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Flight Line Grounding and Bonding of Aircraft

FOREWORD

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TABLE OF CONTENTS

1. SCOPE 2

2. REFERENCES 2

3. BASIC REQUIREMENTS 3

4. BASIS FOR AIRCRAFT GROUNDING 4

4.1 Electrostatic Theory 4
4.2 Energy Sources 5
4.2.1 Triboelectric Effects 5
4.2.2 Induced Charge 6
4.2.3 Friction 7
4.2.4 RF Electromagnetic Energy 9
4.2.5 Lightning 11
4.2.6 Summary 14
4.3 Other Physical Considerations 15
4.4 Airframe/Personnel Electrical Parameters 15
4.5 Damage Threshold Levels 17
4.6 Analysis 18
4.6.1 Source Magnitude 18
4.6.2 Time Duration Consideration 20
4.6.3 Hazards 21
4.6.4 Effects of Grounding 21

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1. SCOPE:

This ARP provides the rationale and theory of charges being present on aircraft while on the ground. The necessary implementation of safety practices are explained and defined.

2. REFERENCES:

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2. (Continued):

13. MIL-HDBK-274, EMCS Electrical Grounding for Aircraft Safety, November 1983.

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3. BASIC REQUIREMENTS:

Grounding is the process of connecting one or more metallic objects and ground conductors to ground electrodes. Bonding is the process of connecting two or more metallic objects together by means of a conductor. Bonding is done to equalize electrostatic potential between two or more conductive objects.

The generation of static electricity cannot be prevented entirely. Its generation is not in itself a hazard provided it can be dissipated safely. The hazard is encountered when changes accumulate to the extent that a spark discharge occurs to some other object in the presence of hazardous atmospheres, dusts, etc. Elimination of such potential hazards, therefore, requires proper grounding or neutralization of the charges to avoid dangerous accumulations.

A well-known example of static electricity is the discharge (sparking) of an accumulated charge built up on a person who has walked on a carpet in a dry room, and touches a metal door handle or radiator.

Further hazards may be encountered due to induced charges resulting from nearby lightning storms.

Aircraft shall be grounded at all times when they are parked. If a suitable ground is not available, aircraft will be bonded to servicing equipment during actual servicing. Perform grounding as follows:

a. A grounding wire will be connected between earth, i.e., ramp ground, or safety ground, and aircraft immediately after the aircraft is parked and should not be removed until just before the aircraft is moved.

   NOTE: A hazardous voltage may be on the aircraft before the ground wire is connected. To prevent a dangerous shock, the ground wire must be connected to the ground rod before making the connection to the aircraft.

b. Grounding wires for ground support equipment (GSE) may be connected to any approved ramp ground, and do not have to be connected to the same ground as the aircraft. See paragraphs 4.2.1 and 4.2.5.2 for recommended ground resistance.

3. (Continued):

c. The connection sequence for the preferred triangular method of grounding/bonding is as follows:

1. Connect grounding wire/cable to a ramp ground.

2. Connect other end of grounding wire/cable to aircraft grounding receptacle or grounding lug.

3. Connect ramp cart/refueler to a ramp ground.

4. Connect ramp cart/refueler to aircraft ground receptacle or grounding lug.

CAUTION: If an approved safety ground is not available for grounding the aircraft, use considerable caution if a thunderstorm is within 20 miles. Servicing and maintenance personnel can be exposed to potentially lethal electrical shocks under these conditions.

There is no way at the present time of predicting electrical discharge activity in clouds without extensive instrumentation and no way for maintenance supervisors to know when to bring personnel off aircraft because of incipient thunderstorm electrical activity. Therefore, it is recommended rather strongly that the only safe way to prevent serious shock hazard and possible fuel vapor ignition is to keep the aircraft continuously grounded.

4. BASIS FOR AIRCRAFT GROUNDING:

This section provides theory, background, and information necessary to understand the rationale behind the requirements for aircraft grounding and bonding. Theory and equations associated with both electrostatic charge generation in aircraft and grounding effects are discussed. The different aircraft servicing situations are introduced with emphasis on the hazards that can be encountered.

4.1 Electrostatic Theory:

Static electricity, by definition "electricity at rest," consists of opposite electrical charges that are usually kept apart by insulators. Potential differences involved may amount to thousands of volts. However, the flow of electricity during generation and accumulation is small, in the range of millionths of an ampere. A primary manifestation of static electricity is the discharge or sparking of the accumulated charges. Static electricity is generated by the separation of like or unlike bodies. Electrostatic charges, positive and negative, always occur in pairs. They become evident when these pairs, having been in contact with each other, are separated. For significant potential to be developed, the bodies holding the charges must become, and remain, insulated from each other. Insulation may occur through complete physical separation of the bodies or because at least one of the bodies is an insulator.

4.2 Energy Sources:

Evaluation of a situation's potential hazards is based on the source mechanism and the source magnitude of the electrical energy. With operations involving aircraft such as maintenance, fueling, and aircraft parking, the following energy sources must be considered:

a. Triboelectric
b. Induced
c. Friction
d. RF Electromagnetic Energy
e. Lightning

The sources listed above are defined and evaluated in the following paragraphs.

4.2.1 Triboelectric Effects: One type of charging mechanism that can create dangerous voltages on ungrounded aircraft is triboelectric effects. These effects are generally associated with the buildup of static charges on an aircraft in flight. High static voltages, however, can result from the interaction of various materials striking a parked aircraft. Wind-blown snow or dust particles are the usual objects responsible for this charge accumulation, commonly called precipitation static or p-static.

A conservative estimate of electrical current for a moderate wind-blown dust situation is 30 microamperes (μA). In an ungrounded aircraft, this current flows from earth to the snow, dust, etc., via the tires and airframe. Thus, the potential between airframe and earth is determined almost entirely by the tire resistance. The worst-case value of 40 megohms (MΩ) for tire resistance is used to compute an airframe potential of:

$$V = IR = (30\ \mu A)(40\ M\Omega) = 1200\ V \qquad \text{(Eq. 1)}$$

These charges will accumulate until a sufficient time to discharge has passed or a person touches the aircraft. Twelve hundred volts (1200 V) exceeds parameters for nonlethal shock to personnel, and could cause a reflex action resulting in injury to personnel.

Connecting the aircraft frame to an approved ground point provides a conductive path back to ground for the static charges as they are generated. A ground point is defined as having less than 300 ohms resistance to earth.

A helicopter exemplifies triboelectric effects. Static voltages of up to 10,000 V are normally generated by a hovering helicopter. In exceptional weather conditions, charges up to 200,000 V and greater have been recorded.

Personnel must use extreme care when approaching a hovering aircraft. Strict observance of the prescribed aircraft manual procedure will prevent the serious injury that is certain to occur if the aircraft is touched prior to grounding.

4.2.2 Induced Charge: Electrical storms involve the relatively slow movement of heavily charged clouds which set up an electrostatic field over a large area of the earth's surface below the cloud. The presence of an electrical field between an active storm cloud system and the earth results in large induced charges on parked aircraft. The negative charge in the cloud attracts a positive charge from the earth onto the aircraft via the tires. This charging usually occurs at a relatively slow rate which results in relatively small current flows that cause no damage to the aircraft. If a person is in contact with the plane throughout the charging period, i.e., as the charged cloud moves slowly overhead, he will probably feel no effect.

4.2.2.1 The situation becomes a potential hazard if a sudden change in the electric field takes place (e.g., a distant lightning strike discharging the overhead cloud). The earth's surface neutralizes more quickly than the ungrounded aircraft (due to the capacitance of the aircraft and the high resistance of the tires), resulting in potentials up to 60 kilovolts (kV) from airframe to ground. A person in contact with the aircraft during this change in the electrical field acts as a resistor connected to ground, facilitating another path to ground for the accumulated charges. This person will probably feel a sharp shock, the severity of which will depend on the extent to which the aircraft was originally charged. The current shock can result in injury to personnel in two different ways:

a. Involuntary reflex movements which can cause fatal or serious injury due to secondary effects, such as falling.

b. Electrical effects which result directly in injury.

4.2.2.2 A person in contact with an aircraft charged by induction to 60 kV could discharge 9 joules (J) of energy from the aircraft.

$$\begin{aligned} U &= 1/2\ CV^2 \\ &= 1/2\ (0.005\ \mu F)\ (60\ kV)^2 \\ &= 9J \end{aligned} \quad \text{(Eq. 2)}$$

This level well exceeds the threshold value for lethal shock and could be fatal. To further analyze potential hazards:

$$t = RC\ln\left(\frac{E_i}{E_s}\right) \quad \text{(Eq. 3)}$$

4.2.2.2 (Continued):

where:

t = time to reach E_S after removal of source
R = aircraft resistance to ground (Ω)
C = aircraft capacitance to ground (F)
E_i = initial (source) voltage (V)
E_S = safe voltage level (V)

Using the ungrounded aircraft resistance of 40 MΩ an aircraft capacitance to ground of 0.005 microfarad (μF), a safe voltage limit of less than 30 V, and 60 kV as the initial voltage.

$$t = (40\ \text{M}\Omega)\ (0.005\ \mu\text{F})\ \ln\left(\frac{60\ \text{kV}}{30}\right) \quad \text{(Eq. 4)}$$

$$= 1.52\ \text{seconds}$$

A person making contact with the aircraft may well shorten the discharge time somewhat. However, heart discoordination (fibrillation) threshold levels have time durations as low as 0.2 second, a fact that makes the 1.52-second discharge time very dangerous and unacceptable.

4.2.3 Friction: Static electricity is generated when certain materials rub together. During such close moving contact between two materials, one of the materials is depleted of electrons, causing a surplus in the second. The magnitude of the static electrical charge thus produced depends on the materials involved and on the amount of humidity present during such friction. With synthetic materials (such as nylon) undergoing friction in a cold, dry climate, the effect is greater.

4.2.3.1 Static electricity is generated on clothing by friction, especially by the action of removing garments. There is also a continuous generation of charges in the garments of a moving clothed person. The total amounts of charge at any time will depend on the rate of charge production and the rate of charge decay. If a person rubs against external objects, charges can be produced on the outside of the garments; otherwise, the charges will be produced within the clothing.

4.2.3.2 It is generally considered that all parts of the skin are sufficiently moist to allow only negligible amounts of charge to be formed between the skin and the garment next to the skin. Provided a person does not remove any garments, the only effect of the charged clothing can be to cause an attraction between the layers (since opposite charges attract) or for the clothing to cling to the body.

4.2.3.3 However, if a person removes the outer garments, a charge of up to 27,000 V can reside on the outside surface of the newly exposed clothing. The positive charge on a wool sweater and the negative charge on a parka are available for “static effects.” The opposite charges on the sweater and parka may easily produce a spark from one to the other.

4.2.3.4 The 27 kV value is used herein as representative of the worst-case static electricity friction hazard levels produced by servicing personnel. Using $U = 1/2\ CV^2$ with C = 500 pF (picofarads) for body capacitance, the amount of available energy is 0.18 J. This is well above the threshold levels for fuel vapor ignition, component damage, and reflex action shock.

4.2.3.5 Fuel Flow: During the fueling process, the passage of fuel from the supply vehicle through the fueling hose to the aircraft provides the mechanism for a recurring electrostatic energy source. The friction effect between the moving fuel and fuel filter, hose, and other surfaces results in charge separation and a consequent buildup of electrostatic charges. Since fuel is normally an excellent insulator, separated charges are easily removed by the flowing fuel to a distant location. If no electrically conductive return path is available, the charge accumulates on metallic surfaces and represents a high potential energy. As the accumulation of charge continues, sufficient electrical potential is generated to cause an arc across insulating barriers. These voltages build up within the aircraft fuel tank and represent a serious danger. If these voltages arc over to points of lower potential when the right fuel-air vapor mixture is present, an explosion will occur. Bonding the aircraft frame to the fuel supply vehicle provides a method of dissipating these high voltages. Bonding does not prevent the generation of high voltages within the fuel hose and the fuel tank, but provides a return path for the accumulated charges as contact is made with the inside fuel tank surface.

4.2.3.6 Studies by Naval Research Laboratory (NRL), German Air Force, United States Air Force (USAF), and others have provided data on the magnitude of voltages and current which might be encountered during the fueling process. Field strengths generated by this process may range to 500 kilovolts/meter (kV/m); thus, at a centimeter distance, a 5 kV potential may be present. The 500 kV/m field is normally confined to the fuel tank interior. However, depending on the locations of the separated charges and the degree of electrical isolation of the aircraft, fields of this intensity may appear on the exterior as charge bleed-off occurs. The resulting voltage on the exterior of the tank is dependent on the physical configuration and could reach breakdown or arcing level near sharp edges. Measurements after fueling aircraft have provided values of 2.5 kV.

4.2.3.7 A person in contact with an aircraft charges by induction to 2.5 kV could discharge 15.6 millijoules (mJ) of energy from the aircraft.

$$U = 1/2\, CV^2$$

$$= 1/2\ (0.005\ \mu F)\ (2.5\ kV)^2 \qquad \text{(Eq. 5)}$$

$$= 15.6\ mJ$$

This level well exceeds the threshold value for reflex shock reaction. To further analyze potential hazards:

$$t = RC \ln\left(\frac{E_i}{E_s}\right) \qquad \text{(Eq. 6)}$$

where:

t = time to reach E_s after removal of source
R = aircraft resistance to ground (Ω)
C = aircraft capacitance to ground (μF)
E_i = initial (source) voltage (V)
E_s = safe voltage level (V)

Using the ungrounded aircraft resistance of 40 MΩ, an aircraft capacitance to ground of 0.005 μF, a safe voltage limit of less than 30 V, and 2.5 kV as the initial voltage.

$$t = (40\ M\Omega)\ (0.005\ \mu F) \ln\left(\frac{2.5\ kV}{30}\right) \qquad \text{(Eq. 7)}$$

$$= 0.88\ \text{second}$$

Heart discoordination (fibrillation) threshold levels have time durations as low as 0.2 second, which makes the 0.88 second discharge time very dangerous and unacceptable.

4.2.4 RF Electromagnetic Energy: Today's environment has many unintended side effects caused by radio frequency (rf) transmitting devices used in conjunction with flight operations. Of concern are those high power communication and radar transmitters which may be located near parked aircraft. An aircraft also may be affected by an adjacent aircraft whose onboard communication system or radar transmitters are being tested.

4.2.4.1 The principal problem is the amount of rf energy which is induced into the aircraft frame and circulated on the aircraft skin. This quantity or level of rf energy is greatly affected by the position of the aircraft relative to a particular rf transmitter, the power output of that transmitter, and the actual frequency of the rf energy being transmitted. It is further affected by the actual location of any connections between the aircraft and ground. Where the position of one ground may have a significant effect on the induced current, other ground connections from different locations on the aircraft to other ground locations may not have the same effect. Any existing aircraft grounding schemes should not be altered in an effort to provide the aircraft with additional protection against rf energy. If the ground connection is broken while the rf transmission is in progress, an electrical arc may be drawn out. This is an important fact to note. If an arc is produced while disconnecting a ground, the source may be rf energy, caused by a local transmitter and the current flow can be high. (A power line short circuit to ground may also produce an arc when the ground is disconnected.) If on the other hand, an arc is drawn while a ground is being attached to the aircraft, the source is static electricity and the current flow will be light.

4.2.4.2 RF arcing is not limited to aircraft only. In high rf fields, arcs generally occur at the discontinuities in conductors (conductor meaning any metal surface). A discontinuity is any place where the nature of the conductor changes. Examples of this include gaps between metal surfaces and places where the type of metal changes or the thickness of the metal changes.

4.2.4.3 Another factor which has an influence on the occurrence of rf arcing is the actual physical dimensions of the metal surface. Not all conductors within an rf field are susceptible to arcing at their discontinuities. Objects which are large with respect to a wavelength (several wavelengths in each direction perpendicular to the line of transmission) tend to reflect the rf energy and are less apt to produce arcing. Objects which are long in one dimension but not in the other tend to be a more favorable site for arcing.

4.2.4.4 RF arcing can be separated into two categories: rf glow discharges and rf arc discharges. In rf glow discharges, a high minimum voltage is necessary to maintain the discharge. The voltage rises linearly to an ignition voltage of 350 V to 500 V, then descreases slightly after the current flow begins. The current flow ceases when the field can no longer sustain the high voltage. Even at very small separations between elements, a minimum voltage of 275 V is necessary to sustain the glow.

4.2.4.5 Conversely, rf arc discharges are sustained at relatively low voltages. The events leading to the formation of the arc plasma are similar to those of glow discharge. However, once the arc plasma forms, the voltage can usually drop as low as 30 V without the arc extinguishing.

4.2.5 Lightning: Lightning is a discharge of atmospheric electricity from one cloud to another, within a cloud, or from a cloud to earth. Table 1 provides a listing of lightning characteristics. The cloud to earth or ground strike is the type of discharge that produces the direct lightning strike. Due to its large amount of energy and potential for destruction, the direct lightning strike is one source of energy that can be very dangerous to personnel and aircraft. A direct lightning strike can damage an aircraft and its equipment. Voltages as high as 500 kV and currents to 200 kiloamperes (kA) have been known to occur.

TABLE 1 - Lightning Characteristics

Characteristic	Specification
Types	Intra/intracloud Cloud-ground Positive Negative
Potential	30-100 million volts
Current	20-200 kA (peak)
Power	10^{12} W nominal (peak)
Energy	5×10^{8} J nominal (200 lb. TNT equivalent per strike)
Extent	3-30 km/strike (path is predominately horizontal)
Spectrum	Peak energy near 10 kHz, some above 10 MHz
Duration	Strike - 100 µs Flash - 0.2 second (1-20 strikes)

4.2.5.1 These high levels could puncture the aircraft if the skin is not sufficiently thick or could possibly cause localized melting. Damage to the aircraft's electronic equipment or ignition of the fuel tank could occur, depending on the location of the strike.

4.2.5.2 A person in contact with the ungrounded aircraft during a direct lightning strike risks death or severe injury. For personnel who wear communication headsets the possibility of occurrence and the severity of injury increase.

The area around an ungrounded aircraft can be extremely hazardous when lightning strikes take place within 20 miles of an aircraft servicing site. These nearby lightning strikes can induce voltages up to 60,000 volts, on an ungrounded aircraft or large GSE. These voltages are potentially lethal, and have caused fatalities. To minimize the problem, the ground rod resistance should preferably be 25 ohms or less; but should not be greater than 300 ohms.

When an electrical discharge occurs in the cloud or from cloud to ground the charge induced in the aircraft is suddenly released. This release of charge from the aircraft capacitance of 500 to 1500 picofarads will have an effective source potential of 30,000 to 100,000 volts and will be equivalent to small impulse voltage generators with these voltage and capacity parameters suddenly fired into the aircraft to be discharged through the tires to ground or through any person or object touching the aircraft. Although we do not know how frequently this happens because of the general problem of ground maintenance personnel not knowing the source of shocks they receive (shocks often erroneously attributed to the aircraft electrical system) it happens sufficiently often that requests have been made as to solutions to this problem. Shocks serious enough to stop breathing have been reported.

4.2.5.3 A typical discharge between cloud and ground starts in the cloud and eventually neutralizes tens of Coulombs of negative cloud charges. The total discharge is called a flash and lasts about 1/2 second. A flash is made up of various discharge components, among which an average of three or four high-current pulses occur, called strokes, and a possible continuing current stage. In the idealized model, electrical storms cause the clouds to acquire a negative charge. The earth, or in this case the aircraft, has an opposite charge and lightning occurs when the electric potential overcomes the insulation in the air.

4.2.5.4 The breakdown within the cloud produces what is called a stepped leader. The leader starts from the cloud and heads toward the ground. The leader advances in a series of rapid discontinuous steps each about 50 meters (m) long and separated by pauses of about 50 µs. The luminous diameter of the stepped leader is between 1 and 10 m, although it is thought that the leader current of about 100 amps flows in a small diameter core at its center. The average propagation velocity is about 10^5 m/s. It looks like a column of light with branches emanating from the sides. The electric potential of the leader channel with respect to the ground is about -1×10^8 V. As the leader tip nears ground or aircraft, the electric field beneath it becomes very large and causes one or more upward-moving discharges which start the attachment process. When one of the upward-moving discharges from the ground contacts the downward-moving leader, the leader tip is connected to ground or aircraft potential. The leader channel is then discharged into the aircraft. The height of the aircraft affects the probability of this happening. The taller the aircraft the more likely it is to happen. Thus, by locally compressing the field, there are more likely to be points where the discharge takes place.

4.2.5.5 Intracloud and intercloud lightning discharges occur between positive and negative cloud charges and have total durations about equal to those of ground discharges (1/2 second). A typical cloud discharge neutralizes 10 to 30 Coulombs (C) of charge over a total path length of 5 to 10 km.

4.2.5.6 Cloud discharges have not been studied as extensively as discharges to ground, and hence much less is known about their detailed physical characteristics. The charge motion produces electric fields whose frequency spectra have roughly the same amplitude distribution as those of ground discharges for frequencies below about 1 kHz and above 100 kHz. Between 1 and 100 kHz, the ground discharge is a more efficient radiator.

4.2.5.7 Energy levels of near strikes can be sufficiently high to damage electronic equipment, again, depending on the location of the strike. Distant lightning strikes and lightning from one cloud to another will also charge an aircraft. Grounding will not keep these induced charges from accumulating on an aircraft, but will reduce the amount of time required to bleed off the charge.

4.2.5.8 The most important parameters of the current waveform are peak current, rate of rise, total duration, charge transferred, and action integral (i2dt). The units of action integral are amp^2 second which may alternatively be expressed in units of joules per ohm since the action integral is proportional to the energy dissipated in a given resistance.

4.2.5.9 The charge transfer, Q, is defined as the integral of the time-varying current over its entire duration, or

$$Q = \int_{O}^{T} i(t)dt \text{ (ampere-seconds or Coulombs)} \qquad \text{(Eq. 8)}$$

and is equivalent to the area beneath the current waveform.

4.2.5.10 The action integral of a current waveform is a measure of the ability of the current to deliver energy and is defined as the integral of the square of the time-varying current over its entire duration.

$$\int_{O}^{T} i(t)^2 \, dt \text{ (ampere}^2\text{-seconds)} \qquad \text{(Eq. 9)}$$

4.2.5.11 Grounding an aircraft offers some protection against lightning, even a direct strike. A major direct lightning strike usually is preceded by less powerful leaders which determine the direction of the main strike. Grounds can control the direction of the leaders away from the tires and consequently control the direction of the main strike. In addition, if a direct strike occurs, the ground wire may vaporize contributing to the conductivity of the ionized path, and thereby minimizing leakage currents through nearby personnel.

An important point here is that it is necessary to connect the aircraft to earth, as opposed to something like a tie down ring that is only embedded in the concrete. If the lightning has to travel through concrete to get to earth, it will often vaporize the water in the concrete, causing the concrete to explode. The fragments can really ding an airplane. A simple ground rod passes the lightning through the concrete and avoids this problem.

4.2.5.12 Lightning discharge through an aircraft to earth is an extremely variable phenomenon. Voltages as high as 0.5 million volts and currents from 200 to 200,000 amps are cited in the literature. At such high levels, grounding will not afford the degree of protection or confidence factor attained for static electricity protection. Nevertheless, a safety ground will aid in protecting personnel and equipment to some extent, especially for the low energy strikes.

4.2.6 Summary: In summary, the levels of electrostatic and electrical energies considered are given in Table 2.

TABLE 2 - Summary of Electrical Energy Source

Triboelectric	---	0.03 mA
Fuel Flow	2.5 kV	0.013 mA
Induced Charge	60 kV	---
Friction	27 kV	---
Ground Power Fault	220 V	200 A
RF Induced	No Established Values	No Established Values
Lightning	500 kV	200 kA

4.3 Other Physical Considerations:

Regardless of energy sources, no fuel ignition hazard is present unless there is a specific fuel-air vapor mixture present. Fuel spills are quite common and provide the necessary vapor source. Since an aviation gasoline, JP-4, or JP-8 vapor mix vary from too rich at the point of the spill to too lean at some distant point, the proper mix for ignition will be present between these points. A second source of vapor is vented from fixed-volume tanks during the fueling process. Again, this vapor is leaned by mixing with air until an explosive mix is reached, possibly at some point external to the fuel tank. These considerations establish that a dangerous fuel-air vapor mix may be present on occasion.

4.3.1 A second consideration is the type of fuel used. JP-4 is considered more hazardous than JP-5 due to the lower flashpoint of JP-4. The possibility of JP-4 being present as fuel vapor greatly increases the potential hazard. In addition, the practice of switch loading (the mixing of two different types of fuel during fueling or defueling operations) often results in a mixture more dangerous than either type individually, further increasing the risks during the fueling operation.

4.3.2 As used herein, electrical grounding is the provision of a conductive path between the airframe and ground or between the refueling vehicle and ground. Bonding is the provision of a conductive path between the airframe and the refueling vehicle. In the case where grounding and bonding are both used, a triangular system is established with electrical paths between the ground point, the vehicle, and the airframe. In the triangle system, the ground path supplies a backup or alternate path in parallel with the bonding cable. This alternate path is valuable since cables are often connected to painted, corroded, or nonconductive composite material surfaces or to isolated metallic components. In each such case, it is doubtful that bonding is adequate. The use of proper electrical grounding is vital in such situations in order to provide a dependable alternate path for electrical current and ensure safe operation.

4.3.3 A more common concern is the use of asphalt (blacktop) as an aircraft parking apron surface. While somewhat variable, this material generally provides a high level of insulation and, therefore, presents a potential hazard if positive grounds are lacking.

4.4 Airframe/Personnel Electrical Parameters:

When energy sources are considered in terms of voltages or current, the electrical characteristics (i.e., tire resistance to ground and airframe capacitance to ground) are required to establish time duration and other parametric relationships (e.g., current to voltage and current or voltage to total energy). Airframe electrical parameters interact with charge generation mechanisms and thereby establish the actual hazard levels and time duration for these hazards. Airframe capacitance to earth and airframe resistance to earth are most relevant. Capacitance establishes the total charges stored due to a particular potential and the time factor required to dissipate a charge from a surface through a particular resistance. Resistance establishes the voltage associated with known current flows and the time factor for charge reduction when the capacitance is known. Resistance was found to be the more variable parameter.

4.4.1 The ability of a body to store electrostatic charge is determined by the capacitance of that body. The amount of charge that can be stored on a capacitor is expressed by the mathematical expression

$$Q = CV \quad \text{(Eq. 10)}$$

where Q is the amount of charge (in Coulombs), C is the capacitance of the body (in farads), and V is the voltage (in volts) developed between the plates of the capacitor. The rate at which the capacitor charges or discharges is determined by the electrical resistance, R (in ohms), through which the capacitor charges or discharges.

4.4.2 Aircraft in their normal environment have electrical properties similar to resistors and capacitors. The resistance is usually determined by tires, mooring chains, or static ground straps.

4.4.3 Aircraft resistance is affected by both the resistances of its tires and runway surface and also by the contact between the tires and the surface. Tire resistance is a highly variable parameter. As a tire wears, its resistance increases due to the breaking of the carbon black chains.

4.4.4 The load on the aircraft and the pressure of the tire affect the resistance of the aircraft by affecting the tires' contact with ground. Increasing tire pressure increases resistance, and increasing load decreases resistance. Laboratory measurements have indicated tire resistances as high as 3400 MΩ.

4.4.5 Finally, the material of the runway is a factor in the resistance of the aircraft to the ground. Dry asphalt has an exceedingly high resistance, while snow and water on surfaces decrease the resistance. Field measurements have measured total aircraft resistance to ground as high as 40 MΩ.

4.4.6 The capacitance of aircraft was found to be a more consistent parameter. Values of 0.002 to 0.005 µF were measured over a wide range of aircraft types and ground plane materials.

4.4.7 In addition to the characteristics of the aircraft, the values of human body electrical parameters are needed. Values of 500 pF capacitance and 50 to 1500 ohms resistance are representative values for description/discussion purposes. The pertinent electrical characteristics are summarized in Table 3.