APPENDIX B

SOME NOTES ON SPARKS AND IGNITION OF FUELS
NASA/TM-2000-210077

March 2000

Report Prepared by

Lightning Technologies Inc.
Pittsfield Massachusetts

Under contract to

National Aeronautics and Space Administration
Langley Research Center

NASA/TM-2000-210077

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Note

The work reported herein was performed as part of a Memorandum of Agreement (Space Act Agreement-SAA#435, May 15, 1998) between NASA LaRC and Lightning Technologies, Inc. This effort complimented a concurrent analysis of the electromagnetic field threat to the fuel system of a transport aircraft that will be reported as a separate NASA Technical Publication (TP-2000-209867).

Acknowledgements

Special thanks are extended to Mr. Kenneth L. Dudley of the NASA Langley Research Center Electromagnetic Research Branch for converting several figures to the electronic form found in this document.

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Abstract

This report compliments a concurrent analysis of the electromagnetic field threat to the fuel system of a transport aircraft. The accompanying effort assessed currents, voltages and power levels that may be induced upon fuel tank wiring from radio transmitters (inside and outside the aircraft). In addition to this, it was also essential to determine how much voltage, current, or power is required to create a fuel-vapor ignition hazard. The widely accepted minimum guideline for aircraft fuel-vapor ignition is the application of a 0.2 millijoule energy level. However, when considering radio frequency (RF) sources, this guideline is seriously inadequate. This report endeavors to bridge the gap between a traditional understanding of electrical breakdown, heating and combustion; and supplement the knowledge with available information regarding aircraft fuel-vapor ignition by RF sources.

1 INTRODUCTION

The question of ignition of aircraft fuel by radio frequency (RF) sources has arisen recently and these notes present some observations gleaned from a short review of the literature and previous experience with ignition of aircraft fuel by electric sparks, such as those that might be developed during lightning strikes. The review was by no means exhaustive and conclusions presented in these notes should not be taken as the definitive word on the subject.

Section 2 discusses some of the aspects of electrical sparks and points out the differences that may exist between sparks taking place across contacts initially separated and sparks and arcs that might occur between current carrying-contacts as the contacts are opened.

Section 3 discusses some of the factors governing ignition of fuel, including the question of what might be the spontaneous ignition temperature of aviation fuel. Reasons for being cautious about accepting a simplistic answer to the question are discussed. Also discussed is the matter of ignition of fuel by electrical sparks and the energy content of sparks that do or do not ignite fuel. Most of the knowledge about electrical ignition has been obtained by studies involving electrical sparks, which inherently are of short duration.

Section 4 discusses some of the factors governing ignition of fuels by RF sources. It is pointed out that energy levels derived for ignition by sparks cannot be used in any simplistic way to evaluate the risk of ignition by RF sources characterized by power, which is only a measure of energy per unit of time.

Some generalized conclusions from the review are presented in Section 5.

2 SPARKS

The term "spark" is commonly used in several different contexts:

a. Electrical breakdown of a dielectric medium produced:

- between electrodes which are initially separated, the circuit initially not carrying current or,
- between electrodes which are initially joined and then separated, the circuit initially carrying current.

b. Ejection of burning particles produced:

- by friction or,
- by excessive current density.

2.1 Electrical Breakdown Between Initially Separated Electrodes

If the electric field gradient around an electrode is increased sufficiently, ionization of the surrounding gas will take place. Ionization can take place in liquids as well, but this document will be concerned only with gasses. If the ionization bridges the space between two electrodes, a complete breakdown may occur, but not always. Breakdown in the common sense of an electrical spark implies that the gas in the intervening space becomes sufficiently conductive that its impedance becomes small compared to the impedance of the external circuit. When this occurs, a spark jumps between the electrodes and the voltage across the electrodes collapses.

Voltages required to cause breakdown across gaps of varying length are shown on Figure 2-1. Spark-over voltage is shown for two types of electrodes; sphere gaps and needle gaps. A sphere gap is said to provide a uniform field configuration, while a needle gap represents an extreme of a non-uniform field configuration. Breakdown voltage is highest for smoothly contoured gaps, such as sphere gaps and can be taken with reasonable accuracy as 31 kV/cm at sea-level conditions. Breakdown voltage depends on air density, the lower the density the less the breakdown voltage. Altitude would be the major factor governing air density, but temperature is also involved. Breakdown voltage for pointed electrodes; e.g. needle-gaps is lower than 31 kV/cm because the field is concentrated around sharp electrodes.

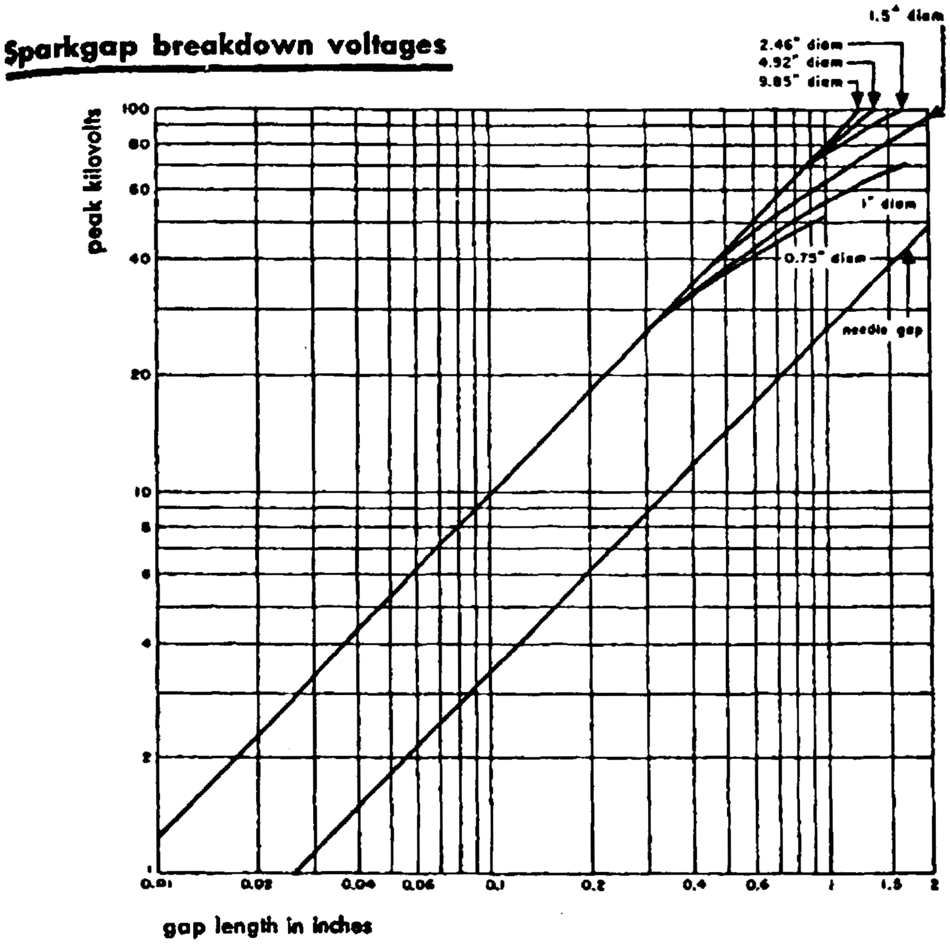

Table of multiplying factors.

pressure		temperature in degrees centigrade					
in Hg	mm Hg	−40	−20	0	20	40	60
5	127	0.26	0.24	0.23	0.21	0.20	0.19
10	254	0.47	0.44	0.42	0.39	0.37	0.34
15	381	0.68	0.64	0.60	0.56	0.53	0.50
20	508	0.87	0.82	0.77	0.72	0.68	0.64
25	635	1.07	0.99	0.93	0.87	0.82	0.77
30	762	1.25	1.17	1.10	1.03	0.97	0.91
35	889	1.43	1.34	1.26	1.19	1.12	1.05
40	1016	1.61	1.51	1.42	1.33	1.25	1.17
45	1143	1.79	1.68	1.58	1.49	1.40	1.31
50	1270	1.96	1.84	1.73	1.63	1.53	1.44
55	1397	2.13	2.01	1.89	1.78	1.67	1.57
60	1524	2.30	2.17	2.04	1.92	1.80	1.69

Figure 2-1 Spark Gap Breakdown Voltages. [2] (This particular figure was reproduced from the 4th edition, but the same data is presented on page 48-4 of the 7th edition, as referenced.)

The different types of field configurations affect the mechanism of ionization and breakdown. In a uniform field the average voltage gradient is obtained simply by dividing the total gap voltage by the gap spacing and at no point is the localized field greater than the average field gradient. In a sphere gap the localized field gradient may be less than the average gradient, but along the axis the field is quite uniform, so long as the spacing of the electrodes is small compared to the radius of the electrodes. The significance of a uniform field is that as soon as voltage is increased to a level to initiate ionization, the entire space between the electrodes becomes ionized. Breakdown then takes place very rapidly and breakdown depends only on the peak value of the voltage, not on its waveshape or frequency. Tests have shown that for small air gaps between spherical electrodes, the breakdown is independent of frequency up to several hundreds of MHz.

Needle gaps represent the other extreme; the localized voltage gradient around the tips of the electrodes will be much greater than the average gradient. Ionization may take place only around the tips of the electrodes and total breakdown depends on how fast, or if, the ionization extends to occupy the whole space between the electrodes. Therefore, breakdown of non-uniform gaps may be strongly influenced by voltage waveshape. Breakdown may depend considerably upon frequency. Data has not been found regarding breakdown of pointed electrodes at high frequencies, but there is probably much more of a dependence on frequency than would be the case for sphere gaps. As an educated guess, it might be taken that the data shown on Figure 2-1 is valid from near dc up to about 10 MHz.

Most places where gap breakdown is of importance will involve electrodes providing a non-uniform field configuration, more nearly approximating the needle gaps rather than uniform field sphere gaps of Figure 2-1.

While breakdown voltage of a gap decreases with decreasing distance or decreasing gas density, there is a minimum breakdown voltage irrespective of gap length. Loosely speaking, sea level breakdown of an air gap is unlikely to occur at peak voltages less than about 330 volts even for very small gaps. The relationship between breakdown voltage, gas density and electrode separation, Paschen's curve, is shown on Figure 2-2. The minimum breakdown voltage, about 330 volts, occurs at 0.6 Torr·cm (0.6 mm-hg x cm). Taking sea level atmospheric pressure to be 760 Torr, breakdown would not occur until the gap separation was reduced to 7.9x10-4 cm. A more practical small gap spacing of 0.05 cm and an atmospheric pressure of 760 Torr gives a product of 38 Torr·cm and a breakdown voltage of about 2.6 kV, a figure in line with the breakdown voltage for sphere gaps shown on Figure 2-1.

Breakdown voltage is also influenced by dielectric surfaces in the vicinity of the electrodes. For two electrodes in contact with an insulating surface, such as a terminal board, breakdown is apt to take place at a lower voltage than if the electrodes were completely in air. This is particularly true should the insulating surface be contaminated in some way, such as by a surface film of some kind or by semiconducting particles.

Once the spark occurs, how hot or how bright it gets depends on the amplitude of current through the spark and how long it flows. The current and its duration are limited by the impedance and voltage of the external circuit. If the spark becomes hot enough, the discharge can take on the characteristics of an arc.

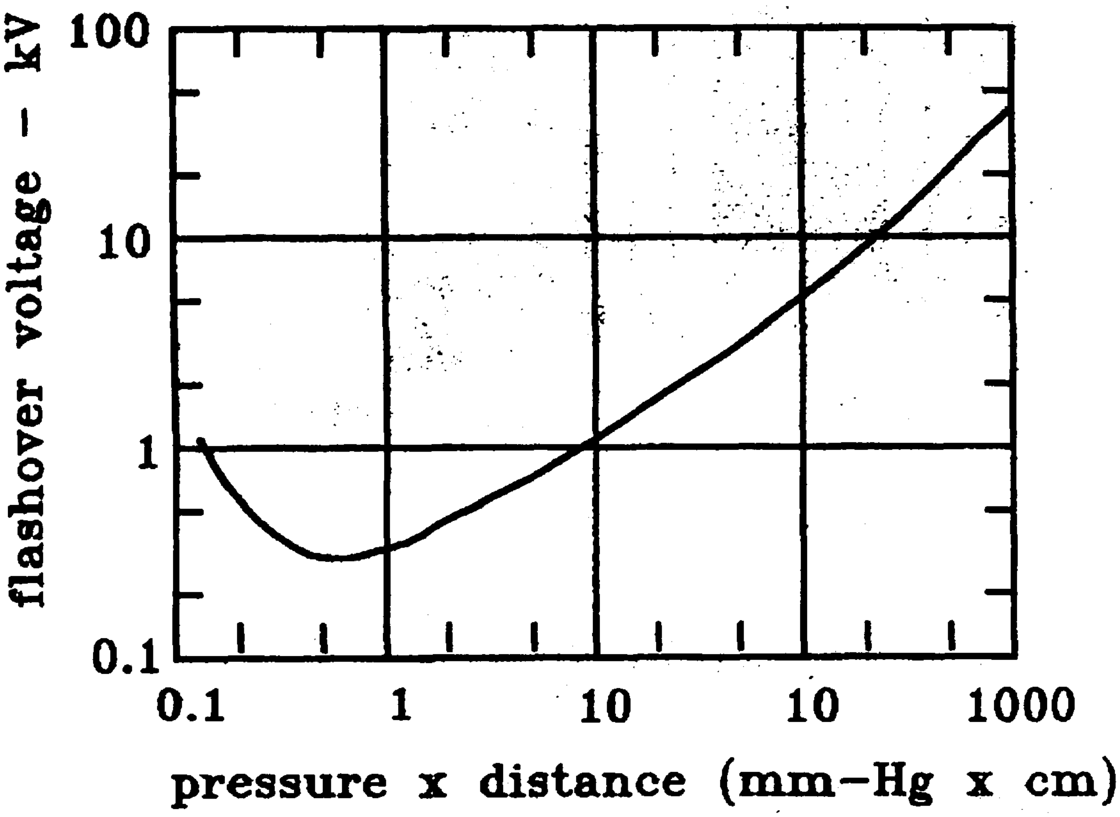

Figure 2-2 Breakdown Voltage vs. P × d - Paschen Curve [3]

There is no clear-cut distinction between a "spark" and an "arc". Generally speaking however, a "spark" designates a transient condition in which the voltage drop across the conducting channel is decreasing with time while an "arc" designates a steady-state condition in which the voltage across the channel has reached a constant and fairly low value. Both sparks and arcs radiate copious amounts of light, though an arc may seem brighter because the light is continuously radiated. The radiation spectrum can extend from deep ultraviolet to well beyond the infrared, which is to say that they are thermally "hot".

Both sparks and arcs are capable of igniting fuel-air mixtures. Continuous arcs are capable of burning or melting metal surfaces. Sparks may or may not damage the electrodes between which they then occur, though certainly any spark capable of damaging a metal electrode would be well capable of igniting a fuel-air mixture.

Sparks and arcs are not the only types of electric discharges that can take place around or between energized electrodes. There can also be localized corona around an electrode or a glow discharge between the electrodes. Corona is a localized ionization phenomenon that occurs when the electric field gradient around an electrode or conductor exceeds about 31 kV/cm. If the ionized region extends all the way between electrodes a spark or an arc usually, but not always, develops.

Corona discharges are generally quite localized and certainly would be so around aircraft wiring. Corona discharges may occupy a region several inches in radius around high voltage transmission lines, but that is a different story and not relevant to aircraft. Visually, corona is evidenced by emission of blue and ultraviolet light and audibly by a hissing sound. Corona does not physically damage the electrode and studies have not shown corona to be capable of igniting fires, even in an ideal fuel-air mixture since corona does not release any significant amount of heat. A piece of paper held in a corona discharge will not be ignited since the amount of current transferred in a corona is quite small, on the order of microamperes.

Corona can develop into a steady glow discharge between electrodes when the impedance of the external source is sufficiently high as to prevent heating the conducting channel sufficiently to form a lower impedance arc. A glow discharge in air is characterized by a voltage gradient considerable higher than a conventional arc and by radiation of blue and ultra-violet light and commonly by a hissing sound. Studies have not been made as to whether a steady glow discharge will ignite a fuel-air mixture, but such a discharge would certainly be cause for concern.

2.2 Electrical Breakdown Between Initially Joined Electrodes

Sparks jumping across initially open contacts are unlikely to occur in fuel tanks because the amount of voltage required is generally far less than the system voltage normally applied to wires in a fuel tank. Sparks due to separation of contacts initially closed, intentionally or otherwise, would seem more likely.

If two electrodes are initially joined and carrying current an arc may develop between the electrodes as they are separated. The arc of a welding torch is a classic example. The arc is initiated by touching the electrodes together to make a direct electrical contact and then drawing them apart to allow the arc to develop. The voltage involved is commonly much less than the 330 volts minimum sparking potential discussed above.

There are several mechanisms for development of arcs between parting contacts, whether they be the intentional contacts of a switch or the inadvertent contacts of wires rubbing against each other. First, contacts never separate instantaneously, moving from completely closed to completely open. Even if the contacts were perfectly smooth, the spacing between contacts would of necessity change with time from zero with the contacts closed to some larger spacing, and during the transition the circuit voltage might be sufficient to bridge the developing gap.

Second, electrodes are never completely smooth. Microscopically, a smooth surface would appear to be covered with bumps and contact between two electrodes would involve contact between many similar bumps of material, each of which carries a portion of the total circuit current. As the electrodes are pulled apart the current will be concentrated into fewer and fewer bumps until finally the current density in the remaining contact points becomes high enough to cause microscopic burning. Such burning causes thermal ionization of the surrounding air, and as the contacts are pulled further apart, current flows in the ionized regions, heating them further and so causing further ionization. If there is sufficient current available, the ionized region may stabilize as an arc, a region in which thermal ionization becomes sufficient to maintain the current.

Arcing due to the preceding mechanisms is seldom a problem as long as the circuit is resistive and the voltages and currents prior to switching are small.

If the circuit contains inductance or capacitance, or both, the switching mechanism is more complex. In an inductive circuit, opening a contact implies reducing the current. Reducing the current in an inductive circuit brings about an increasing voltage $V = L\ di/dt$ across the inductor, which adds to the circuit voltage and may lead to arcing across the opening contacts. Depending on circuit conditions the current may be interrupted without visible arcing, with momentary arcing or with repeated arcing. Phrased a different way, opening of an inductive circuit involves a race between the increasing dielectric strength of the parting contacts as they are moved apart and the increasing voltage as the current in the inductance is reduced.

A simple illustration of the problem is shown on Figure 2-3. An inductor is energized from a dc source with circuit capacitances as shown. With the contacts closed there will be no voltage across the switch. As the contacts move apart, current in the inductor will decrease and an oscillatory voltage will be developed across the switch contacts. If the contacts move apart fast enough, the increasing dielectric strength between the contacts will always be greater than the voltage developing across the contacts, and the inductive current will fall toward zero without arcing taking place across the contacts.

If the switch voltage recovers at a rate faster than the switch regains dielectric strength, an arc will form across the contacts, a restrike, and current will continue to flow until the arc voltage becomes equal to the circuit voltage and forces the current to cease. Generally, the arc voltage will increase with time, partly because the contacts are moving apart and lengthening the arc, and because the decreasing circuit current provides less heating to the arc. Often several cycles of interruption followed by a restrike may occur, particularly if the circuit is energized with ac. Frequently, the process is called a "showering arc". The arc sometimes seen on a household wiring switch will be of this type. Sometimes burning particles are ejected during the process, as discussed further in Section 2.4.

Suppression of the inductive voltage is the reason why reverse diodes are often used across relay coils. Inductance can also exist in circuit wiring, and diodes cannot be used to suppress inductive rises in circuit wiring.

More complicated phenomena can be observed in circuits energized with single or three-phase alternating voltage, but a discussion of such phenomena is beyond the scope of this discussion.

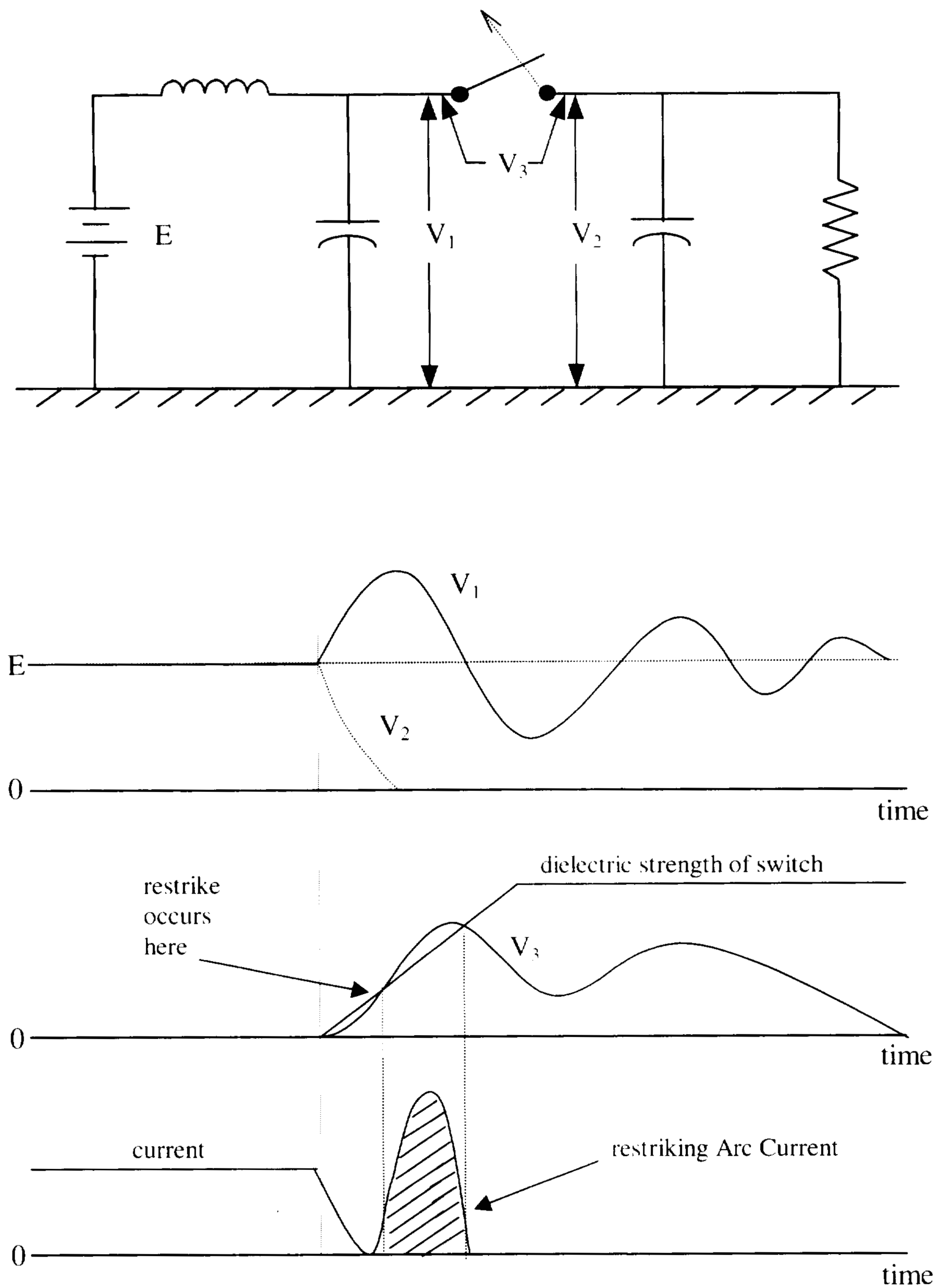

Figure 2-3 Opening of a Switch.

2.3 Burning Particles Produced by Friction

While not of an electrical nature, sparks produced by friction need to be considered when discussing fuel ignition. Sparks, such as those observed by holding a steel tool against a grindstone, are generally considered to be the result of particles, usually metallic particles, burning in the air after being heated sufficiently by friction. Frictional heating alone does not raise the particles to incandescence. Further discussion of frictional heating is beyond the scope of this document, other than to observe that burning particles have clearly been shown capable of igniting fuel-air mixtures.

2.4 Burning Particles Produced by Excessive Current Density

Burning particles can also be caused by excessive current density, as witnessed by rubbing a shorting wire across the terminals of an automotive storage battery. The sparks observed are not the result of excessive voltage causing breakdown through the air, but are instead actual burning particles produced when copper or lead particles are heated sufficiently by excessive current. Current flowing through the resistance of a wire causes heating of the wire, and if the heating is sufficient, the wire melts and possibly ignites.

2.5 Break Sparks

The term "break spark" is sometimes encountered, particularly in the context of one particular type of test used to observe whether a fuel-air mixture can be ignited. The principle of the test is illustrated on Figure 2-4. A circuit is formed through an intermittently-contacting set of electrodes consisting of wire held against a ridged and rotating cylinder or disk. As the cylinder or disk rotates, the wire repeatedly makes and breaks contact with the cylinder or disk. Sparks, if they occur, could be due either to frictional heating or due to excessive current density, or both. Sometimes a rusted iron cylinder or disk has been used to investigate phenomena connected with frictional heating and/or burning of ferrous oxides, a subject discussed is somewhat more detail in Section 3.5.1.

Break sparks are discussed further in Section 4 dealing with sparking induced on circuits excited by continuous wave radio frequency voltages.

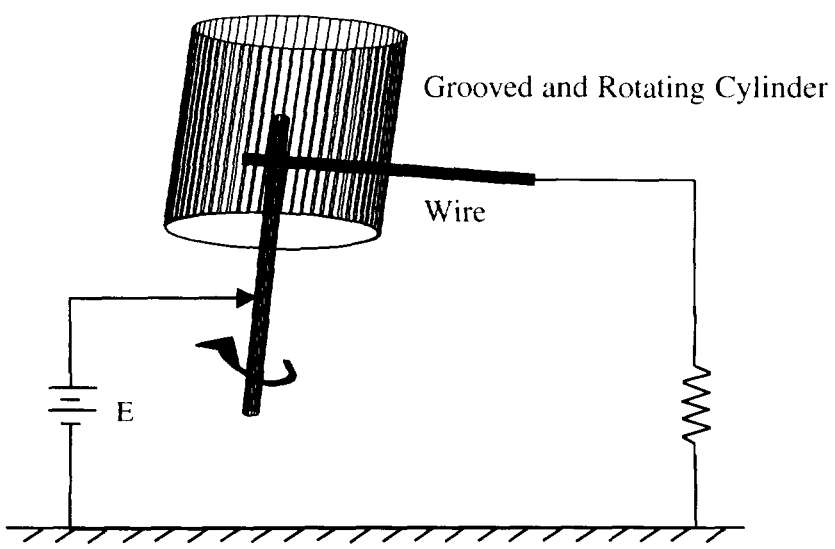

Figure 2-4: Mechanism for Generating Break Sparks.

2.6 Calculation of Wire Heating

Heating and ignition by excessive current density should be considered if discussion is made about the effects of metal fibers in a container. A wire or metal fiber heated to incandescence is apt to burn and burning particles, even if quite small, have been shown to be capable of igniting a fuel-air mixture.

A short computer program has been written that evaluates the temperature rise in a conductor, taking into account the wire or fiber size, the fiber resistivity and its temperature coefficient of resistivity. The essential features of a calculation of temperature rise are:

1. From the wire cross-section area (A) and length (l), calculate the volume $V = A \times l$. (wire length cancels out in the final analysis)

2. From the volume and the material density determine the mass (M).

3. Assume an initial temperature (T).

4. Determine the resistance (R) of the wire, taking into account the cross-sectional area (A), length and material resistivity (ρ).

$$R = \rho\, l \,/\, A.$$

5. For a small increment of action integral (AI) of current determine the heat liberated in the wire

$$W = AI \times R \qquad \text{joules.}$$

6. From the mass and the specific heat calculate the temperature rise produced by injecting a certain amount of heat (W) joules.

$$T = \text{joules} \times 0.2389 \times W. \quad (0.2389 \text{ gm}\bullet\text{calorie per joule})$$

7. From the initial temperature and the temperature rise calculate the temperature after passage of the increment of action integral.

8. From the temperature rise and the materials temperature coefficient of resistivity determine a new value of resistivity.

9. Go back to step 4 and repeat the calculations observing how the temperature increases with increasing action integral.

10. When the temperature has reached the melting point, stop the calculations and observe the action integral of current required to cause such a temperature rise.

The routine assumes resistivity to be a linear function of temperature, which may or may not be the case. If additional data were available the routine could be modified.

3 COMBUSTION

A reasonable question is "What is the spontaneous ignition temperature for aircraft fuel?" A short answer is that it seems to be about 450° F, but as usual the "short answer" is not the "complete answer", which is more nearly "It depends ....."

A document giving considerable information on combustion of aircraft fuels is [1]. The following material is extracted and paraphrased from that report in an attempt to more fully answer the question about spontaneous ignition temperature. The above document will be referred to as [1] and page numbers will be indicated to which reference can be made for a more complete discussion.

3.1 Explosive Combustion (p.54 of [1])

Explosive combustion can be defined as a process leading to uncontrolled increase of temperature, usually accompanied by increase of pressure and/or emission of light. Presumably, this requires that chemical processes liberate heat in some ill-defined zone faster than heat is lost from the zone. Not all combustion processes lead to explosive combustion.

A flammable-air mixture can ignite when exposed to a heat source at some critical temperature, but the "critical" temperature depends strongly on the experimental technique and cannot be well defined in terms of some absolute temperature characteristic of the mixture under study. Decomposition or partial oxidation may be observed below the "critical" temperature, but without complete combustion occurring. Differing experimental techniques result in differing "critical" temperatures. The following material gives some discussion about the different experimental techniques.

3.2 Ignition Temperature as Related to Exposure Times (p.55 of [1])

Ignition temperature varies with the time between exposure of the flammable mixture to the heat source and commencement of ignition. Exposure to a given temperature for a short time may not lead to ignition while exposure to a lower temperature for a longer time may lead to ignition. It is not clear whether the observed delay represents a fundamental property of the flammable mixture or whether higher temperatures permit a critical state to develop in a shorter time.

Ignition temperature also depends on the pressure of the flammable mixture. With a low pressure, higher temperatures may be needed for ignition than would be needed at higher pressures.

3.3 Types of Ignition Process

Three types of ignition processes can be observed, all of which lead to increasing temperatures and possibly, though not necessarily, to explosive combustion.

a. Oxidation

b. Cool flames

c. Normal flames

Figure 3-1 (Figure 25 of [1]) shows some representative data relating temperature and pressure to the type of process that might occur.

3.3.1 Oxidation

Oxidation (sometimes called slow combustion) is a process that liberates heat, but not normally at a rate greater than heat can be carried away to the surroundings. Rusting of iron by this definition can be considered a form of combustion. In the context of a flammable gas mixture, simple oxidation would be associated with temperatures below about 450 F and pressures of 1 atmosphere or less.

Oxidation may lead to normal combustion if the material is confined and heat cannot escape at a sufficient rate. An example would be spontaneous ignition of oily rags stored in a can. In the context of a flammable gas mixture, oxidation may lead to formation of a cool flame and then to a normal explosively-propagating flame if temperature and pressure rise sufficiently.

3.3.2 Cool flames

A cool flame represents a self-sustaining process involving partial oxidation and liberation of heat. Since the process emits light, it has all the characteristics usually associated with a flame. A cool flame may propagate through a mixture, but will not lead to explosive ignition so long as heat is not released at a rate sufficient to allow a build-up of temperature or pressure. If heat is released at a sufficient rate, however, a cool flame can turn into a normal flame of the type associated with fuel explosions.

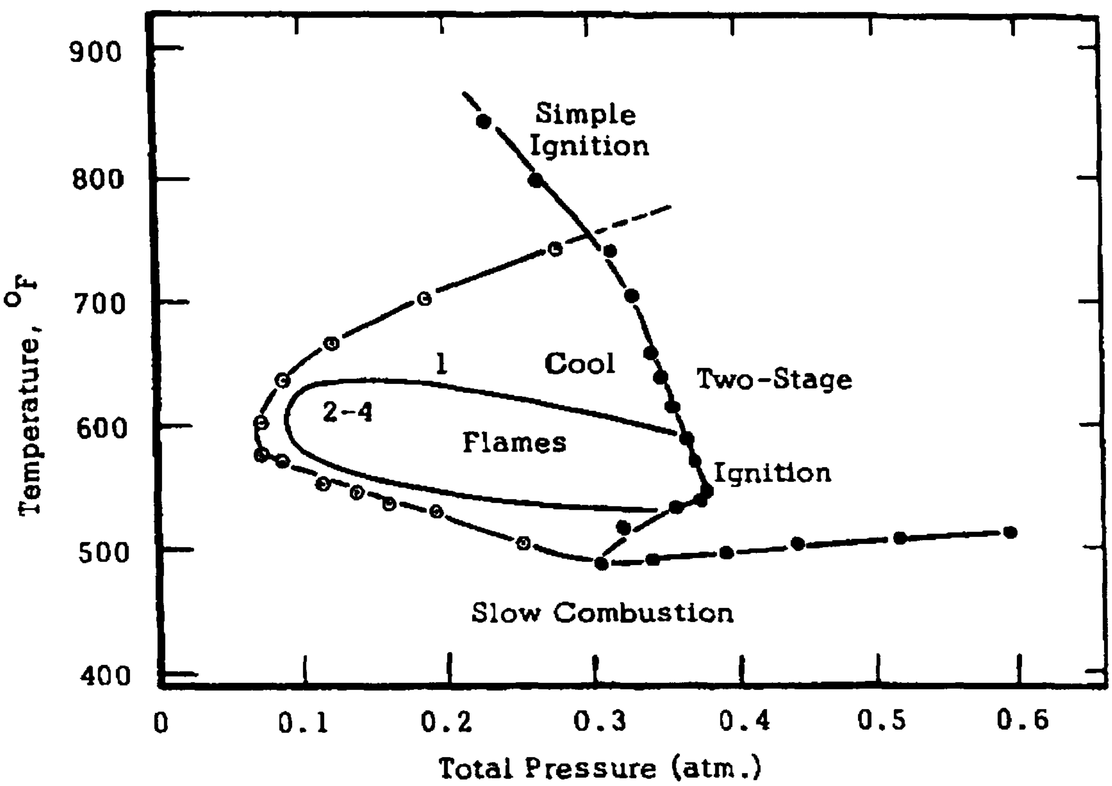

Figure 3-1 Conditions of temperature and pressure for combustion in butane-oxygen mixtures containing 50 percent butane. [1] (The numbers shown indicate the number of cool flames observed)

Broadly speaking, cool flames are associated with temperatures of 500 - 800 F and pressures in the range of 0.1 - 0.3 atmospheres or 30,000 ft. altitude and higher. If a cool flame were to be in existence, an increase in pressure, as, for example, descent from a high altitude, the cool flame might transform into a more normal explosively-propagating flame.

3.3.3 Normal flames.

A normal flame is considered one in which reactions proceed to thermodynamic equilibrium and in which the full temperature rise is achieved. An explosive ignition is almost by definition one involving normal flames, but the mere existence of a normal flame does not by itself imply the beginning of an explosion.

3.4 Ignition by Exposure to High Temperatures

An important set of parameters associated with fuels is the combination of temperatures and pressures leading to various ignition processes. Examples are shown on Figures 3-2, 3-3 and 3-4 (Figures 29, 30 and 36 of [1]), though one must be aware that quoted ignition temperatures may vary depending on the type of experimental procedure used to generate the data.

One of the most widely used thermal ignition tests (p.75 of [1]) consists of dropping a small quantity of liquid fuel into an open cup-shaped container heated to some specific temperature. The container initially contains air. Ignition temperature is defined as the lowest temperature of the container, or a bath surrounding the container, at which a visible or audible evidence of a flame or explosion is observed. It is usually assumed that ignition will occur prior to some arbitrary time interval, usually several minutes. The ASTM autogenous ignition test uses this type of test fixture.

Tests of this type generally give the lowest ignition temperatures reported. The experimental conditions correspond to the deposition of a relatively small quantity of liquid fuel on a heated surface in some sheltered region. Examples of ignition temperature data using this technique are shown on Figure 3-5 (Fig. 35 of [1]) and Tables 3-1 and 3-2 (Tables 10 and 11 of [1]). At 1 atmosphere pressure the ignition temperatures of JP-4 and JP-5 are about 475° F. Ignition temperatures are lower (375 - 410° F) at 5 atmospheres and higher at lower pressures (850° F) at ½ atmosphere.

The observed spontaneous ignition temperature seems to depend to some degree on the material from which the container is made (p.85 of [1]). Surface geometry also affects the ignition temperature. Ignition temperatures observed when dropping fuel into a heated tube providing a sheltered region were uniformly much lower than observed when dropping fuel onto a flat plate that left the vaporizing fuel completely exposed.

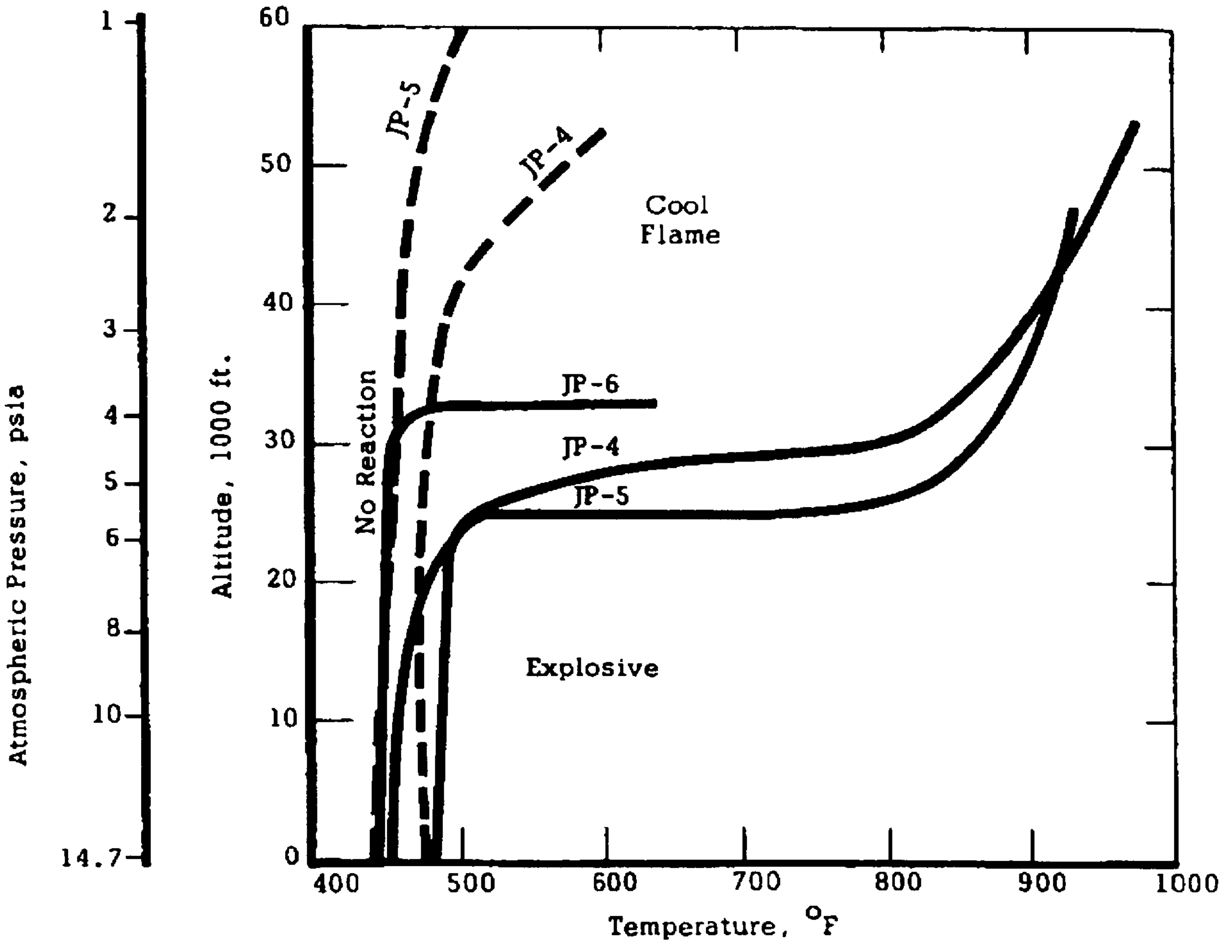

Figure 3-2 Spontaneous ignition reaction zones for JP-type fuels. [1]

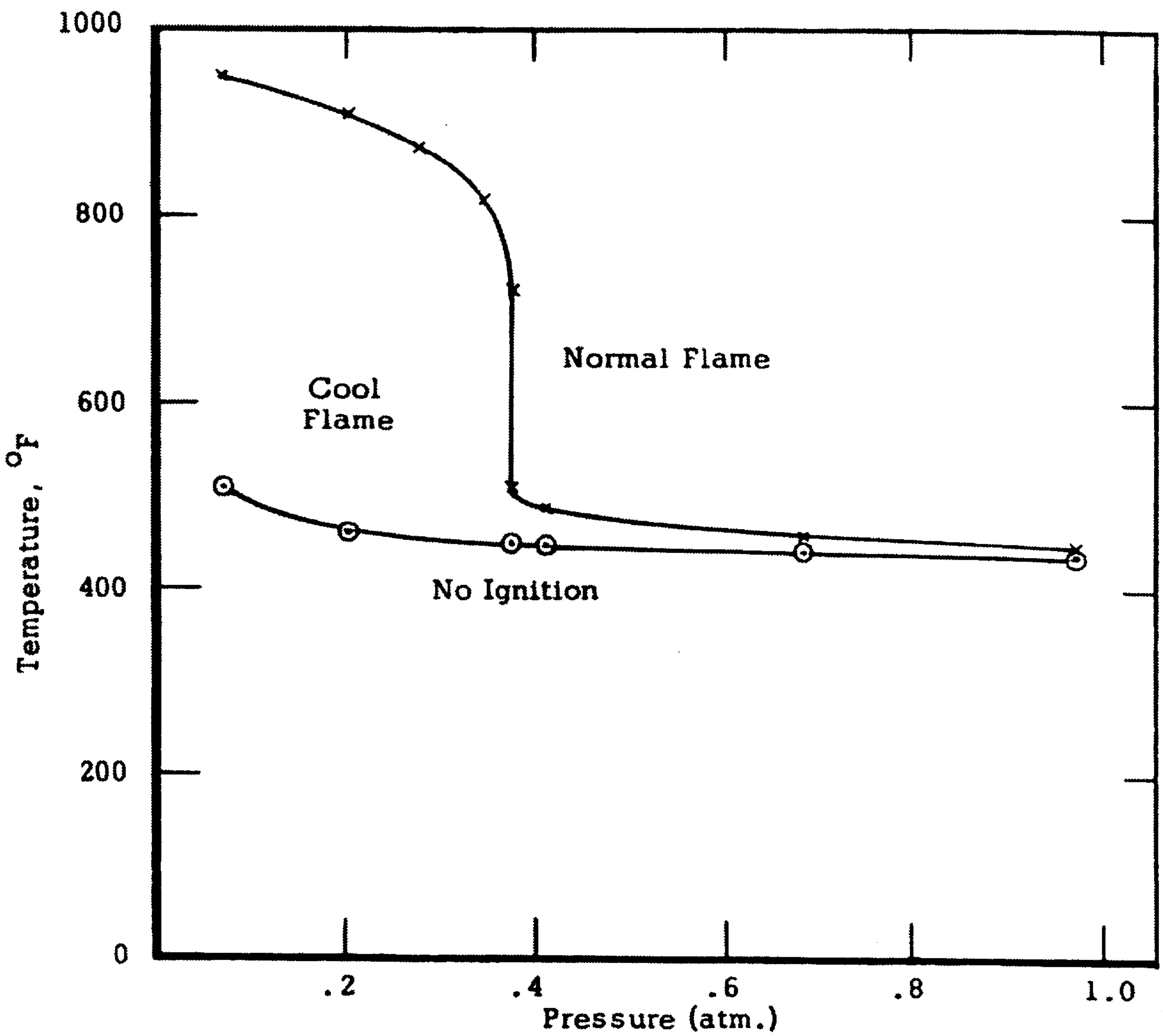

Figure 3-3 Ignition zones for JP-5 as a function of pressure. [1]

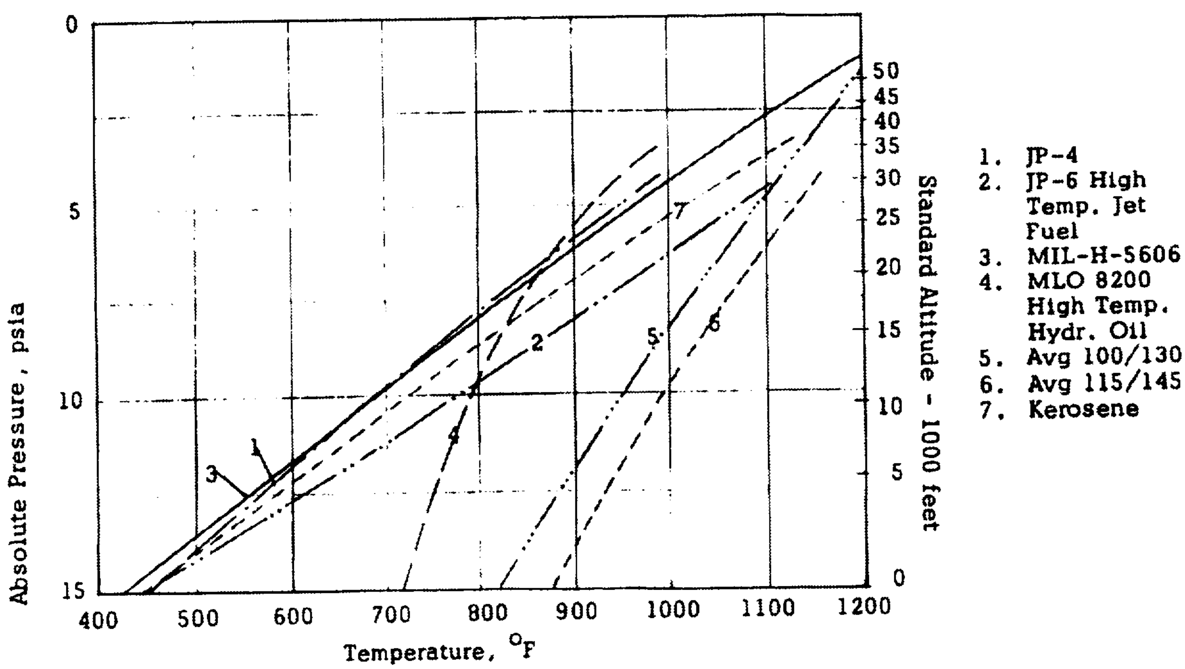

Figure 3-4 Variation of the minimum spontaneous ignition temperature with pressure. [1]

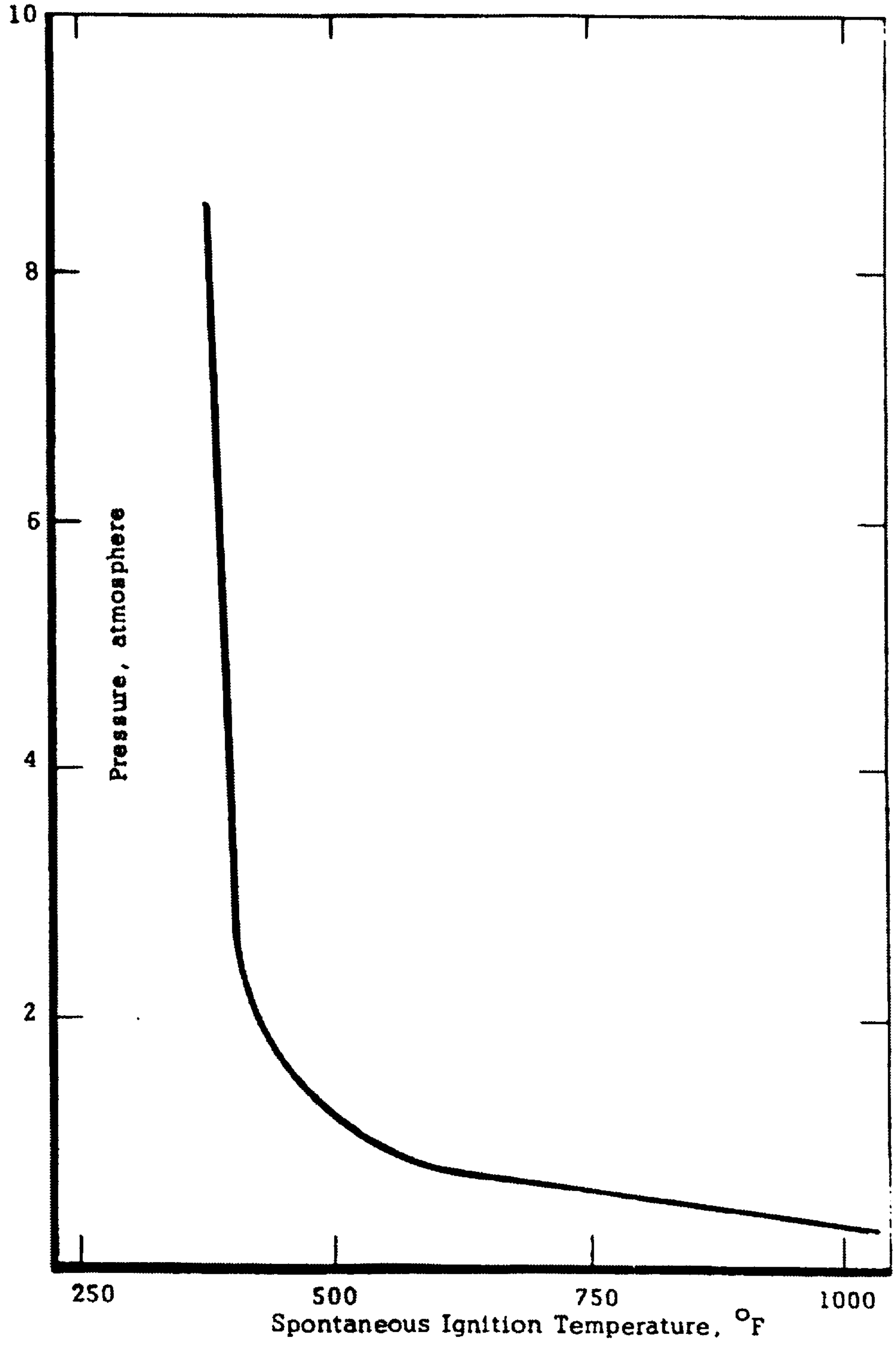

Figure 3-5 Spontaneous ignition temperature of JP-4 as a function of pressure. [1]

Pressure atm.	Ignition Temperature °F	
	JP-4	JP-5
1	484	477
5	376	415
9	378	408

Table 3-1 Variation of ignition temperature with pressure. [1]

Combustible	Pressure	
	1/2 atm.	1 atm.
JP-4	831°F	468°F
JP-3	840	460
JP-1	864	442
Av. Gas 100/130	1027	824
Av. Gas 115/145	1063	880
n-hexane	927	453
n-octane	869	428
n-decane	856	406
Hydraulic Fluid AN-0-366	838	437

Table 3-2 Ignition temperatures of commercial fluids at 2 pressures. [1]

Another type of ignition experiment utilizes a closed bomb in which a fuel-air mixture is heated until ignition occurs (p.87 of [1]). This type of experiment seems to give somewhat higher spontaneous ignition temperatures than those found with the open-cup test method.

Lower ignition temperatures are observed with a large volume bomb until a minimum value is reached, presumably because less heat is lost during the initial stages of combustion because of the smaller ratio of volume to surface area associated with a large bomb as compared to a smaller bomb.

Yet another method by which ignition can be initiated is the introduction of a hot gas into a flammable mixture (p.106 of [1]). In general, the gas temperatures required for ignition are considerably above the spontaneous ignition temperatures recorded in other test methods.

Some work has been done in which individual drops of fuel were dropped into a high temperature furnace (p.107 of [1]). Such tests give the time necessary to reach steady state evaporation, 1, and the additional time necessary for ignition to occur, 2. The total ignition delay is then 1 + 2. Some examples of ignition delays are shown on Figure 3-6 (Figure 48 of [1]), though the data do not relate to ordinary aviation fuel. The most important aspect of the work is that it illustrates the importance of vaporization in the thermal ignition of liquids, but it also illustrates that fuel must be exposed to high temperatures for a certain time before it ignites.

3.5 Ignition by Exposure to Friction sparks (p.109 of [1])

Since friction sparks can occur under damage conditions in flight, such sparks need to be considered. Just how friction sparks are produced by the contact of two surfaces has not yet been clearly explained in spite of the common occurrence of such phenomena. It does appear that the tendency to produce sparks is related to the hardness of the metal, and thus, a ferrous alloy is more likely to produce sparks than an aluminum alloy. The chemical reactivity of the material and the shape and nature of the surface are also important factors.

3.5.1 Oxide Films (p.110 of [1])

Oxide films on a surface, such as rust on ferrous materials, can produce a reaction involving an oxide film on another impacting surface. It has been noted that an aluminum spark adhering to fresh rust can react to produce a temperature high enough to ignite flammable hydrocarbons.

This might be of importance as regards the possible presence of rusted steel wool fibers in an aluminum tank.

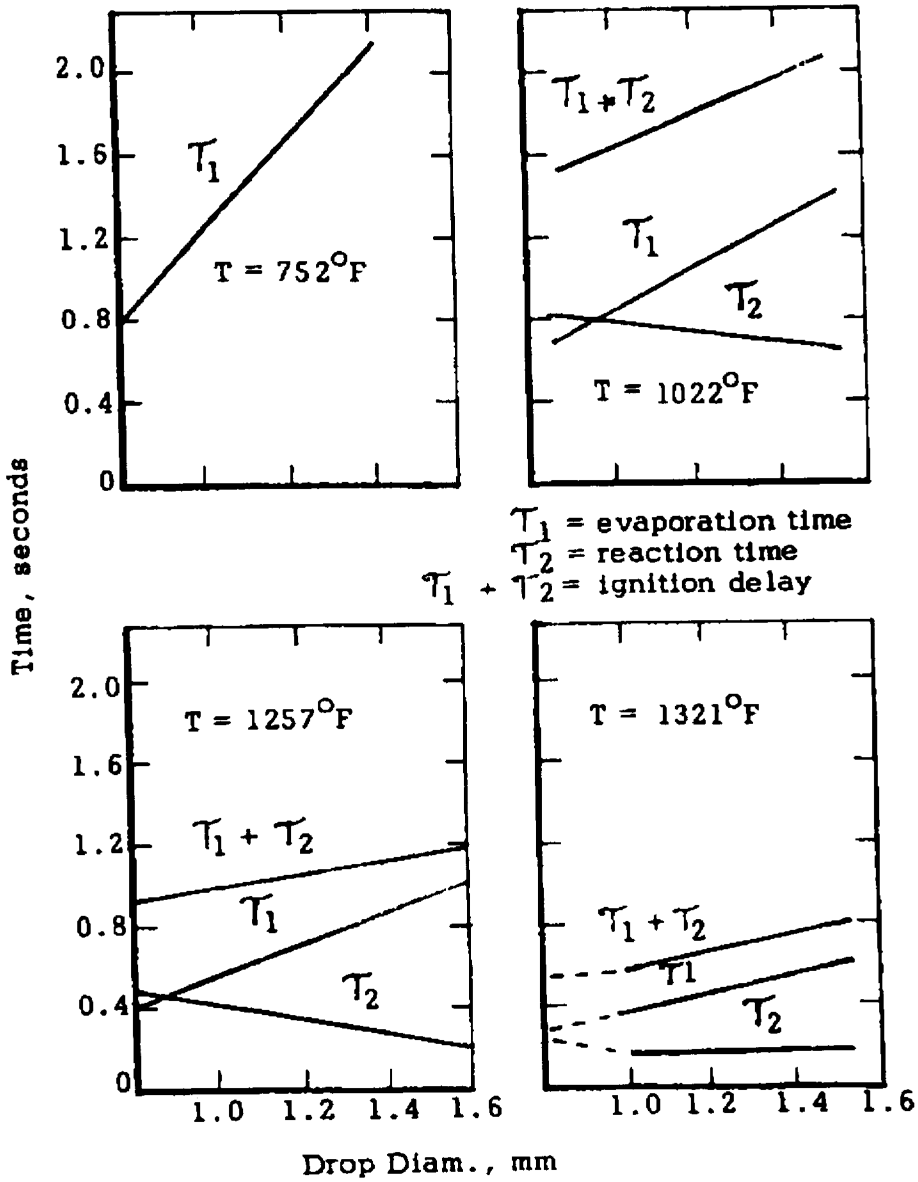

Figure 3-6 Single drop ignition delays for α-Methylnephthalene. [1]

3.6 Ignition by Electrical Sparks (p.111 of [1])

Ignition by electrical sparks generally involves mechanisms different from those involved in ignition by thermal sources. Electrical ignition correlates better with flame velocity and quenching distance than with ignition temperature.

In a typical experiment, a spark is created between two electrodes immersed in a fuel-air mixture. The energy of the spark is varied to observe whether or not the spark creates a flame kernel, which propagates away from the region of the electrodes. The initial kernel is presumed to be somewhat spherical and of a diameter comparable to the spacing between the points of the electrodes. Typically, needle electrodes are used in preference to flanged electrodes, which can act to cool a flame and keep it from propagating. The spark acts to heat an appropriate volume of the mixture and keep it hot enough for a sufficiently long time for the flame to ignite and keep burning. How hot the arc heats the mixture and for what length of time is not measured, though presumably those quantities could be inferred from the characteristics of the energy source and electrodes, coupled with a knowledge of the dynamics of ionized gases.

The required ignition energy decreases asymptotically as the spark is made longer, with the minimum required energy being reached with a spark about 0.1 inch long. Figure 3-7 (Figure 49 of [1]) shows one set of data relating minimum ignition energy as a function of electrode spacing while Figure 2-1, previously shown, shows voltages required to cause breakdown across gaps of varying length.

The ignition energy required depends on the richness of the fuel-air mixture, but the minimum required energy is about 0.2 millijoules. Examples of how ignition energy varies with fuel-air mixture is shown on Figure 3-8 (Figure 50 of [1])

Required ignition energy increases as pressure is decreased, some typical data being shown on Figure 3-9 (Figure 51 of [1]). If we were to assume that a combination of circumstances resulted in the required energy being 3 millijoules delivered to a spark 0.05 inches long from a 200 volt source, then the required capacitance would be 1.5 nF.

Typically, the energy actually delivered to the spark is not measured. Rather, energy is stored on a capacitor and all the stored energy is assumed to be delivered to the spark. The actual spark energy could be less than the stored energy, because of losses in the apparatus, but it can never be greater than the stored energy.

The energy stored on a capacitor is:

$$W = \frac{CV^2}{2} \qquad (3\text{-}1)$$

Breakdown of a 0.1 inch spacing needle gap requires about 3500 volts (at sea level) and for an ignition energy of 0.2 millijoules, the capacitance involved would be only 16 pF, effectively just the stray capacitance associated with the needle gap electrodes themselves.

$$C = \frac{2W}{V^2} \qquad (3\text{-}2)$$

Taking, for numerical simplicity, the critical stored energy to be 1 millijoule, the required capacitance as a function of voltage would be as follows:

Breakdown voltage	Capacitance
3000 volts	222 pF
2000	500 pF
1000	2 nF
500	8 nF
200	50 nF

It needs to be emphasized that the energy figures cited for ignition refer to the energy initially stored in the test apparatus, not the energy actually delivered to the spark or the initially burning kernel of fuel. The same general situation exists when discussing RF ignition of fuel, as discussed in Section 4.

In principle, the energy delivered to arc could be determined by measuring the arc voltage and the arc current as a function of time and then integrating the product of voltage and current as a function of time. Typically this is not done since connecting voltage and current probes for the measurement can introduce enough added capacitance to upset the system.

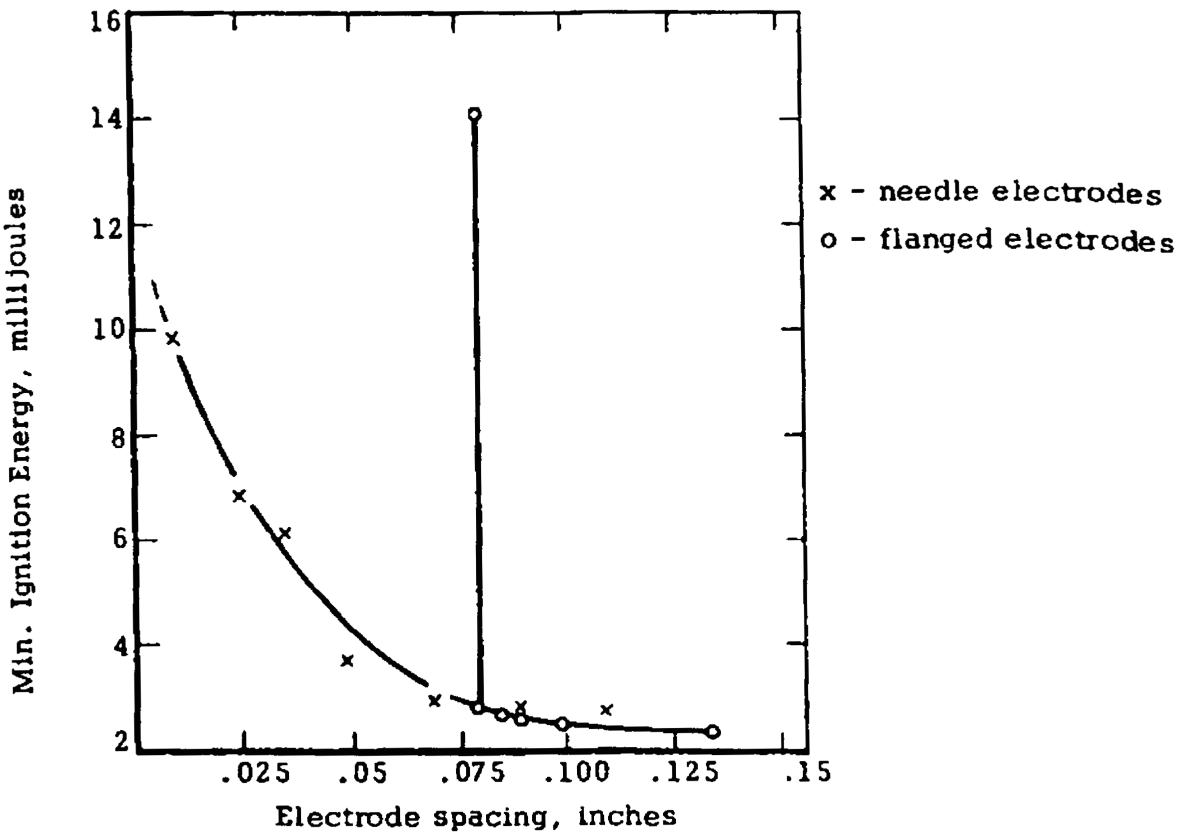

Figure 3-7 Variation of ignition energy with electrode spacing. [1]

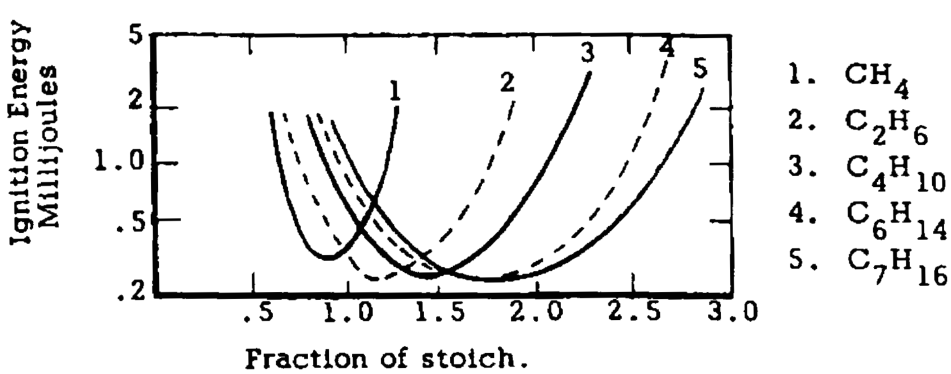

Figure 3-8 Critical ignition energy. [1]

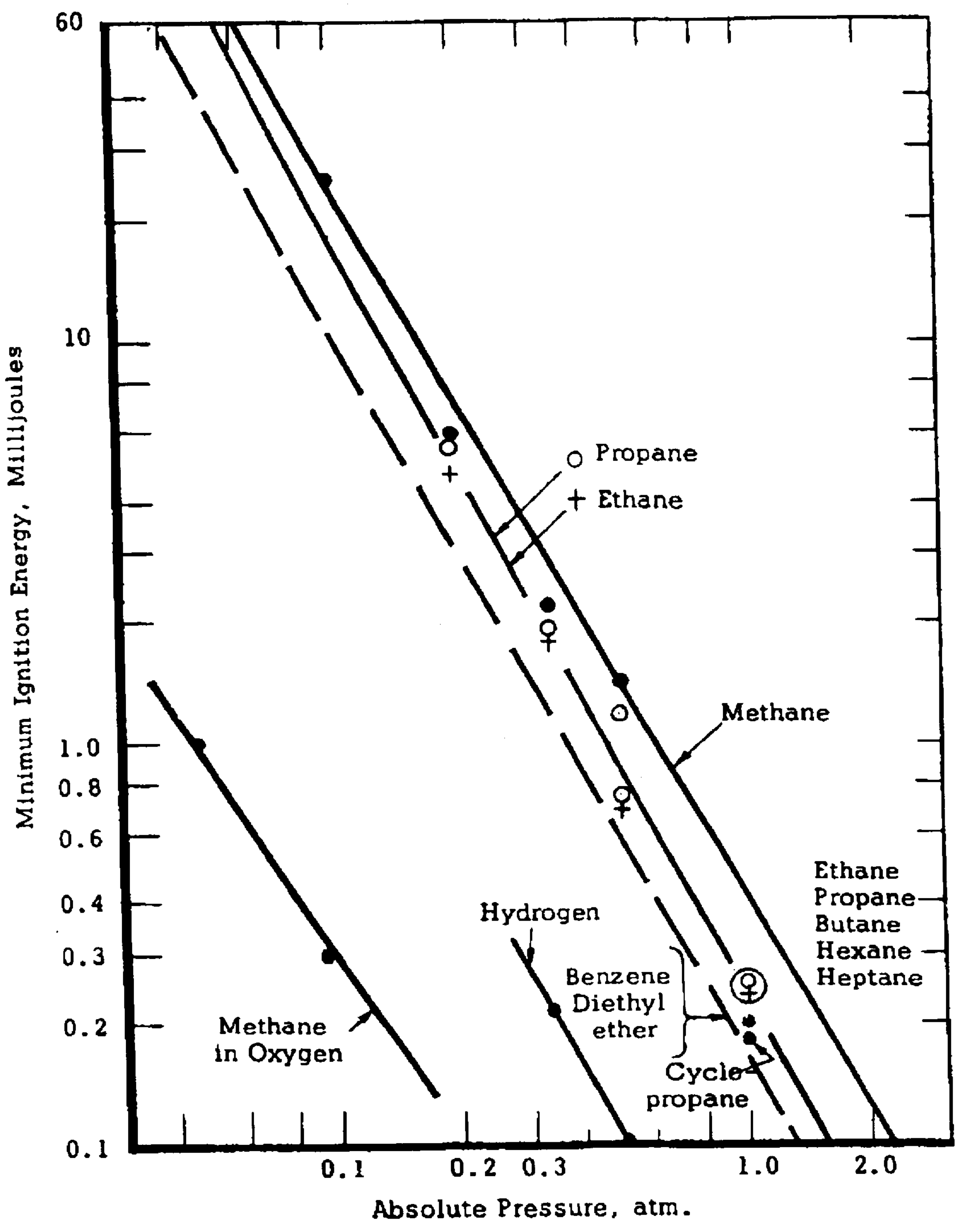

Figure 3-9 Relation of minimum ignition energy to static pressure for hydrocarbon fuels in air. [1]

4 IGNITION BY RF SOURCES

A reasonable question would be "What is the RF power level of devices that pose a risk of ignition of fuel-air mixtures"? As with the question of ignition temperature posed in Section 3, the answer must be "It depends ....."

Considerable work has been done relating RF power levels to probability of ignition, though mostly in relation to safety of industrial facilities, such as gas processing plants. Most of the developed safety regulations concerning such ignition hazards also pertain to industrial facilities. Also, most of the studies have been concerned either with frequencies less than 30 MHz or greater than 200 MHz. The vast majority of high power transmitters either transmit in the HF band at the lower frequencies, broadcasting stations for example, or above 200 MHz, TV transmitters or radar systems as examples. Little work seems to have been done regarding aircraft fuel systems or the types of PEDs, such as might be found in aircraft. The whole question of HIRF has become quite important in recent years as regards aircraft, but the concerns and studies have principally related to electromagnetic interference to communication and control equipment, not to ignition of aircraft fuels.

4.1 What Power is Being Considered?

Most work on ignition of fuel air mixtures has been done with single-spark discharges taking place between needle gaps, as discussed in Section 3.6. As discussed, there the energy figures cited for ignition refer to the energy initially stored in the test apparatus, not the energy actually delivered to the combustible mixture. A similar situation exists with RF sources; the power levels cited basically refer to the power level of the RF source, not the energy delivered to the ignition source. Also, the levels refer to RF power in watts, not energy in watt-seconds (or joules) actually delivered to the region where ignition takes place. Ignition requires that sufficient energy, units of which are watt-seconds or joules, be delivered to a region of the fuel-air mixture to raise the local temperature sufficiently. Watts, or joules per second, is a measure of power, energy per unit of time, and cannot be directly related to energy or ignition temperature.

More specifically, the power levels cited generally refer to the power capable of being delivered from some fixed source to a load of matched impedance. The source may be either a laboratory RF generator or some sort of antenna extracting energy from an electromagnetic field, which field in turn has been established by some external source, usually remote.

The point is illustrated on Figure 4-1(a), in which an RF source having a 50 ohm resistive source impedance is connected to a 50 ohm load. This is the maximum power transfer condition, one that delivers one half of the available power to the load, the rest being dissipated in the internal impedance of the source.

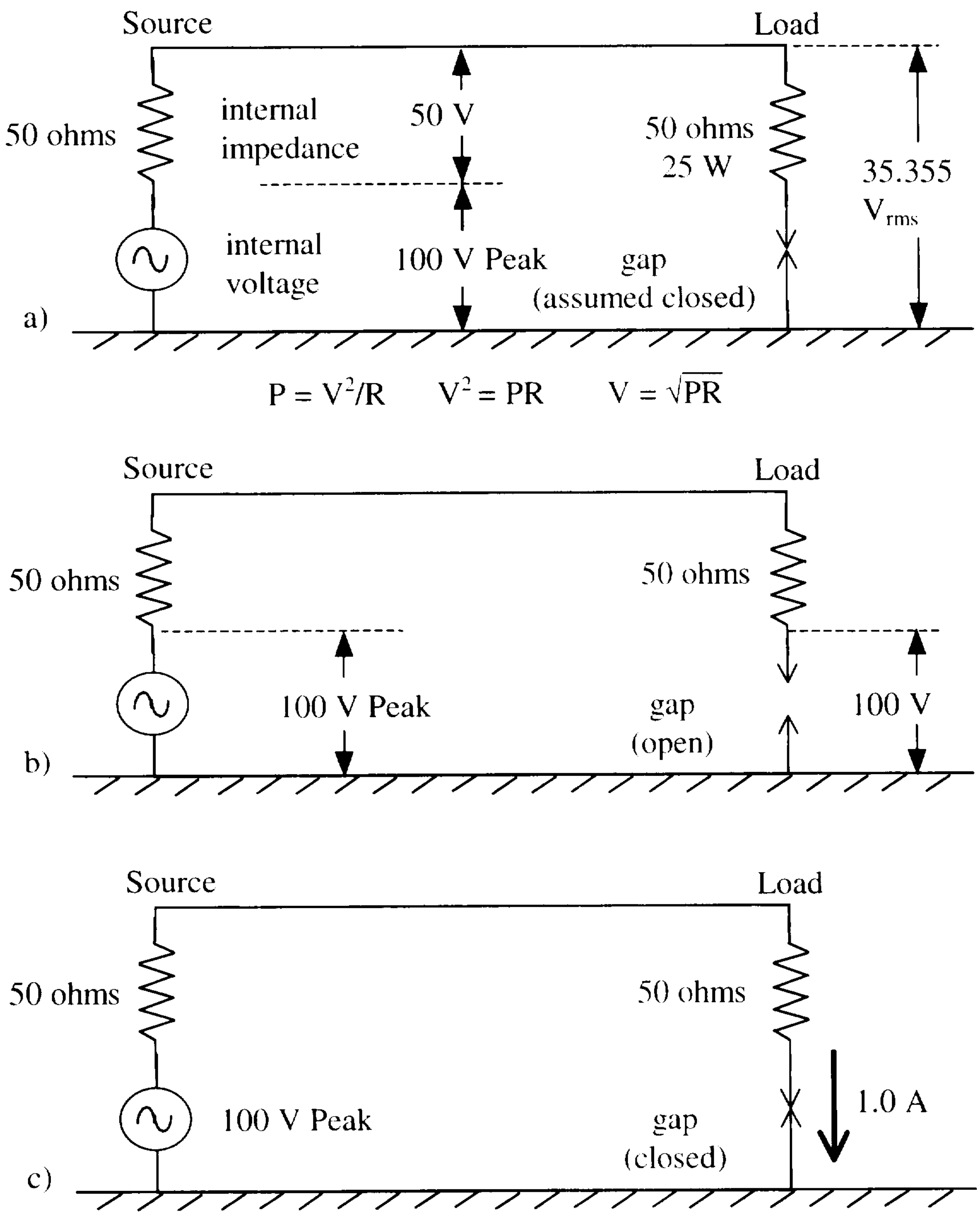

Figure 4-1 Power as Defined in RF Ignition Studies

(a) Power delivered to a matched load

(b) Open-circuit voltage

(c) Short-circuit current

Taking P = 25 watts to be delivered to the load, Z = 50, the voltage across the load is then 35.355 volts RMS or 50 volts peak.

$$V = \sqrt{PZ} \tag{4-1}$$

An equal voltage is developed across the internal impedance of the source, and since the internal voltage of the source is the sum of the two, the total internal voltage is 70.7 volts RMS or 100 volts peak.

In order to provide an ignition source, the RF generator must be connected to some sort of spark gap mechanism, such as an intermittently rubbing wire or the IEC break spark mechanism discussed in Section 3.5. Assuming the power level setting of the generator to be unchanged, a peak voltage of 100 volts would be available to create a spark when the gap mechanism opens the circuit. How much power is actually delivered to fuel mixture within the sparking contacts will be less than the power delivered to the matched load impedance. That power (or energy) could, in principle, be determined by measurement of spark voltage and current.

Studies of ignition by RF sources seem to relate the ignition probability to RF power levels observed on a matched load on the basis that such a power level is easily defined and seems to give a good correlation to observed ignition results, even though power in the matched load implies a condition in which no sparking is taking place. Since ignition must involve sparking or arcing, it might seem appropriate to also (or instead) discuss the nature of the source in terms of the open-circuit voltage and the short-circuit that the source can provide to a spark or arc should one occur. Open-circuit voltage is necessary for sparking to occur in the first place, and a certain amount of current is required to heat any resulting arc to ignition temperature.

A reference to a power level does provide a way to determine open-circuit voltage and short-circuit current in the event of arcing, but only if power level, load impedance and the existence of matched load are all cited together.

A major feature of sparking initiated from an RF source is that the sparking could be more or less continuous, unlike the single spark previously used in ignition studies. Whenever the contacts of the gap mechanism open, a spark can be developed and current could flow through the resulting spark for as long as the contacts remain parted, a time likely to be much longer than the duration of current flow during the single spark studies. Also, a train of sparks could be generated each time the gap opens. Sparks upon opening are emphasized here since it seems unlikely that sufficient voltage could be developed by RF coupling to initiate a spark across an initially open-circuit.

Laboratory RF generators are often constructed so as to provide an internal impedance of 50 ohms resistive, or can be fitted with matching networks or attenuators so as to provide an overall internal impedance of 50 ohms, or some other desired impedance.

Safety studies relating to possible ignition of fuels or vapors generally must consider the possibility of portions of structures acting as antennas and intercepting energy from a surrounding electromagnetic field. Examples of inadvertent antennas (the British term is adventitious antennas) are shown on Figure 4-2, these being inadvertent antenna systems such as might be found in an industrial facility. Antennas, intentional or otherwise, will have an impedance that depends on the physical construction of the antenna and on the frequency of operation. Safety studies and regulations commonly assume the antenna to be resonant at the frequency of the surrounding electromagnetic field, either by appropriate physical size or by being tuned to resonance with a loading capacitor or inductor.

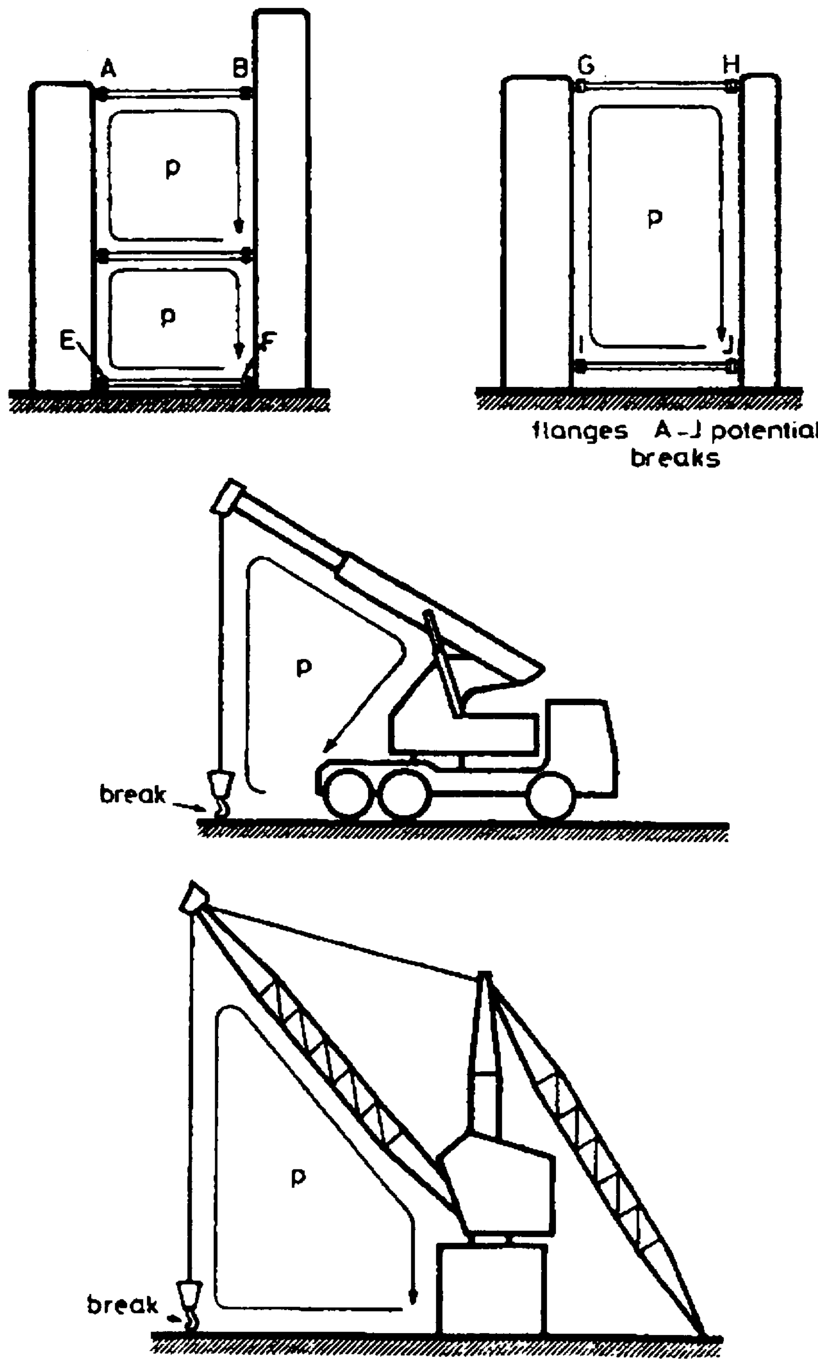

Figure 4-2 Possible Inadvertent Antennas. (From [4], Fig. 2, p. 609)

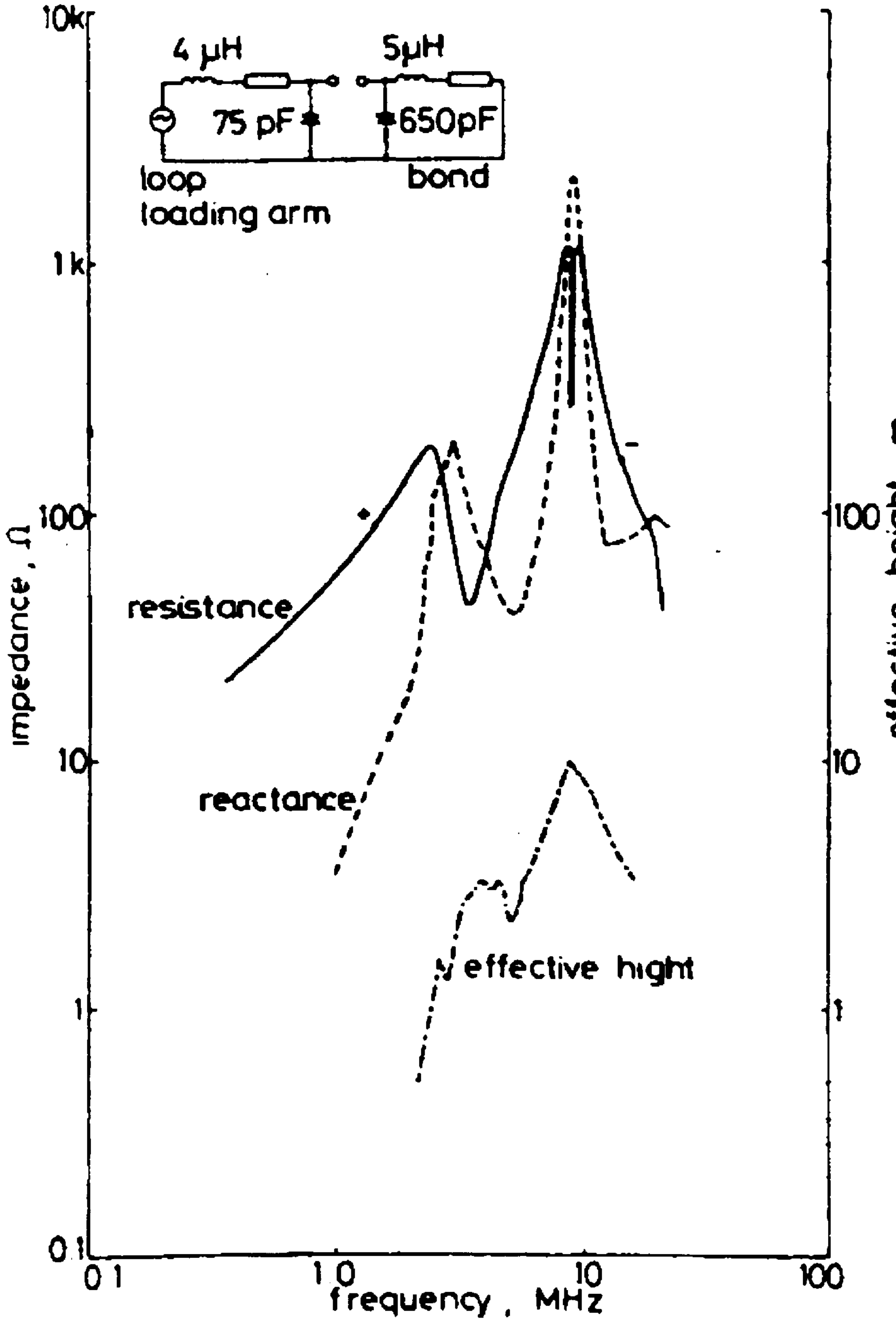

Figure 4-3 Impedance and Effective Height of an Inadvertent Antenna. (From [4], Fig. 1, p. 609)

As an elementary example, consider the vertical quarter wave dipole above a ground plane shown on Figure 4-4. At resonance, $l = \lambda/4$, such an antenna will have an input impedance of about 36 ohms resistive. The total power that can be extracted from an electromagnetic field by such an antenna is:

$$P = \frac{(Eh)^2}{R_l + R_r} \text{ Watts} \qquad (4\text{-}2)$$

where: E = electric field strength, volts per meter

h = effective antenna height, meters

R_l = load resistance, ohms

R_r = antenna radiation resistance, ohms

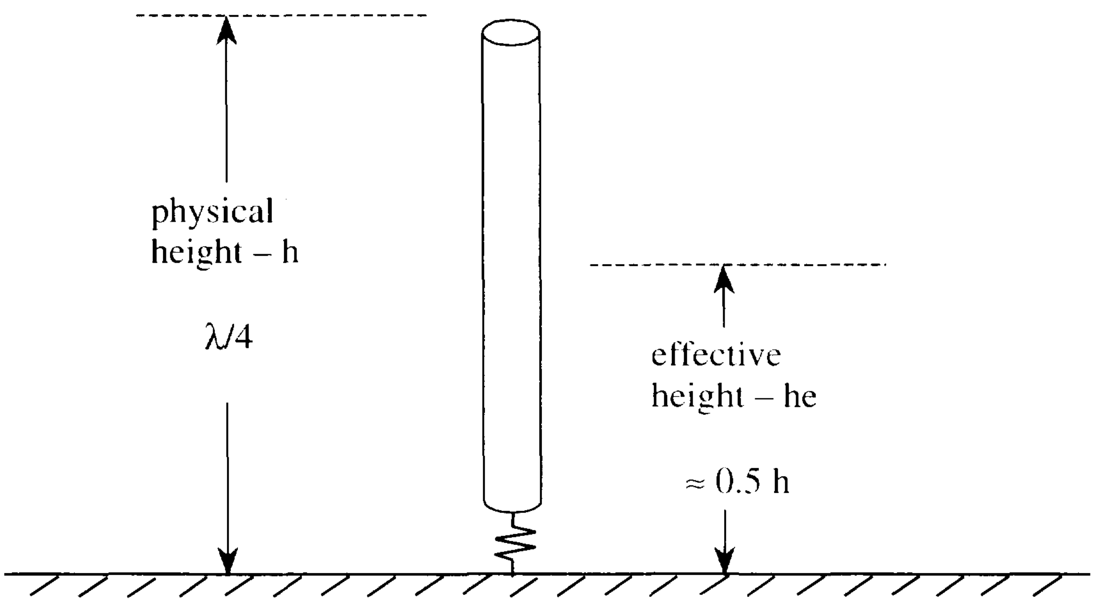

Figure 4-4 Vertical Quarter Wave Antenna Above a Ground Plane. [4]

The maximum power delivered to the load will occur when $R_l = R_r$. Given that the effective height is half the physical height and that half of the intercepted energy will be reradiated, the overall maximum power that can be delivered to the load will be

$$P = \frac{(El)^2}{16R_l} \text{ Watts} \qquad (4\text{-}3)$$

Taking, as an example, a vertical antenna 5 meters high exposed to an electromagnetic field of intensity E = 10 volts per meter and a frequency of 15 MHz (λ = 20 meters, $\lambda/4$ = 5 meters), the power delivered to a 36 ohm load would be 4.9 watts. The voltage developed across the load resistance would be 13.3 volts RMS, or 18.7 volts peak.

Vertical antennas having a resistive input impedance, at resonance, are unlikely to be encountered either in aircraft or industrial facilities. More commonly, an inadvertent antenna will be in the form of a loop, possibly tuned by stray capacitance. Impedance of such an antenna can be calculated, either from first principles or by use of various numerical techniques, or it can be measured with impedance analyzers. In any case, the impedance of the antenna is apt to have both a resistive and an inductive component, R + jX, the values of which vary considerably with frequency and will likely have a magnitude far different from 50 ohms. Figure 4-3 is an example from the literature. The maximum energy extractable from such an antenna occurs when the antenna is connected to a load having a conjugate impedance, R - jX. At any particular narrow band of frequencies the actual impedance of the antenna can be synthesized by a passive RLC network, as illustrated on Figure 4-3.

A review of the matter is beyond the scope of this document, but it should be noted that guidelines have been presented regarding the effective impedance and power gain of various types of antennas and the amount of power that can be extracted by such antennas and delivered to a matched load. Most of the published material has appeared in British publications and safety guides and most of that material has been concerned with industrial facilities, such as gas processing plants around the North Sea. None of the material reviewed so far has dealt with aircraft, aircraft fuels or the field levels likely to be developed by personal electronic devices likely to be found on aircraft.

4.2 Power Levels that Result in Ignition

Some of the published material relating to ignition as a function of power levels will be presented in the following sections. It must be emphasized again that:

a) The power levels cited refer to the power dissipated in a load resistance matched to the output impedance of an RF source, the load being connected in series with some sort of break spark mechanism.

b) The power levels cited do not refer to the power or energy delivered to the sparking contact or the fuel-air mixture in which the break spark mechanism is immersed.

c) Antennas may extract power from an electromagnetic field and deliver a portion of that power to a sparking contact, but the power levels cited do not refer to the power of some radiating device that generates the electromagnetic field.

4.3 Ignition From a 50 Ohm Source

Some examples of breakdown from a 50 ohm source are illustrated on Figure 4-5. Breakdown power levels seemed to be on the order of 20 - 30 watts at frequencies below 10 kHz and up to 50 - 300 watts at higher frequencies, with the results depending considerably on the fuel involved and the type of electrodes involved.

4.4 Ignition From Higher Impedance Sources

Examples of breakdown powers with higher impedance sources are shown on Figure 4-6 while data relating breakdown power to circuit Q is shown on Figure 4-7. Circuit Q can be related to circuit impedance. The breakdown powers were found to be on the order of 3 watts. Since higher impedance implies greater open-circuit voltage available to create sparking, the difference in power levels between high and low impedance circuits is understandable. A power level of 3 watts at an impedance level of 1500 ohms implies an open-circuit voltage from the source of 190 volts.

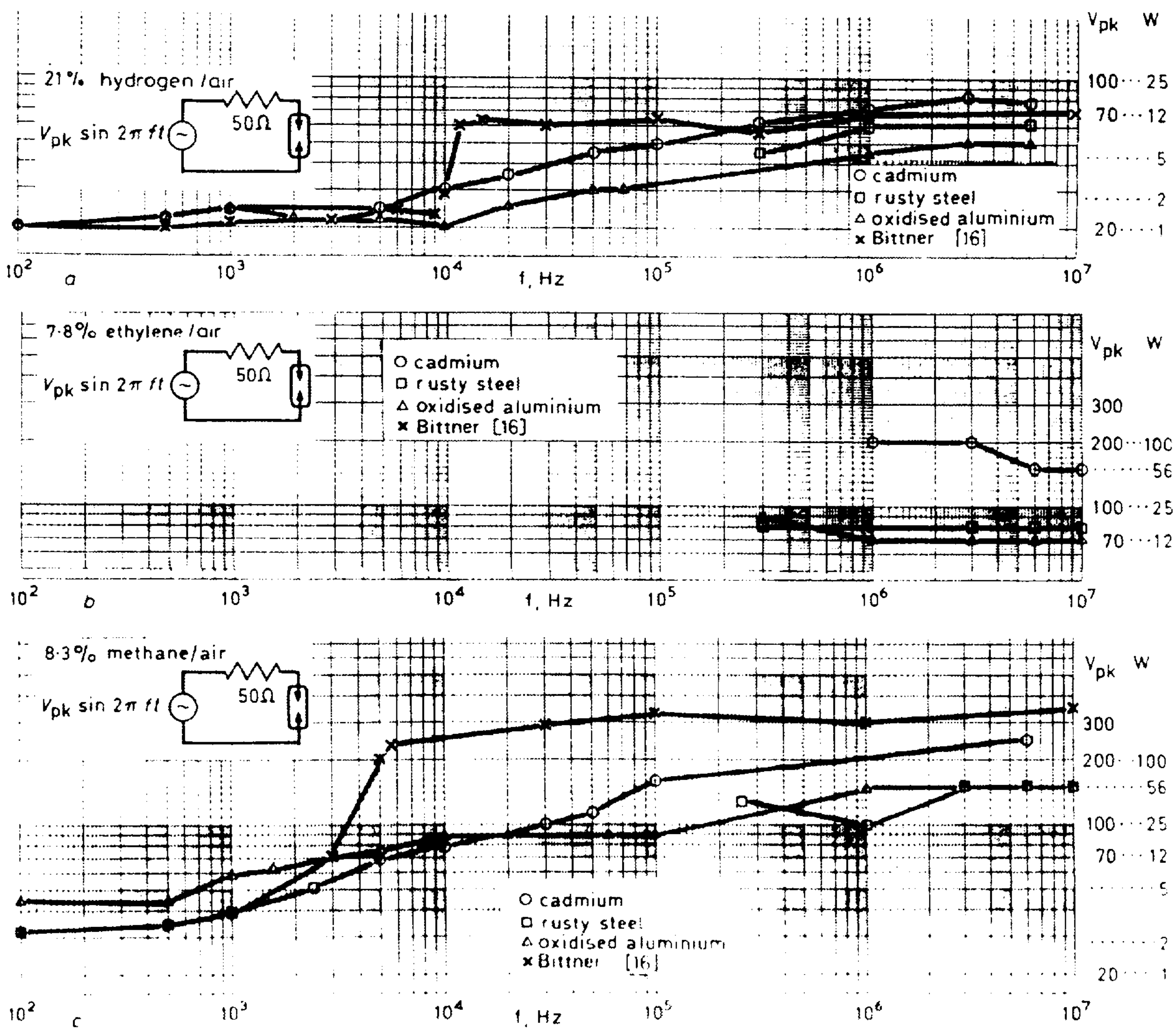

Figure 4-5 Breakdown Power Levels With 50 Ohm Sources. (From [4], Fig. 3, p. 612)

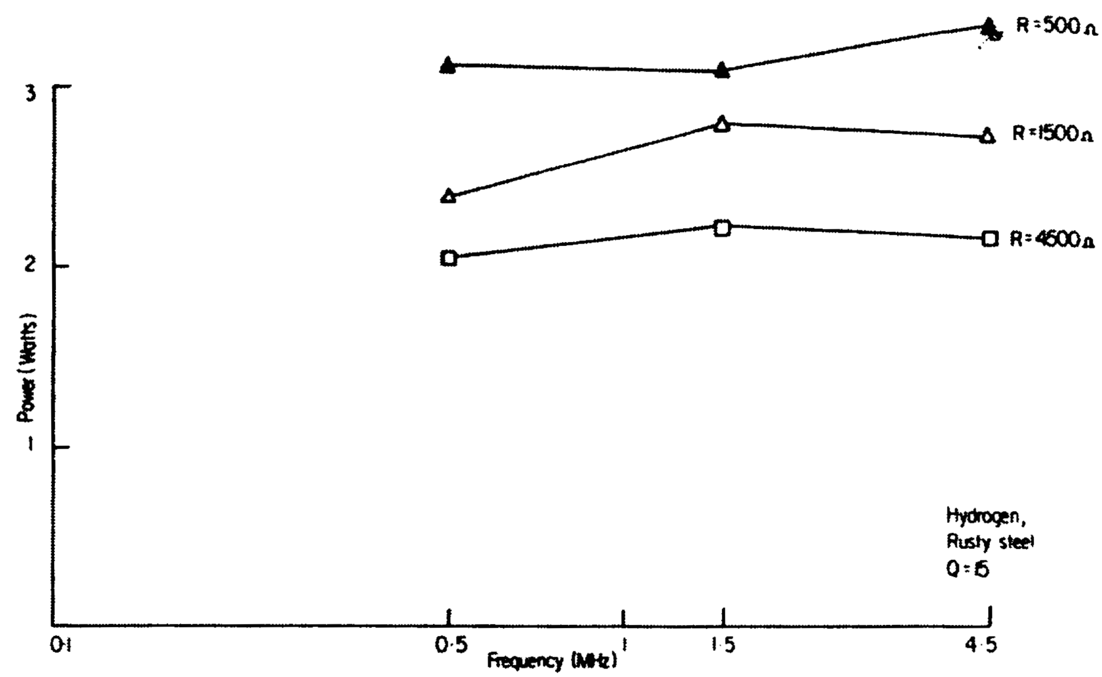

Figure 4-6: Power required for ignition of Hydrogen/Air mixtures as a function of frequency and source resistance for a given Q. (From [5], Fig. 3, p. 148.)

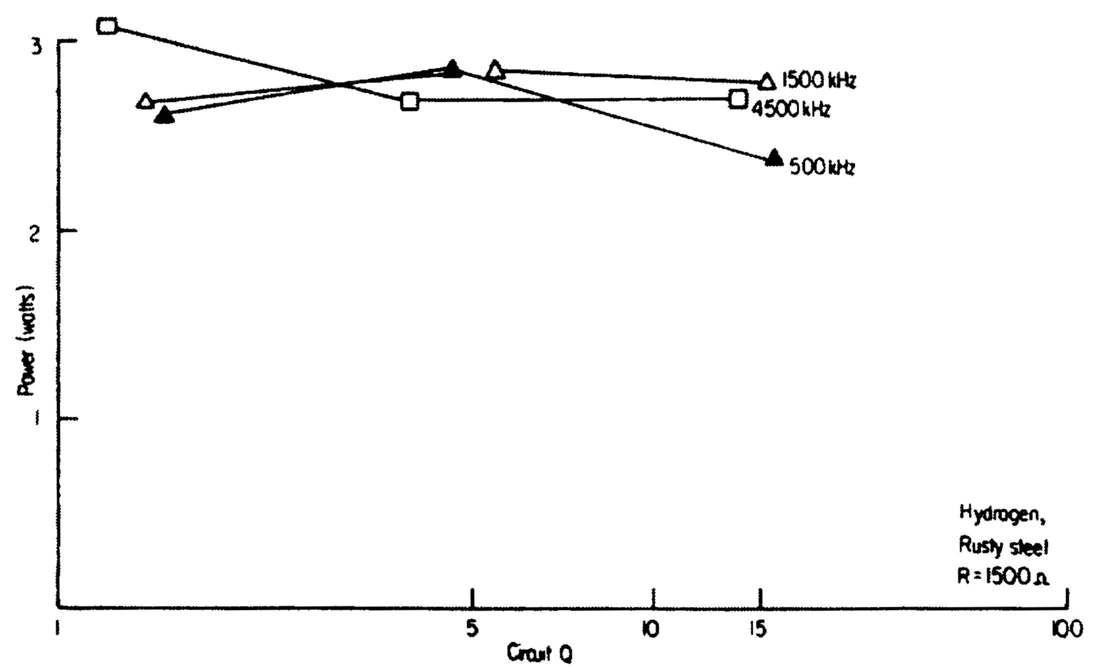

Figure 4-7: Power required for ignition of Hydrogen/Air mixtures as a function of circuit Q-factor for a source resistance of 1500 ohms. (From [5], Fig. 4)

5 OBSERVATIONS AND CONCLUSIONS

An overall conclusion from this brief review of the literature is that none of the studies cited in the literature dealt specifically with fuels used in aircraft and none of the inadvertent antennas cited as examples were particularly relevant to structures and circuits that might be found in aircraft. Guidelines and methods of attack cited in the studies might form the basis for similar guidelines for aircraft, but considerable work would have to be done to develop suitable guidelines.

One important task that would need to be done in order to develop such guidelines for aircraft would be to make a study of what circuits and components might constitute inadvertent antennas and then to evaluate the impedance characteristics of those antennas.

Another task would be to study the levels of electromagnetic fields likely to be encountered in aircraft when portable electronic devices (PEDs), or other sources of electromagnetic radiation are encountered. Some studies of this nature are, of course, presently underway.

A third task would be to develop methods of relating electromagnetic field levels in aircraft to the voltages or powers induced on such inadvertent antennas as might be found in aircraft. Antenna theory is well developed and numerical codes for analysis of RF coupling problems are in wide use, but the skills of those dealing with such matters need to be applied to problems in aircraft. One major difference between the aircraft environment and the environments that have been studied for industrial environments is that of the impedance level of the electromagnetic fields. The industrial environment basically relates to far-field radiation patterns and coupling equations. In an aircraft, near-field environments are apt to predominate, and simplified analysis of near-field coupling may not be practical.

Finally, there is little to suggest that data on ignition levels from high voltage sparking is particularly applicable to sparking from breaking contacts excited from an RF source.

One last point seems worth of note. Works relating to RF ignition and cited in the literature have mostly been conducted by Europeans, primarily British and German works. This fact may indicate that there is not a cadre of American investigators with much background in RF ignition problems.

One simple task that could be undertaken if such studies are to be pursued would be to obtain copies of all the works that have been cited in the literature and make them available to potential investigators. Many of the documents are in foreign journals not too readily available to those in areas remote from major urban or university libraries. This task could readily be assigned to a library service. The task would merely be to obtain copies of articles and books, not to review the articles or abstract the contents.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 2000	Technical Memorandum

4. TITLE AND SUBTITLE
Some Notes on Sparks and Ignition of Fuels

5. FUNDING NUMBERS
WU 522-14-21-51

6. AUTHOR(S)
Franklin A. Fisher

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17966

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2000-210077

11. SUPPLEMENTARY NOTES
Performance of this work by LTI fit the stated purpose of MOA SA #435 as a "cooperative research task to expand technologies related to aircraft protection from lightning and HIRF".

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 33   Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)
This report compliments a concurrent analysis of the electromagnetic field threat to the fuel system of a transport aircraft. The accompanying effort assessed currents, voltages and power levels that may be induced upon fuel tank wiring from radio transmitters (inside and outside the aircraft). In addition to this, it was also essential to determine how much voltage, current, or power is required to create a fuel-vapor ignition hazard. The widely accepted minimum guideline for aircraft fuel-vapor ignition is the application of a 0.2 millijoule energy level. However, when considering radio frequency (RF) sources, this guideline is seriously inadequate. This report endeavors to bridge the gap between a traditional understanding of electrical breakdown, heating and combustion; and supplement the knowledge with available information regarding aircraft fuel-vapor ignition by RF sources

14. SUBJECT TERMS
Fuel, vapor, ignition, arc, spark, RF, HIRF, radio, frequency, electromagnetic

15. NUMBER OF PAGES
40

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL