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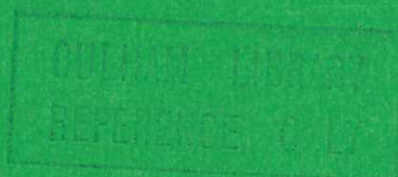
Report

RECOMMENDED PRACTICE FOR LIGHTNING SIMULATION AND TESTING TECHNIQUES FOR AIRCRAFT

J PHILLPOTT

CULHAM LABORATORY
Abingdon Oxfordshire

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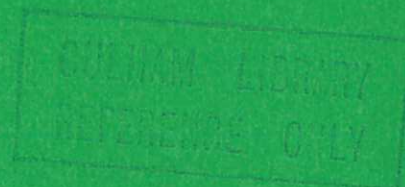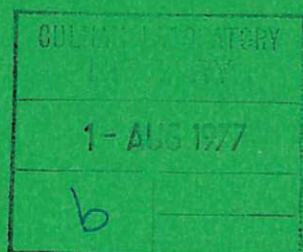
REPORT

RECOMMENDED PRACTICE FOR LIGHTNING SIMULATION
AND TESTING TECHNIQUES FOR AIRCRAFT

J PHILLPOTT

CULHAM LABORATORY
ABINGDON, OXFORDSHIRE

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C O N T E N T S

1.   INTRODUCTION   .

This report recommends test waveforms and techniques for simulating the effects of a lightning strike to aircraft. The current waveforms described, which represent a severe lightning environment, have been accepted in the United Kingdom for testing aircraft systems, structures and equipment to the appropriate level of safety for airworthiness purposes.

This report recommends test waveforms, procedures and precautions based on the available knowledge of the natural lightning environment and practical considerations and limitations associated with laboratory testing. The purpose of the simulation is to produce the significant effects of the environment not the environment itself. Where it has been shown that test conditions can affect the results of the test, test techniques and conditions are specified with the objective of obtaining valid results and consistency of results between laboratories. It is not intended that every waveform and test described herein should be applied to every system requiring lightning verification tests. It is only necessary to test with the wave-form component(s) which is likely to produce failure.

It should be noted that whilst there is more or less world-wide agreement on the current component parameters there is a wide difference of opinion on the voltage waveforms applicable to model attachment point studies. The high current test waveforms and techniques described simulate the direct and indirect effects of lightning attachment to the aircraft.

It is recognised that indirect effects may also occur from nearby lightning flashes which do not contact the aircraft and that these may also affect sensitive electronic equipment. However the present understanding of these phenomena is quite limited and no attempt has been made to include in the report the related test criteria.

Finally the style of this report is such that the reasoning and background information is given in the main body of the text. The appendices serve to highlight the important constraints and numerical values and are intended as a quick reference. A brief bibliography is included in which it is possible to pursue particular studies in greater depth.

2. LIGHTNING PHENOMENA

2.1 Introduction

The generally accepted distribution of electric charge in a typical thunder-cloud is shown in Figure 1. This shows a large positively charged ice crystal region, P, towards the top of the cloud, a large negatively charged water droplet region, N, in the middle of the cloud and a small positively charged region, p, at the base of the cloud. Though the qualitative charge distribution is reasonably well established the actual charge values are uncertain. From the charge distribution three main types of cloud discharge may be expected:

(1)   P-N and N-p discharges in the upper and lower regions of the cloud respectively (intracloud flashes).

(2)   Discharges from a charge centre within one cloud to the opposite charge centre within another cloud (intercloud flashes).

(3)   Discharges from either the N or P region to ground (ground flashes).
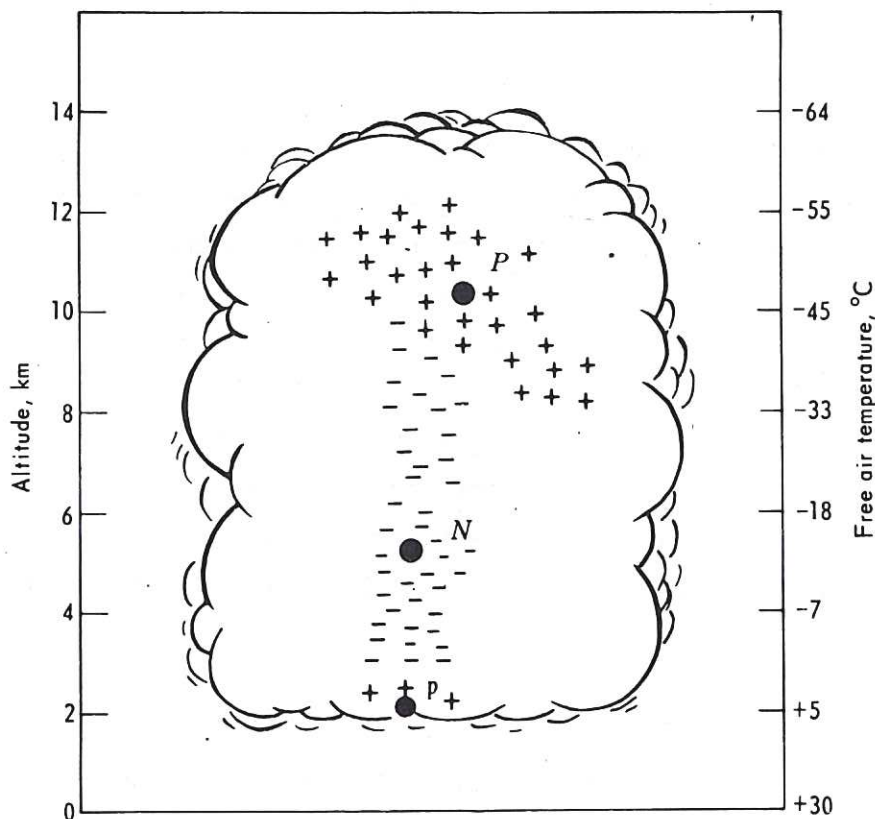

Fig.1 Probable distribution of the thundercloud charges, P, N and p for a South African thundercloud according to Malan.

The conditions under which most strikes to aircraft occur (at about 7000 ft and 0°C) probably means that aircraft most frequently contact intracloud flashes or feeders to the main channel. The evidence from measurements and

the damage seen on aircraft suggest that the intracloud flash is no more
and probably generally less severe than the ground flash. It is therefore
assumed that the worst conditions likely to be encountered by an aircraft
are those associated with the ground flash. In addition the majority of
lightning current measurements have been associated with ground flashes.

2.2   Prestrike Phase

The breakdown process is thought to commence with a local breakdown in the
N-p region for negative discharges from the thundercloud after which a
negatively charged column is propagated to ground or another charge centre
by the resulting electric field. This column, referred to as a stepped
leader, advances in a series of rapid discontinuous steps each on average
about 50m long and separated by pauses of about 50µs. The luminous
diameter of the stepped leader is between 1 and 10m though it is thought
that the leader current of about 100 amps flows in a small diameter core
at its centre. The average propagation velocity is about 1m per micro-
second.

2.3   Electrical Characteristics of Ground Flashes

The current waveforms of the lightning flashes are the most important
factor in deciding first what damage is sustained by the aircraft in flight
and second what tests and facilities are necessary to simulate the same
damage in the laboratory. The most important parameters of the current
waveform are peak current, rate of rise, total duration, charge transferred
and action integral ($\int i^2 dt$). The units of action integral are $A^2 s$ or
alternatively may be expressed in units of joules per ohm since the action
integral is proportional to the energy dissipated in a given resistance.

2.3.1   Positive Ground Flashes

A positive ground flash, shown diagrammatically in Figure 2, is preceded
by a stepped leader and usually comprises only one stroke. The positive
flash occurs less frequently than the negative flash usually between 1%
and 20% of all flashes depending on geographical location. However the
former often has a higher energy content than a negative flash and it
must be taken into account in test recommendations. The energy is
related to the action integral $\int i^2 dt$ and values of $10^7 A^2 s$ and charge
transfers in excess of 300C have been recorded. It is important to note
that a large proportion of the charge transfer can occur at high currents
of 20-50kA flowing for about 1ms.
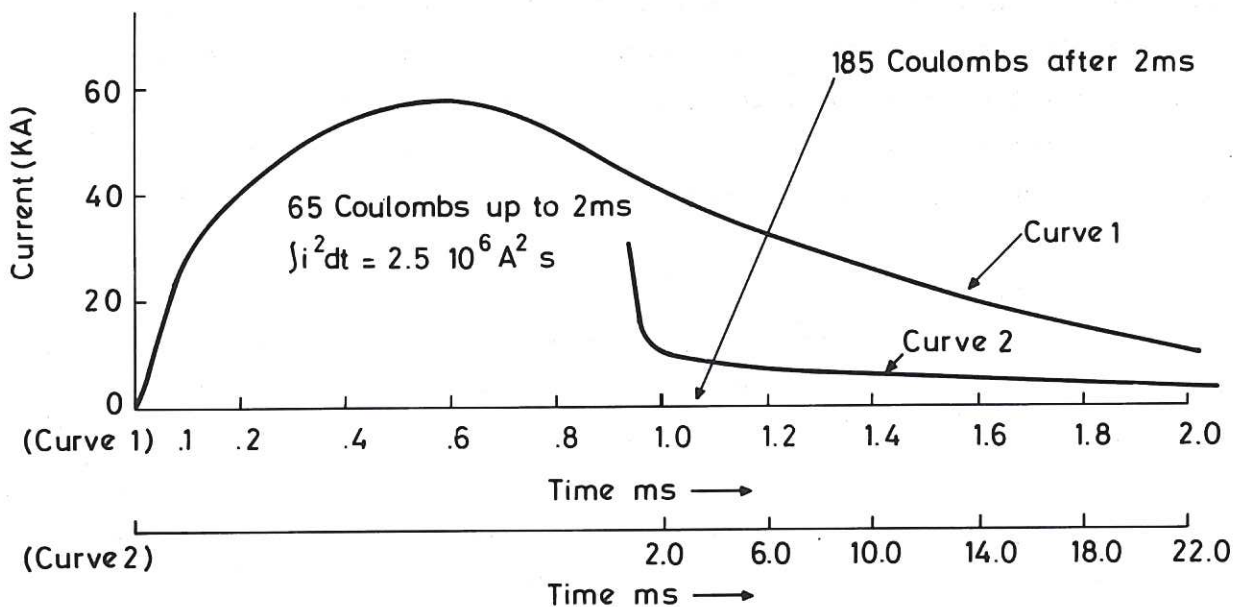
Fig.2 Typical current waveform for positive flash to ground.

2.3.2   Negative Ground Flashes

A negative flash, which is shown diagrammatically in Figure 3, is character-
ised by several strokes of high peak value (high peak current phase) with
low amplitude continuing current (continuing current phase) between some
of the discharges. It should be noted that sometimes the high peak current
phases are extended by intermediate current (intermediate current phase,
about 2kA) flowing for some milliseconds.

(a)   Initial High Peak Current Phase

The high peak current occurs after the stepped leader reaches the ground
- or more precisely an upward leader from the earth. A violent current
surge which is known as a return stroke then occurs and propagates along
the stepped leader channel. Typically the high peak current phase has a
magnitude of 10-30kA but higher currents are possible though less probable.
A peak current of 200kA represents a very severe stroke one that is only
exceeded in about 0.5% of all negative flashes. Whilst 200kA may be
considered a practical maximum value of lightning currents it should be
emphasised that in rare cases a larger current can occur. The current in
the return stroke has a fast rate of rise typically 10 to 20kA per micro-
second and exceeding in rare cases 100kA per microsecond. Typically the
current decays to half its peak value in 50µs. The quoted figures for
peak current and rate of rise of current have been obtained from measure-
ments on earthed structures and although little is known about current in
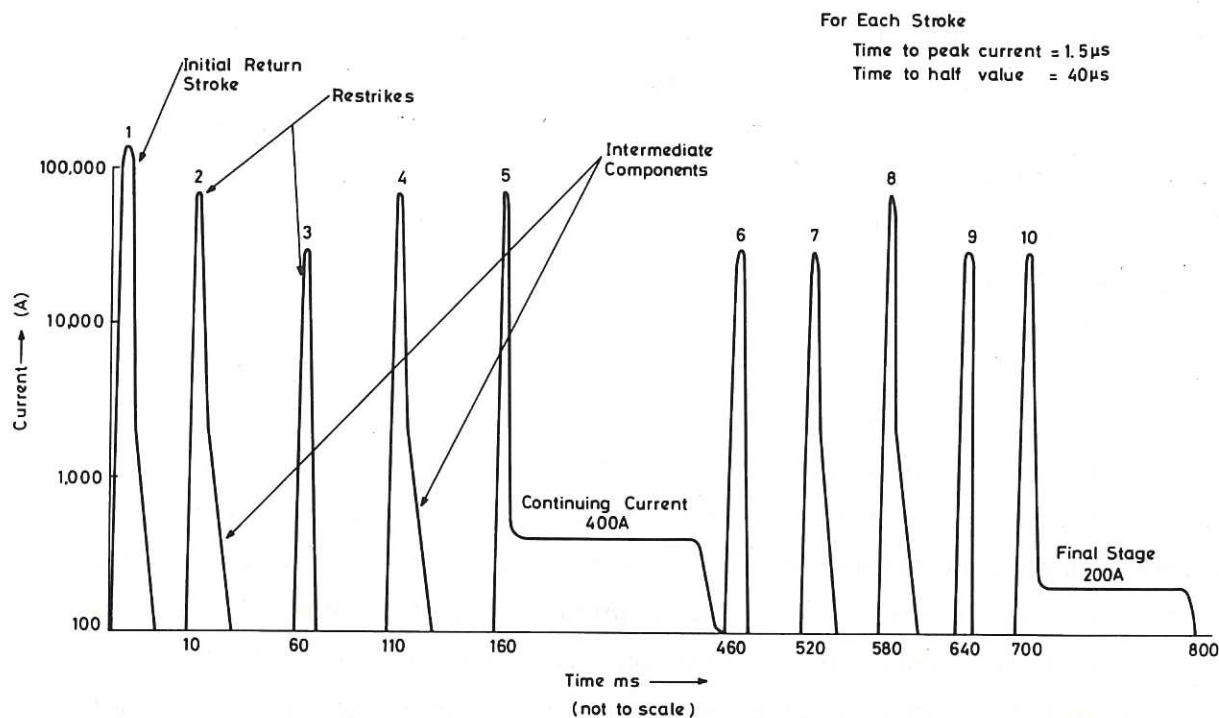
Fig.3 Severe negative lightning flash current waveform.

the lightning channel at higher altitudes (e.g. 7000 ft) it is likely that at those levels the values of current will be lower than those at ground level. The test severity is therefore appropriate to aircraft struck at low altitudes by a cloud to ground flash where the current parameters are likely to be most severe. There appears to be correlation between impulse charge, action integral and peak current for first and following strokes and also between flash duration and flash charge. No correlation has been shown to exist between peak current and rate of rise of current.

(b)   Intermediate Current Phase

After the initial decay following the peak current of some of the strokes there is often a low level current of a few kiloamperes that persists for several milliseconds. This current is termed 'intermediate' current.

(c)   Continuing Current Phase

The total charge transferred by the high current strokes is small only a
few coulombs. However between some of the strokes and more often after the
last stroke a continuing current phase exists for times between 100 and 800ms
during which a current of 100-400 amps may flow. However it is believed
that before a restrike can occur the continuing current must drop to a low
value. (See for example the continuing current in stroke 5 of Figure 3).
Therefore during the stated 100-800ms of continuing current no restrike can
occur. A severe discharge would transfer about 200C during the continuing
current phase.

(d)   Restrike Phase

In a typical negative lightning flash there will be several high current
strokes following the first return stroke. These occur at intervals of
several tens of milliseconds as different charge pockets in the cloud are
tapped and the charge fed into the lightning channel. Typically the peak
amplitude of the restrikes is about one half that of the initial high
current peak but the rate of rise of current is often greater than that of
the first return stroke (over 100kA/µs has been measured). The continuing
current may link some of these successive return strokes or restrikes.
About 25% of the intervals between restrikes or successive return strokes
are found to contain continuing current. About 70% of negative flashes
have more than 2 strokes per flash and only 5% have more than 10 strokes
per flash. Approximately 95% of negative flashes have an interval between
strokes longer than 11ms and 5% longer than 200ms with a mean value of 50ms.
If an interval exceeds about 100ms and does not include continuing current
the succeeding stroke is unlikely to follow the same channel as its pre-
decessor. The duration of intervals that include continuing current is
substantially larger than usual with an average duration of 145ms.

2.4   Lightning Current Test Waveforms

Owing to the complex nature of the various types of lightning discharges
and the limitations of laboratory facilities it is necessary to define an
equivalent test lightning waveform that contains the essential features
of the positive and negative discharge to ground. This equivalent waveform
is defined in Appendix 1.

3.   LIGHTNING AND THE AIRCRAFT

3.1   Initial Attachment

As a lightning stepped leader approaches an extremity of the aircraft high

electrical fields are produced at the surface of the aircraft. These
electrical fields give rise to streamer discharges which propagate away from
the aircraft until one of them contacts the approaching stepped leader.
Propagation of the stepped leader continues from other aircraft extremities
until one of the branches reaches the ground or another charge centre.
This process is illustrated in Figure 4.

Stepped leader channel
approaching aircraft

Leader channel
passing through aircraft

Return stroke passing
back toward cloud
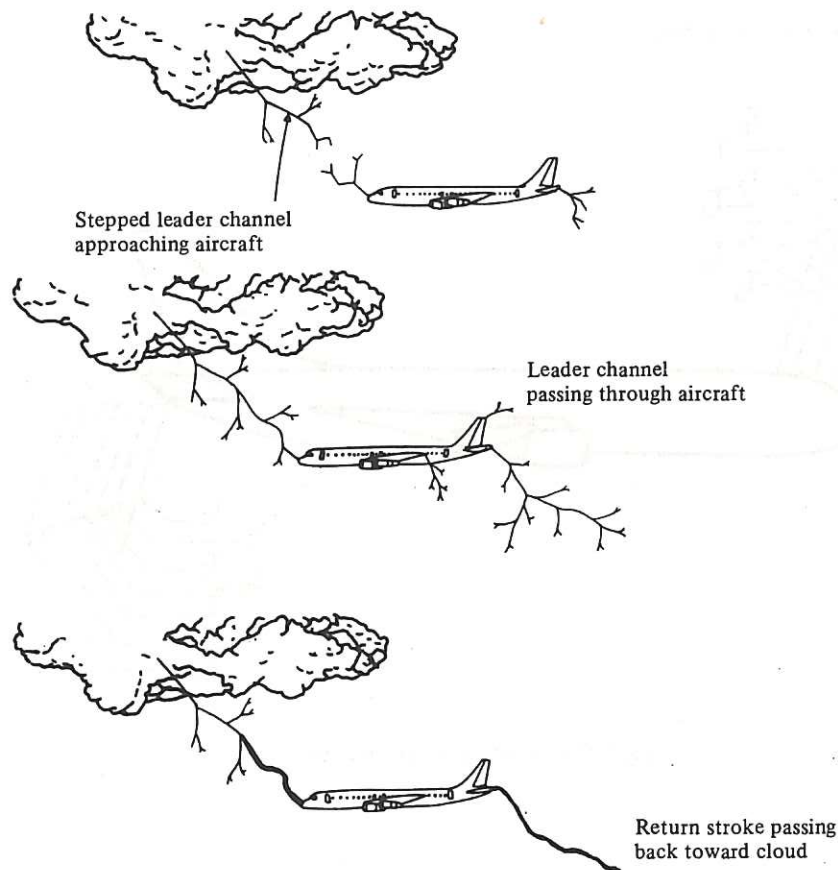
Fig.4 Lightning flash striking an aircraft.

Therefore there will always be at least one entrance and one exit point.
The entry and exit points are termed attachment points. It is not possible
for the aircraft to store any significant amount of the electrical energy
of the lightning flash in the capacitance field of the aircraft. Typically
these initial attachment points are in the high field regions of the air-
craft such as the extremities including nose, wing tip, fin and tail unit
tips, protruding aerials, engine pods and propeller blades. The leader

can also attach to the leading edge of swept wings and some control surfaces. (See section 3.7 and Appendix 3).

3.2   Swept Stroke Phenomena

The lightning channel is effectively stationary in space with the aircraft becoming locally part of the channel. However due to its forward speed, the aircraft moves significantly relative to the stationary channel during the channel's existence. When a forward extremity such as a nose or wing mounted engine pod are involved the surface moves through the lightning channel. Thus with respect to the aircraft the lightning channel is swept back over the surface as illustrated in Figure 5.
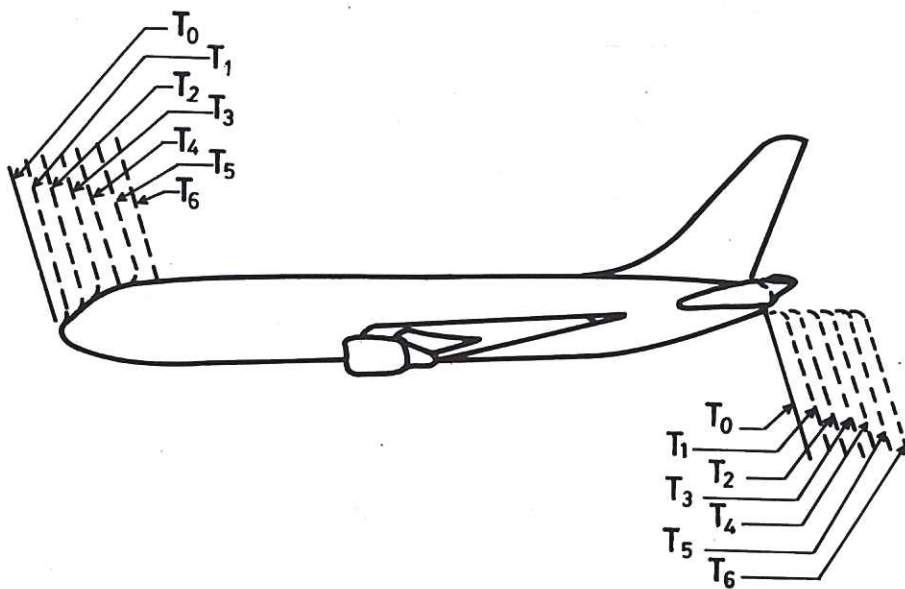
Fig.5 Swept stroke phenomenon.
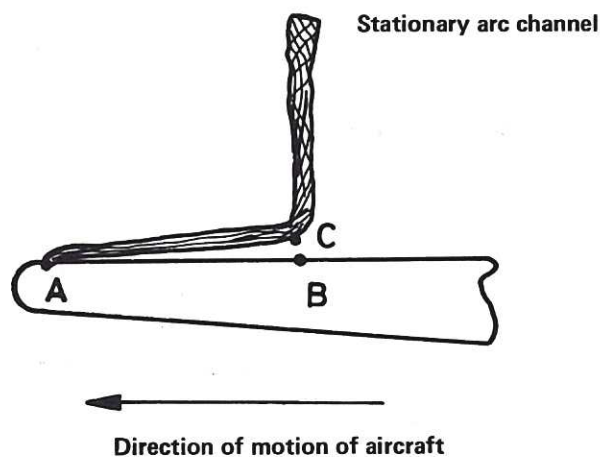
Fig.6 Swept stroke configuration.

The basic mechanism of re-attachment is shown in Figure 6. The arc first attaches to point A and then as a result of the movement of the aircraft the configuration shown in Figure 6 will occur. There is then a possibility of a re-attachment to the surface at point B if the voltage across the gap BC is sufficient to break down the air gap and any insulating coating on the surface. The dwell time is therefore a complex function of the local geometry, nature of the surface, the current waveform and the speed of the aircraft. Consequently the attachment point may dwell at various surface locations for differing periods of time thus resulting in a skipping action which produces a series of discrete attachment points along the sweeping path or possibly in the case of an uninsulated surface a 'skidding' across that surface. The other initial attachment point often occurs to a trailing edge and therefore carries the full current associated with the flash.

The amount of damage produced at any point in a swept stroke region is related to the type of material, the arc dwell time at that point and the waveform of the lightning current. Both high peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce re-attachment of the arc at a new point because:

(a)   the magnitude of the voltage across gap BC is large due to the large inductive component, and

(b)   if the flash is discontinuous for a brief period a new leader will travel along the previous channel since it will still be hot. Consequently a high electric stress can be produced at the aircraft surface. The resulting voltage could be higher than the inductive voltage produced by the changing current and consequently puncture of non-metallic surfaces or dielectric coating is more likely to occur.

When the lightning arc has been swept back to a trailing edge it may remain attached at that point for the remaining duration of the flash. If an initial attachment point occurs at a trailing edge then of course that particular attachment point cannot sweep.

The significance of the swept stroke phenomena is that portions of the air-craft that would not be targets for the initial attachment of a lightning flash may nevertheless be involved in the lightning flash process as a result of the rearward sweeping action. Under these circumstances it should

be noted that except at trailing edges it is unlikely that the total energy
associated with the flash will flow into one point. For this reason it is
convenient to identify the basic failure mechanisms of the aircraft's
system, structure or equipment and to divide the aircraft surface into
zones for damage and assessment purposes. (See sections 3.3 - 3.7). Some
further discussion of swept strokes is given in sections 4.1, 4.2 and 4.3.

3.3   Effects on Aircraft

The effects on the aircraft which should be simulated by laboratory testing
can be divided into two groups referred to as group 1 and group 2. The
need to divide the lightning effects into two groups is primarily brought
about by laboratory facility limitations. Group 1 items cover those
effects such as burning, eroding, blasting and structural deformation (where
the rise time of the pulse is relatively unimportant) as well as the high
pressure shock waves and magnetic forces produced by the associated high
currents. The group 2 effects are predominately those resulting from the
electromagnetic field associated with the lightning current and its inter-
action with the electrical apparatus in the aircraft and are essentially
associated with high peak current and high rate of change of current. It
is therefore desirable to identify in general terms the relationship
between the two groups of effects and the corresponding parameters.
Appendix 2 gives a summary of the group 1 and group 2 effects and the para-
meters of the lightning flash most closely associated with each effect.

Hazardous field effects could in principle be produced by a lightning flash
that did not directly contact the aircraft and hence there would be no
group 1 effects. For instance it is believed from experimental observations
that at frequencies approaching HF (3 to 30MHz) the return stroke is not
the phase of the flash during which the strongest electromagnetic fields
are generated. These strong fields occur during the leader processes, i.e.
before and between strokes. However all the recommended waveforms simulate
various aspects of the return stroke alone and therefore the effects on
group 2 components at higher frequencies may be underestimated. The relevance
of this effect is unknown because it is not yet possible to quantify the
effect.

3.4   Group 1 Effects

The nature of the particular group 1 effects depends upon the component
involved (in particular its location and physical properties) and the
particular phase of the lightning flash.

3.4.1 Burning and Eroding

The burning and eroding of metallic surfaces is mainly coulomb dependent. Therefore the continuing current phase of a lightning flash can cause severe burning and erosion of the aircraft structure. The most severe damage occurs when the lightning channel dwells or hangs on at one point on the aircraft for the entire period resulting in holes of up to several centimetres in diameter depending on material thickness and composition.

3.4.2 Disruptive Pressure

The high peak current phase of the lightning flash transfers a large quantity of energy in a short period of time. This energy transfer which is proportional to the action integral can result in fast thermal vaporisation of material. If this occurs in a confined area a high pressure may be created which may have sufficient magnitude to cause structural damage. This damage mechanism is applicable to composite panels as well as major components such as radomes.

3.4.3 Magnetic Force

During the high peak current phase the flow of current through sharp bends, corners of aircraft structures or arc roots can cause severe magnetic forces to be produced. In certain cases the resultant magnetic forces can twist, rip or distort structures away from rivets, screws and other fasteners. These magnetic forces are proportional to the square of the magnetic field intensity and thus proportional to the square of the lightning current. The effective force is therefore a function of the action integral and the mechanical response of the component.

3.4.4 Ignition Hazards

Fuel vapours and other combustibles may be ignited by a lightning flash in several ways as indicated below:

(a)   It is possible for the lightning current to burn through thin metallic skins over a fuel tank (see section 3.4.1) or alternatively to produce a local hot spot which might cause ignition.

(b)   The flow of current through a poorly bonded aircraft can cause sparking. The degree of sparking is probably related to the local peak current density, the rate of change of current and the action integral. (See section 3.5.2).

(c)   It is possible for transient voltages to be induced by the
           lightning current into the aircraft's electrical system. (See
           section 3.5.1). This voltage could appear on the electrical
           wiring within the tank and could cause insulation failure thus
           resulting in sparking.

(d)   During the prestrike phase high electrical stresses around the
           aircraft produce streamers. If streamering occurs near a fuel
           vent when ignitable vapours are present there is some limited
           evidence to suggest that ignition can occur.

3.4.5   Mechanical Shock

The air channel through which the lightning flash propagates is nearly
instantaneously heated to a high temperature approximately $30,000^{\circ}C$. When
the resulting shock wave impinges upon a surface it may cause mechanical
damage. It should be noted that this over-pressure wave falls rapidly as
the shock front propagates outward from the lightning channel.

3.5   Group 2 Effects

Group 2 effects are those where the important parameters producing the
effect are associated with the peak current, the rate of change of current
during the rise time and the duration of the pulse. These effects are
mainly associated with transient voltages in aircraft wiring and sparking
resulting from current flow through poorly bonded structures.

3.5.1   Induced Voltages in Wiring

The metallic structure of the aircraft does not provide a perfect Faraday
cage or electromagnetic shield and therefore the magnetic fields associated
with the lightning current can penetrate the aircraft in two ways:

(1)   The flux can penetrate directly through apertures or non-metallic
           sections so producing direct flux coupled voltages. The magnitude
           of this voltage will be proportional to the rate of change of
           current, i.e. di/dt. The system response to this voltage will
           be a function of the voltage-time characteristic and will be
           proportional to the second derivative of the current, d^2i/dt^2.
           The manner in which the system responds will also depend upon
           the number of restrikes and the interval between them. This is
           particularly important for digital systems. From the comments
           made in section 3.3 regarding the strongest electromagnetic

fields being associated with the various leader phases it follows
that using the recommended waveforms for induced voltage testing
may underestimate the effects at high frequencies. This could
be serious because of:

(a)   the increasing move to composite material constructions, and

(b)   the operational use of sensitive solid state circuitry.

At this stage no recommendations can be made.

(2)   The field can diffuse through the metallic skin of the aircraft
and hence produce a resistive voltage drop along the inner surface.
This may inject a voltage into circuits using the airframe as a
ground return or may set up electrical stress between circuits
and the airframe. Owing to the skin effect the current is
initially constrained to the outer surface and then diffuses in-
wards so that the resistive voltage drop along the inner surface
exhibits a time delay relative to the current pulse. The
important parameters are the peak current density, the shape and
duration of the pulse and the characteristics of the metallic
skin.

In general terms the first mechanism is likely to produce larger voltage
transients with a higher frequency content than the second. It can be seen
that the important parameters associated with induced voltage studies are
peak current, di/dt, d^2i/dt^2 and the number of restrikes.

3.5.2   Sparking

Fast pulse currents rising in about 5μs flow in the top surface of good
electrical conductors to a depth of only 0.5mm in aluminium alloy and the
current density is not necessarily constant over the conductor surface.
If the surface of two plates forming a joint, e.g. a filler cap, have a
thin insulated coating the current has to take a very tortuous path.
Consequently inductive voltages proportional to di/dt can exist between the
two plates. Although sparking is initiated by the high di/dt component
it is possible that most of the damage could be caused by some of the later
intermediate current component flowing through the spark channels. It
should be noted that although bonding may be adequate at low frequencies
(that is, the d.c. resistance of the bond is low) it may not be adequate
for lightning currents because of the inductive effects.

3.6   Lightning Effects and Electrical Parameters

Appendix 2 gives a summary of the group 1 and group 2 effects and the electrical parameters of the lightning flash most closely associated with each effect.

3.7   Aircraft Zoning

In order to make an assessment of the damage likely to result from a lightning strike it is convenient to divide the aircraft into regions or zones. It is then possible to define the lightning current waveform that will be associated with that zone. Appendix 3 which gives the details of the zoning concept takes into account the initial attachment and the swept stroke effect.

3.8   Effects on Personnel

One of the most troublesome effects on personnel is flash blindness. This often occurs to flight crew members who may be looking out of the aircraft in the direction of the lightning flash. The resulting flash blindness may persist for periods of up to 30 seconds or more rendering the crew member temporarily unable to use his eyes for flight or instrument reading purposes.

Serious electrical shocks may be caused by current and voltages conducted via control cables or wiring leading to the cockpit from control surfaces or other hardware struck by lightning. Shock can also be induced on flight crews under dielectric covers such as canopies by the intense thunderstorm electric fields. This generally occurs without puncture to the dielectric covering. No particular recommendations are made for any tests to cover these phenomena.

4.   RELATIONSHIP BETWEEN AIRCRAFT STRUCTURES, LIGHTNING ATTACHMENT
         LOCATIONS AND CURRENT PARAMETERS

4.1   Introduction

In this section the relationships between the aircraft structure including systems and the location of the lightning attachment points and the current parameters are examined. In Appendix 1 an equivalent current test waveform is defined as having four components. In general it is technically difficult to generate all four components in one waveform and it is not obvious that there is a requirement so to do.

A major problem in deciding the level of severity to which a component

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should be tested is to determine the duration of lightning attachment to one point (the 'dwell time') in the swept stroke zone of the aircraft (zone 2). The dwell time is a complex function of the waveform, the local geometry, the nature of the surface and the speed of the aircraft. As described in sections 3.1 and 3.2 above the mechanism of the arc attachment is fundamentally different from those in zone 1.

4.2 Application of Current Test Waveforms in Various Zones

Appendix 4 gives the recommended current component requirements for testing group 1 and group 2 effects in the various zones. Tests should be applied in the order given. However, under many circumstances not all the current components need to be applied in one waveform. (See section 4.3). Since current flows in zone 3 only by conduction from other zones and there is therefore no arc attachment point, current for zone 3 tests should in all cases be applied through a solid connection not an arc.

Prior to the commencement of a test programme the proposals for the tests which are to be made to given structures in given zones should be agreed with the appropriate airworthiness authorities.

4.3 Combination of Current Components

It is technically difficult to generate the four current components in one waveform and it is not obvious that there is a requirement to do so for the following reasons:

(1)   In order to understand the failure mechanism of a specimen it may be necessary to apply the current components singly.

(2)   Appendix 4 gives the current components that will flow through an aircraft structure or specimen in a given zone. However not all the current components will contribute significantly to the failure mechanism and therefore in principle the non-contributing component(s) could be omitted from the tests, e.g. skin puncture of metallic surfaces in zone 1. The 200kA (component A) will not contribute to skin puncture other than roughening the surface. Therefore there is no necessity to produce a waveform which would include component A for this type of test.

Only in rare circumstances will it be necessary to have a four component

waveform; more usually one or two components are all that is necessary to
undertake a valid test. Moreover there are usually only a few specimens
available for testing and consequently a high level of reliability is
required in the operation of the capacitor banks. Such reliability will
inevitably increase the cost of testing.

4.4   The Effects of Dwell Time

Swept stroke attachment point and dwell time phenomena are of interest for
two main reasons. First if there is an intervening non-metallic surface
along the path over which the arc may be swept it may be necessary to know
whether the non-metallic surface will be punctured or whether the arc will
pass harmlessly across it to the next metallic surface. Second the dwell
time of an arc on a metallic surface is a factor in determining if sufficient
heating can occur to burn a hole or form a hot spot capable of igniting
combustible mixtures or causing other damage. Thus over a fuel tank it is
particularly important that the arc moves freely in order that the metal
skin is not punctured or locally excessively heated.

4.5   The Length of Dwell Time

Preliminary experiments in swept stroke simulators suggest that the dwell
time is of the order of 1-20ms for fixed wing aircraft. It is also
generally agreed that a restrike will cause a re-attachment and that the
mean interval between restrikes (or subsquent strokes) is about 50ms. (See
section 2.3.2, Restrike Phase). Therefore when assessing the ability of a
structure in zone 2A to withstand part of a lightning strike, it is necessary
to determine the dwell time, either by conducting some swept stroke tests
(see section 5) or by making a pessimistic assumption that the dwell time
is 50ms which should include 5ms of intermediate current. This latter
assumption is a compromise between the dwell time obtained on swept stroke
simulators and the 145ms described in section 2.3.2, Restrike Phase.

It is important to note that in natural lightning the intermediate currents
can flow at the end of a subsequent stroke (or restrike) so that in
principle each attachment point could have intermediate currents flowing
into it.

5.   HIGH CURRENT TEST TECHNIQUES

5.1   General Observations

In this section it is not intended to detail all the conditions necessary
to conduct a particular test but to identify those conditions which can

significantly affect the outcome of the results. It is possible to achieve a pass or fail condition merely by varying the manner in which the tests are conducted. There must inevitably be a compromise between the constraints imposed by the facility and the natural lightning environment and it is important that the former do not bias the results. In general terms the more extensive the facility the more realistically is the lightning environment simulated. Generally the results of tests using a simple facility are likely to be pessimistic and cause significant over-design. However it is not unknown for a simple facility to give an optimistic answer in terms of the lightning performance of the aircraft system.

5.2 Return Conductor Configuration

The aircraft is in free space when struck with no local return current paths. In the laboratory it is always necessary to have a return path which will of course produce its own magnetic field. This field in a poorly designed rig can interact adversely with the lightning current flowing in the test specimen and so produce totally misleading results. The location of the conductors is therefore a compromise between the local inductance requirements (facility limitations) and the interaction of the return field with the current in the specimen.

5.3 Arc Testing

5.3.1 Stationary Arc Testing

The test currents are usually delivered from a test electrode positioned vertically above the test specimen thus giving greater arc stability. The electrode material should be a good electrical conductor with the ability to resist the erosion produced by the test currents. Brass, steel, tungsten and carbon are suitable materials. If the test arrangement has a long electrode gap (over 50mm say) a fine fuse wire (say 0.1mm diameter copper) may be used to initiate the discharge without adversely affecting the results. When designing rigs for open arc testing the following properties of arc should be remembered:

(1)   Arcs can interact with magnetic fields to produce motion so the return conductor configuration is important.

(2)   Jets of metallic plasma are emitted from the anode and cathode electrodes. These jets should not be allowed to interact with each other since with short arc testing their interactions tend to produce enhanced burn-through. With long arcs where there is

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virtually no direct interaction the burn-through time tends to increase. The interacting jets also tend to increase the spread of results.

(3)   Painted surfaces have the effect of concentrating the arc root and thus require less energy to produce puncture.

A solution to item (1) above is to have multi-return paths so arranged that the individual return fields summate to near zero in the region of the test piece.

Problems associated with item (2) can be overcome by attaching 'fire clay' to the HV electrode thus producing sideways jets. It is also recommended that an electrode spacing of at least 50mm be employed.

The polarity of the pulse is unimportant since the conditions which are necessary from the simulation viewpoint tend to have the same energy density in the arc root for either polarity. It is necessary to record the test current amplitudes and waveforms during every shot. If the tests are being conducted to determine if puncture of the skin will occur a means of detecting the moment of puncture must be employed (such as a light sensitive diode). It is also advisable to record the arc.discharge on high speed cine film to ensure that there are no jet interactions. It can be advant- ageous to record the arc voltage using a low inductance resistive divider. Arc voltages can fluctuate during the pulse and therefore it is advantageous to feed the arc from a near constant current source (inductive store) rather than a fixed voltage source such as a battery bank or a heavily damped capacitor bank. (See section 9).

5.3.2   Swept Stroke Testing

The basic elements for swept stroke testing are usually a rail electrode and a test specimen and a means of moving the arc at the relative air velocity of the aircraft. The relative velocity should include but not be limited to the minimum in-flight velocity of the aircraft. The minimum velocity in general gives the longest dwell times. During these tests the arc voltage fluctuates wildly (from about 300V to 6kV) and therefore it is vital that the arc behaviour is not limited by the output voltage of the generator. Feeding from a near constant current source (inductive store) will overcome this problem. (See section 9).

The spacing of the electrode should permit the arc to move freely over the specimen and permit the arc to take up a natural configuration near the surface of the specimen. The factors which can influence this on the actual aircraft are:

(a)   the thickness of the boundary layer of air,

(b)   the surface finish of the specimen, and

(c)   the local geometry (e.g. rivets acting as stress raisers).

If a restrike is injected into the current pulse then the continuing current must fall to near zero before the restrike pulse appears. (See section 2.3.2, Continuing Current). This is shown in Figure 7. If the test panel is a cathode a continuous track can be produced on bare metal. This has not been seen on aircraft and therefore it is recommended that testing should be conducted with the specimen as an anode.
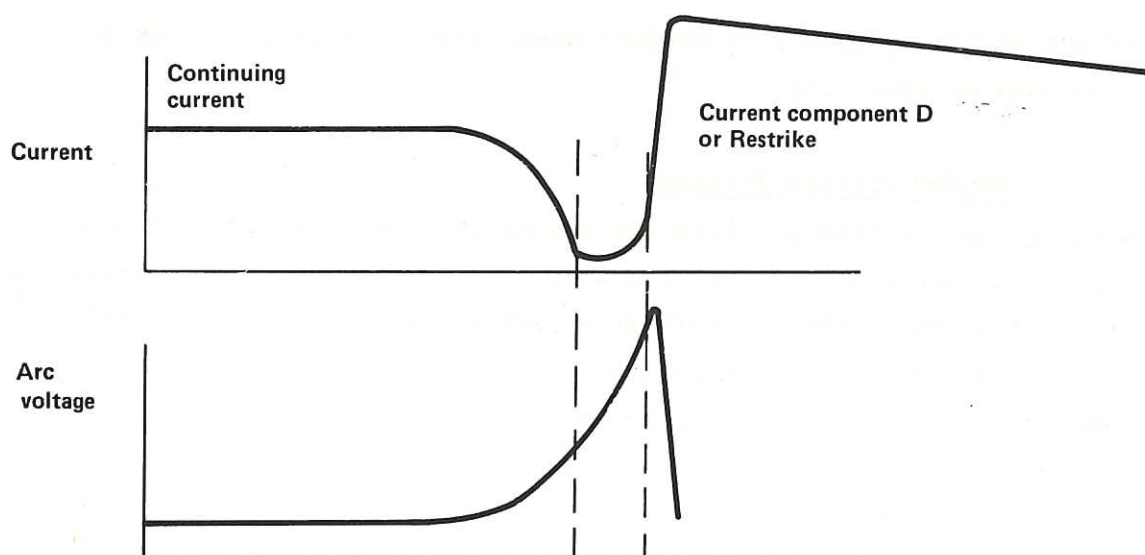
Fig.7 Swept stroke waveforms for tests of non-metallic surfaces.

To determine whether it is possible for dielectric puncture to occur on non-metallic surfaces or coating materials including metallic surfaces with high dielectric strength coatings it is necessary to simulate the high voltage characteristics of the arc. High voltages are caused by:

(a)   current restrikes in an ionised channel, or

(b)   voltage build up along a de-ionised channel.

These characteristics are simulated by a test in which a restrike is applied along a channel previously established by a continuing current. The restrikes must be initiated by a voltage rate of rise of 1000kV/μs or faster (see section 7) and must discharge a high rate of rise current stroke in accordance with Appendix 1. Figure 7 gives a representation of the requirement. Several tests should be applied with the continuing current duration and restrikes applied at differing times in order to produce worst case exposures of the surface and underlying elements to voltage stress.

The most important measurements are those giving the number of attachment points, arc dwell times, breakdown paths followed and the separation between attachment points. These can be determined from high speed cine film of the arc. It is also useful to record the arc voltage since the dwell time can be determined directly from the trace. Measurements should also include the arc velocity and the current waveform.

It is not always necessary to conduct swept stroke tests for items in zone 2A (see section 4.5).

5.4   Induced Voltage Testing

Induced voltage testing involves the use of high rate of rise and high peak current components of the lightning flash and therefore in general the current flows on the aircraft skin surface owing to the 'skin effect'. The values of the current parameters for these tests are given in Appendix 1. The location of the return conductors is of great significance because if they are too close to the test specimen relatively high field values will be produced and significant current may then flow in areas which under free space conditions would carry virtually none. If the return conductors are relatively far from the specimen the circuit inductance will be increased and a much higher voltage generator will be required to drive the recommended currents. As a guide the return conductors should be distributed around the test specimen and the spacing between the conductors and the specimen should be approximately equal to the width of the specimen. For these tests the conductors may be directly connected to the specimen.

To enable the specimen response to be studied the wiring should be terminated with either the actual load or a simulated load impedance associated with the lightning frequencies which are typically 500kHz to near d.c. for the return strokes.

This simulated impedance may be very different from the value normally associated with the operation of the equipment. For instance low frequency power systems may exhibit transmission line characteristics resulting from shock excitation by lightning induced voltages. Conversely RF systems may exhibit lumped constant effects because the normal operating frequency is higher than the frequencies produced by the lightning transient.

Great care must be exercised in deciding the physical circuit arrangement of the diagnostic equipment to the aircraft system in order to ensure that the diagnostic equipment is not influencing the system response. Interference free operation of the voltage measurement system should be verified by measurement of the voltage with the test specimen disconnected and the measurement system open circuited and then short circuited in the vicinity of the test object. Care must be taken to ensure that the measured signal is not being derived from the noise associated with the breakdown of the spark gaps which switch the capacitor bank. Measurements must include the current waveform, its derivative and the induced voltage signal.

It is possible to conduct tests at currents below the maximum parameters and then scale the results (see sections 3.5.1 and 8). Resistive voltages developed as a result of lightning currents flowing in all zones should be scaled to 200kA. Direct coupled voltages in all zones should be scaled to 100kA/μs. There may however be some non-linear elements in the system such as a breakdown of a diode junction or arcing paths affecting the current distribution which could invalidate the results and this effect must be taken into account. This indicates the need for conducting the tests at realistic current levels.

5.5 Fuel Vapour Ignition Testing

If a complete fuel tank is not available or impracticable for test a sample of the tank skin or other specimen representative of the actual structural configuration (including joints, fasteners, substructures, fuel tank fixtures and internal and external surface finishes) should be installed on a light-tight opening or chamber. A photographic method is probably the most reliable method of detecting sparking. The chamber should be fitted with an array of mirrors to make sparks visible to the camera and all extraneous light to the chamber must be excluded. The camera is placed in the test chamber and the shutter left open during the test. Experience indicates that ASA3000 speed film using an aperture of f/4.7 is satisfactory. Any light indications on the film due to external sparking after tests should

be taken as an indication of sparking sufficient to ignite a combustible mixture.

The use of a stoichiometric mixture method for proving the ignition hazard is not recommended because of the statistically unpredictable nature of fuel ignition.

6.   STRIKE POINT LOCATION TESTING

6.1   Introduction

The reason for undertaking these tests is to attempt to establish the probable distribution of attachments points:

(a)   around an aircraft, and

(b)   to a large item (e.g. a radome). (See section 7).

The available information on the aircraft leader interaction is very limited and opinions differ on the mechanisms involved. In addition the similarity between laboratory long path breakdown processes and natural lightning has not been conclusively established. The views expressed below particularly on aircraft model testing are therefore a compromise which may be unaccept-able to some specialists. In any case such tests can only give guidance on attachment points and can never truly represent the variety of natural phenomena encountered by an aircraft in flight and such test results should therefore be used with caution.

6.2   Leader Attachment to Aircraft

The qualitative description of the attachment process is given in section 3.1. However in order to simulate the effects in the laboratory it is necessary to know the rate of rise of electric stress on the aircraft just prior to leader attachment. This information is not known but the time between the commencement of significant air discharge activity at the aircraft and the actual attachment is believed to be between 1 and 500µs.

6.3   Long Path Breakdown

The impulse breakdown of long air gaps is influenced appreciably by the polarity and waveshape of the applied voltage. With a fixed gap length and increasing rise time it is found that with positive rod/plane gaps the breakdown voltage is a minimum with a rise time of 100 to 150µs. Another significant difference between positive and negative polarity breakdown is the spread of breakdown paths. With a positive rod electrode the breakdown paths are very widely spread whereas with a negative rod electrode the breakdown paths are well contained. If an isolated body is

introduced between the HV electrode and the earth plane the position of the body in the gap can significantly affect the distribution of attachment points to it depending on whether the upper or lower gap is bridged first.

Impulse voltage waveforms are described in terms of the time parameters of the rise from zero to crest and the decay after crest. These time parameters are defined in the International Recommendations on High Voltage Test Techniques, IEC Publication 60-2 (1973). An impulse voltage designated 'a/b' has time parameter 'a' for the rise to crest (front) and 'b' for the time to half value on the decay (tail) expressed in microseconds and measured from a virtual origin which is also defined in the IEC Recommendations. The waveshape is abruptly terminated when breakdown occurs and the time to breakdown is measured from the virtual origin to the instant of voltage collapse.

6.4   Model Aircraft Lightning Attachment Point Tests

For these tests a model aircraft is suspended between an HV rod electrode and a ground plane. The test voltage will usually be produced by a high voltage impulse generator and will simulate the electric field produced by lightning but not the lightning current. A large model is preferred since it reduces the scaling errors associated with the corona discharges on the sharp edges. However the models must not be so large relative to the rod plane gap as to affect the breakdown processes at the HV electrode. Similarly the model must not be so close to the ground plane as to cause bridging of the lower gap before the top gap is bridged since it is believed that this will influence the distribution of attachment points. In the UK it is generally agreed that the top gap should be 0.4L where L is the total gap length and the bottom gap should not be less than 2.5d where d is the largest dimension of the model. This is depicted in Figure 8. By assuming a practical limit to the test voltage of 3MV and a switching surge impulse where the total gap between the electrodes is about 6m for negative polarity for 90% probability of breakdown; the upper limit of d is about 1.1m. This of course implies a rather small scale for a large aircraft and concern about the corona scaling can justifiably be expressed.

It is desirable to allow sufficient time for streamers from the model to develop. The development of these streamers will be a function of the rate of rise of voltage which for a given waveshape is affected by the degree of prospective over-voltage across the gap. The variation of pressure around an aircraft is of course not simulated on the model.

Typical values

Model dimension d = 1.1 m
Total gap = 6.0 m
Voltage required
V_{90} = +1.4 MV or −3.0 MV

H.V. Electrode
Switching impulse
(200/ 2000)
either polarity

0.4L

L

Model aircraft
d = largest dimension of model

≮ 2.5 d

Ground plane

10 d
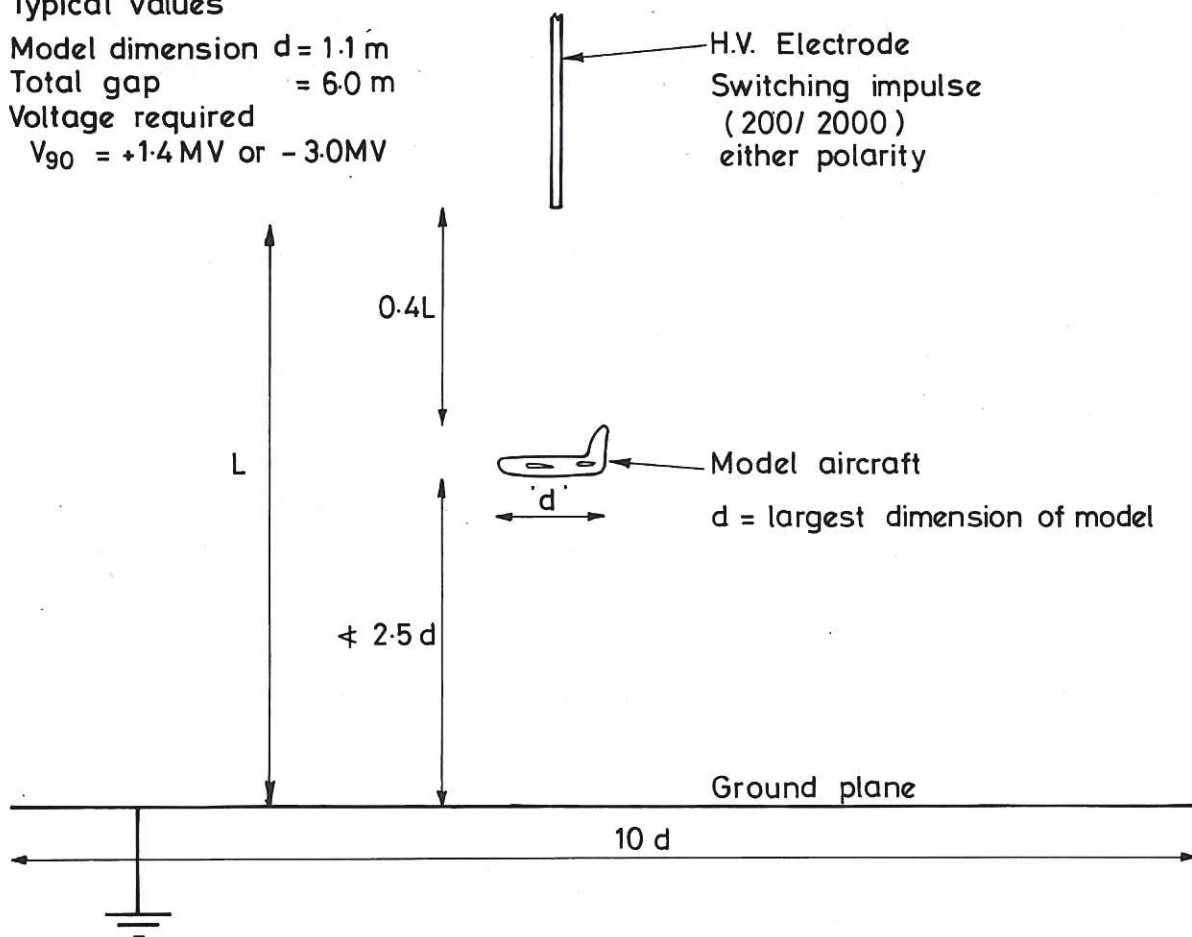
Fig.8 Diagram showing experimental arrangement for strike point location studies.

This pressure variation will affect the corona inception voltage and there-
fore the pattern of streamer development. Because of uncertainties
concerning the rate of rise of stress, the effect of pressure variation and
the validity of scaling breakdown paths there is a divergence of opinion
as to the most suitable waveform to be used for model testing. The UK view
is that a long fronted wave (i.e. 200/2000μs wave) is more representative
of the naturally occurring conditions and should give a higher strike rate
to the low probability region than otherwise might have been expected.
Hence the answer is likely to be pessimistic. The UK recommended conditions
are set out in Appendix 6.

In the past tests have often been performed only with a negative 1.2/50μs
wave which could be expected to give a small variation in breakdown paths.
This method of testing may have resulted from the use of a standard 1.2/50
voltage wave for simulating post breakdown lightning phenomena on ground
power transmission equipment.

An accurate model of the aircraft's exterior should be constructed to a scale determined from the considerations given in Appendix 6. This should include the various possible aircraft configurations. The model's surface should be totally conducting however the model could in principle be made from insulating material which is then metal sprayed.

The orientations of the electrodes with respect to the model should be such as to define all likely attachment points. Typically the electrodes relative to the model are placed at 30° steps in the roll, yaw and pitch planes but exploration in other planes is also desirable. Smaller steps may be required to identify all attachment zones. If rotation of the model significantly changes the gap length it may be necessary to reposition the electrode. Typically three to ten shots depending on the scatter of the results are taken with the aircraft in each orientation.

Photographs preferably with two cameras at right angles to each other should be taken of <u>each</u> shot in order to determine the attachment points. The test voltage waveform applied to the gap should be measured. It is not necessary to take photographs of every test voltage waveform during the test sequence if the circuit parameters of the impulse generator and the length of the total air gap and model remain unchanged.

7.   FULL SIZE HARDWARE ATTACHMENT POINT TESTS

7.1   Introduction

Tests may be required to be conducted on full size hardware to determine either for good dielectric materials the path taken by the lightning arc in reaching a metallic structure, e.g. a radome, or the detailed attachment points on external conducting surfaces, e.g. a diverter rod over a fuel vent outlet. The test conditions for these two items should not necessarily be the same if valid results are to be achieved.

The voltage generators used for these tests are high impedance devices and therefore the test current will be much less than natural lightning currents. Consequently much less damage to the test object will result compared with a natural lightning strike but nevertheless the breakdown of the laboratory gap will follow the path a natural lightning stroke would have taken.

7.2   Hardware Detail

The test object should be a full-scale production line hardware item or a representative prototype since minor changes may invalidate the lightning

test results. All conducting objects within or on non-metallic hardware that are normally connected to the airframe when installed should be electrically connected to any surrounding metallic structure or equipment. In addition surrounding external metallic aircraft structure (or scenery) should be simulated and attached to the test object to make the entire test object as much like the actual aircraft region under test as possible.

7.3 Dielectric Testing

This type of testing is designed to cover items such as radomes where the criteria of success is that the discharge may be allowed to come in contact with the dielectric material but must then pass harmlessly across its surface to a metallic structure rather than puncturing the dielectric surface. With this criterion the purpose of the test is to determine the puncture/flashover characteristics of the hardware. In general terms the short fronted wave 1.2/50 stresses the dielectric material more than a long fronted wave and in addition surface flashover takes time to become established. Therefore it is considered that the short fronted is the most appropriate test voltage waveform for items such as radomes. Tests should be conducted with both polarities.

With this form of testing it is probably more important to ensure that the electric field distribution around the specimen simulates the in-flight condition rather than ensuring that the pre-breakdown streamer activity is correct. Therefore in general terms the specimen should be directly connected to earth. Earthing the specimen has the added advantage that more reproducible results between laboratories are likely to be achieved. The details of the test conditions are given in Appendix 7.

7.4 Conducting Hardware Testing

This type of testing is designed to determine the level of protection afforded to metallic surfaces by the addition of metallic rods. An example of this would be a diverter rod over a fuel vent outlet. The criteria for this form of protection is that the lightning should under no circumstances reach the protected area. It is therefore necessary to simulate the conditions that occur immediately prior to a lightning attachment. For these conditions this is best achieved with a long fronted wave (200/2000). Moreover the lateral spread of leader development is greater for long fronted impulses than it is with short fronted impulses thus increasing the strike probability to the low field region. The details of the test conditions are given in Appendix 7.

With this form of testing it is probably more important to ensure that the streamer activity simulates the in-flight conditions rather than the electric field distribution. It is felt that this can be more realistically achieved by having a small gap or resistor between the test object and the return side of the generator. This will have the effect of reducing the streamer activity to a realistic level. However there is considerable uncertainty about the size of the gap or the value of the resistor therefore in order to achieve reproducible results it is recommended that the specimen should be earthed directly. The details of the test conditions are given in Appendix 7.

7.5   Size of HV Electrode

It is important to simulate the approaching leader which could be up to 5m in diameter just prior to its contact with the aircraft. With full size hardware testing where the HV electrode is unlikely to be more than 3m away from the specimen the simulation is probably more realistic if a large plate electrode is used instead of the more commonly proposed rod electrode. The use of a plate electrode has the additional benefit of increasing the surface electric field at the test specimen for a given distance and voltage compared with a rod electrode.

8.   COMPLETE AIRCRAFT TESTING

The objective of these tests is to determine the level of induced voltage and current in the electrical and avionics systems within a complete air-craft primarily to identify system incompatibilities.

Whilst an aircraft's sub-system may be tested in the laboratory to the full lightning severity it is not always easy to establish how the sub-system will interact with the rest of the aircraft systems. It is however impossible in terms of realistic equipment to produce the full natural lightning current in an aircraft due to the circuit inductance limitations. The results obtained should therefore be scaled either to 200kA for resistive voltages or 100kA/μs for direct flux coupled voltages but it should be noted that this will not take account of non-linear effects (such as electrical breakdown of insulation or arcing paths). It is doubtful if valid results can be obtained with currents less than 4kA and rates of rise of current less than 2kA/μs due to poor signal to noise ratios.

The generator connections to the aircraft should be made to the probable

attachment points. Since lightning strikes occur at differing points the test current should be applied between several representative pairs of attachment points such as nose to tail, wing tip to wing tip. Multiple return conductors should be used to reduce the overall circuit inductance and to give a more representative field distribution around the aircraft.

The test current amplitude, waveform and resulting induced voltages in the aircraft electrical and avionics systems should be measured. Interference free operation of the voltage measuring system should be verified by measurement of voltage with the test specimen disconnected and the measurement system open circuited and then short circuited in the vicinity of the test specimen. Great care must be exercised in determining the physical connection arrangement of the diagnostic system to the aircraft system in order to avoid significant induced voltages being generated in the connection itself.

It should be noted that when undertaking tests on complete aircraft it is essential to ensure that there is no risk of fuel tank explosion resulting from the passage of the simulated lightning current through the aircraft. There is always the risk that as a result of these tests there may be undetected damage to electronics or other equipment.

9.   HIGH CURRENT WAVEFORM GENERATION

9.1   Circuit Configuration

For the current component parameters given in Appendix 1 the energy requirements and circuit performance can be specified assuming the use of capacitor banks as energy storage devices with unidirectional waveforms. These are obtained by either short circuiting (or clamping) the banks at peak current (inductive energy storage) or by critically damping the circuit. The latter method considerably eases the problem of the timing of the switches but it is a more expensive system due to the high capital cost associated with the larger energy requirements.

The circuit for producing a clamped waveform is shown in Figure 9 together with the waveform produced. The principle of operation is that the start switch is closed discharging the capacitor bank into an underdamped circuit. At the first current peak the clamp switch is closed and since most of the energy is in the inductance of the circuit and the clamp leg has a low impedance the current decays unidirectionally around the clamp circuit and load inductance. There is of course the complication of timing the
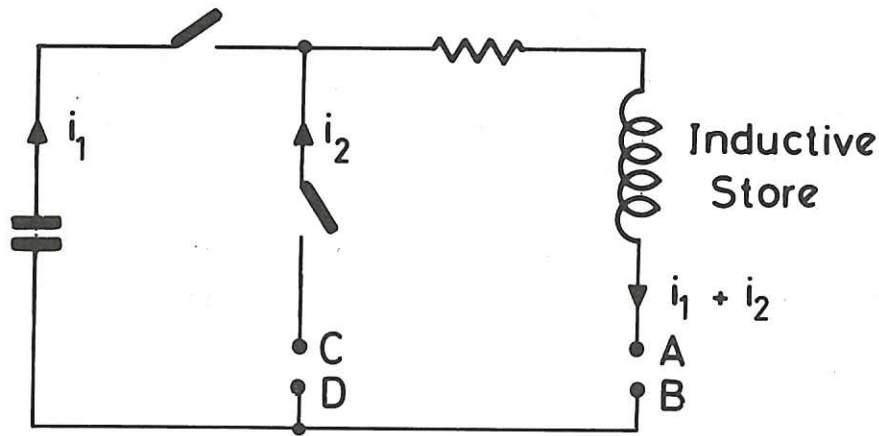
Specimen in either position AB or CD
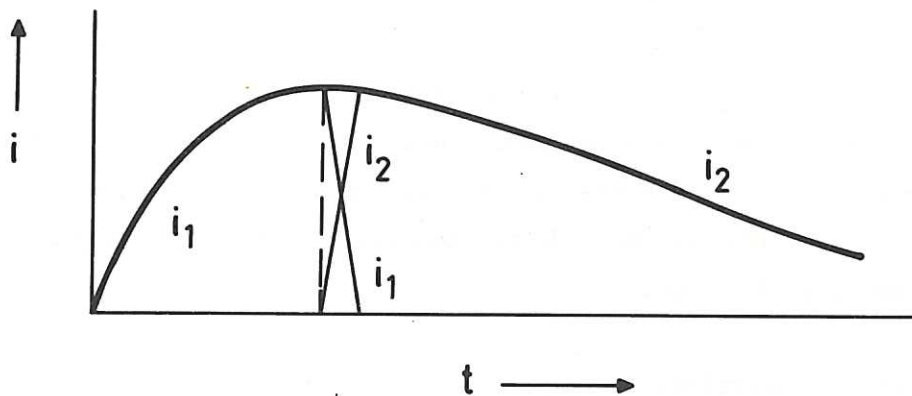other position being shorted.

Fig.9 High current circuit configuration and waveforms.

clamp switch though for the intermediate and continuing current the clamp
switch can be replaced with a diode stack. The major advantage is that
an arc fed from a clamp system is essentially fed from a constant current
source so enabling the arc to take up any configuration without any voltage
limitation.

The test specimen can be mounted in either the start circuit position AB
(necessary for the fast component) or in the clamp switch leg position CD
(for the intermediate and continuing currents). The latter concept is
particularly useful because it gives a short rise time to the intermediate
and continuing currents (about 0.5ms).

9.2   Fast Current Waveform

The requirement is for a 200kA peak current and an action integral of
$2 \ 10^6 \ A^2 s$. A total circuit inductance of 6µH has been assumed and an arc
voltage as high as 8kV. These conditions can be met with either a clamped

system with the specimen in position AB using a 120kJ, 76kV capacitor bank or a critically damped system using an 892kJ, 131kV bank.

9.3   Intermediate Current Waveform

The requirement is for an average current of 2kA and a charge transfer of 10C within 5ms. Assuming an arc voltage of 6kV (for swept stroke testing) the conditions can be met with either a clamped system with the specimen in position CD using a 60kJ, 15kV capacitor bank or a critically damped system using a 75kJ, 15kV bank.

9.4   Continuing Current Waveform

The requirement has been assumed to be 0.8kA decaying linearly (due to an open arc) to zero in 0.5s, i.e. an average current of 400 amps for 0.5s. This can be achieved with a 100kJ, 15kV clamped capacitor bank system with an assumed arc voltage of 500V. Alternatively a battery bank or a transformer/rectifier system could be used. However to improve the constant current characteristics of these latter systems an inductor should be included in the circuit which enables high transient arc voltages to be produced without extinction.

9.5   Restrike Waveform

The requirement for group 1 tests is a peak current of 100kA and an action integral of $0.25 \ 10^6 \ A^2 s$. The requirement for group 2 testing is a peak current of 100kA with an initial rate of rise of current of 100kA/µs which implies a rise time of about 1.5µs. In general terms it is difficult technically to generate this waveform in one pulse. Since for group 1 testing the rate of rise is unimportant the rise time could be as long as 5-10µs in which case a clamped system could be used with a lower voltage bank. Thus with a circuit inductance of 6µH a 30kJ, 94kV clamped capacitor bank system should give a peak current of 100kA and an action integral of $0.25 \ 10^6 \ A^2 s$.

For group 2 testing a 30kJ, 630kV bank should give a peak current of 100kA with a rise time of 1.5µs in an initial rate of rise of 100kA/µs.

9.6   Performance

The performance of these circuits is given in detail in Table 1. The advantage of the clamped circuit is that the open arc can be fed from a near constant current source so permitting the arc to have any voltage drop thus not limiting its motion.

Circuit Configuration	Current Components	Stored Energy kJ	Capacitance µF	Voltage kV	Circuit Inductance H	Rise Time s	Peak Current kA	Charge Transfer C	Action Integral $10^6 A^2 s$	Exponential Time to 1/e s	Linear Decay Time to Zero Current s
clamped	fast	120	42.1	76	$6\ 10^{-6}$	$25\ 10^{-6}$	200	20	2	$100\ 10^{-6}$	
clamped	fast	120	42.1	76	$6\ 10^{-6}$	$25\ 10^{-6}$	200	15	2		$150\ 10^{-6}$
critically damped	fast	892	104	131	$6\ 10^{-6}$	$25\ 10^{-6}$	200	13.6	1.9	$100\ 10^{-6}$	
clamped	intermediate	60	533	15	$7.5\ 10^{-3}$	$3.1\ 10^{-3}$	4.0	10	0.03		$5\ 10^{-3}$
critically damped	intermediate	75	667	15	$1.5\ 10^{-3}$	$1\ 10^{-3}$	3.7	10	0.03	$3\ 10^{-3}$	
clamped	continuing	100	889	15	0.31	$26\ 10^{-3}$	0.8	200			0.5
clamped	restrike group 1 effects	30	6.8	94	$6\ 10^{-6}$	$10\ 10^{-6}$	100		0.25	$50\ 10^{-6}$	
clamped or oscillatory	restrike group 2 effects	30	0.15	630	$6\ 10^{-6}$	$1.5\ 10^{-6}$	100				

TABLE 1   ENERGY REQUIREMENTS

10. HIGH VOLTAGE WAVEFORM GENERATION

The methods of generating the high voltage waveforms referred to in this document together with the associated terminology and definitions are described in IEC Publication 60-2 (1973) and/or Impulse Voltage Testing BS923.

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12. BRIEF BIBLIOGRAPHY

(1) SAE AE4 Committee; Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware. February 1976 (revised May 1976).

(2) T E James, J Phillpott; Simulation of Lightning Strikes to Aircraft. HMSO, CLM-R111, 1971.

(3) R H Golde, A A Hudson, R D Ibbott, E L White; An Aircraft Lightning Strike Test Facility. ERA 71-167.

(4) E T Pierce, N Cianos; A Ground Lightning Environment for Engineering Usage. Stanford Research Institute Report, 1972.

(5) J Phillpott; Simulation of Lightning Current in Relation to Measured Parameters of Natural Lightning. Lightning and Static Electricity Conference, 1975.

(6) E T Pierce; Natural Lightning Parameters and their Simulation in Laboratory Tests. Lightning and Static Electricity Conference, 1975.

(7) J Phillpott, E L White, D J Tedford, R T Waters, H M Ryan; Lightning Strike Point Location Studies on Scale Models. Lightning and Static Electricity Conference, 1975.

(8) D W Clifford; Scale Model Lightning Attachment Point Testing. Lightning and Static Electricity Conference, 1975.

(9) W Brown, D Conti, C McCartney, S Waterman: A study of the Lightning Strike Protection of Radomes. BAC Report No ST15389, 1976.

13.   BRIEF GLOSSARY

Flash - the name given to the total discharge which has a time duration of 0.2-1.0 seconds.

Stroke - the component discharge of a flash which has a typical duration of 100μs. There are usually three or four strokes per flash, each stroke being separated by 40ms or so.

Leader - each stroke begins with a weakly luminous pre-discharge known as a leader which propagates from cloud to ground and which is followed immediately by a very luminous return stroke.

Restrike - another name for the second and subsequent strokes of a flash.

Fast or High Peak Current Phase - the initial current flow after a leader makes contact with the ground or an upward going leader, typically lasting for 100μs with a peak current of 10-30kA (average) or 200kA (severe).

Intermediate Current Phase - after the initial decay of some of the strokes there is often a low level current of a few kiloamperes that persists for several milliseconds. This current is known as the intermediate current.

Continuing Current Phase - between some of the strokes and more often after the last stroke a continuing current exists for times between 100 and 800ms, during which a current of 100-400 amps may flow.

Action Integral $\int i^2 dt$ - action integral (measured in $A^2 s$) is the energy in any portion of the current path per ohm resistance. It also represents the impulse loading on a mechanical system.

Impulse Charge - the charge associated with a stroke, i.e. high peak and intermediate current phases.

APPENDIX 1

LIGHTNING CURRENT TEST WAVEFORMS

Owing to the complex nature of the various types of lightning discharges
and the limitations of laboratory facilities, it is necessary to define an
equivalent lightning waveform for test purposes that contains the worst
features of the positive and negative discharges to ground and cloud to
cloud discharges. For airworthiness purposes it has been decided that a
four component test current waveform having the parameters shown in Table
A1.1 will in most cases give an equivalent effect to that produced by
natural lightning. This together with grouping of the lightning effects
(Appendix 2), zoning concept (Appendix 3) and the waveform requirements
(Appendix 4) should enable realistic simulation tests to be undertaken.

Table A1.1

Component	Parameter	Value	Tolerance
high current component A	peak current	200kA	± 10%
	action integral	$2 \cdot 10^6 \, A^2 s$	± 10%
	pulse length	< 500µs	
	rise time	< 25µs	
intermediate current component B	average amplitude	2kA	± 10%
	charge transfer	10C	± 10%
continuing current component C	amplitude	200-800A	
	charge transfer	200C	± 20%
restrike (group 1 effects)* component D	peak amplitude	100kA	± 10%
	action integral	$0.25 \cdot 10^6 \, A^2 s$	± 10%
	pulse length	< 500µs	

*   See Appendix 2

This waveform is shown diagrammatically in Figure A1.1. It should be
noted that the continuing current should drop to near zero before the
restrike commences.

In natural lightning the restrike component D may have a rate of rise of
current of 100kA/µs in addition to the parameters listed in Table A1.1.
However, this is technically very difficult to simulate in the laboratory
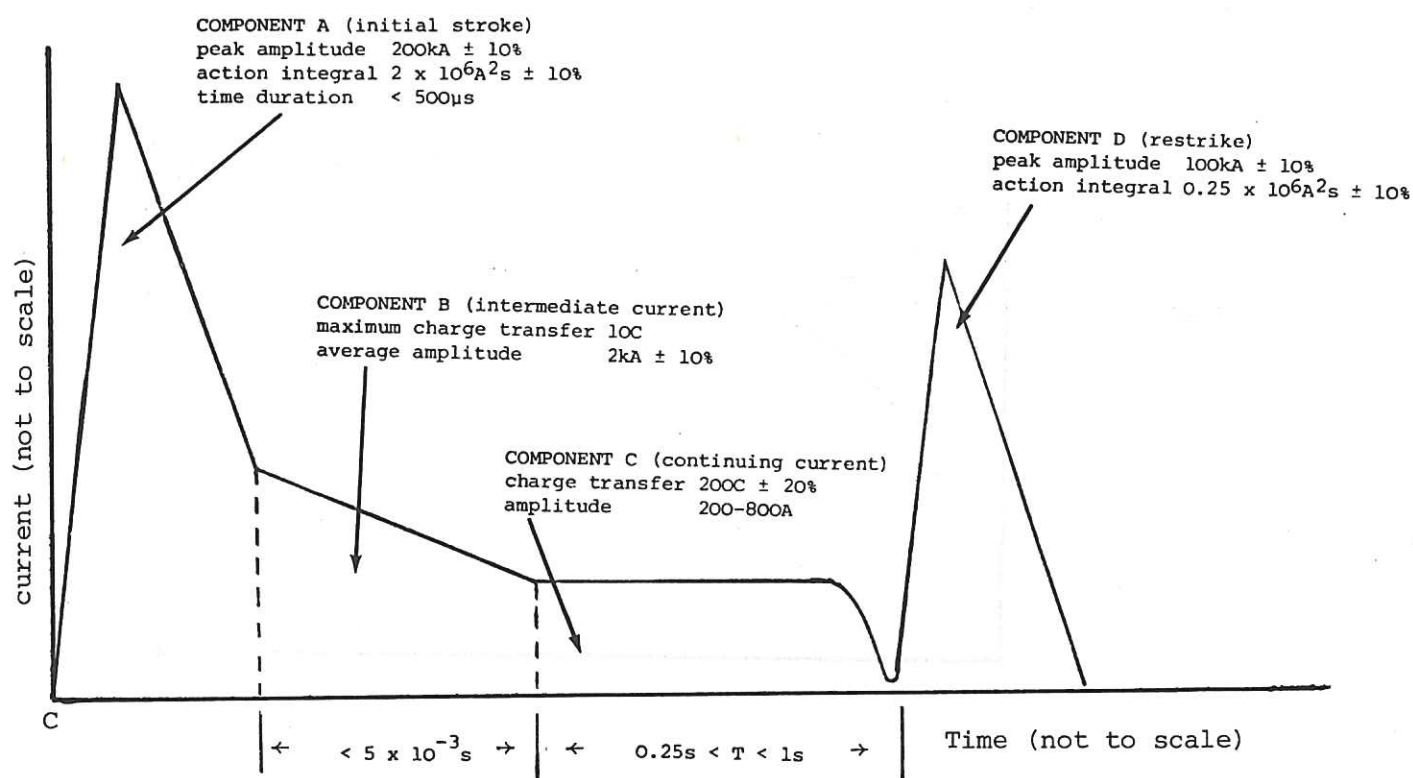in one waveform, but by dividing the lightning effects into two groups

COMPONENT A (initial stroke)
peak amplitude   200kA ± 10%
action integral 2 x $10^6 A^2 s$ ± 10%
time duration   < 500μs

COMPONENT D (restrike)
peak amplitude   100kA ± 10%
action integral 0.25 x $10^6 A^2 s$ ± 10%

COMPONENT B (intermediate current)
maximum charge transfer 10C
average amplitude   2kA ± 10%

COMPONENT C (continuing current)
charge transfer 200C ± 20%
amplitude   200-800A

current (not to scale)

C

← < 5 x 10^{-3} s →   ← 0.25s < T < 1s →   Time (not to scale)

Fig.A1.1 Idealised current test waveform components for evaluation of group 1 effects.

it is possible to overcome this difficulty (see Appendix 2).

Hence for group 2 effects the restrike component should have the parameters given in Table A1.2. It should be noted that when testing physically large aircraft systems it may be necessary to scale the results obtained from reduced level testing. The scaling should not be greater than a factor of five and extreme care should be taken because of non-linear effects (see section 5.4).

Table A1.2

Component	Parameter	Value	Tolerance
restrike (group 2 effects)* component D	peak current	100kA	± 10%
	peak initial rate of rise of current	100kA/μs	± 10%
	time for which di/dt should exceed 25kA/μs	0.5μs	± 10%

*   See Appendix 2.

This waveform is shown diagrammatically in Figure A1.2.

Current

100kA

Time
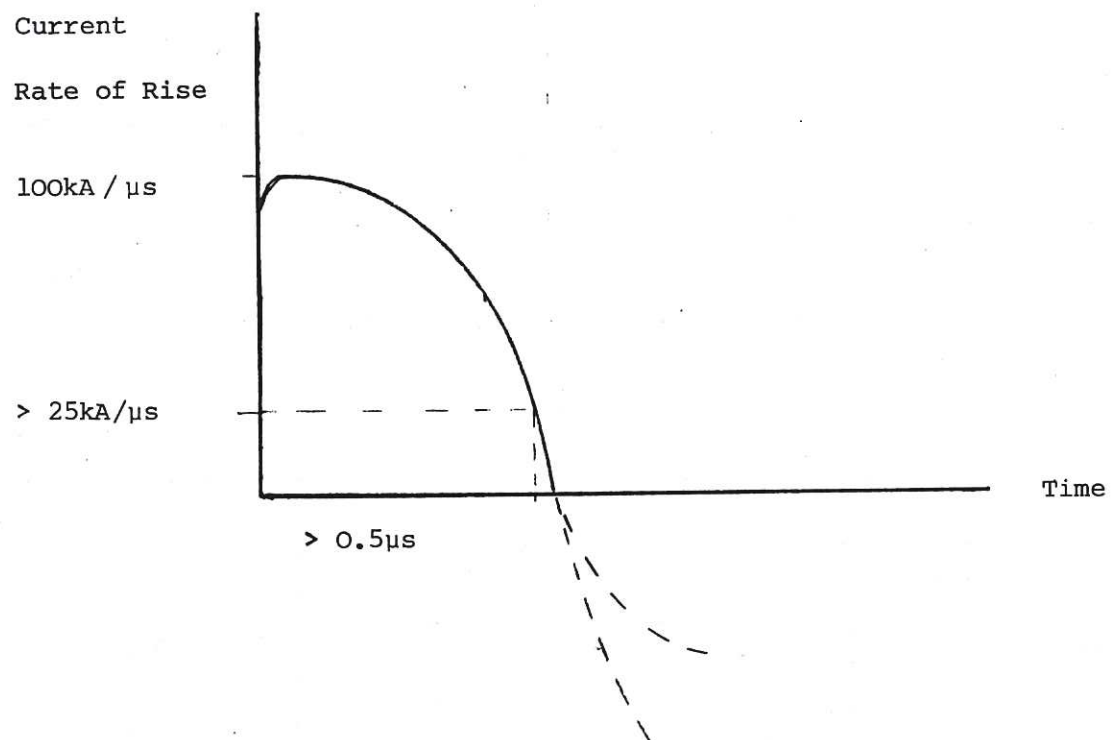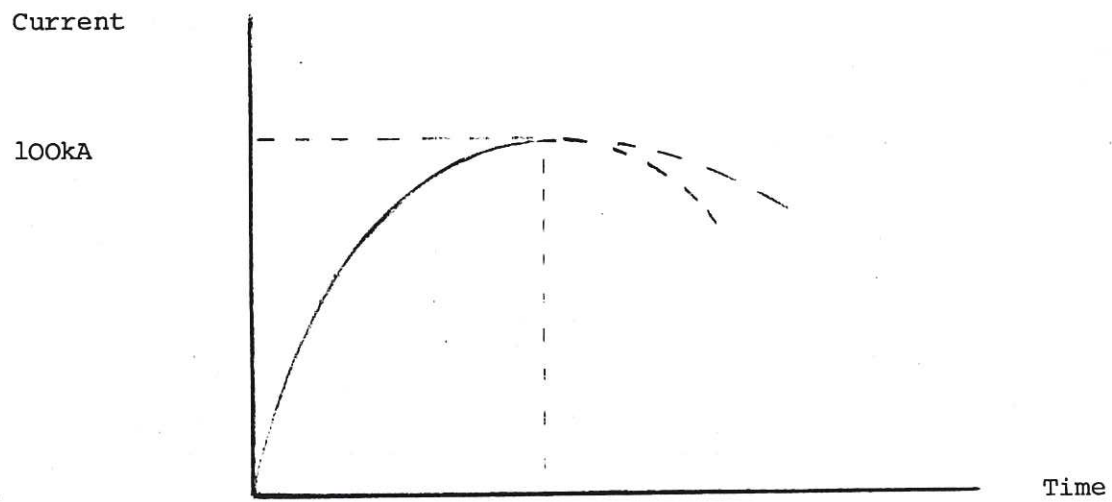
Current

Rate of Rise

100kA / µs

> 25kA/µs

> 0.5µs

Time

Fig.A1.2 Test waveform for calculation of group 2 effects.

LIGHTNING EFFECTS AND ELECTRICAL PARAMETERS

The table below indicates the parameters which are most significant in producing a given effect.

Table A2

Basic Effect	Important Parameter
Group 1 metal skin puncture hot spot formation mechanical damage magnetic forces damage to composite structures fuel ignition damage to lightning arresters sparking	coulombs I^2 $\int i^2 dt$
Group 2 induced voltages voltage flashover sparking fuel ignition	n I di/dt d^2i/dt^2

n is the number of restrikes in a flash

I is the peak value of the current

i is the instantaneous value of the current

APPENDIX 3

LIGHTNING ATTACHMENT ZONES

Aircraft surfaces can be divided into three zones, with each zone having different lightning attachment and/or transfer characteristics. These are defined as follows:

Zone 1   Surfaces of the aeroplane for which there is a high probability of initial lightning flash attachment (entry or exit).

Zone 2   Surfaces of the aeroplane across which there is a high probability of a lightning flash being swept from a zone 1 point of initial flash attachment.

Zone 3   Zone 3 includes all of the aeroplane surface areas other than those covered by zones 1 and 2. In zone 3 there is a low probability of an attachment of the direct lightning flash. However, zone 3 areas may carry substantial lightning currents by direct conduction between two attachment points.

Zones 1 and 2 may be further subdivided into A and B regions, depending on the probability that the flash will hang on for a protracted period of time. An A region is one in which there is a low probability that the arc will remain attached and a B region is one in which there is a high probability that the arc will remain attached. Some examples of zones are:

Zone 1A   Initial attachment point with low probability of flash hang on, such as a leading edge.

Zone 1B   Initial attachment point with high probability of flash hang on, such as a trailing edge.

Zone 2A   A swept stroke zone with low probability of flash hang on, such as wing mid-cord.

Zone 2B   A swept stroke zone with high probability of flash hang on, such as a wing inboard trailing edge.

Figure A3.1 shows a diagram of a conventional aircraft where the zones have been identified. As indicated in the figure, these zones have a finite width which is difficult to define. The existing specifications such as TSS Standard No 8-6 attempt to define the width of these zones, and their definitions are not in conflict with the present state of knowledge and are reproduced below:

Zone 1   These areas are:

(a)   within O.5m of any trailing edge or tail extremity,

(b)   within O.5m of wing tip measured parallel to the tip,

(c)   within O.5m of any sharp leading edge which is likely to form a
          point of attachment for lightning strikes,

(d)   forward unprotected projections (e.g. nose, engine nacelle
          forward of wing),   and

(e)   any other projecting part may constitute a point of attachment.

Zone 2   Extends O.5m laterally to each side of fore and aft line passing
          through zone 1 forward projection points of stroke attachment.
          All fuselage surfaces and surfaces of nacelles not defined as
          zone 1 are included in zone 2 unless it can be shown, for example,
          that certain nacelle surfaces are adequately protected by their
          position relative to the wing.

Zone 3   Surfaces for which there is only an Extremely Remote probability
          of direct or swept strokes. Ignition sources resulting from the
          aircraft contacting a lightning strike are either due to corona
          or streamering or sparking or poorly bonded joints due to the
          passage of lightning current through a zone 3 region. This zone
          includes all surfaces of the aeroplane not coming under the
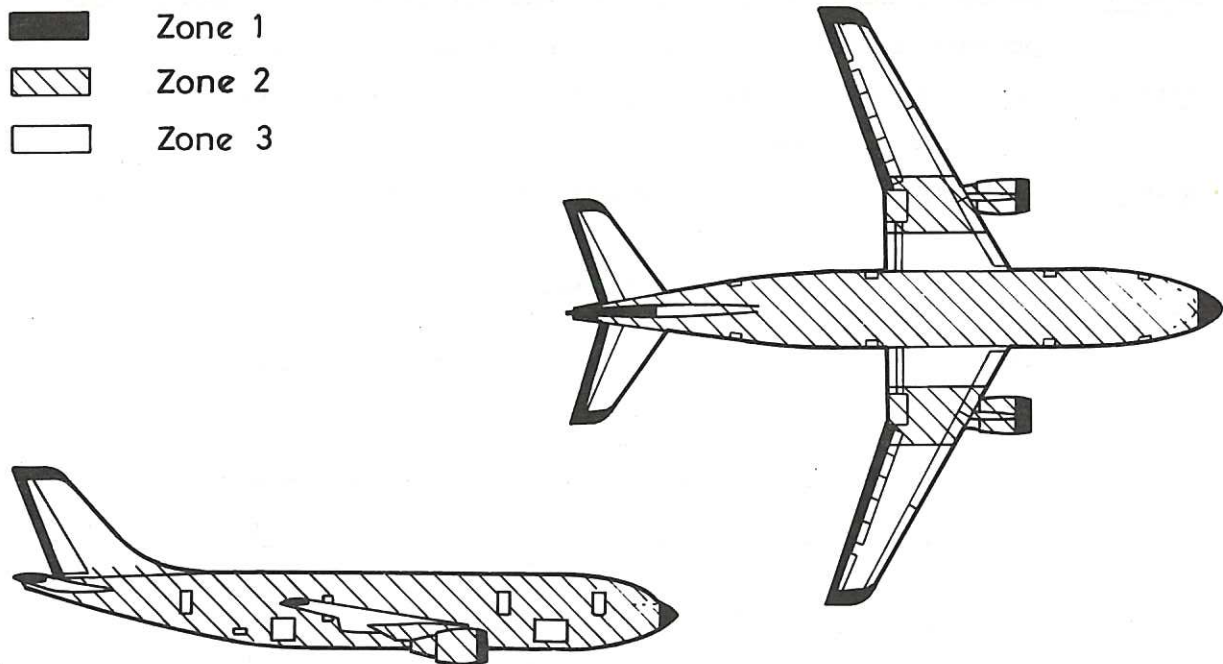   definition of zones 1 and 2.

Zone 1
Zone 2
Zone 3

Fig.A3.1 Typical aircraft lightning strike zones.

APPENDIX 4

WAVEFORM REQUIREMENTS FOR COMPONENT TESTING

The tables below indicate the waveform requirements for testing for group 1 and group 2 effects in the various zones. See Appendix 1 for the definition of the test waveforms, Appendix 2 for the definition of groups and Appendix 3 for the definition of the zones. Prior to the commencement of a test programme, the proposals for the tests which are to be made to given structures in given zones should be agreed with the appropriate airworthiness authority.

Table A4.1

Application of Simulated Lightning Current for Group 1 Tests

Test Zone	Current Component			
	A	B	C	D
1A	x	x	x (note 1)	
1B	x	x	x	x (note 2)
2A		x	x (note 1)	x (note 2)
2B		x	x	x (note 2)
3	x (note 3)		x.(note 3)	

Note 1   Assume a current duration of 45ms for continuing current components unless swept stroke testing shows otherwise.

Note 2   The continuing current should drop to near zero before the restrike commences.

Note 3   Current to be applied through a solid connection not an arc.

Table A4.2

Application of Simulated Lightning Current for Group 2 Tests

Test Zone	Current Component	
	A	D
1A	x	
1B	x	x (note 4)
2		x (note 4)
3	x (note 3)	x (notes 3 & 4)

Note 4   Component D to have a rate of rise of 100kA/μs ± 10% (see Appendix 1)

HIGH CURRENT TEST TECHNIQUES

The table below indicates the diagnostic requirements and the problem areas associated with various types of testing. These are discussed in detail in section 5.

Table A5

High Current Test Techniques

Nature of Tests	Special Problems	Diagnostic Requirements
stationary arc testing	1. return field inter-action 2. jet interaction 3. electrode spacing 4. arc stability	1. current waveform 2. arc voltage waveform 3. puncture detection 4. high speed cine
swept arc testing	1. arc voltage fluc-tuations 2. restrike injection 3. problems with specimen as cathode 4. electrode spacing 5. return field inter-action 6. boundary layer simu-lation	1. current waveform 2. arc voltage waveform 3. high speed cine
induced voltage testing	1. return conductor location 2. non-linear elements 3. diagnostics 4. characteristic imped-ance simulation 5. spark gap noise	1. current waveform 2. di/dt waveform 3. voltage waveform
ignition testing	1. detailed geometry 2. light-tight experiment 3. full view of potential sparking area	1. current waveform 2. spark detection by photographic means

MODEL AIRCRAFT ATTACHMENT POINT TESTS

Figure A6.1 shows the recommended electrode configuration.

Typical values
Model dimension $d = 1.1$ m
Total gap $= 6.0$ m
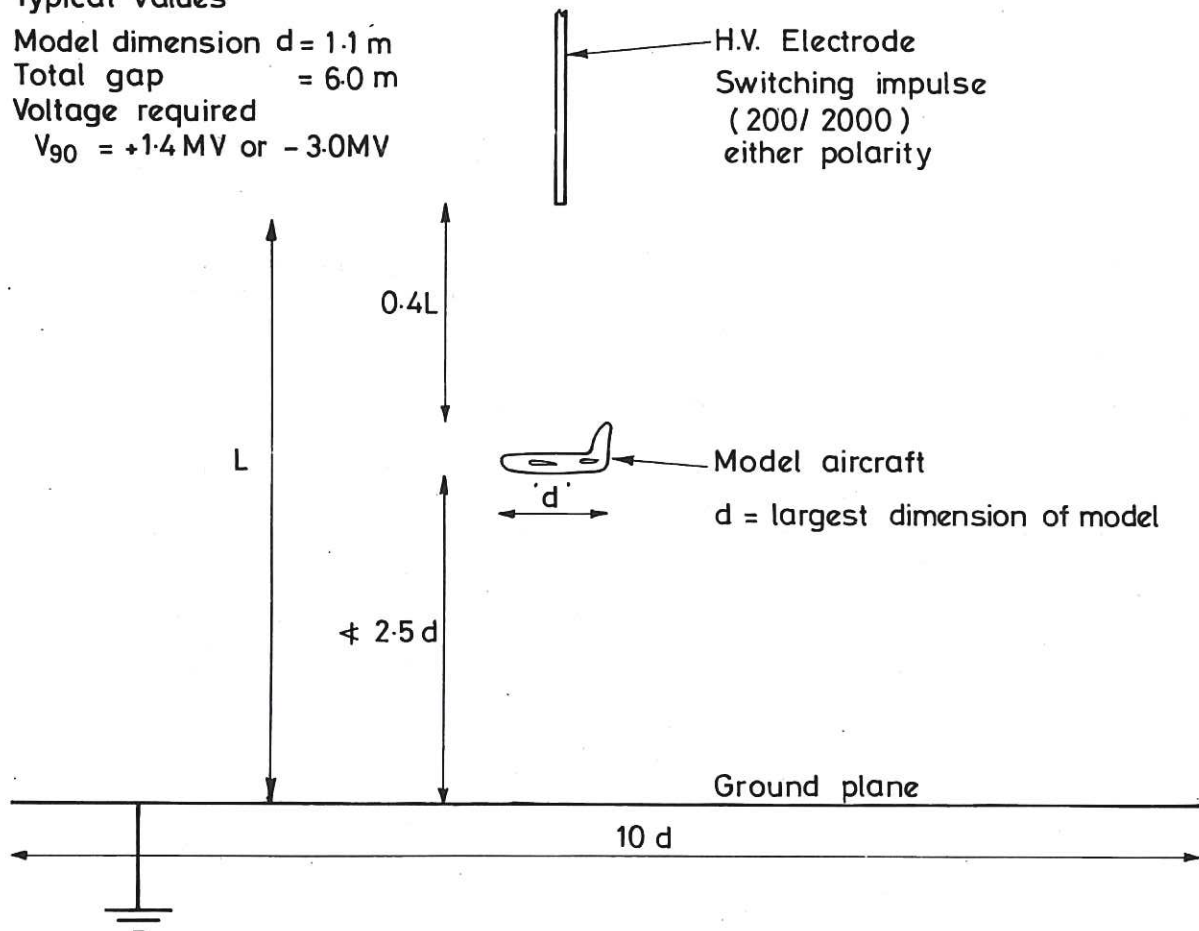**Voltage required**
$V_{90} = +1.4$ MV or -3.0 MV

Fig.A6.1 Diagram showing experimental arrangement for strike point location studies.

The table below gives the recommended conditions for testing.

Table A6

Recommended Conditions for Model Testing

HV rod polarity	positive or negative
waveshape	200/2000µs
over-voltage	voltage giving 90% proability of breakdown
gap length	up to 6m
peak voltage (for 6m gap)	+1.4MV or -3.OMV (approximately)
model	floating

N.B. The above recommendations differ from those produced by the SAE AE4 Committee.

APPENDIX 7

FULL SIZE HARDWARE ATTACHMENT TESTS

1.   Dielectric Testing

When conducting these tests the following points should be remembered:

(a)   Precise modelling of detail is required.

(b)   Metalwork representing structures bonded to the airframe should be directly earthed.

(c)   Short front impulse (1.2/50) preferred.

(d)   Test with each polarity in turn

(e)   The discharge should be photographed.

2.   Conducting Hardware Testing

When conducting these tests the following points should be remembered:

(a)   Precise modelling of detail is required.

(b)   Scenery must be provided.

(c)   Test object earthed directly.

(d)   Test gap as long as available test voltage will permit but not less than 1m.

(e)   Long fronted waves (200/2000) positive or negative.

(f)   The discharge should be photographed.

APPENDIX 8

APPLICATION OF REPORT

The style of this report is such that the reasoning and background information is given in the main body of the text. The appendices serve to highlight the important constraints and numerical values and are intended as a quick reference. The purpose of this appendix is to show how the report can be applied to an aircraft lightning problem. Many of the considerations are specific to a particular system on a particular aircraft and it is difficult to generalise. The comments below therefore are in terms of a worked example.

High Current Testing

Suppose it is required to evaluate the lightning performance of a thin metal skinned fuel tank, then a useful way to proceed is as follows:
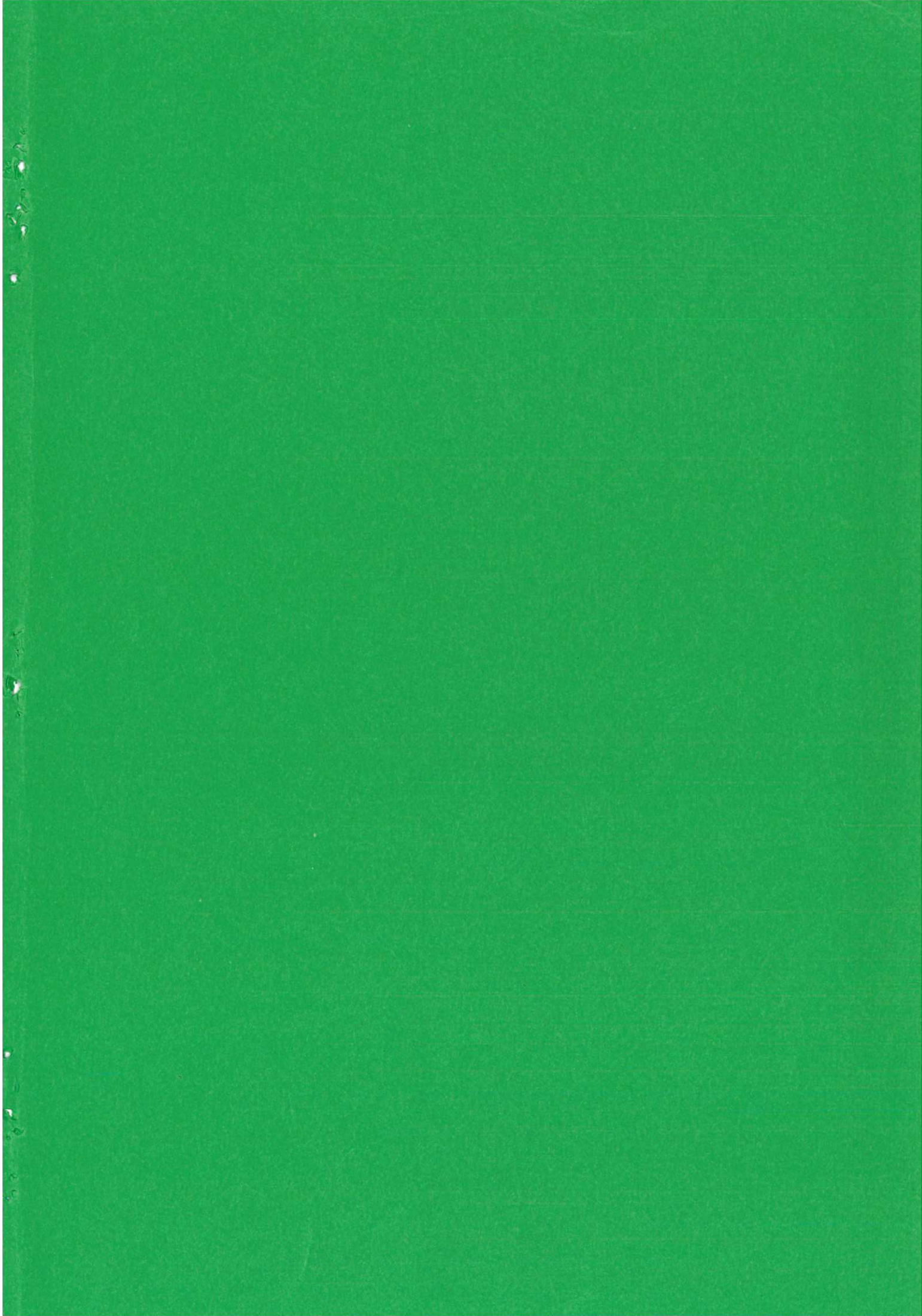
(1)   From general consideration, the most likely problems are associated with the skin's ability to resist arc puncture and whether sparking occurs at the fuel door.

(2)   From Appendix 2 it can be seen that the factors that most affect skin puncture are the number of coulombs passed and the value of the action integral; and for sparking the value of the peak current and the rate of change of current.

(3)   From Appendix 3 it is possible to identify in which zone the system will be located.

(4)   Appendix 4 identifies current components that should be applied; the value of the components being given in Appendix 1.

(5)   Appendix 5 deals with methods of ensuring that the tests are valid. This is experience and knowledge that the aircraft industry could reasonably expect a testing establishment to possess and to apply when carrying out tests for its customers.

(6)   Thus, in terms of the example, assuming that the tank is located in zone 2A, it should be tested for skin puncture with an intermediate current

of 2kA 10C followed immediately by say 400A for 45ms. For sparking at the fuel door, the peak current should be 100kA with an initial rate of rise of 100kA/µs. The special experimental problems centre around return field interaction, electrode spacing, jet interaction and arc stability for puncture tests, and for sparking tests a light tight experiment and adequate photographic equipment are the main factors.

High Voltage Testing

Suppose it is required to ascertain that the protection fitted to a radome is adequate.

(1)   The basic problem is initially to ensure that the radome is not punctured, and this means that it should have a dielectric test.

(2)   From Appendix 7 it can be seen that a 1.2/50 wave should be used, with the specimen and surrounding 'scenery' or 'modelling' directly connected to earth. Positive and negative polarity discharges should then be applied.

(3)   Once the correct distribution of the protection strips has been confirmed, the radome should then be high current tested.