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Section 5.1.6

Effects of Lightning on Assets, Facilities and Structures

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The time to review possible lightning effects upon a particular asset, facility or structure (AFS) is during the design stage. A Lightning Mitigation Plan is conceived from a Hazard Design Analysis. Then a Testing & Verification Program can provide certification that the protective measures will function as engineered. Frequently, lightning problems do not receive consideration during the design stage. It remains then for the lightning safety engineer to analyze the effects of lightning during operations and to provide a rationale for safety-through-redesign modifications to the AFS. The intent of this document is to provide the reader with a review of the effects of lightning. The variety of behavior produced by lightning upon AFS can be divided into four areas:

1. DIRECT EFFECTS

These are caused by current transfer via direct attachment. They will be considered individually.

1.1 Ohmic Heating: Thermal Damage. When a lightning current pulse whose instantaneous value is i flows through a conductor of resistance R, the heat generated by the whole pulse is RSi2dt joules. The quantity Si2dt is called the action integral of the pulse and is measured in A2s or joules per ohm. Practically the whole of this heat is devoted to raising the temperature, since no significant portion of the heat can flow to the surroundings during the very short duration pulse. Thus the temperature rise is proportional to the resistance of the conductor multiplied by the action integral of the pulse. Parts of the AFS which may carry the lightning current therefore need to be designed with a cross-sectional area large enough to keep the temperature rise well below a critical value such as the ignition point or melting point of the material. The design also needs to account for the fact that rapidly changing current in the lightning pulse tends concentrate at the surface of the conductor (skin effect). The maximum surface temperature reached is greater therefore than it would be if the current was distributed uniformly over the whole cross-section.

1**.2 Ohmic Heating: Disruptive Mechanical Forces**. When a conductor of small cross section carrying lightning current is constrained to carry a substantial part of the lightning current, it is likely to fuse explosively, especially if situated in a confined space. The literature describes structural damage in terms of equivalent tons of TNT (Golde, 1975) from lightning channel pressures in excess of 10 atmospheres (Uman, 1984). Moisture trapped in a dielectric honeycomb of fiberglas or carbon fiber compounds (CFC) or masonry building materials can be vaporized as rapid steam formations occur. Arcing, sparking, or dielectric breakdown also can have a similar effect.

1.3 Arc Root (attachment point) Damage. At an arc root (attachment point) on the surface of AFS the lightning current is focused in a small area, producing high temperatures which may produce a transient hot spot. Depending on the thickness of the surface material and the magnitude and duration of the current, burn through may occur. The arc burning voltage V is almost always constant so that for a metal skin the heat generated is very nearly VSidt joules, that is, proportional to the charge Sidt coulombs in the lightning pulse.

If the AFS skin is of high resistivity such as CFC, several conditions may be present. Because the resistivity is up to 1000 times greater than that of metal, the ohmic heat RSi2dt becomes important; the arc heat VSidt is also higher because the burning voltage is higher due to carbon contamination. Conditions are also different because CFC has properties (for example, electrical and thermal conductivity and coefficient of thermal expansion) which are different for the along-fiber and cross-fiber directions. Arc root damage to CFC usually is manifest in the "tufting" of the fibers due to vaporization of the resin matrix and delamination due to inter-lamina stress resulting from differential expansion.

For dielectric materials there is no arc attachment, but punctures may occur through high voltage breakdown. If the arc root parameters are insufficient to cause the melting of metallic skins or burn through damage to CFC panels, a hotspot still will be formed on the under surface. Such an occurrence could be an ignition hazard if the skin surface encloses volatiles and if ignition temperatures for volatiles (aviation fuels, solid and liquid explosives) approximate those present at burn through. For example: aluminum melts at 660 degrees C; burn through for CFC is about 800 degrees C; titanium melts at about 1800 degrees C; the auto ignition temperature for aircraft fuel is about 230 degrees C.

1.4 Acoustic Shock Wave. At the beginning of the first high current stroke, there is a rapid pinching of the arc channel due to the increase in the magnetic field, and this produces a radical acoustic shock wave which can cause indentations on metal skins. At the attachment point there are more local (axial) acoustic forces and these combined with the magnetic forces also present may enhance the thermal damage. The severity of the acoustic shock depends on both current magnitude and the rate of rise of the current.

1.5 Magnetic Pressure and Forces. An isolated conductor carrying a current suffers a radially inward pinching effect. Where the current is of sufficient magnitude to produce a very high surface magnetic intensity (of the order of several MA/m) severe mechanical distortion may occur. For example, a conductor of 5 mm diameter carrying a peak current of 200kA would experience a pressure of 1000 atmospheres (10 x 8 N/m2). The pressure is proportional to the square of the current and inversely proportional to the square of the diameter. The effect can be important in conductors whose purpose is to protect the AFS by carrying the lightning current. The magnetic pressure produces a temperature rise but this usually is insufficient compared with ohmic heating due to current flow. The pressure may be sufficient to stress the material beyond its yield point, which will be lowered due to the increased temperature caused by the current flow.

Because the current density is very high at the arc root, the magnetic pressure there also will be very high, approximately 6000 atmospheres for a current that rises rapidly to 200kA peak. This pressure accelerates the burn through process by its tendency to expel the thermally weakened skin.

In addition to the magnetic pressure on an isolated conductor, there are interactive forces between two adjacent conductors carrying current. The force is proportional to the product of the currents and inversely proportional to the distance between them. An adjacent second conductor may be an arc channel itself, so that current in the AFS may produce a reactive force with the current in the nearby lightning channel. When the same current is flowing in both conductors, the instantaneous force is proportional to i2 but the ultimate effect in terms of stress or movement is a complicated function of the current waveform shape and duration and the mechanical response characteristics of the conductors and their mountings.

1.6 Sparking. Voltage and Thermal sparking may occur either separately or together. Voltage sparking is the result of dielectric breakdown including tracking or flashover across dielectric surfaces. It could arise inductively in a loop or bend, or from the resistive drop in a high resistance material, especially at joints. Thermal sparking consists of burning fragments of melted material thrown out from hot spots such as high resistance contacts having a high current concentration, or at acute changes of geometry.

The temperatures of both types of spark are high and are potential sources of fire or explosion. The incendivity of a spark depends to a large extent upon its total energy content but also on time over which the energy is deposited. It is difficult to measure the incendivity of sparks, however it is typical and prudent to regard any which occur in a vulnerable region as a hazard.

1.7 "Exploding Arcs" and Hydraulic Shock. A high current arc formed in an enclosed space will generate a shock wave due to the rapid heating of air. Such arcs, and especially long arcs, can be very disruptive and have been known to fracture massive objects, e.g. solid rock. When an exploding arc occurs in a fluid within a tank, the fluid tends to concentrate and focus the shock to an extent that even large metallic support members can be fractured.

2. NEAR FIELD (INDIRECT) EFFECTS

2.1 Transients Due to Lightning Current. Essentially a lightning current pulse flowing through a AFC, or in a nearby flash (100 m ?), injects a voltage into the metallics. The consequent current that flows depends upon the impedance of the circuit. The induced voltage waveforms often are very complex but usually consist of one or more of the following three components:

a. A voltage proportional to the lightning current due to resistive coupling (for example, the voltage gradient on the inner surface of a metallic skin) or to inductive coupling where the magnetic flux has diffused through a high resistive skin (such as CFC) and in so doing has effectively undergone an integrating process. The peak voltage will then be proportional to the lightning current.

b. A voltage proportional to the rate of change of lightning current (di/dt), due to direct coupling with the magnetic field that has penetrated through apertures (sometimes referred to as aperture flux or fast flux). The peak voltage then will be proportional to the maximum value of di/dt, that is, the greatest slope of the rising front of the lightning current pulse.

c. High frequency damped sinusoidal oscillations usually in the range of 2 to 50 MHz. These are shock-excited oscillations corresponding to natural resonances of the AFS and its electrical subsystem; the frequencies and damping of the oscillations (but not their amplitudes) are independent of the shape of the lightning pulse.

2.2 Transients Due to Electric Field. When a lightning channel attaches to a body (no matter if that body is attached to or isolated from ground) or passes nearby it. it causes the body to experience an electric field having a high intensity and a rapid rate of change. This is in addition to the high static electric field which may be present under thunderstorm conditions.

The rate of change of the electric field may be as high as 10 x 13 V/m per second. When a changing electric field terminates on a conductor the displacement (capacitive) current of the field enters the conductor, the current density being EdE/dt A/m2 where E is the permittivity of air; a rate of field change of 10 x 13 V/m per second corresponds to a current density of about 88 A/m2. Thus conductors such as the braided shields on cables, or unshielded wires, will have significant transient currents flowing in them in regions exposed to electric fields. Besides currents proportional to dE/dt there are the dampened sinusoidal transient oscillations which are shock excited by the sudden application of the disturbance mentioned in 2.1.c, above. For a cloud to ground strike there are in fact two such shock excitations, one at the instant of leader attachment and another at a later time at the instant of electric field collapse due to the arrival of the return stroke.

High field levels (above some 2 kV) also may give rise to corona discharges at sharp edges or protrusions of the AFS and these produce RF emissions which may constitute an additional possible hazard. Although not a lightning phenomenon, it may be noted that a dielectric surface can accumulate electrostatic charge, which may reach such an intensity that a local discharge occurs; this may puncture a thin dielectric, or if (as is more likely) the discharge is to an adjacent conducting part of the surface, may be the source of RF emissions.

2.3 Sparking and Dielectric Breakdown. Induced voltages may cause breakdown of insulation in wiring, at connectors and in electrical components, or breakdown of air. This may produce sparking which would constitute a hazard when in the presence of volatiles similar to that mentioned in 1.6, above.

Depending on the resistance to ground at various parts of the AFS, very high voltages with subsequent risk of insulation breakdown can occur across data links and at sensors where they are positioned remote from the data processing point. These effects, however, can be guarded against if data links and power lines are
protected adequately.

3. FAR FIELD (INDIRECT) EFFECTS

These are the effects that occur when the AFS acts as a receiving antenna, being in the far field of the lightning channel which is acting as a transmitter. The transients predominantly will be damped sinusoidal oscillations with frequencies related to the electrical resonances of the AFS and its electrical system. All of the effects of induced transients mentioned under 2., above are still possible but less likely because of the lower intensity. In general, if the AFS has been designed to resists direct and near field effects, the more distant far field effects will not present a hazard.

4. LEADER PHASE EFFECTS

4.1 Attachment. The process of lightning attachment to a AFS involves the formation of high electric field concentration (corona) at the extremities, sharp edges, and protuberances, with the consequent formation of streamers which launch in attempts to connect with the downward leader channel. It is possible that the presence of an additional electric field concentration source caused by the presence of a conducting body in an already high electric field (examples: an airborne vehicle; HVAC on a rooftop structure; a power transformer on a utility pole; ballast on high mast lightning) may trigger a lightning flash that otherwise would not have occurred.

It is seen that the probability of a strike to a particular region of the AFS surface largely is a matter of the local geometry coupled to variable voltages, field conditions, rise times and waveforms. The permutations here are manifold and for the most part negate any prediction of lightning attachment points.

4.2 Dielectric Puncture. Conductors may be located behind a dielectric surface, as in radar domes, antenna covers, fiberglass enclosures, and the like. Attachment is not prevented by this dielectric intervention and shield puncturing or shattering is a result of the lightning penetration.

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