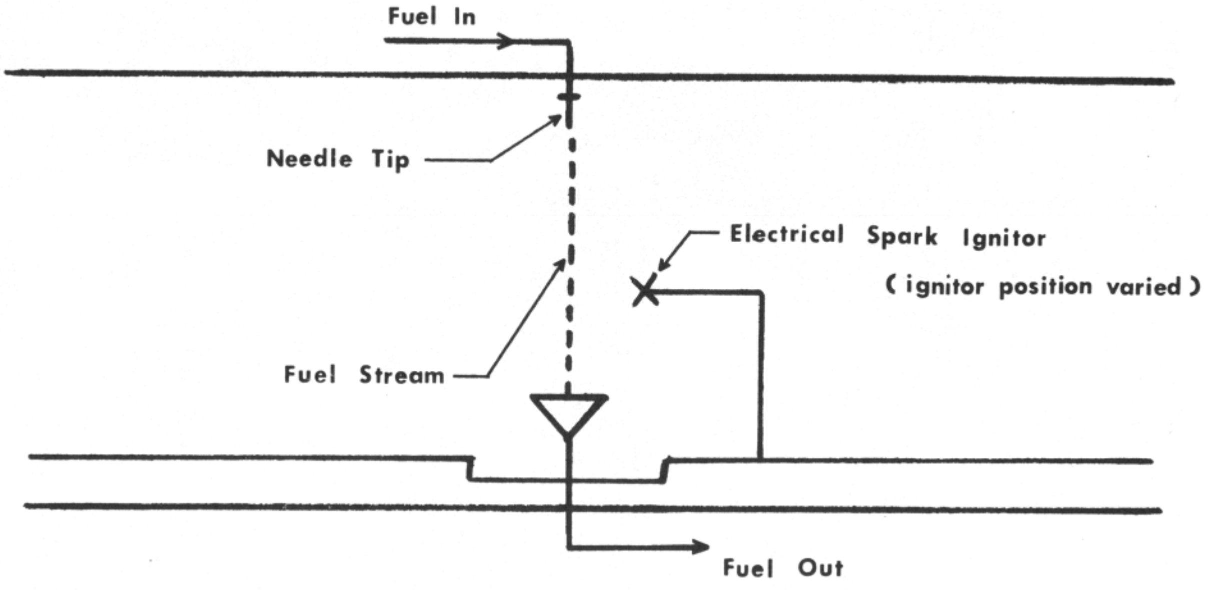


FIGURE 1-2

Wind Tunnel Test Apparatus



OPEN FLAME IGNITION CONFIGURATION



ELECTRICAL SPARK IGNITION CONFIGURATION

FIGURE 1-3

Schematic of the Test Section Configuration
for Stream Ignition and Flame Climbing Tests

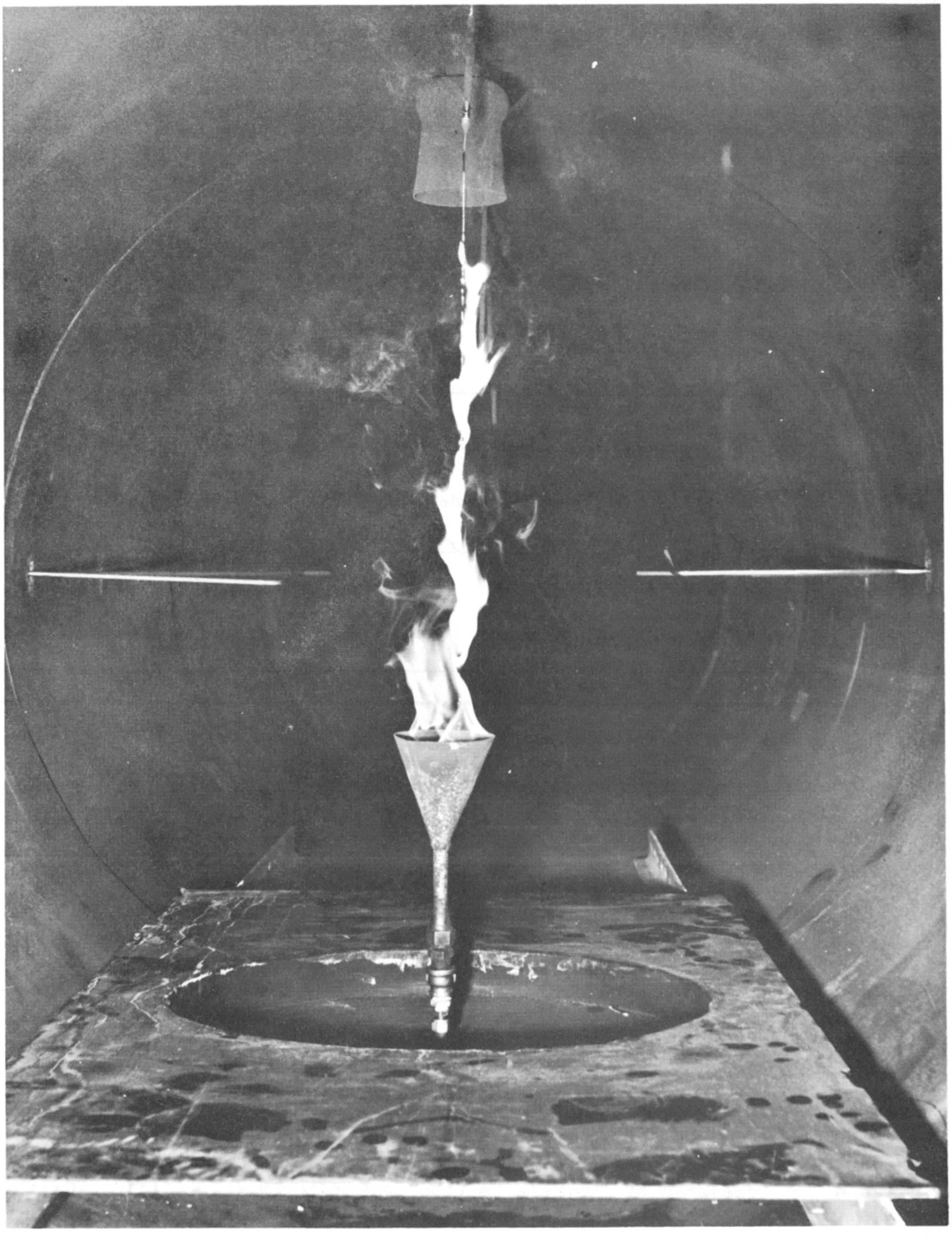


FIGURE 1-4

Burning Stream after Ignition and During Flame Climbing

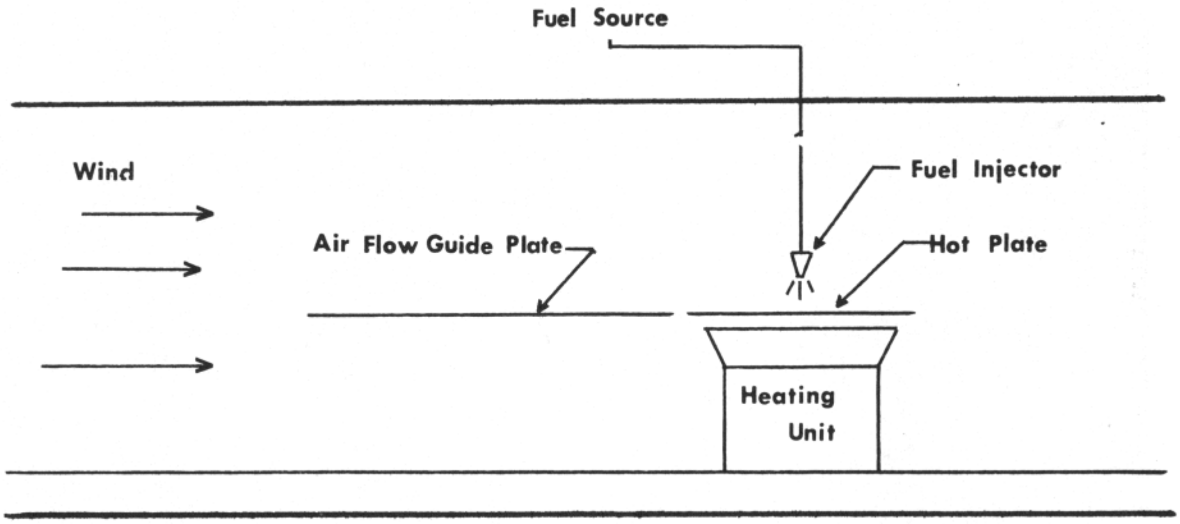


FIGURE 1-5

Schematic of the Test Section Configuration
for the Hot Surface Ignition Tests

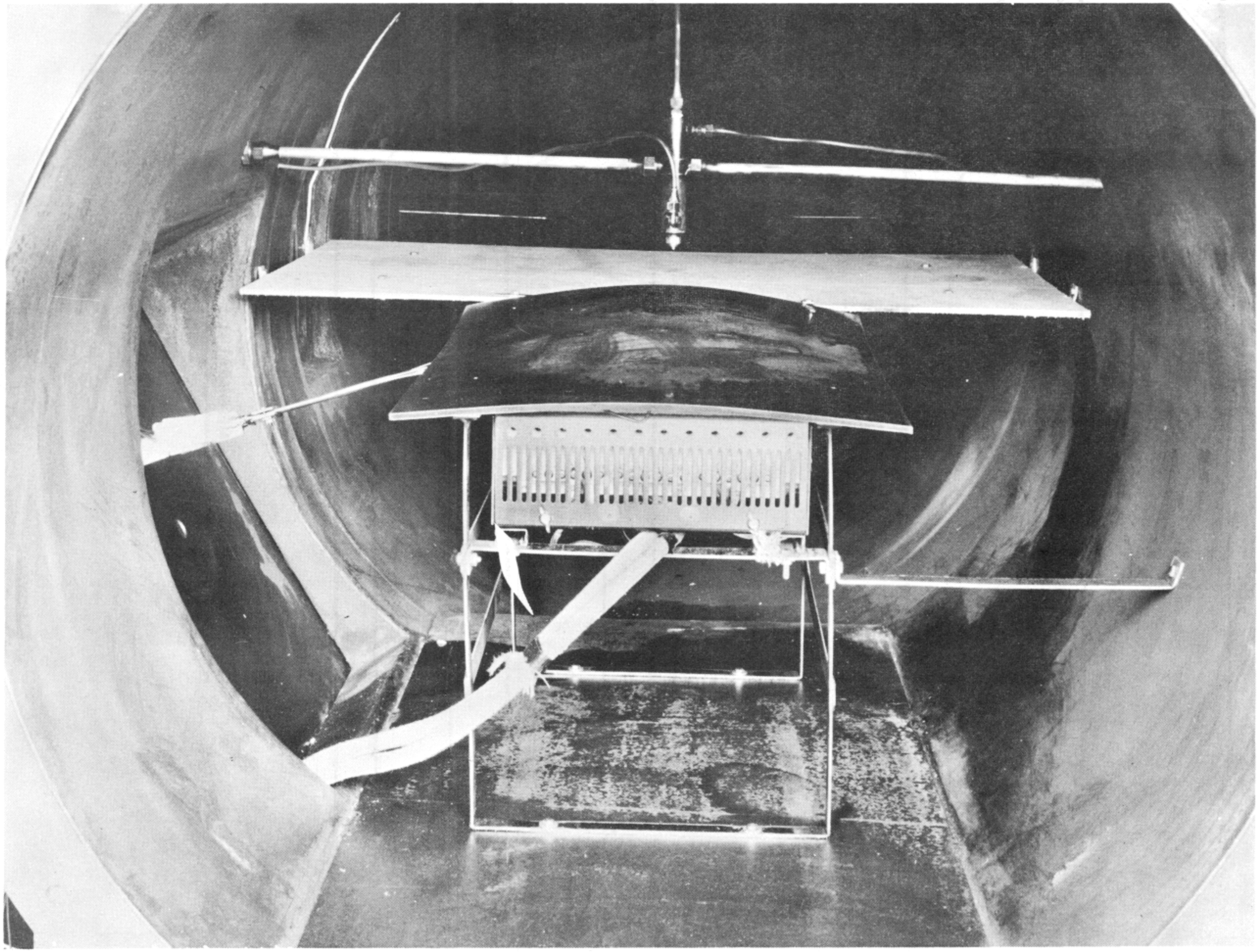
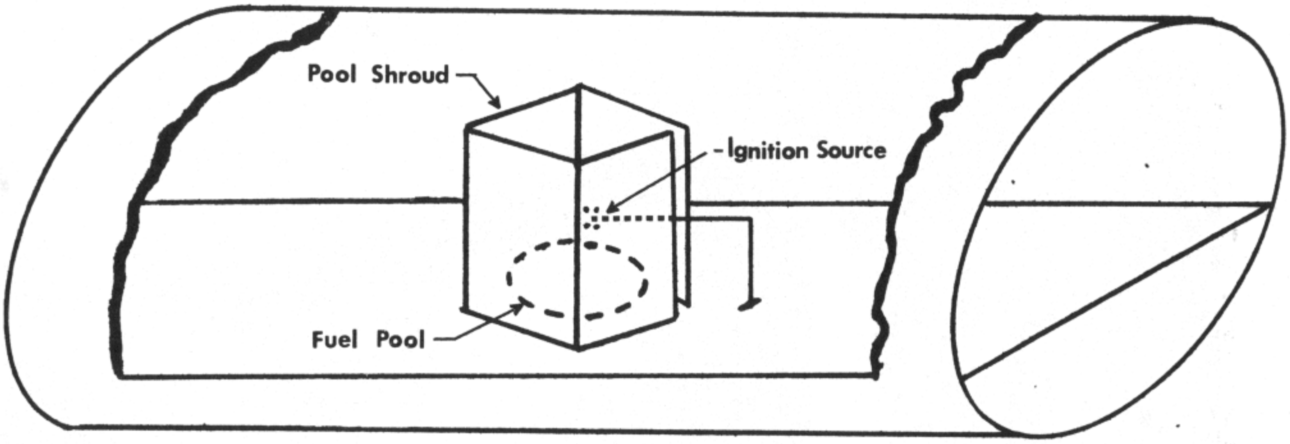
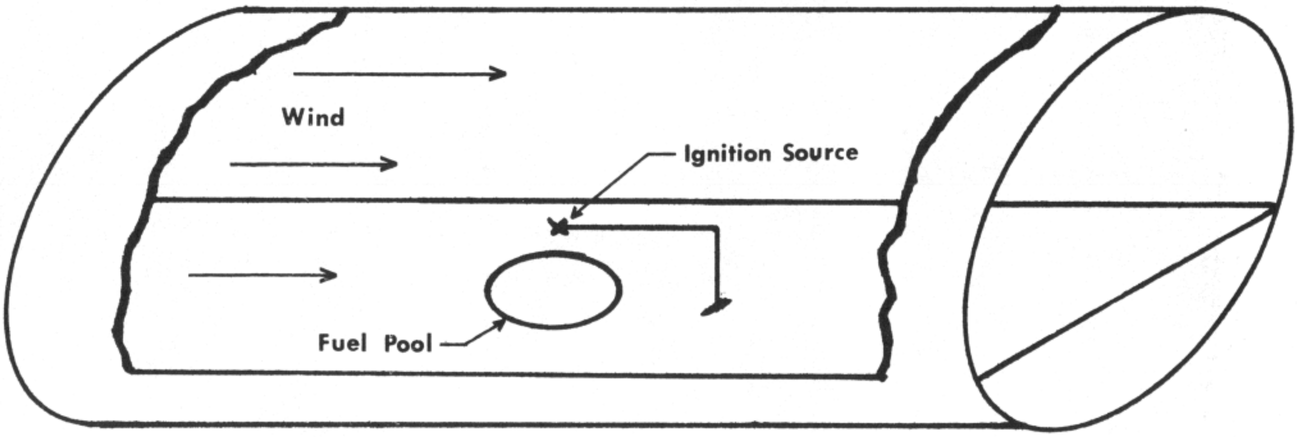


FIGURE 1-6

Hot Surface Ignition Apparatus



SHROUDED CONFIGURATION



UNSHROUDED CONFIGURATION

FIGURE 1-7

Schematic of the Test Section Configuration for Pool Tests

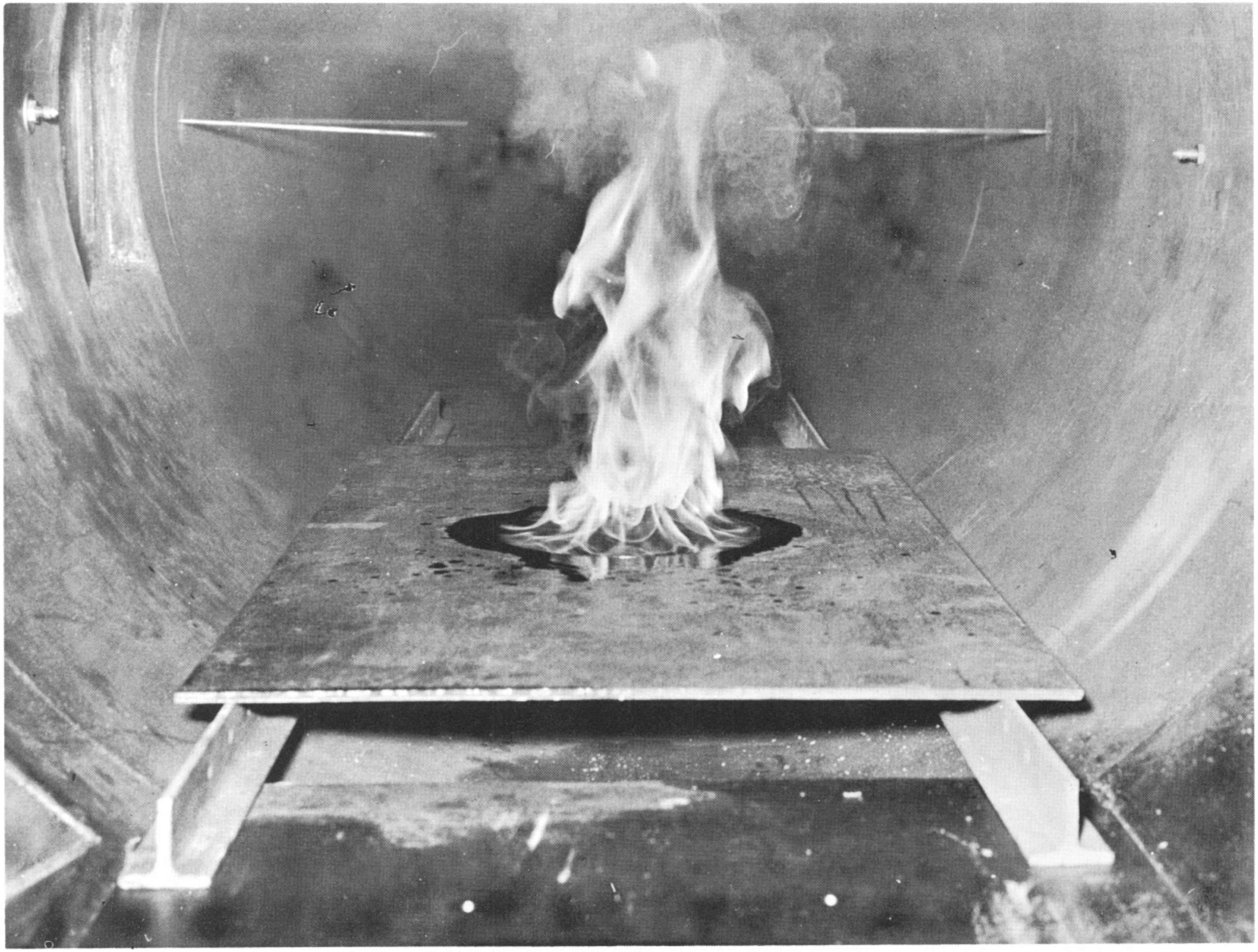


FIGURE 1-8

Typical Pool Fire

APPENDIX B

The following table lists the typical properties of the test fuels employed.

TABLE 2-1

FUEL	JP-4	Kerosene
Gravity, Specific, 60/60 °F	0.7567	0.8309
Gravity, °API, 60/60 °F	55.5	38.8
Reid Vapor Pressure, lb/in^2	2.60	0.13
Distillation, I.B.P. °F	160	350
5% over °F	186	380
10% over °F	194	388
20% over °F	208	400
30% over °F	220	412
40% over °F	234	422
50% over °F	250	432
60% over °F	260	444
70% over °F	280	456
80% over °F	310	468
90% over °F	370	484
95% over °F	438	500
End Point °F	454	504
Recovery % vol.	98.5	98.0
Residue % vol.	1.1	1.2
Loss % vol.	0.4	0.8
Sulfur, % wt.	0.15	0.36
F.I.A. Saturates, % vol.	75.00	75.34
Olefins, % vol.	2.63	5.47
Aromatics, % vol.	22.37	19.18
Aniline Point, °C	49.0	61.6
Aniline - Gravity Constant	6,671	5,544
Heat of Combustion, BTU/lb	18,668	18,451
Freeze Point, °F	-52	-60
Flash Point, °F	-6	142
Viscosity, cks., 100°F	0.64	1.75
-30°F	1.74	12.88

APPENDIX C

REFERENCES

1. "Tangents," SAE Journal 78 (5), 1970.

2. Pinkel, I. I., Weiss, S., Preston, G. M., Pesman, G. J., "Origin and Prevention of Crash Fires in Turbojet Aircraft," NACA TN 3973, May 1957.

3. Pinkel, I. I., Preston, G. M. Pesman, G. J., "Mechanism of Start and Development of Aircraft Crash Fires," NACA REP. 1133, 1953.

4. Scull, W. E., "Relation between Inflammables and Ignition Sources in Aircraft Environments," NACA TN 2227, December 1950.

5. Levin, S. M., "Surviving the Crash," Space/Aeronautics 49 (5), p. 88-99, 1968.

6. Spalding, D. B., "The Combustion of Liquid Fuels," Fourth International Symposium on Combustion, p. 847-864, Baltimore: The Williams and Wilkins Company, 1953.

7. Isoda, H., Kamagai, S., "New Aspects of Droplet Combustion," Seventh International Symposium on Combustion, p. 523-531, London: Butterworths Scientific Publications, 1959.

8. Goodall, D. G., Ingle, R., "The Ignition of Inflammable Fluids by Hot Surfaces," Aircraft Engineering 38 (4), p. 20, 24, 29, 35, 1966.

9. MacDonald, J. A., "Ignition of Aviation Kerosene by Hot Pipes," Royal Aircraft Establishment TR 67162, 1967. AD 824289

10. MacDonald, J. A., Royal Aircraft Establishment, Private Communication, May 1970.

11. Glassman, I., Hansel, J. G., "Some Thoughts and Experiments on Liquid Fuel Spreading, Steady Burning, and Ignitability in Quiescent Atmospheres," Princeton University Aerospace and Mechanical Laboratory Report 841, July 1968.

12. British Ministry of Aviation, "Report of the Working Party on Aviation Kerosene and Wide-Cut Gasoline," C.A.P. 177, 1962.

13. Blinov, V. I., Khudiahov, G. N., "Certain Laws Governing Diffusive Burning of Liquids," Acad. Nauk, SSSR Doklady, 113, p. 1094, 1957.

14. Kuchta, J. M., Furno, A. L., Martindill, G. H., Imhof, A. C., "Crash Fire Hazard Rating System for Controlled Flammability Fuels," FAA, NAFEC, Report No. NA-69-17, March 1969. AD 684089

15. Walker, J. R., "The Effect of Wind on Uncontrolled Buoyant Diffusion Flames from Burning Liquids," Ph. D. Thesis, University of Oklahoma, Norman, Oklahoma, 1965.

16. Hirst, R., Sutton, D., "The Effect of Reduced Pressure and Airflow on Liquid Surface Diffusion Flames," Combustion and Flame 5, p. 319-330, 1961.

17. "Standard Method of Test for Flash Point by Pensky-Martens Closed Tester," ASTM Standard D93-66, Part 17, p. 24-36, American Society for Testing Materials, Phila., Pa., 1969.

18. Burgoyne, J. H., Cohen, L., "The Effect of Drop Size on Flame Propagation in Liquid Aerosols," Proceedings of the Royal Society of London, Series A, Vol. 225, p. 375-392, 1954.

19. Anson, D., "Influence of the Quality of Atomization on the Stability of Combustion of Liquid Fuel Sprays," Fuel 32, p. 39-51, January 1953.

20. Williams, F. A., "Monodisperse Spray Deflagration," Progress in Astronautics and Aeronautics, Vol. 2, p. 229-264, New York: Academic Press, 1960.

21. Liebman, I., Spolan, I., Kuchta, J. M., Zabetakis, M. G., "Ignition of Tank Atmospheres during Fuel Loading," API Division of Refining Meeting, Paper No. 36-65, API Proc. 45 (3) p. 218-230, 1965.

22. Campbell, J. A., "Appraisal of the Hazards of Friction-Spark Ignition on Aircraft Crash Fires," NACA TN 4024, May 1957.

23. Spraying Systems Company, Bellwood, Illinois, Private Communication, April 1970.

24. Fraser, R. P., "Liquid Fuel Atomization," Sixth International Symposium on Combustion, p. 687-701, New York: Reinhold Publishing Corporation, 1957

25. Wood, B. J., Rosser, W. A., Wise, H., "The Ignition and Combustion of Drops in Sprays of No. 2 Heating Oil," API Research Conference on Distillate Fuel Combustion, Conference Paper CP 63-67, 1963.

26. Wood, B. J., Rosser, W. A., Wise, H., "The Effect of Fuel Droplet Prevaporization on Flame Propagation Velocities," Combustion and Flame 13, p. 663, 1969.

27. Zabetakis, M. G., Jones, G. W., Scott, G. S., Furno, A. L., "Research on the Flammability Characteristics of Aircraft Fuels," WADC Technical Report 52-35, Supplement 4, p. 21, January 1956.