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AN EVALUATION OF THE RELATIVE FIRE HAZARDS OF JET A AND JET B FOR COMMERCIAL FLIGHT

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ABSTRACT

The relative fire hazards of Jet A and Jet B aircraft fuels are evaluated. The evaluation is based on a consideration of the presence of and/or the generation of flammable mixtures in fuel systems, the ignition characteristics, and the flame propagation rates for the two fuel types. Three distinct aircraft operating regimes where fuel type may be a factor in fire hazards are considered. These are (1) ground handling and refueling, (2) flight, and (3) crash. The evaluation indicates that the overall fire hazards for Jet A are less than for Jet B fuel.

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INTRODUCTION

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The question is raised periodically as to whether there is any significant difference in the fire hazards between the kerosene type Jet A and the more volatile Jet B when used as fuels for gas turbine powered aircraft. There has been little commercial usage of Jet B in recent years but the present energy crisis and the reduced availability of petroleum products may put one or the other of these two fuels in short supply. Therefore, economic pressures may re-open the question as to the relative fire hazards of these fuels.

The kerosene types are the commercial Jet A and Jet A-1 (these differ only in freezing point) fuels and the military JP-8 and JP-5 fuels. JP-8 is identical with Jet A-1 and JP-5 is slightly less volatile than either but is still classed as a kerosene type fuel. The more volatile jet fuels now in use are the commercial Jet B and the military JP-4; Jet B and JP-4 have identical specifications insofar as they relate to fire hazards. There are also the Air Force JP-6 and JP-7 fuels, both intermediate in volatility between the JP-4 and kerosene types, but these are special application fuels in limited use and will not be discussed further.

With the exception of extreme altitude flame out and relight characteristics where the more volatile fuels are slightly superior, all of the above fuels perform equally well in modern jet engines. Commercial operations are at lower altitudes than military so that performance at extreme altitudes is not a factor. The choice between fuels is then based only on their cost and on safety and possibly on availability in times of fuel shortages. The relative costs of Jet A and Jet B vary with time and place and are not considered herein. The safety aspect is the subject of this report.

The relative safety between these two classes of fuels has been reviewed several times, most thoroughly by the Coordinating Research Council (CRC) for commercial fuels in 1964 (ref. 1), by the U.S. Air Force Aero Propulsion Laboratory for military fuels in 1966 (ref. 2), and by the Air Safety Group for commercial fuels in 1967 (ref. 3). Two divergent conclusions were reached. The Air Force report (ref. 2) concluded that "...utilization of a lower volatility fuel such as JP-5 would contribute little, if any, improvement in the current Air Force safety record." The CRC had a somewhat less specific conclusion (ref. 1) that "...adoption of a single type of aviation turbine fuel...would not significantly improve the overall excellent safety record of commercial aviation." This statement implies, but does not directly state, that the more volatile Jet B is no more hazardous than Jet A. The rationale behind this statement is that Jet B was little used and, therefore, the change from a small usage of Jet B to zero usage would not improve safety. The Air Safety Group report (ref. 3) is admittedly "...not a technical treatise..." but used much of the CRC report data to arrive at a quite different conclusion. This report concluded that "...the fire and death rate with kerosene (Jet A) is at present but a small fraction of that with JP-4 (Jet B)" and that "...if JP-4 should gain wide acceptance, the fire and death rate for turbine powered aircraft could be expected at least to equal and probably much exceed that for piston engine aircraft" and that "...kerosene fueled transport has halved at least the piston engine fire death rate.".

These divergent conclusions result, in part, from the weak statistical base against which relative fuel hazards can be compared. Air Force operations have been almost entirely with JP-4 and an earlier use of the even more volatile JP-3, Naval operations with the very low volatility JP-5, and commercial operations largely with Jet A. Each of these groups uses predominantly or exclusively a different type fuel and each flies a different type of operation. Therefore, accident statistics which might be fuel related cannot be compared between groups with confidence. The Air Safety Group (ref. 3) put considerable weight in a comparison of the accident statistics of kerosene fueled turbine powered aircraft and gasoline fueled piston engine powered craft. The implication here is that experience with the volatile gasoline in piston powered aircraft may be indicative of what could be expected if turbine powered commercial aircraft had used the more volatile Jet B. However, there are such great differences between piston and jet aircraft in airframe size and configuration, in engine related ignition sources, and in flight operations that such comparisons are of doubtful value. Both the CRC (ref. 1) and the Air Force (ref. 2) have relied more on comparisons between the combustion qualities of the fuels as measured in bench scale experiments, that is, the conditions that yield flammable mixtures, the ignition requirements, and the flame propagation rates.

This report is an evaluation of the relative fire hazards associated with Jet A and Jet B fuels. Much of the supporting data are the same as that used in references 1 and 2. While there has been ongoing research since these reports were published, most of the newer results only confirm or but slightly modify earlier understandings. Therefore, the present

report is not based primarily on new data but is rather a re-evaluation of combustion phenomena as they relate to fire hazards in commercial turbojet operations.

ANALYSIS

There are three separate and distinct aircraft operating regimes where fuel type may be a factor in fire hazards. These are (1) ground handling and refueling, (2) the conditions encountered in flight, and (3) those encountered in crashes. Most important of the last are the survivable crashes where the presence or absence of fire or the intensity of fire can be a very important factor in the loss of life; these occur most often during takeoff or landing. Jet A and Jet B are compared herein as to their fire hazards under each of these regimes. The specifications for these two fuels and for the several military fuels are listed in the appendix. Also given are the properties for typical samples of Jet A and Jet B. There is also a discussion in the appendix of the several combustion related properties that may influence aircraft fire hazards.

We will, for each operating regime, outline the environments that may be encountered and comment on the relative flammable hazards incurred with each fuel using information given in the appendix.

Fire Hazards in Ground Handling and Refueling

Fixed tankage and that on mobile refuelers will be considered first. These tanks may be at near equilibrium conditions with the ullage space having a fuel vapor - air composition that can be calculated from vapor pressure - temperature considerations. The probability that this space will be flammable is then dependent on fuel type and temperature. Tank pressure should not be a variable since the tanks are usually vented to ambient and the ambient pressure will be approximately 1 atmosphere at all but a very few airports.

Some data on fuel temperatures in airport storage is given in reference 1. This reference included a survey of United States airports that showed that fuel temperatures exceeded 95° F (35° C) only 1 percent of the time, were above 60° F (16° C) 63 percent of the time and above 32° F (0° C) 95 percent of the time. The same report considered the maximum fuel temperature that might be encountered on the ground, worldwide, and found 105° F (41° C) as the highest reported for 13 airports in hot climates. Therefore, most stored fuel temperatures are between 32° F (0° C) and 95° F (35° C) and rarely, if ever, exceed 105° F (41° C).

Figure A-2 from the appendix gives, for both sea level and altitude conditions, the upper and lower temperature limits for flammability for the typical Jet A and Jet B fuels. Below the lower temperature, the ullage space will be too lean to burn and above the upper temperature it will be

too rich, under equilibrium conditions. The figure shows that at sea level the ullage of Jet A will not be flammable at temperatures below 125° F (52° C) but that the ullage of Jet B will be flammable at fuel temperatures between -15° F (-26° C) and 55° F (13° C). From these limiting temperatures and the probable fuel temperatures given in the preceding paragraph, we can conclude that Jet A will never yield a flammable vapor-air mixture under ground handling conditions but that there will be an explosive hazard with Jet B about 30 percent of the time at U.S. airports. The rest of the time the Jet B tankage temperature will be above 55° F (130° C) and, therefore, too rich to burn. All this is under equilibrium conditions where the ullage space is fully saturated as to fuel vapor.

The flammable range can, under nonequilibrium conditions, be extended beyond the temperatures listed above. A finite period is required to attain equilibrium after any disturbance to a closed system because it takes time for fuel to vaporize or condense, for fuel vapors to mix throughout an ullage space so that the same concentrations are found everywhere, and for suspended mists and foams to settle back into the bulk liquid. Therefore, the flammable range of temperatures can be extended for some period of time through the inbreathing of air through tank vents, through the stratification of fuel vapors immediately after a fill, and during the period when mists and foams are settling back after having been formed by the mechanical action of filling or acceleration in mobile fuel systems. The length of time that nonequilibrium exists varies with the disturbance.

Mists and foams can extend the lean flammable limits to temperatures lower than those at equilibrium as shown in figure A-3. This is significant only for Jet A since the effect is to render a tank hazardous at temperatures lower than the normal lean limit of 125° F (52° C); a hazard thereby exists under normal ambient conditions whereas there is none at equilibrium. The same misting effect would also extend the lean limit of Jet B to lower temperatures but this temperature is already down to -15° F (-26° C) so that this effect is mainly of academic interest. However, this nonequilibrium transient is fairly short lived. Mists with droplets smaller than 10 microns (μm) in diameter are very hard to form through mechanical action and the settling rate of 10 micron drops is about 0.01 foot (0.003 m) per second. Therefore, a 5-minute settling time would completely clear a 3-foot (1-m) deep ullage space and a 20-foot (6-m) ullage would be free of suspended drops in about 1 hour. Under most conditions, such as fuel splashing during fill, the bulk of the droplets are much larger than 10 microns and would settle out in much shorter times. In any case, splashing can be avoided by undersurface discharge during tank filling.

In summary, misting effects can extend the flammable regime of Jet A to below 125° F (52° C) but in practice this nonequilibrium effect is short lived and adds very little to the flammable hazards incurred in the ground handling of this fuel. Jet A tankage remains safe at normal ambient temperatures most of the time.

Nonequilibrium due to tank inbreathing and stratification is more prevalent and persists for much longer times. We have no data on fuel storage tanks but reference 7 gives both an analysis and experimental data on a smaller (225 gal) tank that shows the magnitude of the problem. In their case, a rectangular tank 3 feet by 3 feet by 3 feet 4 inches deep (0.9- by 0.9- by 1.0-m) was 80 percent filled with JP-4 (Jet B) and fuel withdrawn from the bottom at 0.5 gallon (0.0019 m^3) per minute. The tank emptied in 6 hours at this rate. Air entered at the top of the tank during this time and the degree of stratification, ranging from an equilibrium fuel concentration at the liquid surface to pure air right at the vent, was both calculated and measured. The analysis suggested that extreme stratification was probable for quite long times and the experiment showed this to be even more severe than the analysis. For example, $1\frac{1}{2}$ hours after the fuel withdrawal started the fuel concentration in the upper 18 inches (0.45 m) of the 40-inch (1.0 m) deep tank was less than one-half the equilibrium value.

With a mixing process this slow in a relatively small tank, the time to establish equilibrium in a large, fixed storage tank must be measured in days. The time for full mixing in a truck transporter would be shortened somewhat by vapor phase mixing induced by fuel sloshing. Nevertheless, the probability of achieving a measure of safety because Jet B tanks are equilibrium over-rich at temperatures above 55° F (13° C) is greatly reduced in tankage where there is any filling and withdrawal activity.

It might be argued that this same process would reduce fuel vapor concentrations in Jet B tanks so that the ullage would be too lean to burn. However, at most operating temperatures the equilibrium mixture contains sufficient fuel vapor so that the ullage would still be flammable after considerable dilution. There would still be flammable strata down to a temperature of -15° F (-26° C) in any case.

In summary relative to tank storage, the Jet A ullage space is never flammable except possibly for very brief periods when the tank is being filled. Even these periods can be avoided by controlling rate and fill geometry. On the other hand, the ullage over Jet B is always flammable except in tanks with fuel temperatures exceeding 55° F (13° C) and where there has been no withdrawal of fuel in times of the order of days.

The tanks of aircraft on the ground before, during, or after refueling present conditions that are often similar to those encountered in the ground storage tanks. However, fuel temperatures may be somewhat higher or somewhat lower than those of the storage tanks. The unused fuel remaining in the tanks at landing will usually be at a lower temperature than that on the ground and the tank fuel temperature can go well above ambient while an aircraft is parked in the open on hot days. Assuming equilibrium conditions, the lowered temperature should generally increase the flammable hazard with Jet B since the fuel temperature is rarely below the -15° F (-26° C) low temperature limit. At the same time, the increased temperature is not likely to increase the hazard with Jet A since fuel temperatures

would rarely exceed 125° F (52° C) even in the hottest climates. Therefore at equilibrium, just as in the ground storage case, Jet B is much more likely to form flammable mixtures in aircraft fuel tanks than is Jet A while the craft is on the ground.

Refueling introduces nonequilibrium transients so that flammable mixtures can again be found, as in the case of ground storage, at fuel temperatures beyond those that define the equilibrium boundaries. Figures 1(a) and (b) give data on these transients. These figures are direct copies of figures 6(a) and (b) in reference 1 where they were credited to reference 14. Reference 14 was not available and there appears to be some discrepancy as to the fuel loading rate since the lower rate with Jet B brought up the liquid fuel level more rapidly than the higher rate with Jet A; perhaps different sized tanks were used. Nevertheless figure 1(a) shows a transient flammable zone during Jet B fueling at 70° F (21° C); that is, above the upper equilibrium temperature of 55° F(13° C). And figure 1(b) shows a flammable zone with Jet A due to the mist formed by splashing fuel at 85° F (29° C); that is, below the lower equilibrium flammable limit of 125° F (52° C) for this fuel. These transients are of the same type that can be encountered in ground handling but should be much shorter lived in the smaller aircraft tanks. In general, just as in the larger tanks, the Jet B presents the greater hazard as shown by the greater volume in which flammable mixtures may transiently occur.

Finally, any consideration of flammable hazards must consider the ease of ignition along with the probability of having a flammable mixture. Electrical sparks are the most likely ignition source within the tank but flames can also propagate through vents after ignition by external sources. For spark ignition, figure A-4 shows Jet B to be more easily ignited than Jet A. And as for flame propagation through vents, this is more probable for Jet B vapors since it is far less likely that Jet A mists would both fill an ullage space and spill out a vent to supply a path that would allow a flash back from an external ignition source. Therefore, the probability of ignition of a flammable mixture, if present, is less with Jet A than with Jet B.

In summary, the ground handling and refueling hazards are less with Jet A than with Jet B, both as to the probability of having flammable mixtures and as to the ignition energy requirements.

Fire Hazards in Flight

These hazards are again related to the probability of having a flammable mixture and the possibility of their ignition. Flight introduces three new variables into the consideration of fire hazards. First, the pressure is no longer near 1 atmosphere. Second, fuel temperatures can change more rapidly and the ranges of temperatures encountered are much wider than in ground handling. And third, there are increased dynamic factors such as agitation due to turbulence and tank breathing due to changes in altitude that cause nonequilibrium effects.

Regarding the effect of pressure on flammable limits, figure A-2 shows how the temperature limits go down with increasing altitude. For example, an equilibrium tank containing Jet A at 100° F (38° C) is not flammable at sea level but becomes so on rapid climb to 20 000 feet (6100 m). Similarly a Jet B tank at 20° F (7° C) has a flammable ullage but this becomes nonflammable under equilibrium conditions at 20 000 feet (6100 m).

Both of the above examples assume no change in fuel temperature during climb. However, the ambient air at altitude is usually very much colder than that on the ground so that the fuel in the tanks cool with time in flight. This temperature-time history will vary with aircraft type, aircraft tank, aircraft flight profile, and air temperatures. Only a limited amount of fuel temperature data have been recorded in flight but examples are given in figure 2, reproduced in part from figure 10 of reference 1. Similar data are given in reference 2 but for greater extremes in initial fuel temperatures.

The altitude-fuel temperature flammable envelopes from figures A-2 and A-3 along with time-temperature curves of figure 2 then permit estimates to be made of the times during flight that tank ullages would be flammable. The curves from figure A-2 would be used to estimate this hazard under equilibrium conditions and those from figure A-3 for nonequilibrium. Figure 3 shows these results for Jet A and Jet B.

Figure 3(a) shows that the ullage space over typical Jet B will often be within flammable limits at equilibrium, especially with the colder fuels. Furthermore, portions of the ullage space will almost always be flammable at any fuel temperature when the fuel is degassing during climb or when air is entering the vents to replace fuel consumed or during descent. The ullage over Jet A is rarely flammable at equilibrium and then only for a very short time provided the fuel is quite warm (fig. 3(b)); however, this space can always be rendered flammable if mists are formed.

The relative flammable hazards of Jet A against Jet B then depend, in part, on the fraction of flight time that tanks are at or near equilibrium and the probability that two quite different nonequilibrium processes take place. Of the latter, the first is the leaning out of over-rich mixtures with air and the second is the enrichment of too lean mixtures with mists. At equilibrium, the preference is for Jet A since this fuel rarely forms a flammable mixture. For the nonequilibrium conditions, the preference again must be for Jet A. The fuel degassing during climb, the replacement of fuel with air during cruise, and the inbreathing of air during descent are conditions that increase hazards only with Jet B and all of these processes are inevitable. Reference 7 shows that these nonequilibrium processes do occur and persist even in relatively small tanks; the larger tanks in aircraft would present greater problems. On the other hand, the augmented hazard with Jet A due to mist formation is only present during turbulent flight and the mists would settle out very rapidly.

As for ignition sources in flight, these might be from lightning strikes, from internal electric shorts, or from hot metal thrown from a

badly failed engine. It is likely that these ignition sources would all be sufficiently energetic to ignite either fuel. However, if the ignition energy is borderline, the Jet A again becomes the preferred fuel as shown in figure A-4. Jet A is also far less easily ignited by gunfire than is JP-4 (Jet B) as shown by the data given in reference 9. However, this may not be germane to commercial operations.

Finally, there is the question of the damage incurred if the tank contents do catch fire in flight. Here the advantage is again with Jet A. Reference 9 reports the results when 10 gallons of fuel were loaded into a 75-gallon tank and then spark ignited while vigorously shaking the tank. These results are shown in figure 4 as tank overpressure as a function of fuel temperature for both fuels. For the temperatures of greatest interest, below 60° F (16° C), the pressure generated with JP-8 (Jet A) is very much lower than with JP-4 (Jet B). Furthermore, and as stated in reference 9 "...flammable mixtures of JP-4 are more conducive to involvement of adjacent tanks by propagation through vent lines with consequently more destructive and total damage."

In summary, Jet B presents greater hazards in flight than Jet A in all respects. Jet B has a greater probability of forming flammable mixtures, these mixtures when formed are easier to ignite, and if ignited the probable extent of damage is greater.

Fire Hazards in Survivable Crashes

Aircraft crashes in which some or all of the passengers and crew may survive usually occur during takeoff or landing. Conditions in these crashes are so variable that it is very difficult to make quantitative statements as to the effect of fuel type on loss of life. Different aircraft, different crash severities, different degrees of airframe breakup and fuel spillage, different terrain and different weather all deny the possibility of a direct comparison among fuels. Therefore, we prefer not to cite loss of life statistics in the evaluation of relative hazards as others have done (refs. 1 and 3). Nevertheless, a qualitative comparison of the fire hazards associated with Jet A and Jet B can be developed based on the flammable characteristics of these fuels. The factors relevant to the fire hazards in survivable crashes are:

(1) The probability of forming flammable mixture

(2) The probability of having an ignition source

(3) The probability of the flammable mixture encountering an ignition source

(4) The time between first flame and the envelopment of the aircraft

(5) The intensity of the fire

These factors will be discussed in turn.

The probability of having a flammable system must be considered to be near unity in any crash where fuel is spilled. There is no chance of having a too rich and therefore nonflammable mixture as in the case where warm Jet B is held in confined space. And even a cold pool of a low volatility fuel like Jet A can be ignited if an energetic ignition source rests on its surface. Furthermore, the dynamics of a crash may form mist-air systems which are highly flammable with either fuel. Therefore, a potentially flammable situation is always possible whenever fuel is spilled with the possible exception of a spill on a foamed runway.

The probability of having an ignition source in a crash is also very high. There can be electric shorts, friction sparks, and electrostatic sparks, all with energies very much greater than the minimum ignition energies of hydrocarbon fuels. Fuels can also be ignited by hot engine parts, especially those of turbine engines which operate with hot end metal temperature of from 1000° to 1800° F (538° to 982° C) depending on engine power. There should be little difference in the ease of ignition of Jet A and Jet B by the latter sources (hot metal) since both fuels have spontaneous ignition temperatures of only about 480° F (249° C), well below those found in the engine. But spark ignition energies are always less for Jet B (see fig. A-4). In general, we believe that there will be ignition sources capable of igniting either fuel in most severe but still survivable crashes. However, if there is a preference, this must be for Jet A since it is somewhat harder to ignite under borderline conditions.

While Jet A and Jet B differ little in the probability of creating a potentially flammable situation and also in the probability that a sufficient source for ignition is present, there can be significant differences between these fuels in the probability that flammable systems will encounter ignition sources. This factor will depend on the crash environment. Severe crashes involving tank rupture and strong deceleration forces can form clouds of fuel mists (ref. 15). These mists are easily ignited by any of the sources mentioned above. Reference 15 showed that the ingestion of mists into a turbine engine that was coasting down in speed after a crash resulted in ignition and the rapid spread of flames to the outside of the engine nacelle. There should be little difference between the hazards of Jet A and Jet B if fuel mists are formed which envelope the airframe.

However, there should be significant differences between fuels in the transport of flammable mixtures to a potential ignition source in milder crashes where fuel may be spilled but not atomized. At any temperature above about -15° F (-26° C) the vapor pressure of Jet B is sufficient to form flammable vapor-air mixtures at the surface of spilled fuel. These vapors can be carried downwind and possibly to an ignition source. The vapors are soon diluted with air until they are too lean to burn and, therefore, the downstream range of the flammable concentrations will depend on the extent of the spill, the fuel temperature, and the wind velocity. This distance may be quite small but in all cases presents a hazard that is not found with Jet A. Jet A can form flammable vapor air mixtures only

under the very unlikely condition of the fuel temperature exceeding 125° F (52° C). An added factor is that a pool of Jet B will continue to generate a flammable mixture whereas the Jet A mist formed in a severe crash will soon settle out and, therefore, constitutes only a transient hazard. Overall, Jet B is clearly more hazardous than Jet A as to the probability that flammable mixtures will be carried to an ignition source. This is especially true in mild crashes where fuel may be spilled but not atomized.

The elapsed time between first flame in spilled fuel and the envelopment of the fuselage can also be important to passenger survival. The aircraft may come to rest on ground that becomes soaked with fuel while the first flame is some distance away; any appreciable time delay may allow passengers and crew to escape. The rate of flame spreading then becomes most important and figure A-5 compares Jet A and Jet B in this respect. At a given temperature the spreading rate is always lower for Jet A and is 20 to 30 times lower between 40° and 120° F (4° and 49° C), the fuel temperatures most likely to exist in a crash. Smaller bench scale experiments show even greater differences in favor of Jet A (see appendix). A very significant advantage rests with Jet A in this regard.

Finally, there is the question as to the intensity of the fire once it is well established. Here again, the preference must be for Jet A since equal amounts of spilled fuel give larger flames with Jet B than with Jet A. The radiant heat intensity is also greater with Jet B (see appendix).

In summary, the fire hazards after a survivable crash are clearly greater with Jet B than with Jet A. Five factors were considered and Jet A is either slightly or, significantly, the safer fuel for all five.

CONCLUSION

The only conclusion possible from this study is that Jet A is a safer fuel than Jet B as far as fire hazards are concerned. This is for commercial operation but reference 9 comes to the same conclusion in comparing the flammable hazards of JP-8 (equivalent to Jet A) and JP-4 (equivalent to Jet B) for military operations. This unqualified conclusion can be made because Jet A presents reduced flammable hazards under all conditions, that is, in ground handling, in flight, and after survivable crashes. No quantitative assessment of the relative hazards between Jet A and Jet B appears possible for these various types of operation but none is needed since the one fuel is preferable under all conditions.

This conclusion differs from that reached by references 1 and 2 where both found that there should be no significant difference in the flammable hazards of the two fuels. The reason for this difference in opinion is this. Both references 1 and 2 rightly conclude that an analysis based on equilibrium flammable considerations alone is not valid. But both cite only the misting of Jet A as an extension of the equilibrium hazards whereas the leaning out of over-rich Jet B vapor mixtures by degassing and the inbreathing of air and the stratification of vapor-air mixtures can also

extend flammable hazards beyond those at equilibrium. Reference 7, written since references 1 and 2, shows these latter nonequilibrium processes to be long lived and we believe that these are much more important to aircraft safety in closed tank situations than the misting process. (In open air situations, the mist hazard is the same with both fuels and, therefore, does not influence their relative ratings.) Otherwise and in all respects we find Jet A to be the preferred fuel for commercial operations.

APPENDIX - PROPERTIES OF JET FUELS

The specified and average values of the properties of the two types of jet fuels considered in this report are given in table I. Only those properties that may have some bearing on flammable hazards are listed. There are many other specifications that relate to aircraft operations and overall flight safety, (e.g., sulfur content, thermal stability, gum content, etc.) but these are a measure of the trace impurities of fuels and do not influence combustion properties. The freezing point, although not related to combustion, is also listed in table I to point out that this is the only specification difference between Jet A and Jet A-1; there is an occasional misunderstanding in this regard. The Reid Vapor Pressure is not specified and is not determined for Jet A fuels since it is a number too small to be accurately measured by this test. Similarly, the Flash Point is neither specified nor measured for Jet B fuels since it would be well below room temperature where the test method is not applicable. The specifications were taken from reference 4. The average values shown for the Jet A and Jet B fuels were taken from reference 5.

The kerosene type (Jet A) and the wide-cut (Jet B) are both derived from the simple distillation of petroleum. Little, if any, cracked or reformed stocks are used. The two types of fuel differ primarily in their distillation range, the wide-cut fuels having a much lower initial boiling temperature and a slightly lower final boiling temperature than the kerosene types. The wide-cut fuels have the greater distillation range and therefore can be obtained in greater yield from the simple distillation of crudes. This greater potential availability is the reason for the past military preference for JP-4. The bulk properties of petroleum fractions are closely interrelated. Therefore, because of the differences in distillation, the wide-cut fuels (Jet B) have higher vapor pressures, lower densities, lower viscosities, and lower molecular weights than the kerosene types.

Some combustion related properties can be estimated from the values listed in table A-1 while others have either been directly determined for similar fuels or can be reliably estimated from a general knowledge of hydrocarbon combustion qualities. These properties are given in the following sections for the average kerosene type (Jet A) and the average wide-cut (Jet B) fuels.

Vapor pressure. - Vapor pressures for these fuels were calculated from distillation and flash point data for Jet A and from distillation and Reid Vapor Pressure data for Jet B using the methods of reference 6. These are presented in figure A-1 over the range of temperatures and pressures of interest to aircraft operations. The Jet B has considerably higher vapor pressures than Jet A over the operating temperature range.

Flammable limits. - Flames can be ignited and propagate only between definite fuel-air concentration limits. For the vapors of jet fuels in air, these limits are given in reference 6 as

$$L = \frac{1.87\text{x}10^6}{QM} \qquad \text{(A-1)}$$

and

$$R = L + \frac{143}{M^{0.7}} \tag{A-2}$$

where

L lean flammable limit in percent by volume of fuel in air

R rich flammable limit, also in percent by volume fuel in air

Q lower heat of combustion of fuel, Btu/lb

M molecular weight of fuel

The molecular weights and heats of combustion that should be used are those of the vaporized portion of the fuel and not those of the whole fuel. These molecular weights can be estimated from the 10 percent distillation temperature (ref. 6, fig. 20). The heats of combustion of hydrocarbons of these molecular weights can be estimated from standard thermodynamic sources. The lean and rich limits as calculated from equations (A-1) and (A-2) for the average Jet A and Jet B are listed below:

	Jet A	Jet B
Lean limit, volume percent	0.74	1.16
Rich limit, volume percent	5.32	7.63

The flammable concentration limits listed above stay substantially the same over the ranges of temperature and pressure encountered in flight. This permits temperature - altitude envelopes to be calculated that define the conditions that will yield flammable mixtures in the tank ullage space under equilibrium conditions. These envelopes are presented in figure A-2 for the typical Jet A and Jet B. The fuel vapor-air system is flammable within the boundaries shown. At lower temperatures, the ullage space will be too lean to burn. At higher temperatures, it will be too rich.

The flammable envelope boundaries for a given type fuel as shown in figure A-2 are not absolute limits. These boundaries can vary somewhat with the method of calculation but considerably more with the quality of the specific fuel sample that was used in the calculation. The boundaries shown in figure A-2 are for an "average" Jet B having a Reid Vapor Pressure of 2.6 psia (18 kN/m^2) and an "average" Jet A having a Flash Point of 129° F (54° C). The survey (ref. 5) that was used to compile these averages lists individual samples of Jet B having RVP's ranging from 2.3 to 2.9 psia (16 to 20 kN/m^2) and individual samples of Jet A having Flash Points ranging from 112° to 148° F (44° to 64° C). The result is that extreme samples (but still well within specification values) of fuels can have lower and upper flammable boundaries that are as much as 20° F (11° C) higher or lower than those shown in figure A-2.

There are nonequilibrium processes that extend the flammable region to temperatures and altitudes (pressures) outside those shown in figure A-2. These include mist and foam formation, the release of dissolved gases from the fuel, and the inbreathing of air into the tank.

Finely divided fuel mists and foams in air are as flammable as vapor-air systems and have substantially the same lean and rich limits in terms of mass concentrations (ref. 8, p. 88). These two-phase systems can be formed during refueling, during rapid reductions in pressure (aircraft climb), or by mechanical action as in turbulent flight. Under these conditions, the flammable limits can be extended to lower temperatures for both Jet A and Jet B than those shown in figure A-2.

The release of dissolved gases from the fuel as tank pressure is lowered effectively lowers the percent of fuel in the ullage space and, thereby extends the upper or rich limit to higher temperatures. The released gas is also somewhat enriched in oxygen relative to air since oxygen is more soluble in fuel than is nitrogen. This increases the hazard. However, the effects of dissolved gas release are relatively small as shown by data in reference 7 and the process is further discussed in reference 1.

A third nonequilibrium factor is the leaning out of the ullage space in level flight by the air that enters through the vents as fuel is withdrawn. Reference 7 gives data in this regard and shows that there are zones in the ullage where fuel concentrations are only 15 to 50 percent of their equilibrium value due to this process. Therefore, equilibrium rich tanks are easily leaned down to a flammable condition during level flight as air replaces the fuel consumed.

Finally, the inbreathing of air during descent will render too rich mixtures temporarily flammable until equilibrium is re-established. The time that the mixture is not in equilibrium is a function of tank and vent sizes and geometry, the rate of descent, the amount of tank vibration and also depends on the type of fuel. Reference 7 shows substantial departures from equilibrium for over 20 minutes with JP-4 (Jet B) but much lesser departures with Jet A. The reason for the difference between fuels is not known (ref. 7). The data suggests that the over-rich mixtures of Jet B shown in figure A-2 are very easily leaned out to become flammable and this significantly increases the hazard with this fuel.

The results of these several nonequilibrium processes are shown for Jet A and Jet B in figure A-3. The overall conclusion is that flammable conditions at equilibrium are most likely to be met with Jet B but that both fuels can form flammable mixtures under nonequilibrium conditions over all ranges of temperature and pressure that may be encountered in flight.

Ignition Temperatures and Energies

The minimum ignition temperature is the lowest surface temperature that will ignite a fuel. Reference 8 (p. 106) shows that a kerosene (Jet A),

a JP-4 (Jet B), and two samples of JP-5 all have minimum ignition temperatures between 473° and 484° F (245° and 251° C). Therefore, there is no significant difference between Jet A and Jet B in this regard.

The minimum spark energy needed to ignite many pure hydrocarbon-air systems is about 0.2 millijoule (ref. 8, table XXXII). Reference 9 (table 2) gives the minimum spark energy as 0.20 millijoule for both Jet A and JP-4 (Jet B). These energies were determined for ideal concentrations of fuel in air under ideal laboratory conditions; however, somewhat higher energies are required to ignite practical fuel-air systems. Figure A-4 taken from reference 14 shows the energies needed to ignite sprays of Jet A and Jet B as a function of temperature. The Flash Point temperatures, that is, the minimum fuel temperatures needed to bring the fuel vapor pressures up to a level where flammable mixtures are formed, are shown for both fuels and the minimum ignition energy is about 6 millijoules for both at these temperatures. At temperatures lower than the Flash Point, some of the spark energy is required to help vaporize the fuel and, therefore, the ignition energy increases with decreasing temperature as shown for Jet A. At temperatures higher than the Flash Point the fuel vapor pressure increases to form more nearly ideal flammable mixtures so that the spark ignition energy decreases and approaches the value of 0.2 millijoule cited in references 8 and 9; this is shown by the curve for Jet B.

The important conclusion to be drawn from figure A-4 is that, at a given temperature, the minimum spark ignition energy for Jet A is about 10 times higher than for Jet B over the temperatures encountered in aircraft operations.

Finally, a comparison of JP-4 (Jet B) and kerosene (Jet A) as to the ease of ignition by friction sparks showed the JP-4 to be somewhat more easily ignited (ref. 12). These sparks can be struck in crash situations when metals are abraded on runway or other hard surfaces.

Flame Propagation and Spreading Rates

Flame speed, or the rate of laminar flame propagation in closed systems, is a fairly slow process and of the order of 1 foot (0.3 m) per second for most hydrocarbons. It is substantially the same for JP-1 (Jet A) and JP-4 (Jet B) as shown in the appendix of reference 8. Turbulent flame propagation and detonations are very much faster processes but we know of no data directly comparing Jet A and Jet B in these combustion processes. We believe that there should be no difference between Jet A and Jet B as to any of the flame propagation processes in confined areas provided the same weight concentrations of fuel in air are involved.

The rate of flame spreading over the surface of liquid fuel in open air is quite different and is very much a function of fuel vapor pressure. Figure A-5 taken from reference 11 shows the flame spreading rate over troughs of fuel in the open. The rate for JP-4 (Jet B) is about 30 times greater than for aviation kerosene (Jet A) at the temperatures most often

encountered. Even greater differences are reported for bench scale experiments in reference 10 where the spreading rate for JP-4 (Jet B) is given as 7.3 feet (2.4 m) per second and that for JP-8 (Jet A) is less than 0.01 foot (0.003 m) per second.

Energy Release Rates

In closed systems, this rate depends on the concentration of fuel in air in the ullage space, on pressure, and on temperature. There should be no significant differences between Jet A and Jet B in this rate if these factors are the same.

Open systems, that is, spilled fuels in open air, are much more complex and quantitative comparisons between Jet A and Jet B are more difficult. Much of the data available on fire intensity or energy release rates have been developed through research on gelled or emulsified fuels. These thickened fuels have been proposed for the added safety they might confer in survivable crash situations. The early use of such fuels is not likely for commercial aviation and these are not discussed herein.

However, the programs on thickened fuels have reported some data on the relative fire intensity of unmodified wide-cut (Jet B) and kerosene (Jet A) type fuels. Reference 13 gives the maximum flame height observed when 2.6 pounds (1.2 kg) of fuel in a glass container was dropped onto concrete next to a pilot flame. This height was 10 feet (3.1 m) for JP-4 (Jet B) and 3 feet (0.9 m) for JP-8 (Jet A). A similar experiment was conducted and reported in reference 10 with 5 pounds (2.4 kg) of fuel and both the size of the fireball and the maximum radiant intensity at 30 feet distance was measured. The results are listed below for times less than 10 seconds after the drop.

	JP-4 (Jet B)	JP-5
Max flame height, ft (m)	19 (5.8)	9.5 (2.9)
Max radiant intensity, w/ft^2	500	47

The JP-5 is not identical to Jet A but there is the clear conclusion that the less volatile fuel has the lower rate of heat release in this type of experiment. However, the fire will persist longer with the less volatile fuel.

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TABLE A-I. - SPECIFICATION AND AVERAGE VALUES OF PROPERTIES OF AVIATION TURBINE FUELS

Property	Kerosene type jet fuels					Wide-cut jet fuels			
	ASTM Jet A-1	ASTM Jet A	IATA	Military JP-8	Jet A Average	ASTM Jet B	IATA	Military JP-4	Jet B Average
Gravity °API	← 39 to 45 →				42.8	← 45 to 57 →			54.5
Specific Gravity, 60° F (15.6° C)	← 0.830 to 0.775 →				0.812	← 0.751 to 0.802 →			0.760
Distillation, °F (°C)									
Initial boiling point	--	--	--	--	336	--	--	--	144
10% evaporated	← 400 (204) max →				370	--	--	--	214
20% evaporated	--	--	--	--	284	← 290 (143) max →			238
50% evaporated	← 450 (232) max →				414	← 370 (188) max →			290
90% evaporated	--	--	--	--	470	← 470 (243) max →			393
Final boiling point	← 550 (288) max →				512	--	--	--	451
Flash point, °F (°C)	← 110-150 (43-66) →		100-150 (38-66)	110(43) min	129	--	--	--	--
Reid vapor pres., psi	--	--	--	--	--	← 3.0 max →		2.0-3.0	2.6
Freezing point max, °F (°C)	← -54(-48)	-36(-38)	-58(-50)	-51(-46)	-50(-46)	-56(-49)	-58(-50)	-72(-58)	-76(-60)
Viscosity at -30° F (-34° C), cs	← 15 max →			16 max	9.4	--	--	--	3.0
Aromatics, vol %	← 20 max →			25 max	16.2	← 20 max →		25 max	10.8
Olefins, vol %	--	--	--	5 max	0.8	--	--	5 max	0.8
Heat of combustion, Btu/lb	← 18 400 min →				18 580	← 18 400 min →			18 725

FIGURE 1(a)

VERTICAL PROFILES OF FLAMMABLE ZONES IN A SIMULATED AIRCRAFT WING TANK DURING FUEL LOADING

Fuel Flow Rate: 150 gpm Downward Inlet
Temperature: 70°F Fuel: Jet B
* Composition of vapors to vent shown at 30 in. level

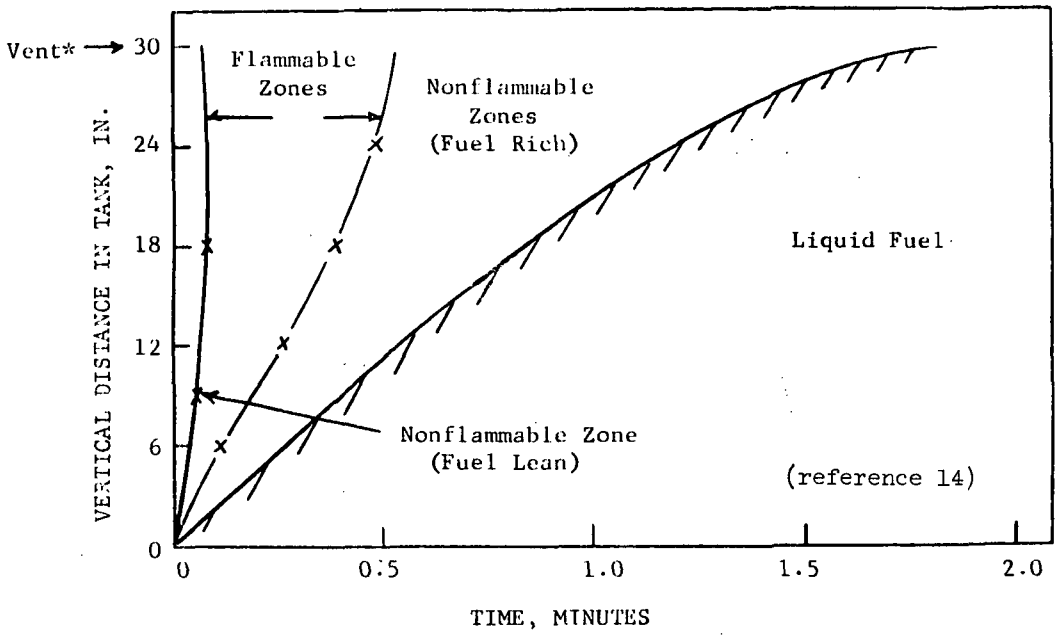


FIGURE 1(b)

FLAMMABLE ZONES IN A SIMULATED AIRCRAFT WING TANK DURING FUEL LOADING

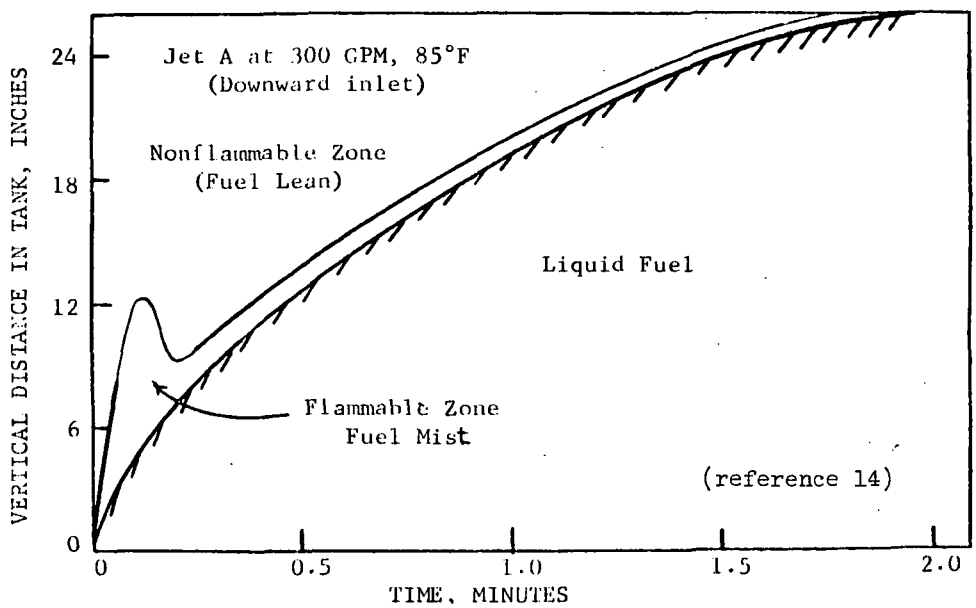
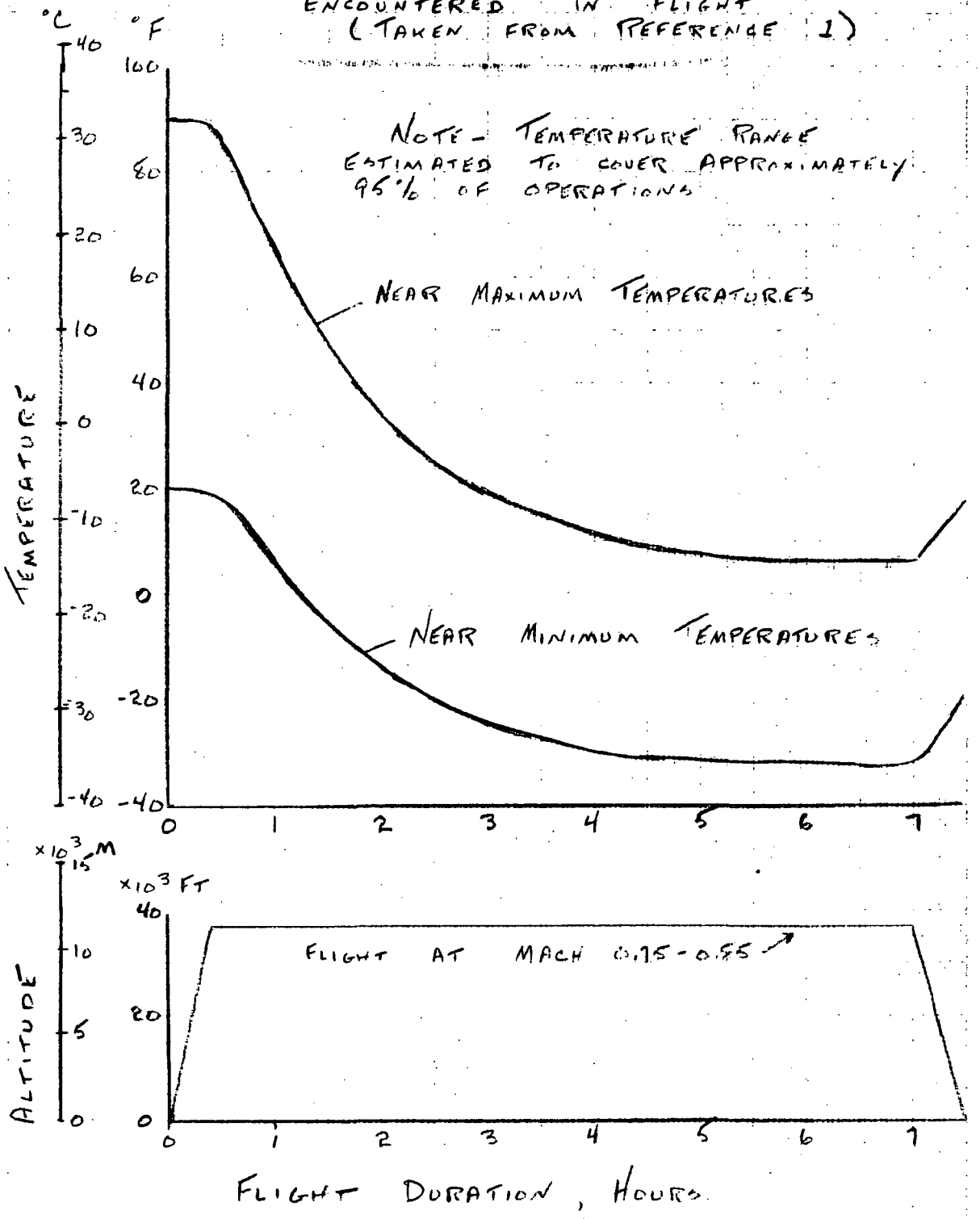


FIG 2

RANGE OF FUEL TEMPERATURES ENCOUNTERED IN FLIGHT (TAKEN FROM REFERENCE 1)



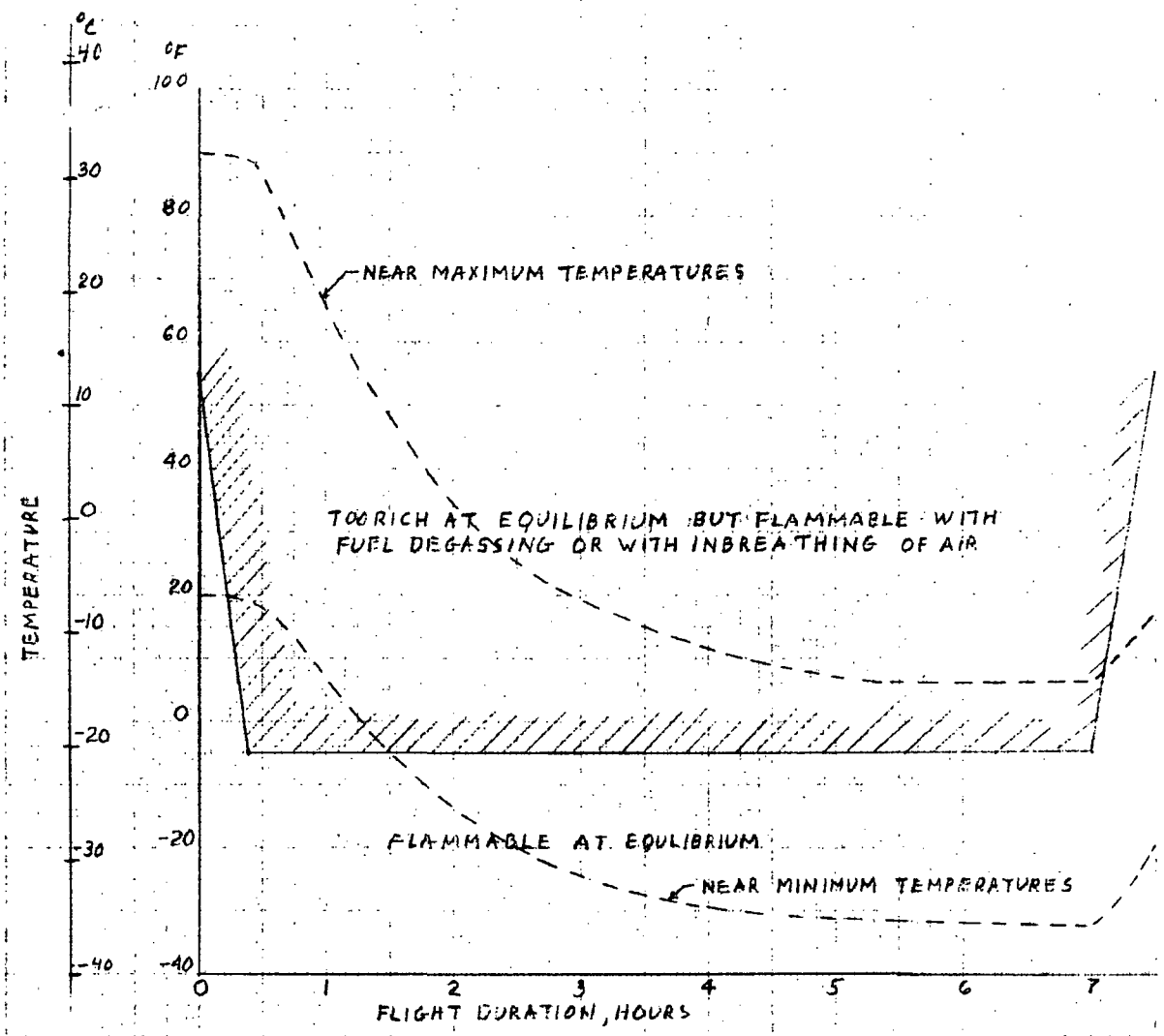


Fig. 3 FLAMMABLE RANGES IN FLIGHT
(a) FOR JET B FUEL

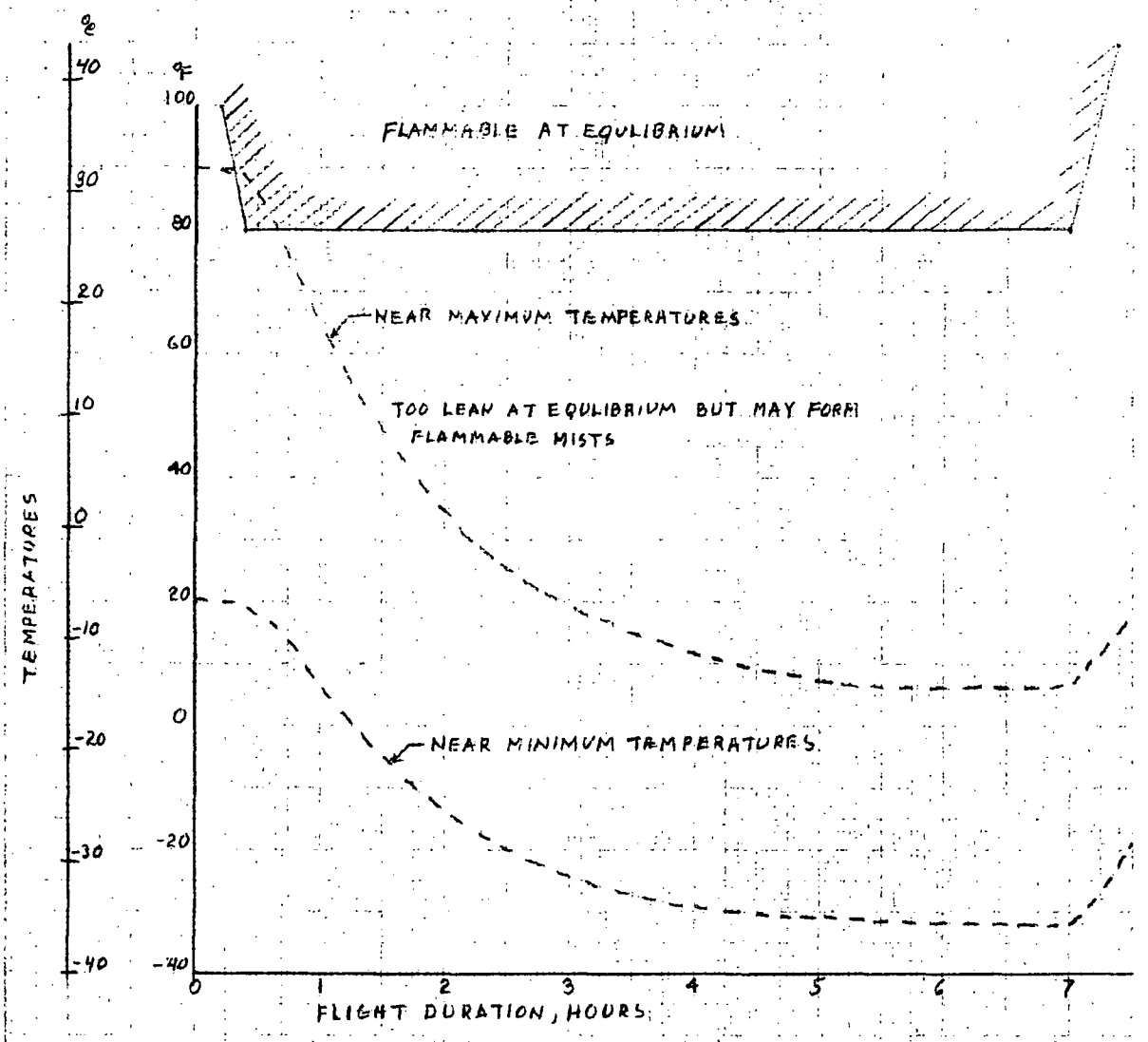


Fig. 3 Continued. FLAMMABLE RANGES IN FLIGHT
(b) FOR JET A FUEL

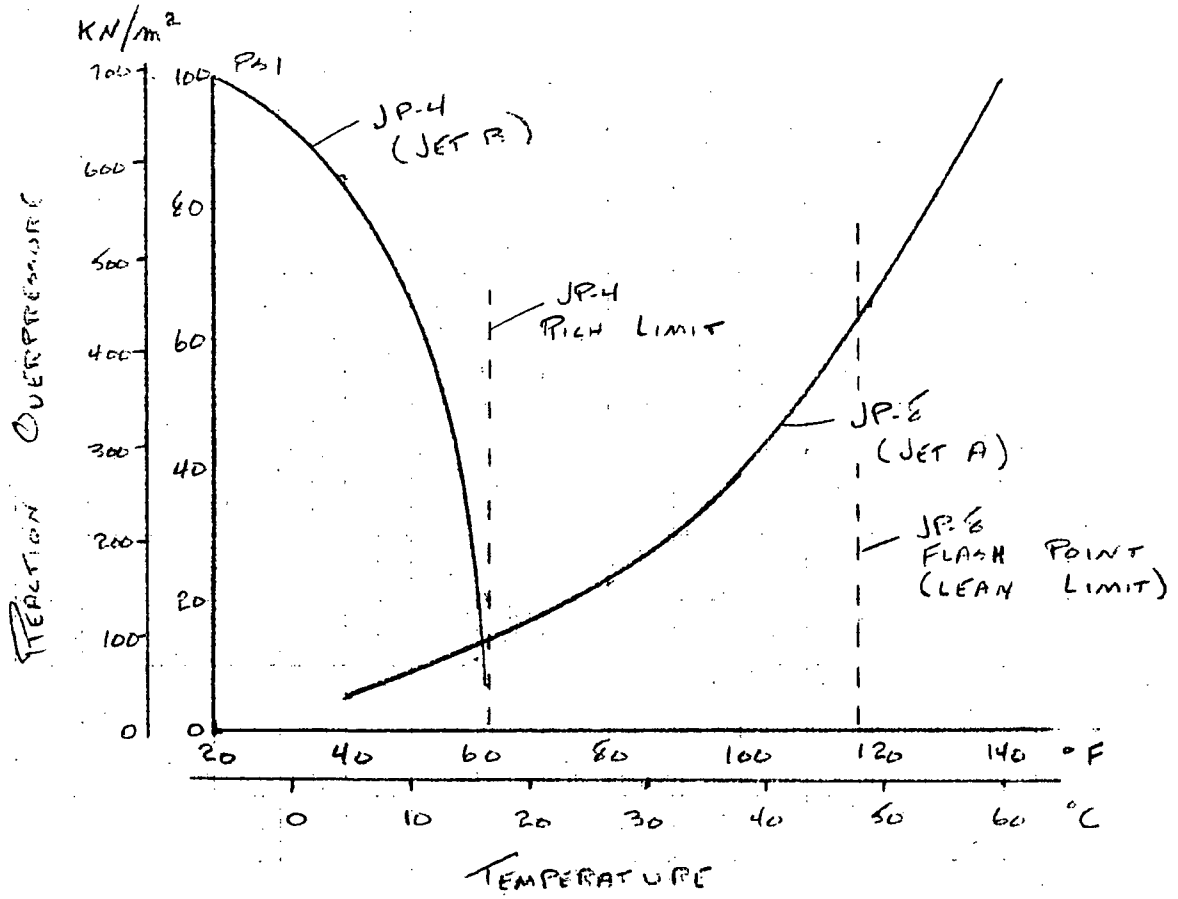


FIG 4 PRESSURES GENERATED ON IGNITION OF PARTIALLY FILLED FUEL TANKS UNDER SLOSHING CONDITIONS (TAKEN FROM REF 9)

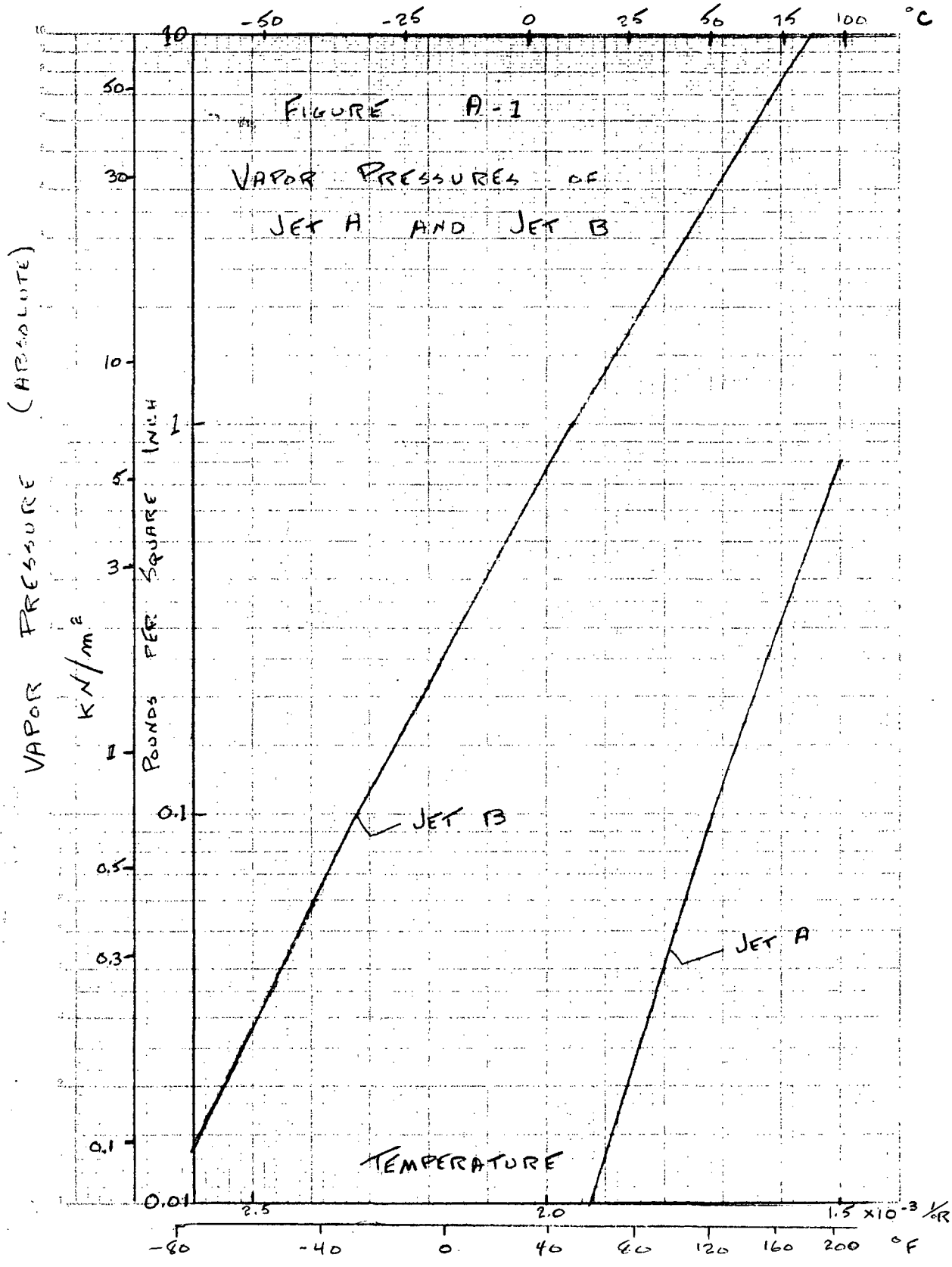


FIGURE A-1
VAPOR PRESSURES OF
JET A AND JET B
VAPOR PRESSURE (ABSOLUTE)
kN/m²
POUNDS PER SQUARE INCH
TEMPERATURE
JET B
JET A
°C
-50
-25
0
25
50
75
100
10
50
30
10
1
5
3
1
0.1
0.5
0.3
0.1
0.01
2.5
2.0
1.5 x10⁻³ 1/°R
-80
-40
0
40
80
120
160
200
°F

FIG. A-2 FLAMMABLE ENVELOPES AT EQUILIBRIUM FOR AVERAGE JET A AND JET B

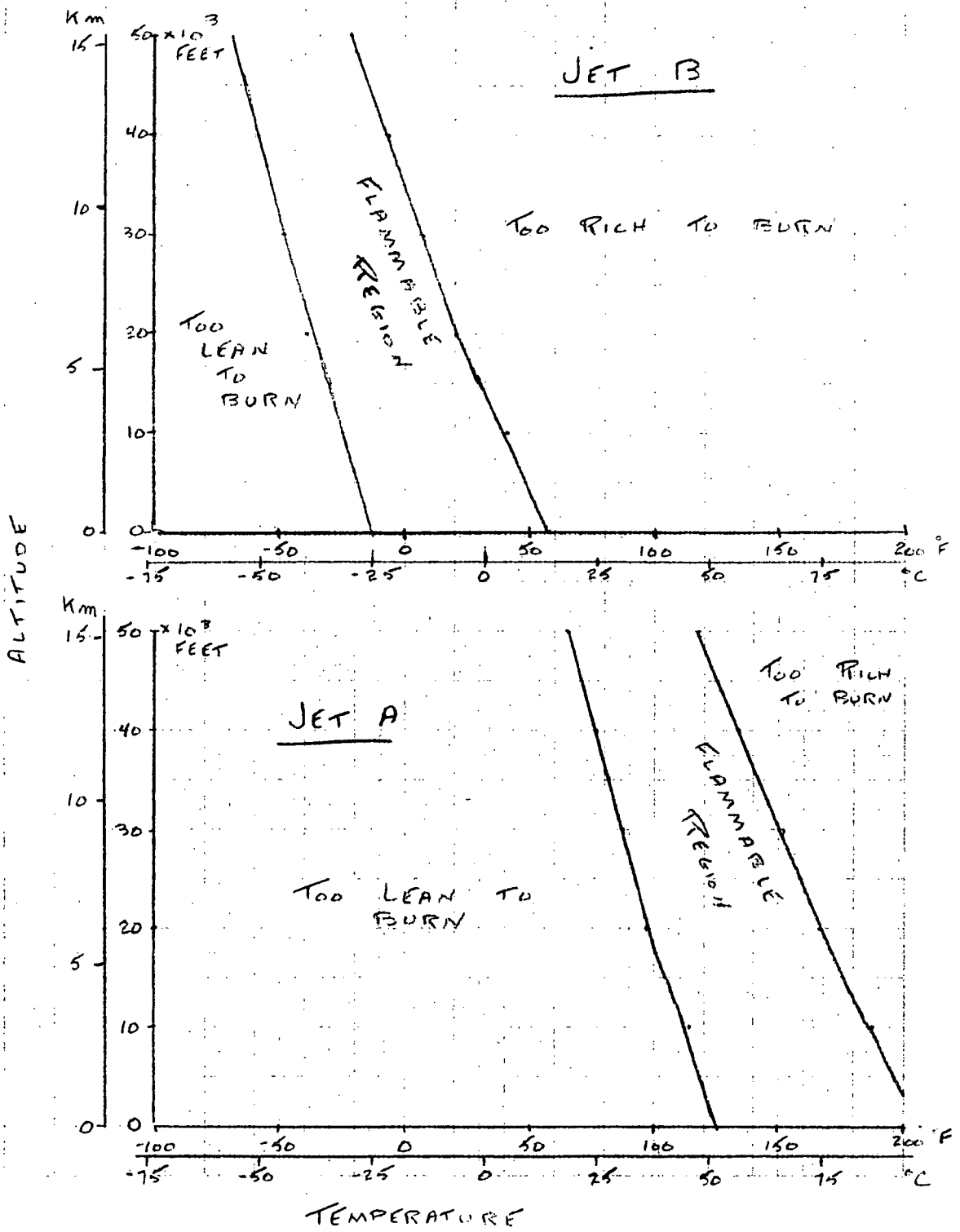


FIG A-3 FLAMMABLE REGIONS UNDER NON-EQUILIBRIUM CONDITIONS FOR AVERAGE JET A AND JET B

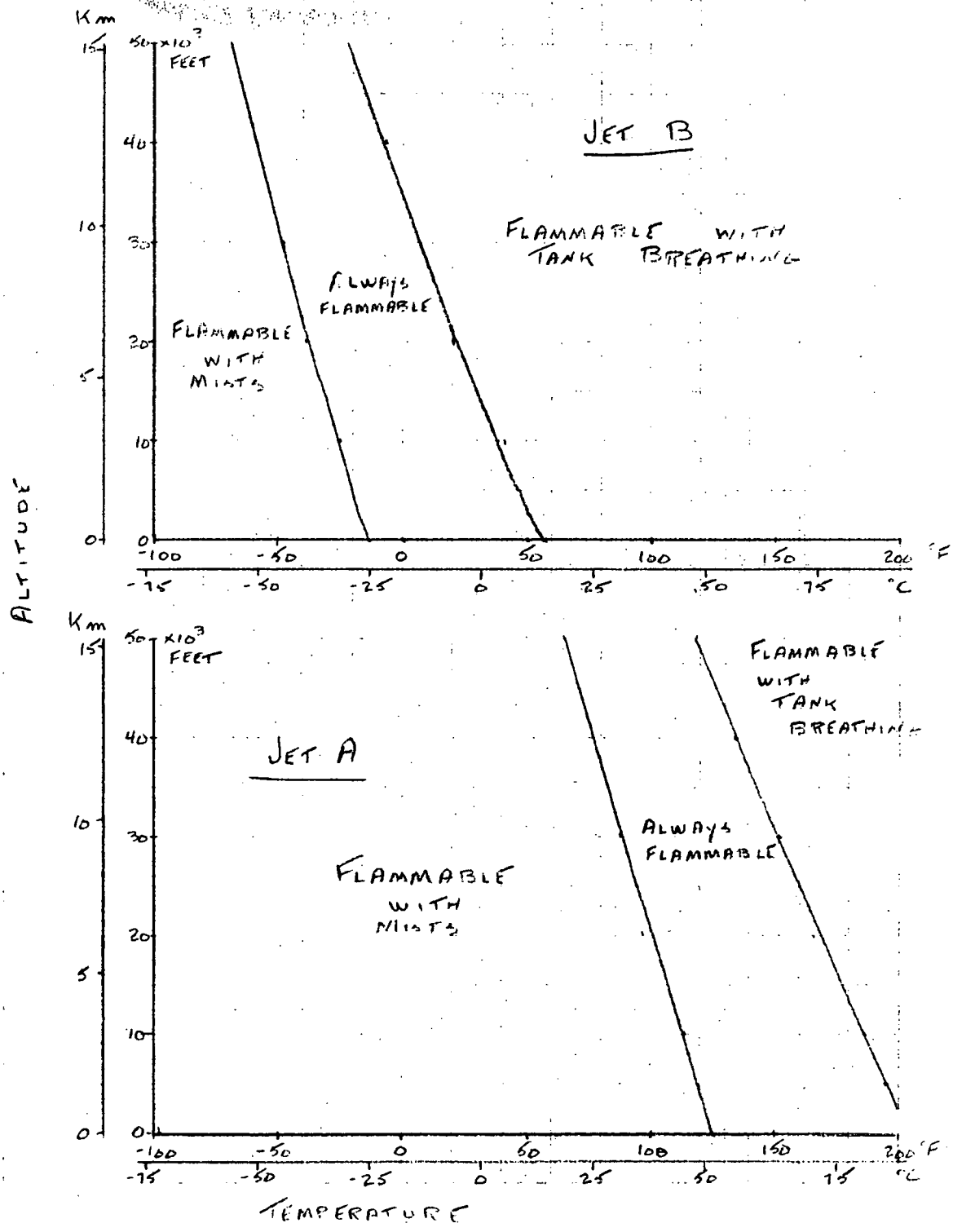
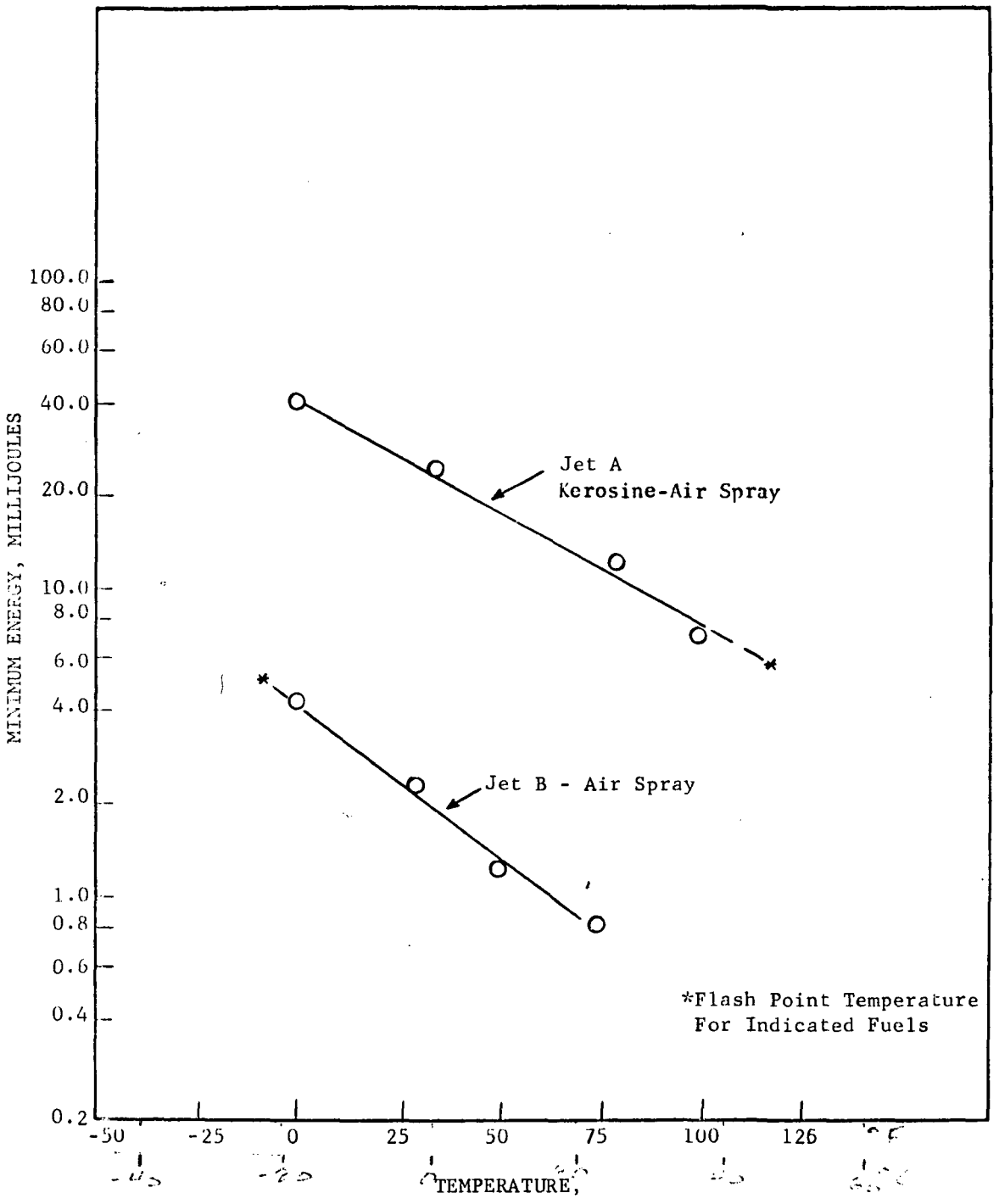


FIGURE A-4

MINIMUM SPARK IGNITION ENERGIES
FOR FUEL-AIR SPRAY MIXTURES
(reference 1)



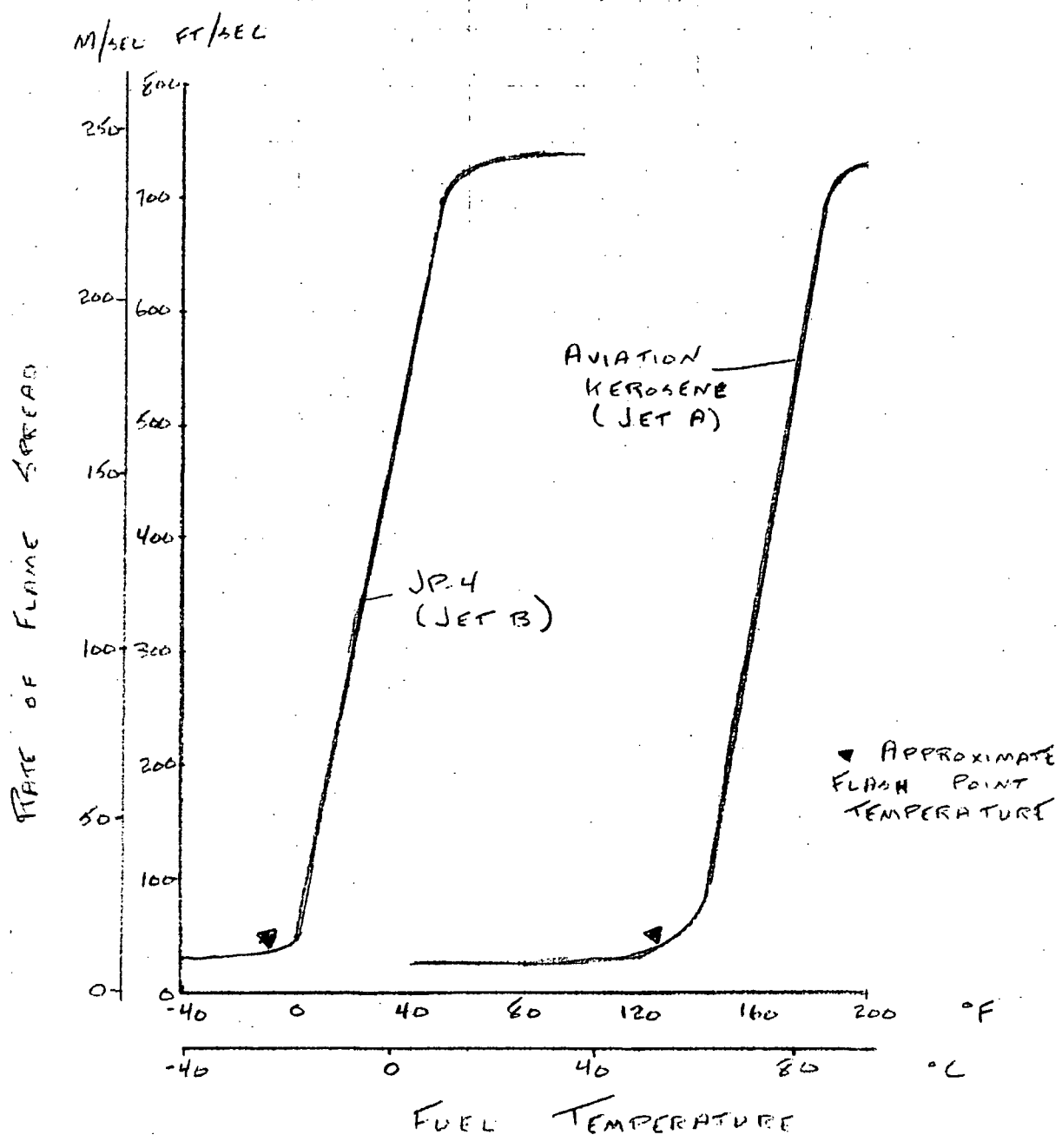


FIG A-5 RATE OF FLAME SPREAD ACROSS A LAYER OF FUEL (FROM REF 1)