



AEROSPACE INFORMATION REPORT

AIR6127™

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Managing Higher Voltages in Aerospace Electrical Systems

RATIONALE

This SAE Aerospace Information Report (AIR) considers ways of managing high voltages in aerospace vehicles. This document provides a basis for identifying high voltage design risks, defines areas of concern as a function of environment, potential risk mitigation methods and test and evaluation techniques.

AIR6127 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This SAE Aerospace Information Report (AIR) considers the issue of proper design guidance for high voltage electrical systems used in aerospace applications. This document is focused on electrical discharge mechanisms including partial discharge and does not address personnel safety. Key areas of concern when using high voltage in aerospace applications are power conversion devices, electrical machines, connectors and cabling/wiring. The interaction between components and subsystems will be discussed.

The AIR is intended for application to high voltage systems used in aerospace vehicles operating to a maximum altitude of 30000 m (approximately 100000 feet), and maximum operating voltages of below 1500 VRMS (AC)/1500 V peak (DC). These upper voltage limits have been incorporated because this report focuses on extending the operating voltage of non-propulsive electrical systems beyond that of existing aerospace systems. It is noted that electrical systems for electrical propulsion may consider operating voltages beyond 1500 VAC/DC.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

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2.2 Definitions

2.2.1 DISRUPTIVE DISCHARGE

The passage of an arc following dielectric breakdown.

2.2.2 PARTIAL DISCHARGE

An electrical discharge that only partially bridges the insulation between conductors.

2.2.3 TRACKING

The progressive formation of conductive paths, which are produced on the surface or within a solid insulating material, due to the combined effects of electric stress and electrolytic contamination.

2.2.4 ARC

Self-maintained gas conduction for which most of the charge carriers are electrons supplied by primary electron emission.

2.2.5 CORONA

A type of partial discharge in a gas, immediately adjacent to an uninsulated or lightly insulated conductor which creates a highly divergent field remote from other conductors.

2.2.6 HIGH VOLTAGE

Any voltage above that which can cause partial or disruptive discharges in air, typically about 300 V peak.

2.3 Glossary

AC	Alternating current
AIR	Aerospace Information Report
ASTM	American Society for Testing and Materials
BAR	Metric unit of pressure
C	Celsius
DC	Direct current
EMI	Electromagnetic Interference
ft	feet
IEC	International Electrotechnical Commission
IPC	Global electronics trade organization
HV	High-voltage
Hz	Hertz
kHz	Kilo-hertz
MHz	Mega-hertz
kV	Kilo-volt
kVA	Kilo-volt-amps

m	meters
MEMS	Microelectromechanical systems
Pa-m	Pascal-meter
PCB	Printed Circuit boards
PDIV	Partial Discharge Inception Voltage
PDEV	Partial Discharge Extinction Voltage
PWM	Pulse-width modulation
RF	Radio Frequency
RMS	Root-mean-square
V	Volt
VDC	Voltage-Direct current

3. ELECTRICAL DISCHARGES IN AEROSPACE HIGH VOLTAGE SYSTEMS

It is known that electrical and electronic equipment used in aircraft applications must be designed to operate over a wide range of environmental conditions that include variations in pressure, temperature, and humidity.

Aircraft are now being operated at higher voltages; both at the primary power system level as well as within aircraft sub-systems (e.g., flight actuation, invertors, window heating, etc.). The increases in the operating voltage of aircraft have been gradual. Aircraft electrical systems operated at 14.25 VDC in 1936, rose to 28 VDC in 1946 [1] which was slowly phased out in the 1950s for larger aircraft but kept as the standard for low voltage sections of aircraft electrical systems. In the 1930s, development of single and three phase alternating current systems began with the Boeing XB-15 having single phase 120 VAC-800 Hz power, and the Douglas XB-19 having the first 3-phase 120/207 VAC-400 Hz system. In the late 1940's the transition to a 115/200 VAC-400 Hz standard began with the British "Brabazon" civil aircraft and the American B-36 "Peacemaker" military aircraft. Today, 115/200 VAC-400 Hz systems are used in the majority of civil aircraft. 270 VDC was selected by the military to provide further weight savings in the 1980s [2]. The current aircraft in operation with a more electric architecture include the Boeing 787 which has 500 kVA of electrical generation capability on each engine [3]. To support the generation levels without a significant weight penalty, the Boeing Company has moved from a 115 VAC-400Hz system to a combined 230/400 VAC-360-800Hz and ± 270 VDC (540 VDC) systems [3]. Airbus is also using high voltages for distribution on the A350 platform. Although various military aircraft have employed "double voltage" (230/400 VAC) primary power systems, these two civilian aircraft represent a significant change in the industry with potentially thousands of aircraft to be produced over the next few decades.

While these voltages are relatively low in terms of those found on land-based power systems, moving to higher voltage thresholds introduces an increased likelihood of electrical discharge [4], particularly the risk of continuous partial discharge that does not cause instant failure but reduces the life of insulation systems over time. While it is reasonably straightforward to design an insulation system that will prevent discharge, the need to minimize weight and the constrained volumes that are available in aircraft mean that there can be a conflict between achieving maximum reliability and the lowest possible weight and volume. The design of an insulation system is further complicated given insulation systems may be designed for mechanical robustness well beyond the HV needs to support installation or other needs.

An optimal design must be achieved in widely varying environmental conditions. Parts of the aircraft system that are in an unpressurized zone will see a low pressure for most of the flight and temperatures reaching average lows of around -56 °C [5] with many modern systems now being designed for -65 °C. However, localized heat sources can lead to systems having to operate at very high temperatures up to several hundred degrees. Any systems located in the engine (including the starter generators that are being considered for future aircraft) can be subject to high pressure (HP) compressor delivery air which can be at around 400 °C. Engine accessories, such as generators, can have ambient temperatures exceeding 180 °C, and power terminations can exceed 240 °C. In any pressurized location, flight critical equipment must be designed to ensure that failure does not take place should the aircraft suffer a loss of cabin pressure. This means that equipment has to be designed to function over a wide range of pressure and temperature.

There is a clear need to guarantee the reliability of any equipment operating at high voltage. Consideration must therefore be given to issues such as the insulating material lifetime. Insulation lifetime can be reduced by a number of factors including exposure to high temperatures, thermal cycling, vibration, chemical attack and electrical discharges. In addition to the bulk dielectric life issues, surface dielectric deterioration and effects must be considered as well. Primarily for maintenance and corrosion prevention reasons, civilian aircraft electrical power terminations are not coated. Therefore, an understanding of the material, voltage stresses and contamination exposure, nearly always reconstituted in aqueous form, over the life of the aircraft is very important.

Past work has identified a number of the concerns of operating electrical systems at higher voltages in an aerospace environment. Bilodeau, Dunbar and Sarjeant discussed the increased demand for higher voltage usage in space power systems owing to the need to reduce the weight that would result from the use of lower voltage systems and the necessary test regimes [6]. Many papers examine some of the basic issues relating to the operation/testing of higher voltage systems in a low pressure environment. Dunbar [7] stressed a wire with high voltage to determine the effect of high frequency at high altitudes. His results indicate a reduction in the partial discharge inception voltage of around 15% at frequencies above 40 kHz for an altitude of 33000 feet. Dunbar states in another paper [8] that partial discharge can cause significant numbers of failures in high voltage systems. Brockschmidt [9] also discusses the problems associated with the operation of higher voltage systems in a low pressure environment and states that the voltage required to sustain partial discharge can be lower than that required to initiate it. Karady et al. [10] examined the corona inception voltage of simple electrode geometries including ones that involved thin layers of electrical insulation. The authors show that for certain experimental arrangements, corona inception can take place at voltages lower than Paschen's minimum. Hammoud and Stavnes [11] conducted breakdown tests on different types of aerospace cable observing a reduction in the breakdown voltage of 20% occurred when using a testing frequency of 400 Hz at 200 °C. A study was conducted on polypropylene cable by [12] at different frequencies, ranging from 50 to 400 Hz. The results of these tests correlated with [11] in that breakdown voltages of such insulation could fall as a function of frequency.

A key document that while dated provides excellent information across many of the pertinent issues was produced by Dunbar [12]. This describes the operating environment of an aircraft, the types of electrical discharge that could take place and provides guidelines and precautions to be taken into consideration in the insulation design of electrical and electronic equipment. It also provides guidelines for monitoring and testing. More recent literature includes an overview of the key damage mechanisms in higher voltage aerospace systems along with an examination of the optimum voltage level of cabling systems.

This document seeks to provide the reader with a thorough overview of the risks that are involved in using high voltages in an aerospace environment and the methods that can be used to mitigate the risk both in terms of the selection of appropriate insulation systems and through the use of electrical test. Totally mitigating the risk of electrical discharge occurring is, however, unlikely to be achievable given the impact that other failures may have. For example, pressure seals may reduce the pressure below the value for which clearances have been designed, or component failures could emit clouds of ionised gas/deposit conductive pollution onto surfaces.

This document will use the term "high voltage" to define any voltage above that which can cause partial or disruptive discharges in air, typically about 300 V peak. This will include systems with nominal operation at less than 300 V, but in which abnormal conditions can elevate the voltage above this level. Other organizations have specific legal definition, such as 600 V per the National Electric Code (NEC) or 1000 V by various IEEE standards. Other standards adopt specific limits such as BS EN 60071-1:2006:2010 that is applicable to terrestrial three-phase AC systems above 1 kV rms. This voltage level is known to be where high voltage effects such as electrical discharge become apparent in an electrical system. However, the standard is not intended for use in aerospace applications.

4. OVERVIEW OF ELECTRICAL DISCHARGE TYPES

In the context of aerospace systems, electrical discharges can be generally subdivided into three types; disruptive discharge, partial discharge and tracking. For discharges that take place wholly or partly within the air, an understanding of Paschen's law is particularly useful. This law describes the impact of any variation in pressure on electrical discharges.

4.1 Paschen's Law

Paschen's law states that the breakdown characteristics of a gap are a function of the product of the gas pressure and the gap length. Paschen's law has been defined using experiments with electrodes that generate a near uniform electric field between them (generally this implies a large radius of curvature of electrode as compared with the gap size). To describe the reason for the variation in breakdown voltage of a gap varying with pressure, it is useful to consider a simple gap consisting of two metallic electrodes and air.

A disruptive discharge takes place in a gap when there is a continuous flow of electrons across the gap. Initially, the presence of an electric field accelerates free electrons in a gap towards the anode. These electrons collide with another atom or molecule and will cause ionisation if they are travelling quickly enough. Ionisation will produce a positive ion and a further free electron. This process continues with the number of electrons rapidly multiplying as they head towards the anode while the positive ions move towards the cathode. When the positive ions impact the cathode, further free electrons are liberated which are then able to restart the process.

Raising the voltage across a gap or reducing the gap distance with a fixed voltage increases the electric field which causes more rapid acceleration of electrons and therefore a higher likelihood of an ionising collision (they will be travelling faster when they hit another atom/molecule).

Variations of breakdown voltage as a function of gap distance are in contrast to voltage variations due to the changes in pressure. A change in pressure changes the mean free path of electrons (the average distance that an electron travels before colliding with another molecule). A lower pressure increases this distance and allows electrons to have gained a higher velocity before collision and therefore be more likely to cause an ionising collision.

The classical Paschen's curve for air is shown in Figure 1. As pressure is reduced the breakdown voltage initially falls. It reaches a minimum and then, as pressure is further reduced, rises steeply again. This rise in strength of a gap is reached once the mean free path of an electron becomes comparable with the size of the gap (meaning the likelihood of ionising collisions is very low).

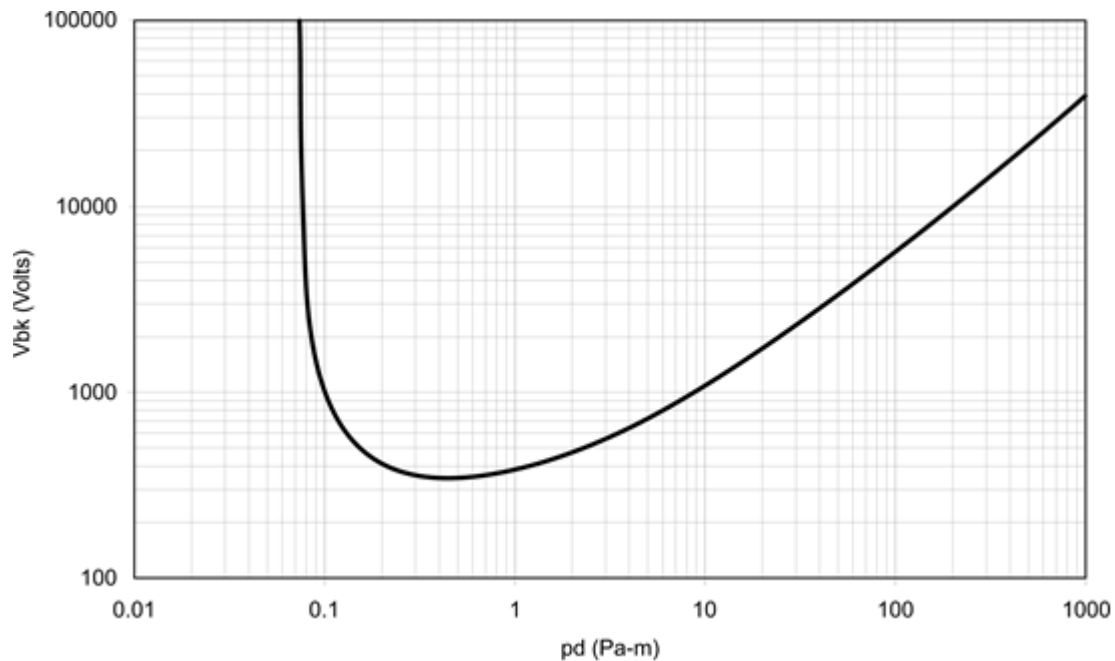


Figure 1 - Paschen's curve for air, for a uniform electric field (y-axis - breakdown voltage [volts-peak], x-axis - pressure-distance [Pa-m]) [13]

The curve effectively describes the peak voltage (whether DC, AC or transient/pulse) required to cause the breakdown of a gap of a given distance at a given pressure (the 'pd' product on the x-axis being derived from the multiplication of the pressure and distance). In reality there is a finite time needed to cause the breakdown of a gap but this is extremely low and should be ignored.

The minimum point of this curve is Paschen's minimum. In air, this is 327 V for a pressure distance product of 0.754 Pa-m [14]. Classically, it is considered that below this voltage, breakdown of an airgap cannot take place, hence the lack of consideration given to some forms of electrical discharges in previous designs of aircraft operating at lower levels of voltage. It should be noted that discharges can occur at voltages below the Paschen minimum when the excitation is in the RF range. This phenomenon, known as multipactor, is not typically found at power distribution frequencies.

Other researchers have produced a modified form of Paschen's curve that accounts for field emission processes that are seen in very small gaps with high electric fields. The development of this modified curve has traditionally been associated with research into MEMS devices. This shows lower breakdown voltages associated with smaller gaps [15].

Replotting Paschen's curve with distance only on the x-axis provides a better overview of how the breakdown voltage of a gap varies as a function of pressure as shown in Figure 2. It is clear that the same voltage requires a larger gap to prevent breakdown as pressure falls/altitude increases.

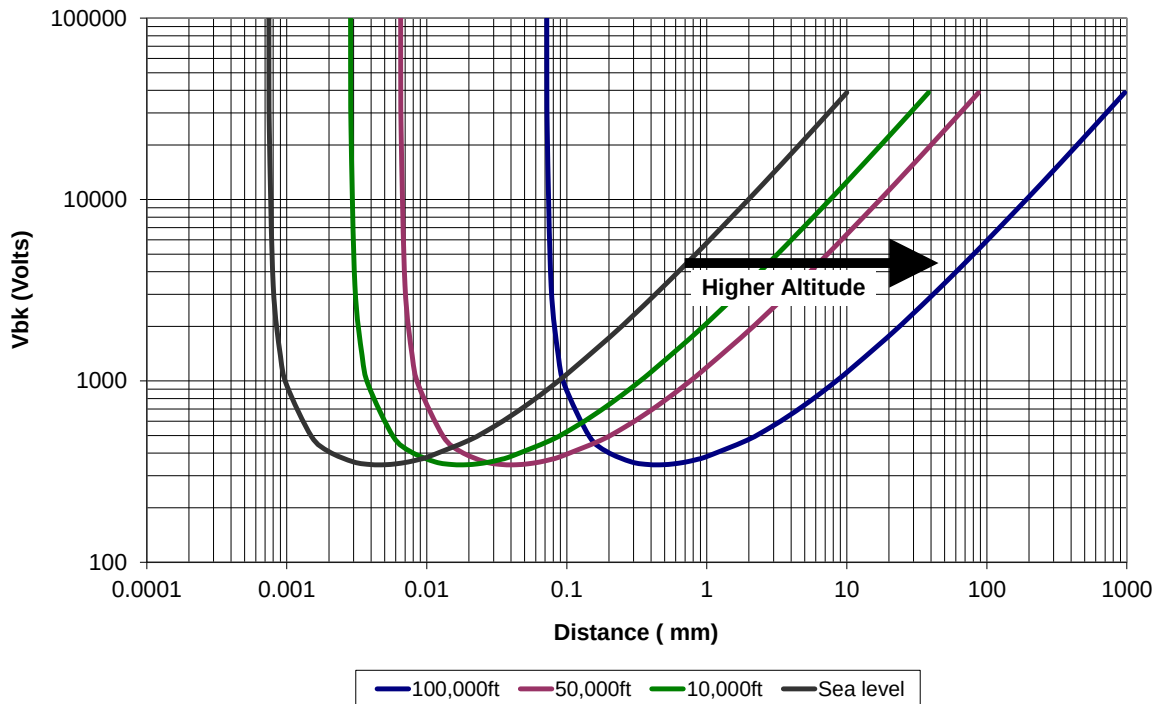


Figure 2 - Breakdown voltage of air according to paschen's law at a range of pressures (y-axis - breakdown voltage [volts-peak]) [13]

Paschen's curve does vary according to the type of gas (some gases such as helium have much lower minimum voltages than those observed for air) and will vary according to the type of electrodes although this variation is relatively small. Kopisetty et al. [16] have reported Paschen curve-like behavior for non-uniform field, point-to-plane gaps, which can be representative of practical geometries in equipment. While these experiments were performed in nitrogen, they do demonstrate the difference between breakdown voltages with DC voltage compared to those with 20 kHz unipolar (DC-biased) sinusoid excitation. In either case, the point electrode was at positive potential and the grounded plane was negative. For this configuration, the 20 kHz breakdown values were typically 20% lower than the DC breakdown values. It is anticipated that the comparison would be different for a configuration with reversed polarity (i.e., negative point; positive ground), but such data was not reported.

4.2 Disruptive Discharges

A disruptive discharge results in a flow of fault current between two conductors and would usually necessitate the operation of some form of power system protection to clear the fault. An example of where a disruptive discharge could occur is in an air gap between two uninsulated conductors should these not be kept a sufficient distance apart. In this case, it is likely that the discharge process is a Townsend type mechanism that gives rise to the Paschen curve [17].

Disruptive discharges can also take place through liquid and solid insulation if the insulation layers are not thick enough. The breakdown processes are governed by the form of insulation used and are not usually sensitive to pressure. The strength of solid and liquid insulation is also usually magnitudes higher than that of air but is more sensitive to variations in both temperature and the type of test voltage (usually reducing in strength at higher frequencies).

4.3 Partial Discharges

Partial discharges are small discharges that do not completely bridge a gap between two conductors. For partial discharges in cable insulation voids, discharges between adjacent insulated conductors and similar modes, these will take the form of a discharge in air – these therefore also require a voltage exceeding Paschen's minimum.

Figure 3 shows a sampling of generic geometries where partial discharge is likely to take place. As an example, a partial discharge would occur when an insufficient thickness of insulation around a wire allowed sufficient electric field to build up in the gap between that outside of the wire and another grounded conductor. This effect is particularly pronounced in areas where cables enter connectors (and therefore have small distances between wires). Figure 4 shows an example of an aerospace cable where partial discharges form in the air gap near the P-clip. Partial discharges can also take place across surfaces, around sharp conductors (usually referred to as corona when the conductor is remote from ground) and within insulation systems containing gas bubbles (voids). A key characteristic of partial discharges is that they will usually not result in the flow of fault current (and therefore will not instigate the operation of power system protection).

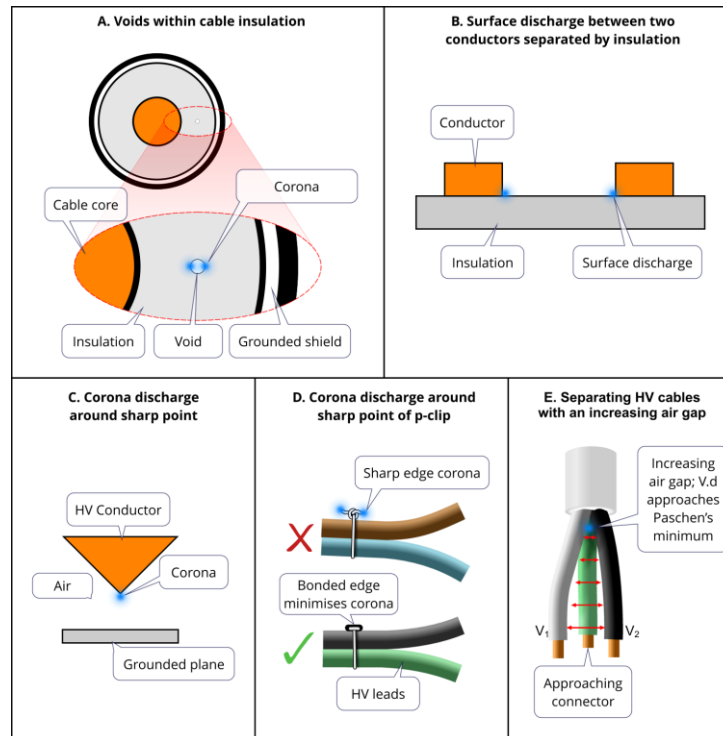


Figure 3 - Illustration of systems that could be vulnerable to partial discharge

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The presence of partial discharge can reduce the service life of a system by degrading insulation. Repetitive discharge events can cause irreversible mechanical and chemical deterioration of the insulating material. Damage can be caused by the energy dissipated by high-energy electrons or ions, ultraviolet light from the discharges and ozone attacking the insulation. The chemical transformation of the dielectric can also tend to increase the electrical conductivity of any surrounding dielectric material and can increase the electrical stress in the remaining unaffected insulation leading to an acceleration of the breakdown process. Repetitive continuous partial discharges can lead to a disruptive discharge, eventually. For example, magnet wire insulation in random-wound motors, fed by pulse-width-modulated drives will result in premature winding failures, if the winding insulation system is not designed for such service [18].

Partial discharge activity is also linked with the production of significant high frequency electromagnetic emissions which have been stated as being potentially harmful to aircraft avionic systems should these couple into system wiring/equipment.

The inception voltage of partial discharge and the number of discharges will vary significantly depending on the nature of the system voltage. Corona will take place in any region where the electric field is elevated above a given level. The frequency of corona pulses will not have a significant dependence on the type of voltage providing the electric stress but will depend on the magnitude of the voltage. In contrast, partial discharge within voids or in an air gap between insulated conductors will have a different inception voltage for AC and DC. It will also have a significantly lower repetition rate for DC systems (with discharges probably happening at an extremely low frequency of no more than a few hertz). In an AC system, the number of discharges (but not the magnitude) will generally increase with system frequency. This has particular implications for insulation stressed with high frequency waveforms such as pulse width modulation [19].

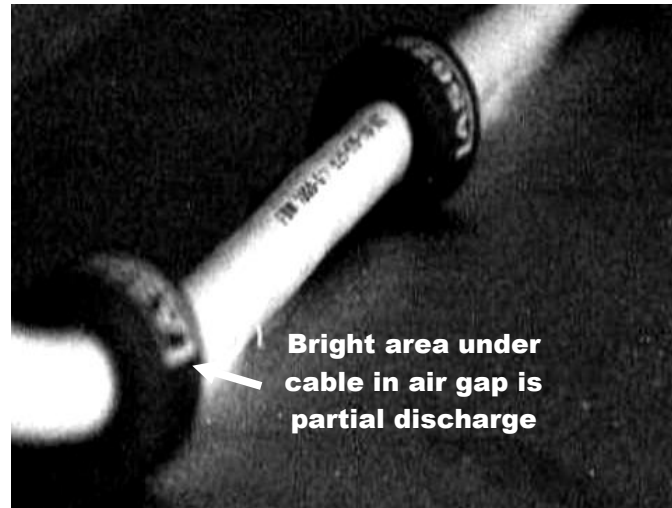


Figure 4 - Partial discharge between an aerospace cable and a grounded electrode

There are clear opportunities to manage partial discharge through the use of shielded systems. Using the example of cabling, the insulation could be coated with a conductive and grounded layer. This would eliminate any electric field in the air gap between individual wires. Partial discharge in the air gap between wires would therefore not take place. However, there could still be partial discharge within voids in the insulation of the wires themselves.

4.4 Tracking

Tracking can occur at any voltage (well below the Paschen minimum) and is typically connected with the evaporation of a liquid layer from an insulation surface across which an electric field is present [20]. Tracking can also occur across dry surfaces although the voltages required are generally much higher [20]. The process of tracking across a small gap contaminated with a conductive aqueous contaminant is illustrated in Figure 5. When a liquid layer is deposited between two conductors, a current will flow in the liquid. Heating of this liquid layer will lead to evaporation. This will often take place in the middle of the gap away from the conductors which stabilize the temperature of the nearby liquid. As the liquid evaporates, a spark will develop across the new dry band. The spark, if energetic enough, can damage the underlying insulation. Should carbonaceous deposits develop, this can accelerate further damage owing to the reduction in the 'healthy' insulation within the gap. The severity of the damage will depend on the voltage and current of the arc along with the characteristics of the material itself. In 'Dry Band Arcing' (DBA), the insulation material properties plays a dominate role. Materials with a high Comparative Tracking Index (CTI), as measured by ASTM D3638 or IEC 60112, are desirable. It should also be noted that some contaminants form a conductive residue of carbonates and metal salts that will result in surface breakdown (i.e., flashover) even on very high CTI materials. For installations exposed to runway contaminants or other fluids, this must be considered in the insulation design (e.g., materials, geometry, drainage) and the installation (spray barriers, drip-loops, coatings, etc.).

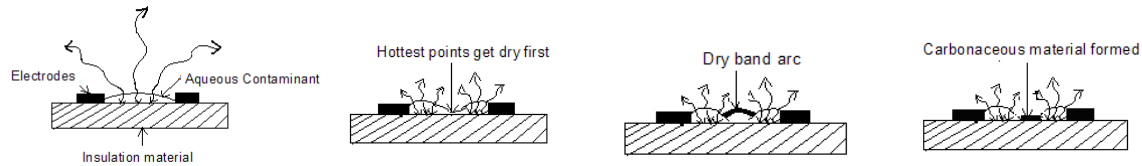


Figure 5 - Basic process of tracking across an insulating surface contaminated with an aqueous layer

Higher voltages are more likely to cause electrical tracking owing to the increased level of heating that can occur in contamination deposited in a given size gap. In addition, having a voltage above Paschen's minimum means that there is a chance of re-ignition of the arc (particularly important in an AC system where it will extinguish every half cycle). As liquid boiling points lower with decreasing pressure, larger separations of conductors become necessary at altitude unless systems can be guaranteed to be located in an environment that will not be subject to ingress of liquids in any form. However, in practice, this is very difficult to accomplish. Line-Replaceable Units (LRUs) exposed to pressure cycling can slowly draw moisture internally through seals and through cabling. Often, adding thicker layers of conformal coating to mitigate moisture intrusion only results in a delay before poor reliability due to tracking or dielectric failure re-occurs in an LRU.

In aircraft systems, existing standards deal with the phenomena of arc tracking on cabling including wet arc tracking, dry arc tracking and series arc tracking. PCBs are notorious for absorbing water vapor which adds weight and reduces the dielectric strength. Generally, these events take place in locations where the insulation system has been compromised. Discharge activity in the form of an arc then burns surrounding insulation allowing damage to propagate over long distances. More details of these phenomena can be found in [21] and [22].

Tracking behaviour can differ significantly between AC and DC energized systems. Despite this, DC based wet tracking test methods are less well established [23].

All of the above forms of electrical discharge must be considered in the design process to ensure that the electrical system remains functional over its intended lifetime.

In general, the ranking of relative voltage level/electric-field stress (from high to low) for various disruptive discharge failure mechanisms are as follows:

- Partial discharge/insulation deterioration
- Dry flashover on the surface of an insulator
- Wet flashover - aqueous contamination with dry band formation (DBA)
- Wet flashover - frozen or frost with contamination
- Wet flashover - with self-carbonizing or conductive residue contaminates
- Foreign object debris - conductive debris (e.g., carbon dust, metal shavings, etc.)

5. CONTROLLING ELECTRICAL DISCHARGES

It is important to ensure that systems are designed in such a way that the presence of electrical discharge of any type is eliminated, or managed, both at the start and end of aircraft design life. This life may clearly vary between components and aircraft type. For example, systems on military aircraft are generally required to function for a shorter lifetime than their commercial equivalents. Many forms of electrical discharge must be avoided in any system throughout the lifetime of the equipment. Tracking cannot be allowed as it could cause carbonization of insulation surfaces, system failure and possibly fire. Disruptive discharges cannot be allowed to occur as they will normally require the operation of circuit protection to clear. It is possible that partial discharges could be tolerated on the system as long as the equipment remains safe, functional and reliable over the aircraft lifetime and no interference is caused to other systems. In some components such as electrical machines it is particularly difficult to eliminate partial discharge without an unacceptable increase in size, weight factor and as such this must be controlled over the lifetime of the equipment.