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SIMULATION OF LIGHTNING STRIKES TO AIRCRAFT

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Culham Laboratory
Abingdon Berkshire

1971

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SIMULATION OF LIGHTNING STRIKES TO AIRCRAFT

by

T.E. James
J. Phillpott

ABSTRACT

Lightning simulation tests to aircraft components are becoming more important due to **the** increased use of boron and carbon fibre constructions, solid state circuitry, and high strength materials. For some components, the existing test specifications are becoming the limiting factor in the design and may be responsible for an unnecessary weight penalty.

This report review the aspects of natural lightning and identifies the major parameters relevant to aircraft damage. The simulation of this damage in the laboratory, the general studies deemed necessary, and the design of the high current simulation facilities are considered, together with comments on the existing test waveforms and a proposed future test specification. The problem of predicting strike point locations and the validity of model tests using a high voltage generator are discussed, together with comments on methods of determining the value of probability of a strike to a given region.

U.K.A.E.A. Research Group,
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Abingdon,
Berks.

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1. INTRODUCTION

1.1 General background

This report contains the major part of a feasibility study on the simulation of lightning strikes to aircraft undertaken for the Ministry of Aviation Supply. It is appreciated that workers in this field will already be familiar with many of the aspects discussed in this report. However it is hoped that the discussion below will prove useful as a summary of the state of the art and its possible developments, with particular reference to failure mechanisms, existing specifications, future investigations, and the design of future test facilities.

The terms of reference specified by the Avionic Department, Royal Aircraft Establishment, Farnborough (Thomas, 1970), which reflect on the design of future test facilities can be summarised as follows:-

(a) Comment on the ARB (British Air Registration Board and FAA (American Federal Aviation Agency) simulated lightning stroke specifications for high current tests on aircraft components.

(b) Investigate the design of high current test facilities to perform the tests under (a).

(c) Study the feasibility of ascertaining the initial strike point location tests using scale models of complete aircraft and a multi-megavolt impulse generator.

When the feasibility study was initiated early in 1970, it was considered that the facilities available to the aircraft industry in the UK for performing the tests described above were inadequate. The ARB (Perry, 1968), FAA (Auburn, 1968), and Ministry of Defence (MOD) have also emphasised the need for further research work in this field to obtain the necessary data on which to base future test specifications. It is anticipated that such lightning simulation tests may become increasingly important in the future, the more significant reasons for this being:-

(i) The increasing use of composite materials (boron and carbon fibre) on the outer surface of aircraft.

(ii) The increasing use of insulating cemented joints.

(iii) Changes in aircraft geometry which may affect the probable strike point locations.

(iv) Increasingly stringent test requirements.

A further reason for the increasing importance of lightning simulation tests is that these requirements are now becoming the limiting factor in the design of components such as very light high strength wing structures or helicopter rotors. In the past the material thickness required for the mechanical strength of these components was more than adequate to satisfy lightning protection requirements.

Up to 1970 high current tests required by UK manufacturers were usually carried out by the Lightning and Transient Research Institute, (LTRI), Minneapolis or Miami, USA. LTRI have also carried out extensive general studies on the effect of lightning strikes to aircraft (Newman, 1968). During 1970 at the request of Ministry of Aviation Supply temporary high current facilities have been made available at UKAEA, Culham to meet the ARB/FAA test specifications. As far as is known no other suitable facility is available in Europe.

1.2 Summary of the Report

To comment adequately on the high current test specifications accepted by ARB and FAA (para. 1.1(a) above), and the strike point location tests on aircraft models (para. 1.1(c) above) it has been necessary to consider the natural lightning phenomena in some detail. The aspects of this subject relevant to aircraft lightning strikes are given in Section 2 of this report. Much of this information has been obtained from M.A. Uman's book on Lightning (1969) and from a review paper by K. Berger (1967) to which reference should be made for further information.

The nature of the damage occurring to aircraft struck by lightning is given in Section 3. Discussion of this damage and the general studies deemed necessary using high current facilities are based on (a) experimental work on high current arcs at Culham (b) discussion with ARB, RAE Farnborough, (c) UK and US research laboratories and (d) UK and US aircraft manufacturers (see Appendix 9.1). At the time of writing the most recent published information on aircraft lightning problems was given in the Proceedings of the Lightning and Static Electricity Conference, Miami, December 1968 (AFAL-TR-68-270). A further such conference has since been held at San Diego in December 1970. Relevant aspects of the papers presented at this latter conference are summarised in Appendix 9.2.

The recommended general studies that need investigation are given in Section 4. Included in this section are comments on the existing simulation test waveforms, a proposed future test specification, and a discussion on the rating and size of high current facilities.

The problems of predicting strike point locations and the validity of model tests using a high voltage impulse generator are discussed in Section 5. Some reservations have been expressed by research staff concerned with long path breakdown at Liverpool University (Meek, 1970) and staff at UK and US industrial HV laboratories. It was suggested that the effect of waveshape parameters and electrode geometry should be investigated. Recent research, mainly by Russian workers (Aleksandrov et al, 1969) on the breakdown of very long gaps ($\simeq$ 10 m) may provide some useful data relevant to model tests and to the final approach stages of a leader stroke to an aircraft. In spite of the problems posed by model tests these are still probably the most practical method of evaluating the probable strike point distribution.

General conclusions from the work, and a summary of the recommendations for future studies and test equipment specifications, are given in Section 6.

2. LIGHTNING PHENOMENA

2.1 Types of Lightning Discharges

Lightning can take place entirely within a cloud (intracloud or cloud discharges), between two clouds (cloud-to-cloud discharges), between a cloud and earth (ground discharges) or between a cloud and the surrounding air (air discharges).

The generally accepted distribution of electric charge in a typical thundercloud is shown in Fig.2.1. The values of the positive and negative charges given in Fig.2.1 have been deduced by Malan (1952, 1963) from electric field measurements near thunderclouds assuming that space charge effects are negligible. Kasemir (1965) has taken the latter into account and has deduced that the upper positive charge P is 60 coulombs, the negative charge N is -340 coulombs and the positive charge p at the base of the cloud is +50 coulombs, compared with values of +40, -40, and +10 coulombs respectively deduced by Malan. Thus, though the qualitative charge distribution is reasonably well established, the actual charge values are uncertain.

From the charge distribution in Fig.2.1, two main types of cloud discharge may be expected, P - N and N - p discharges in the upper and lower regions of the cloud respectively (Schonland 1951). The N - p discharge may develop into an air discharge below the cloud base and if the latter is sufficiently low, proceed to earth as a cloud-to-ground flash. The predominant number of current measurements to ground structures indicates that negative charge is lowered, thus implying an origin in the N region. Out of 100 such measurements by Berger (1967) on discharges initiated by downward moving leaders, only 18% have transferred positive charge to earth. These positive discharges to ground are assumed to originate from the upper P region of the cloud.

The conditions under which most strikes to aircraft occur (at 7,500 feet and $0^{o}C$) exist in the lower regions of the typical thundercloud shown in Fig.2.1. Probably the aircraft most frequently contacts intracloud discharges or feeders to the main discharge channel but there is little experimental information available concerning their characteristics. It has been suggested that the charge transferred in intracloud and cloud-to-ground discharges may be of the same order (Uman, 1969 , Smith, 1957). Newman (1968) however suggests that most discharges intercepted by aircraft are low coulomb intracloud discharges and that although the probability of intercepting ground discharges is lower, much greater currents and coulombs will be involved. Analysis of 55 strikes made to instrumental aircraft (Fitzgerald 1968) at altitudes from 10,000 to 30,000 feet, and therefore probably intracloud discharges, show the most probable peak currents to be only about 10 per cent of those of ground discharges.

In view of this conflicting information on intracloud discharges and as there is no evidence to suggest that cloud discharges are more severe than discharges to ground, it is assumed in the present study that the worst conditions likely to be encountered by an aircraft are those associated with ground discharges. This assumption is necessary because data on the current waveforms is only available for the latter. It can also be justified because the damage to aircraft components due to lightning strikes is comparable with that obtained in the laboratory using waveforms with roughly the same amount of charge transfer to that measured for the worst ground discharges.

2.2 Breakdown Processes

A lightning discharge which lowers negative charge to ground, consists of several intermittent discharges; the complete discharge being known as a 'flash' and lasting typically 0.25 s. Each component discharge known as a stroke occurs about every 40 ms in negative ground discharges.

As a result of the photographic observations by Schonland (1933) in South Africa the time sequence of events in a ground discharge was deduced as shown diagramatically in Fig.2.2. The breakdown process is thought to commence with a local breakdown in the N - p region for negative discharges from the thundercloud (Fig.2.1) after which a negatively charged column is propagated to ground by the resulting electric field. This column, referred to as a stepped leader, advances in a series of rapid discontinuous steps each about 50 m long and separated by pauses ranging from 40 to 100 μs. The luminous diameter of the stepped-leader is between 1 and 10 m though it is thought that the leader current of about 100 amps flows in a small diameter core at its centre (Uman, 1969).

As the leader nears the ground it will make contact with one of a number of upward moving streamers and initiate a return stroke. The latter retraces and discharges the leader channel at a speed of about 5.0×10^7 m/sec. The peak current in the return stroke typically rises to about 20 kA in a few microseconds and decays to half value in about 50 μs. Thereafter currents of a few hundred amps may continue to flow for several milliseconds. Upward moving leaders can also originate from tall buildings such as the Empire State Building (Hagenguth & Anderson, 1952) or from mountain peaks (Berger 1967).

After the first return stroke further strokes may occur in which higher areas in the N - region are discharged. If a subsequent stroke occurs in less than about 100 ms after the previous stroke a continuous or 'dart leader' will traverse the discharge channel smoothly at a speed of about 2×10^6 m/sec. If the time interval between strokes is greater than about 100 ms a dart-stepped leader occurs which initially travels continuously but later becomes a stepped leader.

There are typically 3 strokes per flash though numbers from 1 to 26 have been observed in negative discharge. First return strokes have slower rates of rise of current, higher peak currents and generally a larger charge transfer than subsequent strokes. When the current continues to flow in at least one interval between strokes, the total charge transfer is about twice as much for flashes without a continuing current interval (Uman, 1969).

Flashes lowering positive charge to ground which occur less frequently than negative discharges, are preceded by stepped leaders and usually consist of only one stroke. These flashes have a rate of rise of current about five times slower and a charge transfer 50% greater than for negative discharges (Berger, 1967).

2.3 Parameters of Lightning Discharges

The data and information given by Uman (1969) in Table 2.1 can be used as a very approximate guide to the parameters of the negative lightning discharge to ground. It is based on the work of Hagenguth and Anderson (1952), Schonland (1956), Workman et al (1960), Brook and Kitagawa (1960), Kitagawa et al (1962), Brook et al (1962), Williams and Brook (1963), Berger and Vogelsanger (1965, 1966), and Berger (1967). Note that the maximum coulomb and peak current given here are not consistent with other data.

TABLE 2.1

PARAMETERS OF NEGATIVE DISCHARGE TO GROUND

		Minimum	Typical	Maximum
Stepped Leader*				
Length of step	(m)	3	50	200
Time interval between steps	(μs)	30	50	125
Mean velocity	(m/s)	$1\cdot0 \times 10^{5}$	$1\cdot5 \times 10^{5}$	$1\cdot6 \times 10^{6}$
Charge on channel	(C)	3	5	20
Dart Leader				
Velocity	(m/s)	$1\cdot0 \times 10^{6}$	$2\cdot0 \times 10^{6}$	$2\cdot1 \times 10^{7}$
Charge on channel	(C)	0·2	1·0	6·0
Return Stroke				
Velocity	(m/s)	$2\cdot0 \times 10^{7}$	$5\cdot0 \times 10^{7}$	$1\cdot4 \times 10^{8}$
Current rate of increase	(kA/μs)	< 1	10	> 80
Time to peak current	(μs)	< 1	2	30
Peak current**	(kA)		10–20	110
Decay time to half peak	(μs)	10	40	250
Charge (ex. continuous current)	(C)	0·2	2·5	20
Channel length	(km)	2	5	14
Lightning Flash				
No. of strokes per flash		1	3–4	26
Time interval between strokes (without continuing current)	(ms)	3	40	100
Time duration of flash	(s)	10^{-2}	0·2	2
Total charge**	(C)	3	25	90

* The first three parameters given for the stepped leader do not necessarily exist together in a given event.

** The maximum peak current and coulombs given here are not consistent with other data.

The current waveforms of lightning discharges are the most important factor in deciding firstly what damage is sustained by aircraft in flight and secondly what test facilities are necessary to simulate the same damage in the laboratory. These waveforms will therefore now be considered in detail.

From the discussion in Section 2.1 it follows that typical negative lightning flashes consisting of three strokes will be very approximately as in Fig.2.3. There is however a considerable spread in the measured value of peak current, coulombs and rate of rise of current as shown by the results of Berger and Vogelsanger (1965) in Fig.2.5. It should be noted that whereas the first strokes (curve 1) have the highest peak current and coulombs, the subsequent strokes have much higher rates of rise of current (curve 2). Data from other workers has been summarised by Uman (1969) for values of peak current, rate of rise of current, current rise time and decay time to half peak current as given in Fig.2.6 a, b, c and d respectively for negative ground discharges (except Fig.2.6 a, which includes positive ground discharge data). A representative current waveform for a positive ground discharge measured by Berger and Vogelsanger (1965) is shown in Fig.2.4. The total coulombs transferred and the $\int i^2dt$ value for positive and negative ground discharges are given in Fig.2.7 a, b, and c (Berger, 1967). The maximum values of these parameters given in the literature are 218 kA peak current (Lewis and Foust, 1945); rate of rise of current 80 kA/µs (negative) and 8 kA/µs (positive); decay time 250 µs (negative) and 1500 µs (positive); and 200 coulombs/flash (negative) and 310 (positive) (Berger and Vogelsanger, 1965). Maximum recorded I^2t values by Berger (1967) are 0.8×10^6 (negative) and 5×10^6 A^2s (positive).

It is important to note that the above coulomb values represent the total coulombs per flash whereas the actual coulombs transferred during a current peak in one stroke of a negative discharge is only a few coulombs as shown in Fig.2.7 b. Therefore most of the coulombs in a multiple stroke negative flash are transferred either by intermediate currents of a few kiloamps flowing for several milliseconds or by continuing currents of a few hundred amps flowing for several hundred milliseconds. Positive discharges have usually only one stroke with much longer rise and decay times (Berger and Vogelsanger, 1965) therefore a large proportion of the charge transfer and I^2t can occur at high currents of say 20 to 50 kA flowing for about 1 ms (see Fig.2.4). The maximum total duration of a lightning flash measured by Berger (1967) is nearly 1 s for negative discharges and 0·18 or 0·28 s for positive discharges initiated by downward or upward leaders respectively.

In proposing a current waveform to simulate a lightning strike for test purposes, it is necessary to rationalise the large amount of data reported for natural lightning discharges. This can be done by replacing the multiple stroke flash with a single effective composite waveform having three components:-

(a) a 'Fast' component to give the correct peak current I and di/dt.

(b) An 'Intermediate' component to give the correct coulombs and I^2t at currents below 50 kA.

(c) A continuing component to represent continuing currents of less than 1000 amps.

Probable maximum effective values for these three components based on ground discharge measurements are given in Table 2.2.

Three component waveforms have also been proposed by Newman (1968) and are included in some lightning simulation test specifications (Table 4.2 below). However none of these specifications adequately represents the coulombs and I^2t values in the intermediate component when compared with experimental data on positive ground discharges. The large value of I^2t for positive discharges (more than five times the negative discharge value) is very significant when specifications for lightning simulation tests are being considered. Although there are fewer positive than negative discharges, the former still represent about 20% of ground discharges initiated by downward moving leaders and therefore must be taken into account in lightning simulation studies and tests.

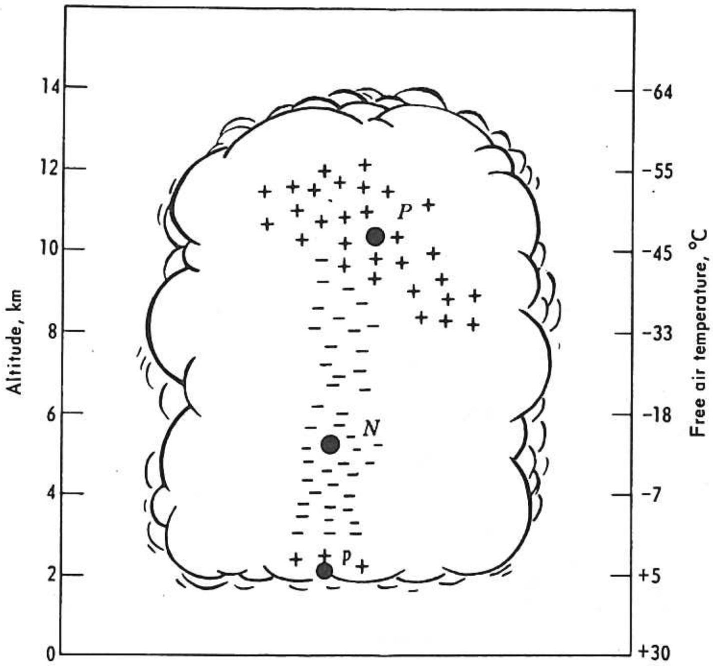

Altitude, km
0
2
4
6
8
10
12
14
Free air temperature, °C
+30
+5
-7
-18
-33
-45
-55
-64
P
N
p

Fig. 2.1 *Probable distribution of the thundercloud charges, P, N and p for a South African thundercloud according to Malan (1952, 1963). Solid black circles indicate locations of effective point charges, typically P = +40 coul, N = −40 coul, and p = +10 coul, to give observed electric field intensity in the vicinity of the thundercloud.*

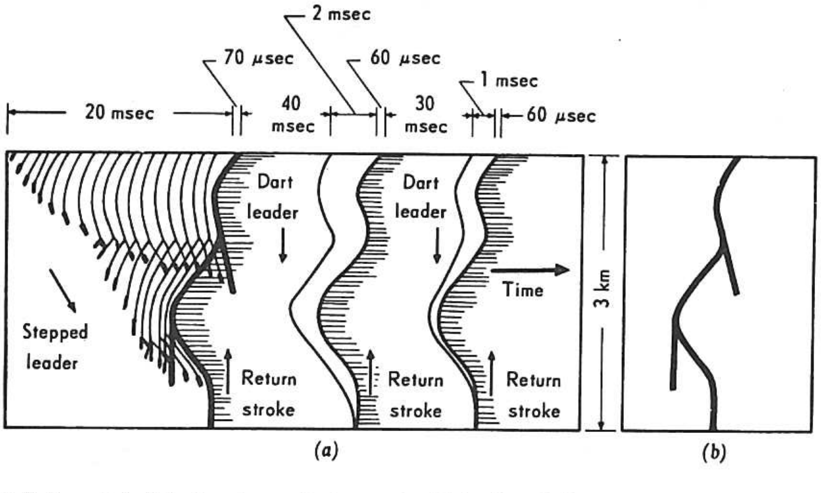
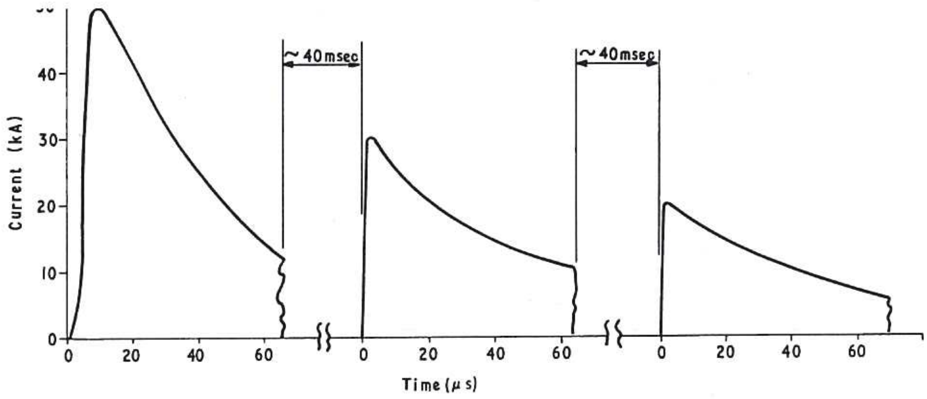
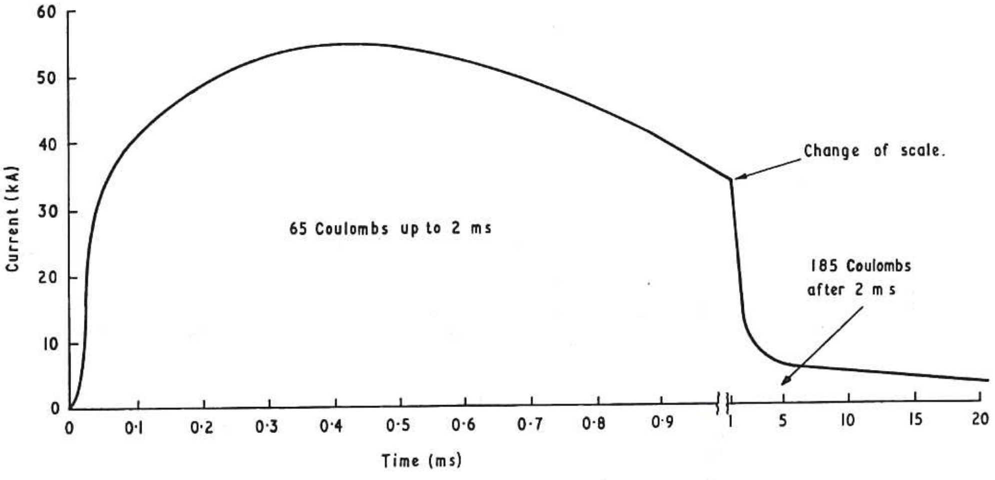

20 msec
70 μsec
40 msec
2 msec
60 μsec
30 msec
1 msec
60 μsec
Stepped leader
Dart leader
Return stroke
Dart leader
Return stroke
Return stroke
Time
3 km
(a)
(b)

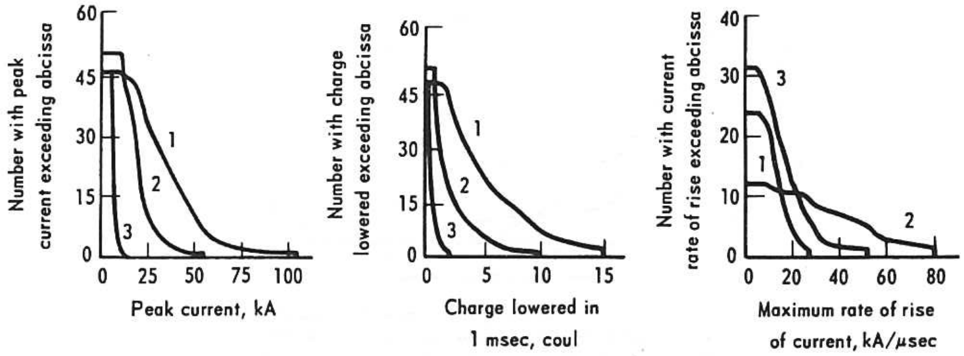
Fig. 2.2 *(a) The luminous features of a lightning flash as would be recorded by a camera with fixed lens and moving film. Increasing time is to the right. For clarity the time scale has been distorted. (b) The same lightning flash as recorded by a camera with stationary film.*



Typical current waveform for negative multiple stroke flash to ground
Fig. 2·3



Typical current waveform for positive stroke to ground
Fig. 2·4



(a) (b) (c)

Fig. 2.5 *Properties of lightning strokes initiated by downward-moving, negatively charged leaders. (1) First strokes initiated by downward-moving stepped leaders; (2) subsequent strokes initiated by downward-moving dart leaders; (3) negative strokes within flashes originating with upward-moving leaders. Only strokes with peak currents equal to or greater than 10 ka are considered. (Data adapted from Berger and Vogelsanger (1965).)*

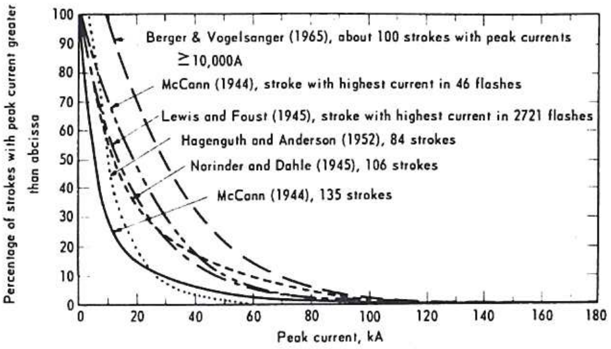


Fig. 2.6(a) *Frequency distribution of peak current for lightning strokes initiated by downward-moving leaders. Strokes lowering negative charge and strokes lowering positive charge are both included.*

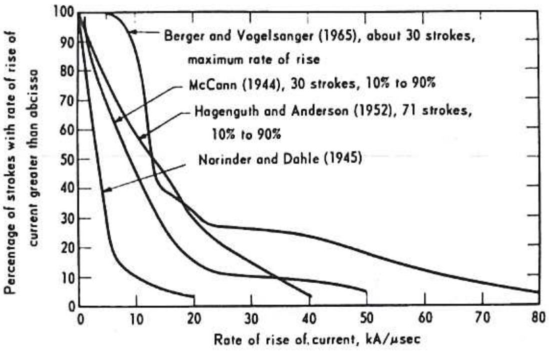


Fig. 2.6(b) *Frequency distribution for rate of rise of current for lightning strokes initiated by downward-moving, negatively charged leaders. Data of McCann (1944) and Hagenguth and Anderson (1952) represent slope of line through points on current wavefront at 10 percent and 90 percent of peak current; data of Berger and Vogelsanger (1965) represent maximum rate of rise of current on wavefront.*

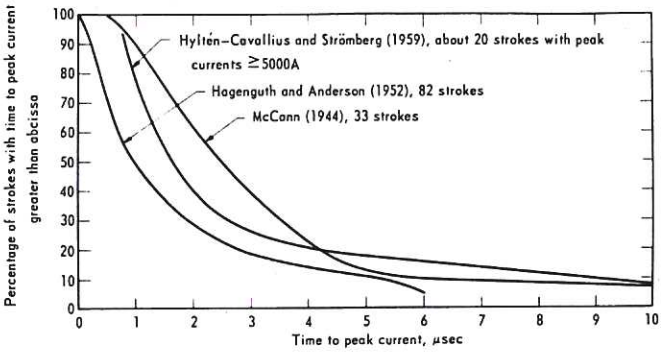


Fig. 2.6(c) *Frequency distribution of time to peak current for lightning strokes initiated by downward-moving, negatively charged leaders.*

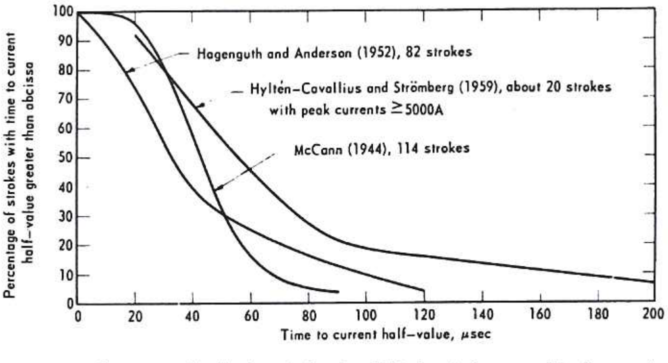


Fig. 2.6(d) *Frequency distribution of time for lightning stroke current to decrease to half peak value for strokes initiated by downward-moving, negatively charged leaders.*

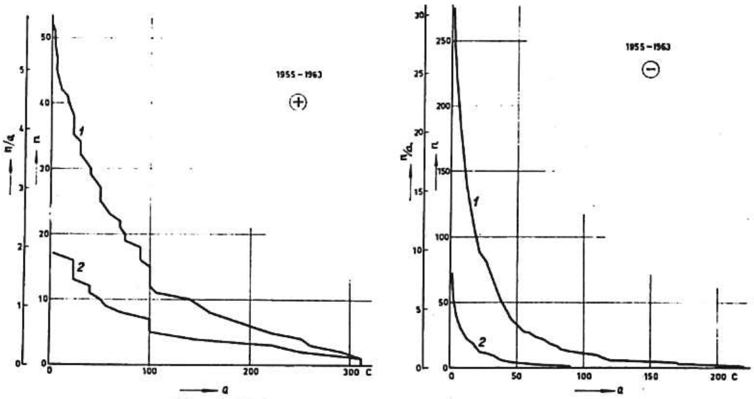
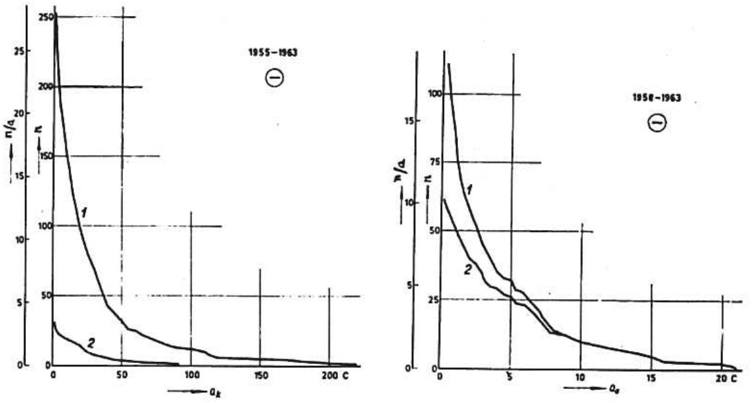


Fig. 2.7(a) Q Electric charges (Coulombs) in a flash.



Q_k Electric charges in continuing currents.

Q_e Electric charges in impulse currents.

Fig. 2.7(b)

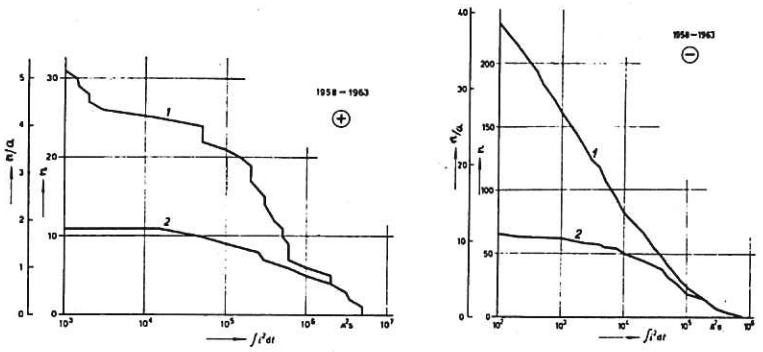


Fig. 2.7(c) $\int i^2 dt$ calculated values (A^2 sec) for a flash.

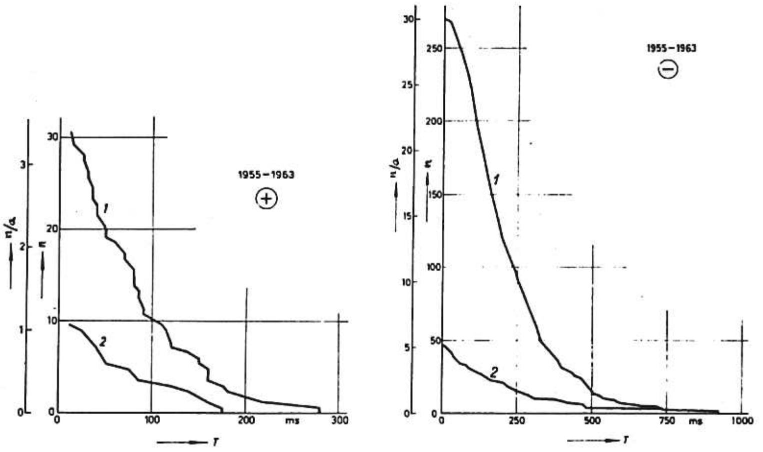


Fig. 2.7(d) T total duration of a flash (ms).

n number of lightning flashes measured within the period indicated against each curve, with parameters at least equal to the abscissa value; n/a number as above but per annum (mean value). Polarities are indicated against each curve. (1) All flashes; (2) Only downward flashes.

TABLE 2.2

MAXIMUM EFFECTIVE PARAMETERS FOR COMPOSITE CURRENT WAVEFORM

Component		Negative Discharge	Positive Discharge
(1) Fast			
Peak current I	(kA)	200	200
di/dt	(kA/μs)	80	8
Pulse time τ	(μs)	10	100
Coulombs	(C)	2	20
I^2t	$10^6 (A^2s)$	0·2	2·0
(2) Intermediate			
Peak current I	(kA)	50	50
Pulse time τ	(ms)	0·4	2
Coulombs	(C)	20	100
I^2t	$10^6 (A^2s)$	0·5	2·5
(3) Continuing			
Peak current	(kA)	1	1
Pulse time	(ms)	200	200
Coulombs	(C)	200	200
I^2t	$10^6 (A^2s)$	0·2	0·2
Total coulombs	(C)	~220	~320
Total I^2t	$10^6 (A^2s)$	0·9	4·7

3. EFFECT OF LIGHTNING STRIKES ON AIRCRAFT AND HELICOPTERS

Statistical records for world-wide commercial flights show that each aircraft is struck by lightning once every year (or once every 2700 flying hours) though on certain routes particularly in Europe the rate is considerably greater than this, once every 800 hours. Information on strikes to British commercial aircraft reported by Perry (1968) shows that the maximum strike rate to aircraft occurs at a height of about 7000 feet and a temperature of 0°C. This rate has not been corrected for the time spent at any altitude. About 27 per cent of all strikes burn a hole in the structure or radome, 45 per cent cause slight damage and 28 per cent no damage. The strike point locations that have been reported for a Trident aircraft are given in Fig.3.1 (Perry, 1968). It will be noted that a large number of the strikes are to the nose, tail and wing tips (as would be expected) and also along the fuselage. Some of the latter are thought to be due to the forward motion of the aircraft changing the arc root position and are referred to as 'swept strokes'.

As it was thought that strike points were confined to specific surfaces of the aircraft, the FAA defined, in circular AC 20-53 (Protection of Fuel Systems), zones according to the severity or likelihood of strokes expected. These zones are briefly as follows:-

Zone 1 (Direct strokes)

(i) Surfaces within 18 inches of the wing-tip, wing leading edge (if the leading edge sweep is more than 45°), and tips and trailing edges of the tail group.

(ii) Projections such as engine nacelles, external fuel tanks, propellor disc and fuselage nose.

Zone 2 (Swept strokes)

Surfaces for which there is a probability of strokes being swept rearward from Zone 1.

Zone 3

Surfaces other than those covered by Zones 1 and 2.

It follows that components likely to be damaged by lightning strikes may be divided into (a) those that have to withstand a complete lightning flash into one strike point, and (b) those subject to 'swept' strokes for a limited period of the total time of the flash, and (c) those located elsewhere but subject to consequential damage (e.g. induced voltages).

3.1 Metal Skin Punctures and Hot Spots

The time to produce 'burn-through' of aluminium alloy plates of 0.5 to 8 mm thickness at currents of up to 2000 amps has been investigated by the Boeing Company, Seattle (Brick, 1968), using a 400 V battery and therefore presumably an arc length of a few millimeters. These results show a large variation in coulombs required to produce 'burn-through' at various currents and times; being about 11 coulombs at 500 amps and 500 coulombs at 200 amps for a 2 mm plate. These results, which are very surprising and would not have been anticipated on theoretical grounds, have an important influence both on the rating of test facilities and on aircraft design problems. A similar study was therefore made at UKAEA, Culham (Phillpott 1970) using 2 mm aluminium alloy plate (HE 15) with currents in the range

100 amps to 50 kA with an arc length of 2 mm. Values of peak current I, coulombs $I\tau$ and I^2t (where pulse length $\tau = \frac{\text{coulombs}}{I}$) are given in Figs. 3.2, 3.3 and 3.4 respectively for a 2 mm arc as a function of pulse time to produce 'burn-through'. For high currents greater than 50 kA a 'burn-through' can occur after the current pulse has ended. The curve obtained by Boeing has also been added to Figs 3.2 and 3.3 and it will be seen that the Culham results show a much smaller variation in coulombs of only about 2 to 1 over the entire current range of 200 amps to 50 kA, a minimum value of 50 coulombs occurring at 1000 amps. The extrapolated portion of the Boeing results (shown dotted) which suggests a value of 1000 coulombs at 200 kA is also not confirmed by the Culham results which indicate a value of 100 coulombs. Further work at Boeing has been reported (Brick, 1968) on the time and coulombs required to produce local hot spots in titanium which could cause fuel ignition. These results give almost constant coulombs as a function of current in contrast to the results for aluminium alloy.

As many of the studies on simulated lightning strikes (e.g. swept strokes) have to be performed with arc lengths of about 20 cm, the work at Culham was extended into this range using a 200 kJ capacitor bank with a 'clamped' inductive circuit (Phillpott, 1970). The coulombs required a burn through a 2 mm aluminium alloy plate are given in Fig.3.5 for arc lengths up to 30 cm and peak currents of about 15 kA for unpainted and epoxy painted surfaces (~ 0.1 mm coating). It will be noted that for unpainted surfaces with long arcs considerably more coulombs are required to cause puncture although even with a painted surface twice the coulombs can be absorbed with a 30 cm arc compared with a 1 cm arc length. The reason for this variation of coulombs with arc length is thought to be because with longer arcs on an unpainted surface it is possible for the arc root to move appreciably from its initial strike point, thus reducing the energy density at the metal surface. The fact that under these unpainted long arc conditions the results have a much wider spread would support this conclusion since variations from shot to shot would result from differences in arc movement. The geometry of the connections under these test conditions could greatly enhance this wandering especially when a non symmetrical feed is used.

A further important factor which can influence 'burn-through' times is variation in the current waveshape even though the total coulombs are constant. A significant difference between natural lightning and laboratory test waveforms is that the former can consist of multiple strokes (Fig.2.3), whereas the latter are invariably single pulses. To investigate the effect of a late high current pulse on the damage to a 2 mm aluminium alloy plate, a 200 kA, 4 coulomb pulse from a 'triggered' 40 kV capacitor bank was superimposed on a rectangular DC pulse at the beginning, half-way through, and at the end of the latter (Phillpott, 1970).

The DC pulse was 280 amps for 0.2 s (56 coulombs) for each of the three tests, the results of which are shown in Fig.3.6. With the fast pulse applied at the beginning of the DC pulse (as in the FAA test specifications) no 'burn-through' occurred whereas if the fast pulse is delayed for 0.2 s a 1.0 cm diameter hole is produced in the plate. This significant difference is considered to be due to the fact that if a high current pulse is applied to an arc spot which has already been melted or 'puddled', its high magnetic pressure (say 25000 lb/in^2 for a 5 mm diameter arc) will quickly displace a large quantity of material and finally punch a hole right through the weakened plate. The clean nature of the holes produced by the late fast current pulses is evidence that this is probably the correct explanation. Thus it follows that multiple stroke lightning flashes will produce significantly more damage than single pulse waveforms. This phenomena may also be important in swept stroke studies since new arc roots may be initiated by subsequent strokes or the latter may produce punctures as discussed above.

The specifications for lightning simulation tests in use at present appear to have largely originated from low current comparative tests with single pulses at LTRI which produce the same damage as resulted from actual lightning strikes in service (Newman, 1968, Little and Newman, 1968). From these tests it has been deduced that 300 to 500 coulombs at currents of a few hundred amps are generally necessary in the laboratory to produce the same damage as in service. While this has been a most useful guide as to the test conditions required, in view of the various arc phenomena discussed above that can affect such results, it can only give very approximate information (say within a factor of 2 or 3) about the coulombs or waveshape that actually occurred in the strike to the aircraft. It is also desirable that in future such comparative tests are adequately documented so that for example, current, waveshape, arc length, geometry of current connections and metal surface conditions are specified.

To adequately resolve this important problem further studies are required to investigate the effect of various factors such as (a) metal properties, (b) surface coatings and (c) the length, temperature and current density of the arc. To obtain the necessary data on arc parameters and dynamic movements, spectroscopic, microwave, laser and fast photography diagnostics could be used. These techniques which are available in plasma physics laboratories have been developed to a high standard in the last ten years.

A theoretical analysis of the above factors may be possible based on the model given in Fig.3.7 where an arc radius r_a carrying a pulsed current I for a time τ is in contact with a metal plate of thickness t_p in which the current skin depth is t_i. The heat input to the metal occurs as (a) ohmic heating which diffuses rapidly ($\sim 10^{-3}$ m/ms) through the plate and (b), thermal conduction from the arc channel which occurs much more slowly ($\sim 10^{-4}$ m/ms). Heating of the back surface opposite the arc occurs by means of radial and axial thermal diffusion. Kofoid (1970) has considered this problem and proposed the following simplifying assumptions:-

(a) the arc current density (I/r_a^2) is constant $5 \times 10^4 \mathrm{A/cm^2}$ for titanium and $2.5\ 10^4 \mathrm{A/cm^2}$ for aluminium;

(b) the arc temperature T is constant (4500°C);

(c) the arc channel is stationary.

Details of Kofoid's analysis are not available but based on these assumptions his calculated results predict that between 500 A and 5 kA approximately constant coulombs are required to attain a critical temperature on the plate surface opposite the arc. This prediction is in general agreement with the Culham results in Fig.3.2 and 3.3.

At very high currents of about 200 kA for pulse times of less than 1.0 ms the above assumptions are not likely to be applicable. In this regime the arc may not have reached dynamic or thermal equilibrium so that its diameter will not be given by a constant current density. Furthermore for short current pulses the current will be flowing in a small diameter arc and a thin skin in the metal where the metal temperature is dependent only on the surface magnetic field. Under these conditions the metal temperature will be nearing its melting point (Furth et al, 1957) as discussed in Section 3.3. The resulting high magnetic field pressure may displace or cause the metal to flow so that puncture can be produced by a different mechanism than heat condition from the arc root.

3.2 Swept Strokes

The mechanism of swept strokes will be discussed with reference to Fig.3.8. The arc channel of a stroke which initially made contact with a leading edge at A will as a result of the movement of the aircraft take up the configuration shown. There is then a possibility of a restrike to the flat 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. This problem has been investigated at LTRI with an arc striking a rotating disc (Brick, 1968). Experiments have also been performed at LTRI (Newman, 1968) by placing an arc between an almost parallel rod and plate electrode assembly in an air stream up to 250 mph. The probability of a re-strike is considered to be very dependent on the surface coating used; for example, an arc was swept several feet without restriking on an anodised surface.

The re-strike voltage may arise during the period between strokes due to the IR voltage drop along the arc which may be about 30 volts/cm (James, 1970) in atmospheric air. Thus if this is the correct mechanism, restrikes that have been noted in service about 1 metre apart will have been produced by a voltage of only 3 kV. Alternatively if a subsequent stroke occurs under the conditions shown in Fig.3.6 then a voltage Ldi/dt also exists between B and C where L is the arc inductance between A and C (~ 0.2 nH/m). Thus if di/dt is 80 kA/μs, a voltage of ~ 20 kV will exist across BC for a one metre arc. Thus the restrike produced by a subsequent stroke appears to be the most likely mechanism as suggested by Plumer (1970). The time between subsequent strokes is given in Table 2.1 as 3 to 100 ms during which time a 300 mph (135 m/sec) aircraft would travel 0.4 to 14 m. It is therefore possible for some restrikes to be produced by subsequent strokes, though it is doubtful whether restrikes occurring more closely than 0.5 m for an aircraft velocity of 300 mph would be produced by this mechanism. It is therefore probable that some restrikes are produced only by resistive voltages without the occurrence of a subsequent stroke. In view of the extra damage produced by subsequent strokes into an existing arc spot (Phillpott, 1970) it is very desirable that these should always result in a restrike thus providing a new arc position.

It appears that the laboratory tests have been performed so far with continuous low current pulses. Further tests with a superimposed high current pulse would yield useful information in deciding between the two mechanisms. The study of swept strokes to ascertain the 'dwell time' at one position is considered to be one of the most urgent outstanding lightning simulation studies (Brick, 1968). This is because the recommended 2 mm aluminium alloy skin thickness cannot withstand the 500 coulomb test specification and therefore further research is required to provide a basis for a modified specification (Perry, 1968). This study should proceed in parallel with that proposed for stationary arcs in the previous section.

Of the two methods used by LTRI for simulating swept strokes, the rotating disc with a stationary arc best simulates the conditions on an aircraft, but an arc movement of more than 0.5 m may be difficult to achieve. A further possible method is to use a parallel rod and plate electrode system where the arc is driven by a transverse magnetic field, thus permitting studies to be performed at speeds up to 1000 mph. In this case, the equipment would comprise a rail electrode and test sheet. A coil around the rail-sheet electrodes, would produce a field at right angles to the arc, thus driving it along the electrodes.

3.3 Magnetic Forces

In regions where lightning currents flow at a high current density, such as at the arc root or in protective and bonding strips, high magnetic forces can be exerted on the current carrying component. The magnetic field on the surface of a conductor carrying a current density of 10 kA/mm width is 12.6 Tesla which will exert a pressure of $63 \times 10^6 N/m^2$ (or 9500 lbs/in^2) normal to the surface of the conductor. The magnetic pressure and magnetic forces are proportional to the square of the magnetic field and total current respectively.

During the short duration of high current pulses the mass of the conductor may prevent it being displaced appreciably due to its relatively slow mechanical response time, although it can absorb appreciable kinetic energy in this time. Maximum mechanical stresses occur at maximum deflection when the kinetic energy is converted into strain energy. For a simple mechanical system having an angular frequency ω subjected to a rapidly applied force decaying exponentially in a time $\frac{\tau}{2}$ it can be shown that the maximum transient stress is only a function of $(\tau\omega)$ and the maximum magnetic force P_o at peak current. For design purposes it is convenient to define an effective transient force P_t which would result in the same stress as if the force P_t were applied slowly but continuously. This transient force P_t can be calculated for a given value of P_o from the general relationship between (P_t/P_o) and $(\tau\omega)$ (James, 1959).

In most practical applications the angular frequency ω will be between about 10^3 and 10^4 for heavy flexible and light stiff systems respectively. Values of P_t/P_o for these frequencies and the three current components given for a positive discharge in Table 2.2 are given in Table 3.1 where τ is the current decay time constant. The peak force P_o is normalised to a relative peak value of 1.0 for a peak current of 50 kA.

TABLE 3.1

EFFECTIVE TRANSIENT MAGNETIC FORCE P_t

I (kA)	τ (ms)	Coulombs (C)	I^2t $10^6 (A^2s)$	P_o (Relative Units)	P_t/P_o		P_t (Relative Units)	
					$\omega=10^3$	$\omega=10^4$	$\omega=10^3$	$\omega=10^4$
200 (Fast)	0.1	20	2.0	16.0	0.05	0.45	0.8	7.2
50 (Int)	2.0	100	2.5	1.0	0.75	1.73	0.75	1.73
1.0 (Cont)	200	200	0.1	.0004	2.0	2.0	0.0008	0.0008

The values of the effective transient force P_t deduced in Table 3.1 show that:

(a) Continuing current pulses do not give rise to a high effective force because I^2 and therefore the peak magnetic forces are too low.

(b) If $\tau \ll \frac{1}{\omega}$ as for relatively heavy flexible systems $(\omega = 10^3)$ the effective force is roughly proportional to I^2t. Thus the fast and intermediate components give about the same effective force although the peak forces are very different.

(c) If $\tau \gg \frac{1}{\omega}$ as for relatively light stiff systems $(\omega = 10^4)$ the effective force equals twice the peak force and is therefore proportional to I^2. For this doubling of the peak force to occur it is assumed that the current rise time is $\ll \frac{1}{\omega}$.

(d) If $\tau \approx \frac{1}{\omega}$ the effective force is 45% of the peak force, for the case of the fast component with $\omega = 10^4$. This alternative also gives the highest effective force because the high value of I^2 more than compensates for the effects of a small value of τ.

The effect of magnetic forces on current carrying components is influenced by a large number of parameters but the contribution from the continuing current is negligible. Therefore it is clear that future studies of, and tests on, components likely to be damaged by magnetic forces should be performed with a waveform having values of I and I^2t similar to those of the fast component of the positive ground discharge (Table 2.2).

Damage caused by high magnetic forces can be increased considerably if the current density and magnetic field B are so high that softening or melting of the conductor results. Furth et al (1957) have shown that for short current pulses the maximum conductor surface temperature in $^{\circ}$C is $0.36\ B^2$ where B is in Tesla. The temperature rise is virtually independent of the metal resistivity and the pulse length provided the pulse duration is so short that the current flows in a thin skin. In lightning strikes to aircraft such high magnetic fields are most likely to occur near the arc root at peak current in high di/dt discharges. An arc having a peak current of 200 kA rising in a few microseconds will have a diameter of about 2 mm and hence its maximum magnetic field will be about 40 Tesla producing a magnetic pressure approaching $0.63 \times 10^9\ \mathrm{N/m^2}$ (150,000 $\mathrm{lb/in^2}$). The corresponding metal temperature will be about 600°C or near the melting point of aluminium alloy. Under these conditions the metal can be rapidly displaced by the magnetic pressure and possibly structural failure may result. The significance of this phenomena in accelerating 'burn through' of metal skins especially with subsequent strokes has already been discussed in Section 3.1.

3.4 Sparking Phenomena

Sparking at bolted joints in such components as bonding strips and access doors in fuel tanks, and at cemented joints can give rise to (a) damage to the joint itself, (b) sparking on the inside of the door which could ignite the fuel and (c) high voltages between internal wiring and the structure (Robb, 1968). Fig.3.9 shows a bolted joint configuration which could give rise to some of these problems.

Fast pulse currents rising in about 5 μs flow in the top surface of good electrical conductors to a depth of only 0.5 mm in aluminium alloy. If, in addition, the surface of two plates forming a bolted joint have a thin insulating coating, the current i is forced to take a very tortuous path as shown in Fig.3.9. Conditions are made even worse if the screws are badly fitted as at B. As a result of this current flow pattern, large inductive voltages proportional to $d\varphi/dt$ can exist between the two plates due to the changing magnetic flux φ produced by the current through the screw. The inductance associated with this magnetic flux could be of the order of 2.0 nH and thus if di/dt is 80 kA/μs a voltage of 160 volts will exist between the two plates along HE and DG across very small insulating gaps. The resulting high electric stress may break down the latter and sparking will result. Arcing damage may also be caused to the screws if these are badly fitted or not fully tightened as at B, or a large proportion of the current flows through the screw threads as at F. If these problems are to be avoided it is essential that good metal-to-metal joints about 3 mm wide are made at G on the periphery of the access door as recommended in the ARB test specifications.

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 channel. Studies of sparking phenomena must therefore be performed with a current waveform which includes these two components.

3.5 Composite Structures

The possible introduction of composites, such as boron and carbon fibre reinforced epoxy laminates, in aircraft structures represents a very significant departure from the virtually all-metal aircraft. Many lightning protection problems which are now reasonably well understood for metal aircraft will therefore require further study if composite structures are used. Their introduction gives rise to two types of problem; firstly, those associated with the damage to the composite material itself and secondly, those associated with increased induced effects in wiring due to the absence of an electromagnetic screen. The latter problem will be discussed in Section 3.6.

Glass fibre-epoxy laminates are already used extensively in such components as radomes. Because of their high resistivity, lightning discharges are usually conducted in an arc along their external surfaces unless internal arcing is produced to embedded metal conductors. This can lead to vaporisation of the resins, very high internal gas pressures and serious structural damage (Robb, 1968). The combination of fibre glass epoxy outer skins enclosing an aluminium honey-comb internal structure will also lead to the same result due to the 'exploding foil' effect in the latter.

Boron and carbon fibres have very low resistivities (compared with fibre glass) of 850 Ω-cm and 0.0025 Ω-cm respectively so that the current will initially flow through them and not as a surface discharge (Robb, 1968). A further important difference between the two classes of material is that it is possible to divert strikes away from glass fibre sections by placing conducting strips on their outside surface, whereas strike points on to composite sections will be the same as for a metal surface. This is because the resistivity of the composite materials is sufficiently low for the electric field distribution to be the same as if the surface were metallic. Thus composite components will be subject both to initial strikes and 'swept strokes'.

The effect of a high current arc strikes to the surface of 1 mm thick composite epoxy laminates has been studied by Kelly and Schwartz (1968). Considerable damage is reported at currents up to 100 kA and only 2 coulombs for both unpainted and aluminium painted panels. Severe cracking occurred at the strike point and in some cases a hole was produced through the panel. It is concluded that the boron fibres fail mechanically due to thermal stresses cracking the central conducting tungsten core, the epoxy being thermally insulated from the core by the surrounding boron sheath. In carbon composites the epoxy matrix is heated by being directly in contact with the carbon fibres and therefore is probably degraded thermally.

Fassel et al (1968) have studied the effect of high currents (38 kA, 0.5 coulombs) being conducted through boron and carbon 6" × 0·5" × 0·1" specimens. The external connections were by means of metal conductors and not through an arc. It was found that at 30 kA, 0.5 coulombs boron filaments failed structurally and their resistance increased four times, whereas carbon composites did not degrade. No permanent change in carbon composite resistance was noted though a transient change occurred which was a function of current (four times the resistance at 2 kA).

It will be seen from the above discussion that composite materials act as very high resistance conductors to lightning currents. They therefore absorb considerable amounts of energy if the I^2t component of the stroke is appreciable. Reference to Table 2.2 shows that the contribution to this thermal energy from the 'continuing' components is negligible while the 'fast' and 'intermediate' components contribute 4.5×10^6 and 0.7×10^6 A^2s for positive and negative strokes respectively. The resistive energy deposited by these components in the fibres of a carbon composite panel about 30 cm diameter and 1 mm thick by current flowing radially from a 1 cm diameter arc would be of the order of 30 kJ and 7 kJ. In the case of boron fibres these values would be several thousand megajoules as pointed out by Robb (1968). Since it is unlikely that these materials can absorb such large quantities of energy without failure, protective measures, for example conducting paints or thin metal coatings, to prevent the lightning currents entering the composite material are required. The extra weight associated with these protective coatings may however reduce the weight advantage of these materials significantly.

3.6 Electrical Systems

Electrical wiring associated with electronics, power systems and measuring, transmitting and receiving equipment may be damaged by lightning strikes in the following ways:-

(a) Direct strikes to external components;
(b) Induced and resistive voltages, due to currents in adjacent structures.

As a result of work at LTRI protection of the inboard equipment against the consequences of direct strikes to (a) antennae has been achieved by using lightning arrestors and (b) externally mounted fittings by earthed screens. These methods can be adequately checked by simulated tests. Problems due to resistive voltages can generally be overcome by using adequate bonding techniques as discussed above for bolted joints in access doors. Large resistive voltages can still however occur along the length of the aircraft which may cause problems on electrical circuits (Reynolds et al, 1968). Induced voltages in wiring due to magnetic coupling to lightning currents in adjacent structures represent an increasingly difficult problem to overcome. This is because of the increased use of integrated circuits, semi-conductor devices and the absence of metal screening where glass fibre or composite materials are used. Military aircraft probably present greater problems as their electronic equipment may be particularly susceptible to malfunction due to induced voltages.

Fig.3.10 shows a possible configuration (adapted from Robb, 1968) which illustrates the induced voltage problem. If a strike occurs at A the current i will produce a magnetic flux φ, through the space between an unscreened conductor 1 and the structure. If the inductance represented by this flux is L_1, with conductor 1 earthed to the structure at A, a voltage $V_1 = L_1\,di/dt$ will be induced between a point B on the conductor and the structure. If conductor 1 is about 10 cm away from the structure, L_1 will be of the order of 0.2 μH/m length of conductor and therefore if di/dt is 80 kA/μs, V_1 will be of the order of 16 kV/m.

If the current pulse time τ is so long that the magnetic flux φ_2 diffuses through the skin of the structure, between it and an internal conductor 2 earthed at C, (Fig.3.10) an induced voltage V_2 will appear between point D on the conductor and the structure. The magnitude of the internal field depends on the current waveform and distribution in the metal skin and is likely to be greatest where the current flow is non-uniform near the strike point and very small where it is uniform. For example, no voltage would be induced in a conductor placed inside a cylinder with uniform axial current flow. The problem of magnetic field diffusion through thin-walled metal structures in non-symmetrical configurations is extremely complex. Digital computer solutions for axi-symmetrical systems are available (Phillpott et al, 1969) and also design data for diffusion into infinitely thick slabs (Medford et al, 1967).

The internal magnetic field B_i in arbitrary units 2 mm below the surface of an infinite slab of aluminium alloy for various waveforms has been calculated from Medford's data and is given in Fig.3.11. The waveforms are specified as peak current (rise time/exponential decay time constant τ), e.g. 200 kA (0.1/1.2 ms). Pulses of 250 coulombs and varying peak currents (full lines) and 200 kA peak current and varying pulse times (dotted lines) are considered. Possible waveforms might be 40 kA (0.2/2.4 ms) with a maximum di/dt of 0.3 kA/μs, or 100 kA (2/24 μs) and a di/dt of about 80 kA/μs, which give peak internal magnetic fields (at depth of 2 mm) of 70% and 25% of the external magnetic field respectively in the infinite slab approximation.

To obtain an estimate of the voltage induced in a screened conductor compared with an unscreened conductor, the influence of the following factors must be assessed:-

(a) The ratio α of the magnetic field inside and outside the metal skin under DC conditions. This depends on the geometry and current flow and in the calculation below will be assumed to be 0.1.

(b) The ratio of the peak values of B_i/B_e due to diffusion effects. This has been obtained from the infinite slab approximation, (Medford, 1967).

(c) The ratio of the rise times t_e/t_i of the external and internal magnetic fields. This is assumed to be as given by Fig.3.11.

An effective loop inductance L_2/metre can be defined such that the voltage V_2 induced in the loop formed by conductor 2 and the structure at D in Fig.3.10 equals $L_2\,di/dt$ per metre length. If conductor 2 is roughly the same distance (~ 10 cm) away from the current carrying structure surface as the unscreened conductor it follows that the ratio L_2/L_1 and hence V_2/V_1 (for the same di/dt) are given by:-

$$\frac{L_2}{L_1} \approx \left(\alpha \cdot \frac{B_i}{B_e} \cdot \frac{t_e}{t_i}\right)$$

and

$$\frac{V_2}{L_2} = \frac{V_1}{L_1} = \frac{di}{dt} .$$

Estimated approximate values of L_2 and V_2 and other relevant parameters are given in Table 3.2 for the two waveforms discussed above. The fast 80 kA/μs waveform induces a voltage of 10 V/M which may be significant for low voltage circuits though it is only 0.06 per cent of that in the unscreened conductor. It should be noted that the inductance L_2 is an effective value and only applies to a given current waveshape.

TABLE 3.2

APPROXIMATE INDUCED VOLTAGES IN CONDUCTORS/METRE LENGTH

Conductor	Unscreened No. 1 Fast	 Slow	Screened No. 2 Fast	 Slow
Peak current (kA)	100	40	100	40
Current rise time (μs)	2	200	2	200
di/dt (kA/μs)	80	0.3	80	0.3
Peak B_i/B_e			0.25	0.7
t_e/t_i			0.025	0.4
$\alpha \cdot \frac{B_i}{B_e} \cdot \frac{t_e}{t_i}$			0.0006	0.028
Inductance (nH/m)	200	200	0.12	5.6
Induced voltage (V/m)	16000	60	9.6	1.7

The induced voltages V_1 and V_2 can be avoided if conductors 1 and 2 in Fig.3.10 are surrounded by an earthed outer screen which is bonded to the structure at B and D respectively. This will however give rise to very high currents directly fed into the earthed screen limited only by its self inductance L_c estimated to be about 0.9 μH/m. The fraction of the total current fed into the screen is $L_1/(L_1+ L_c)$ which is about 18 per cent, say 20 kA, as L_1 is about 0.2 μH/m as discussed above. These currents will also flow in the unscreened conductor if a voltage breakdown occurs from B to the structure which is a very probable event at 16 kV. The currents in the earthed outer screen of conductor 1 can only be drastically reduced if the screen is placed on and bonded to the outside surface of the structure to make L_1 negligible (Reynolds, 1968).

In the case of conductor 2, based on the parameters in Table 3.2, and assuming that a voltage breakdown had occurred at point D the fraction of the total current flowing in the conductor would be about 0.1 per cent, or 100 amps. Such a low current for several microseconds should not cause much damage to the conductor unless its heat capacity could not absorb the I^2t energy.

In spite of the very approximate nature of the above estimates the results suggest that significant voltages and currents can be induced in completely screened conductors by lightning strokes. In view of this, future accurate theoretical and experimental studies of specific problems are required to see if these fears are justified. These transient current flow problems are also considered by LTRI to need further investigation (Newman, 1968).

Plumer (1970) has suggested a method of investigating this problem based on non-destructive tests performed on actual aircraft at the correct frequency but low di/dt. The voltage produced in the wiring may be separated into a component due to the magnetic coupling through an effective mutual inductance and a resistive component produced by the current flowing along the fuselage or wing. If a simulated lightning wave is passed through the aircraft component and the open circuit voltage measured, the effective inductance and resistance can be found. Hence it is possible to predict the voltage for any waveform assuming that the diffusion of magnetic flux does not significantly alter the effective inductance and resistance.

3.7 Fuel Systems

The loss of a Boeing 707 near Elkton, Maryland due to a supposed lightning strike to the fuel system in 1963 brought the lightning strike hazard to the fore. The resulting investigations were responsible for a considerable increase in the understanding and identification of the hazards of lightning to aircraft fuel systems (Auburn, 1968). Bragg (1968) gives information of the flammability of the various fuel states for temperature, altitude, fuel vapour and percentage oxygen, and also shows that

(a) all fuel/oxygen mixtures are spontaneously reactive above 200^{o}C (400^{o}F);

(b) case temperature above 230^{o}C (450^{o}F) due to component overheating can cause ignition;

(c) mixing of various fuel grades can extend the flammability region beyond that of either fuel type used by itself;

(d) the percentage oxygen in the foam can increase from the normal 21 per cent (by volume) to over 30 per cent when the aircraft is climbing. This is due to the preferential evolution of oxygen from the fuel, and affects the ignition limits.

Litchfield (1968) discusses the problems associated with spark ignition and suggests that a few millijoules is sufficient to cause ignition under certain fuel conditions.

Fuel systems are endangered by:-

(i) Puncture of the wall or 'hot spots' due to direct or swept strokes.

(ii) Internal sparking caused by high di/dt at bolted joints and filler caps.

(iii) Intense electric fields producing corona at or near fuel vents and flame front propagating up the vent. This situation could arise due to a lightning strike just missing the aircraft.

(iv) Electrostatic charging of the fuel.

Section 3.1 covers various aspects of metal puncture and the production of hot spots by direct or swept strokes. As aluminium melts at about 650^{o}C (1200^{o}F), and Bragg (1968) states that 230^{o}C (450^{o}F) can cause ignition, the hot spot temperature is probably the limiting factor as this requires a smaller number of coulombs than that required to puncture.

Section 3.3 covers the aspects of arcing and sparking and as only a few millijoules are required for ignition there must be no sparking in the tank. The design of fuel door flanges to prevent internal sparking is however now reasonably understood as discussed in Section 3.3.

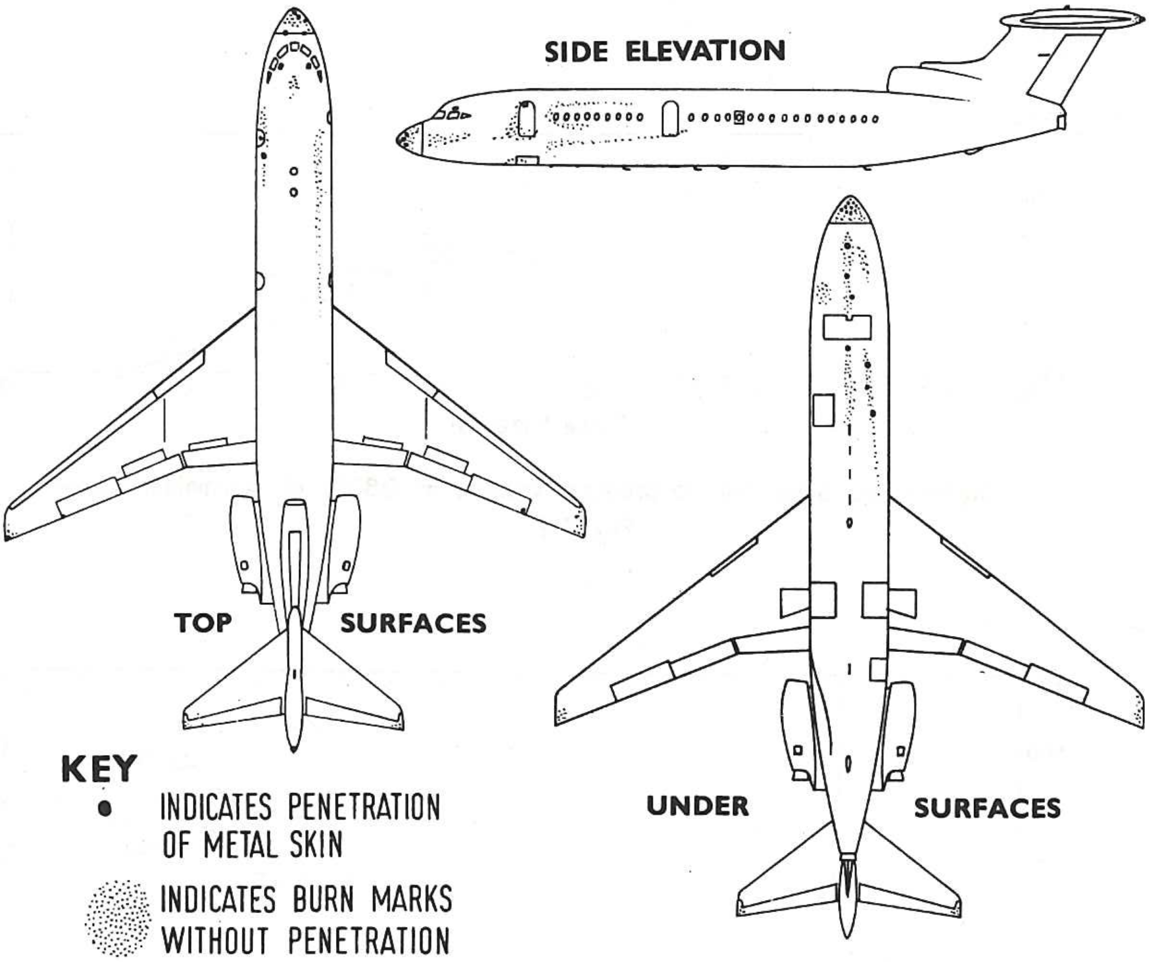
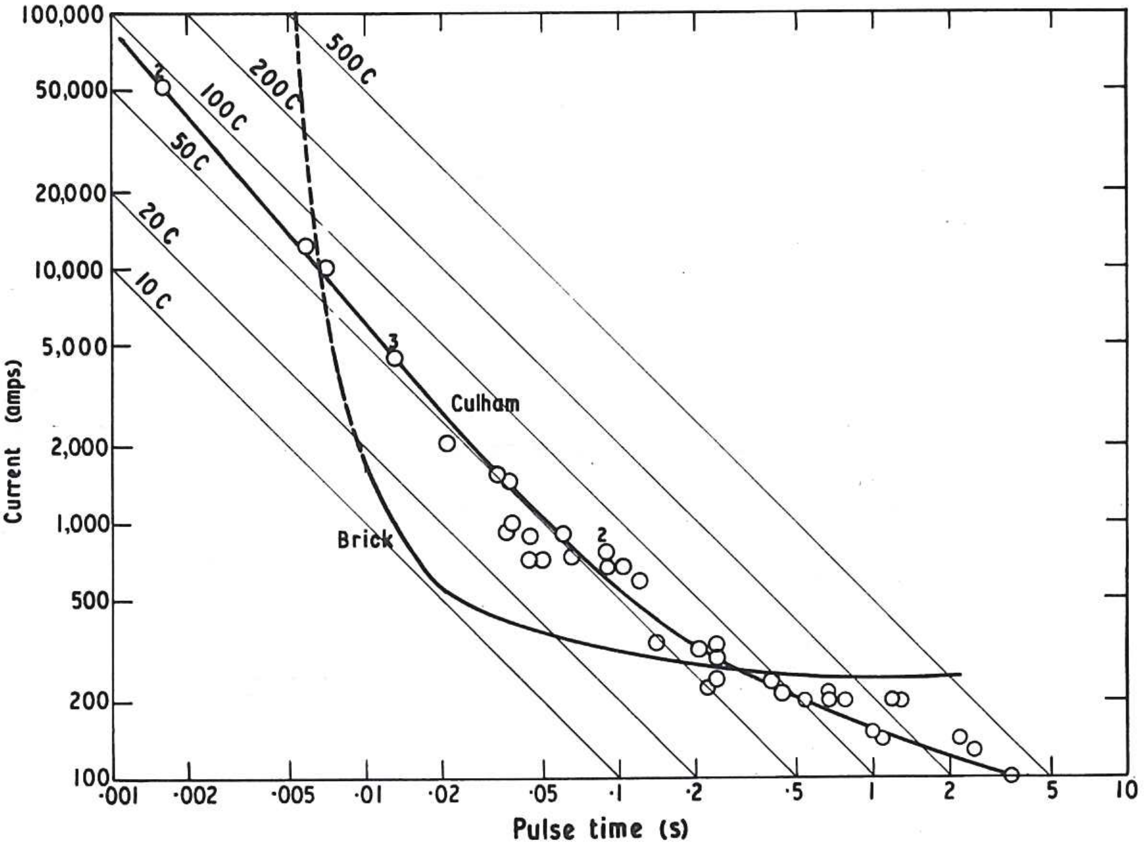
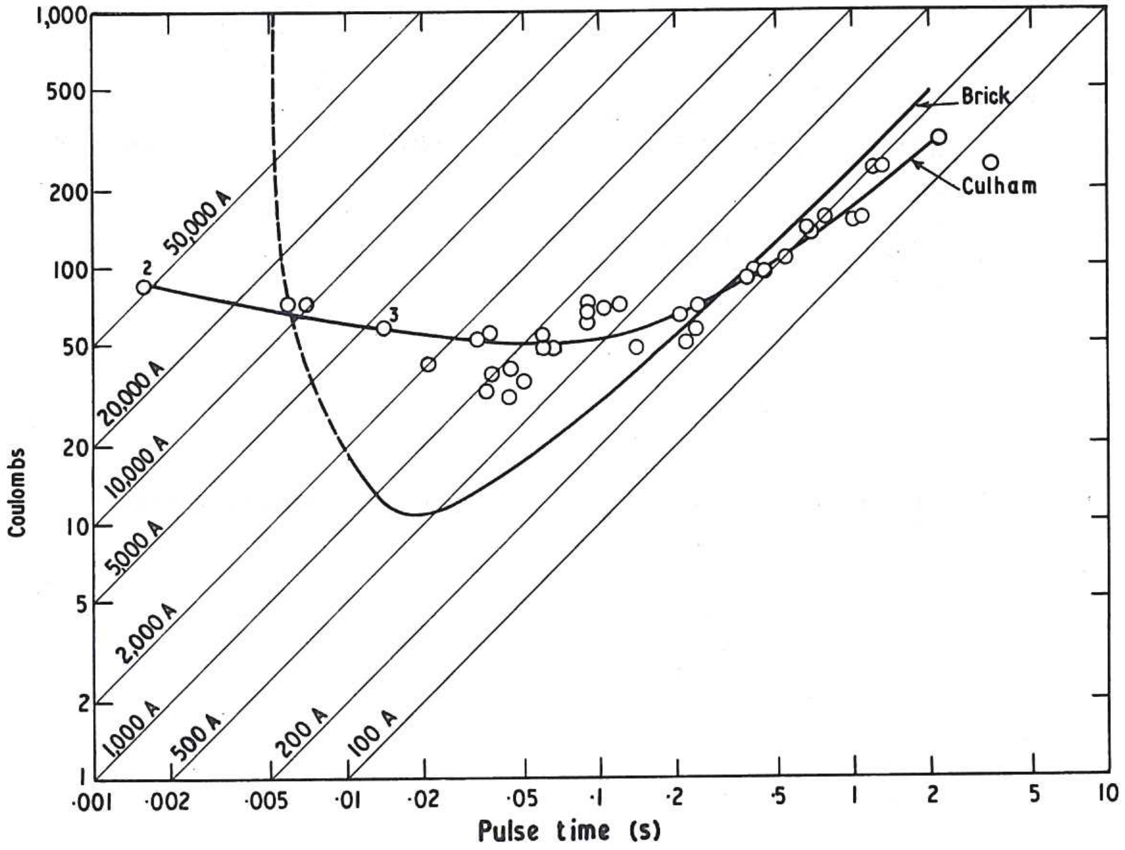

SIDE ELEVATION
TOP SURFACES
UNDER SURFACES
KEY
● INDICATES PENETRATION OF METAL SKIN
INDICATES BURN MARKS WITHOUT PENETRATION

Fig. 3.1 **Position of Lightning Strikes on Trident Aircraft — May 1964 to June 1968**



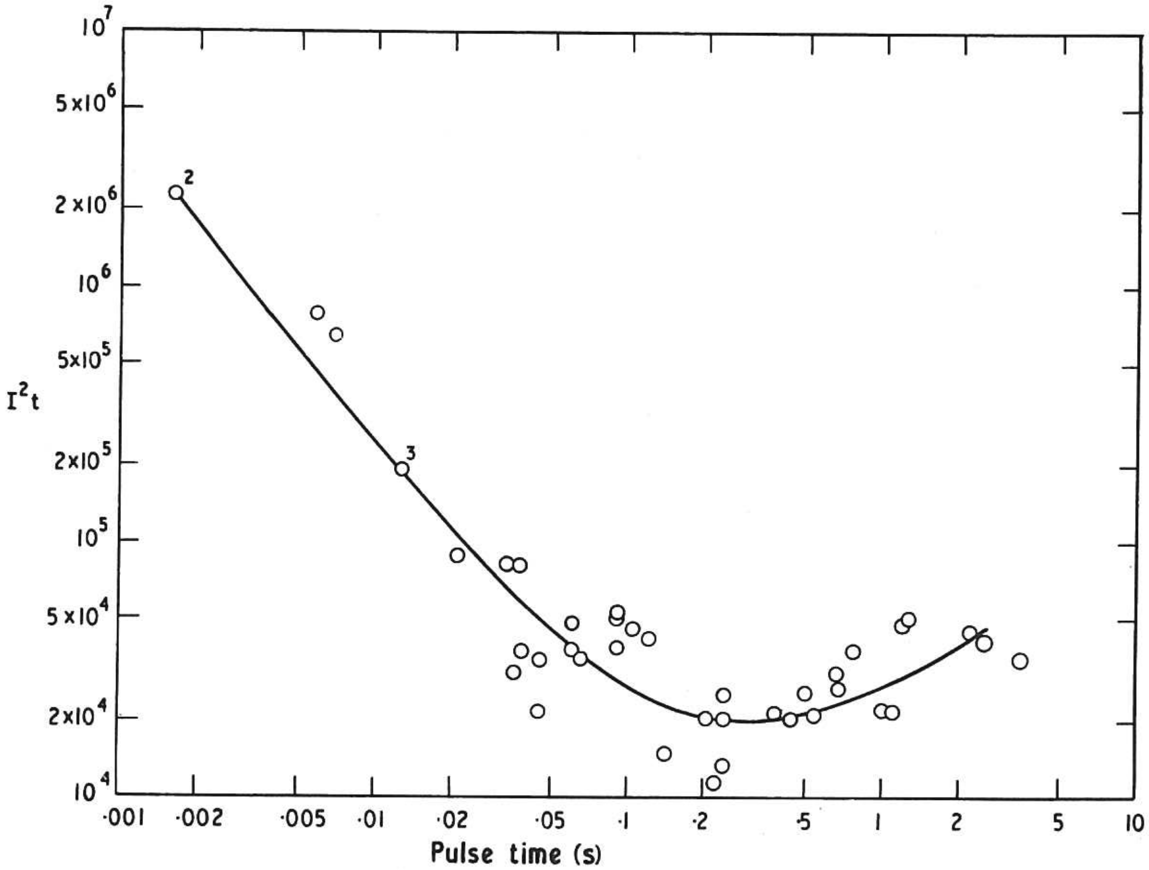
Current and pulse time to produce puncture in ·080 in of Aluminium Alloy.

Fig. 3·2



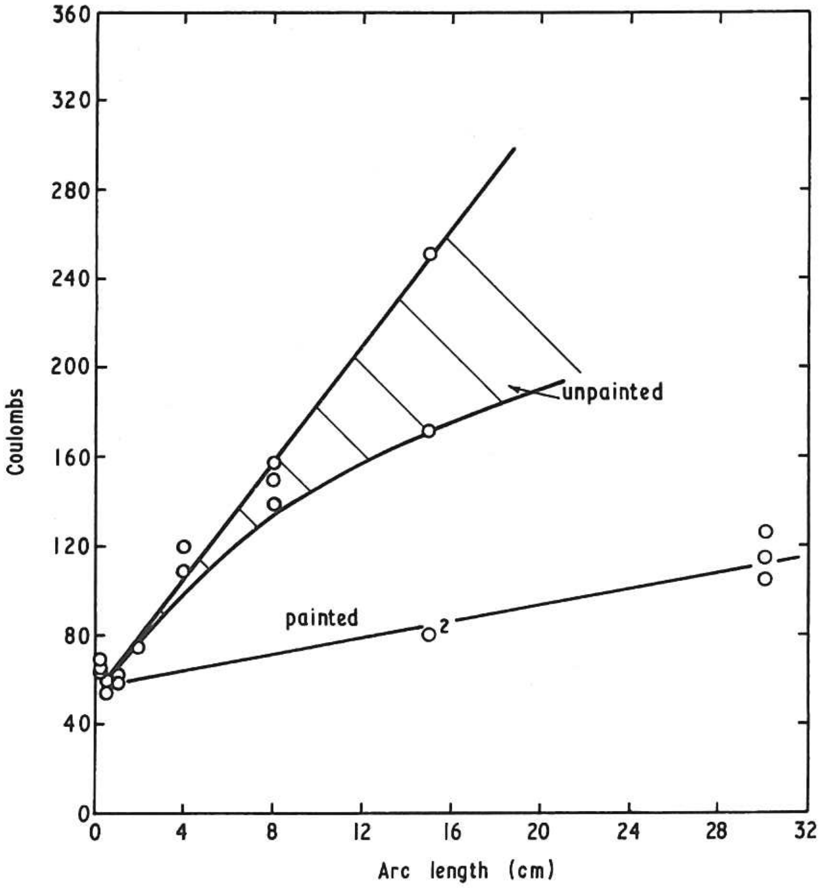
Coulombs and pulse time to produce puncture in ·080 in. of Aluminium Alloy

Fig. 3·3



I^2t and pulse time to produce puncture in ·080 in. of Aluminium Alloy

Fig. 3-4



Coulombs required to puncture ·080 ins of al. alloy against arc length for currents ≃ 10kA

Fig. 3·5

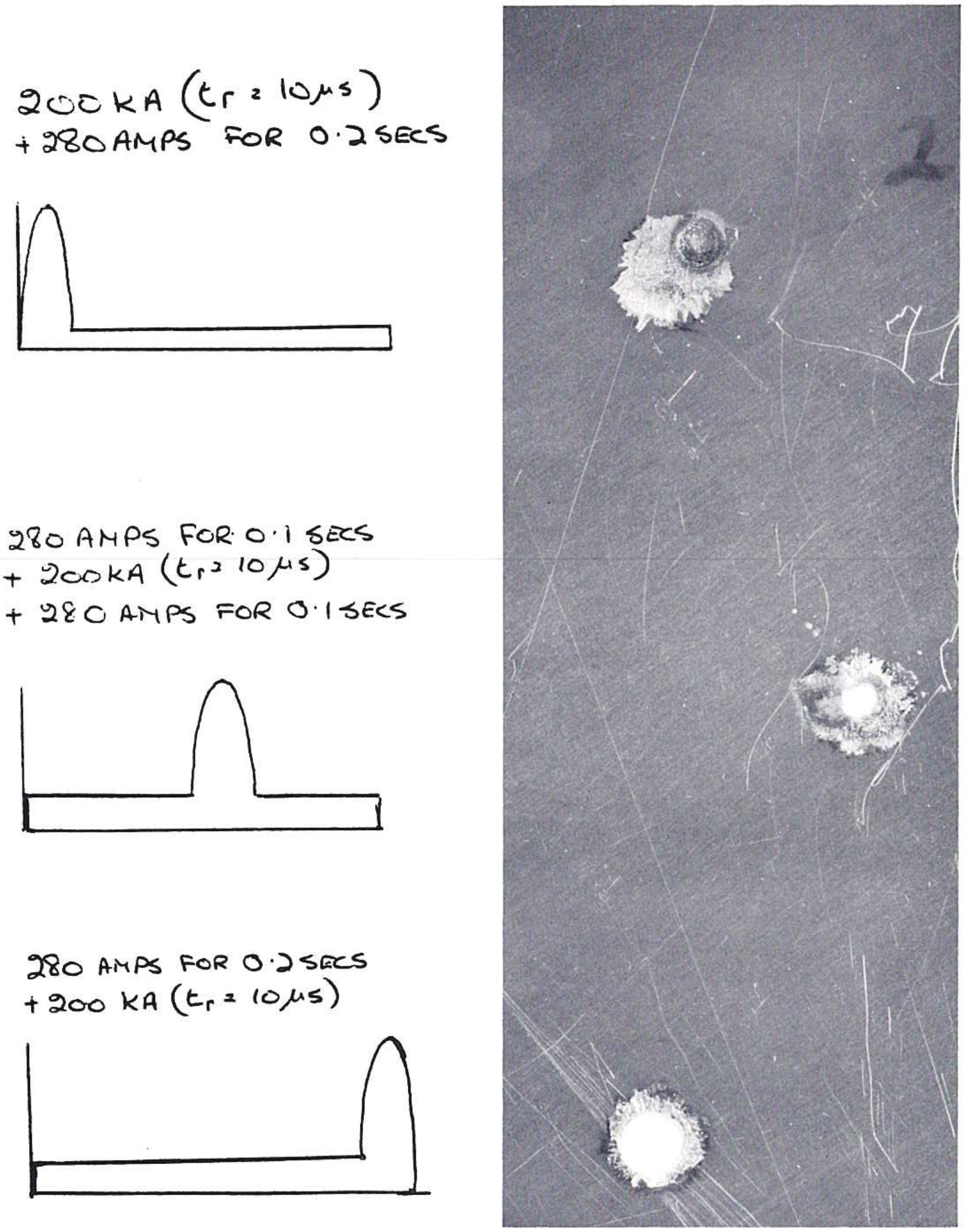
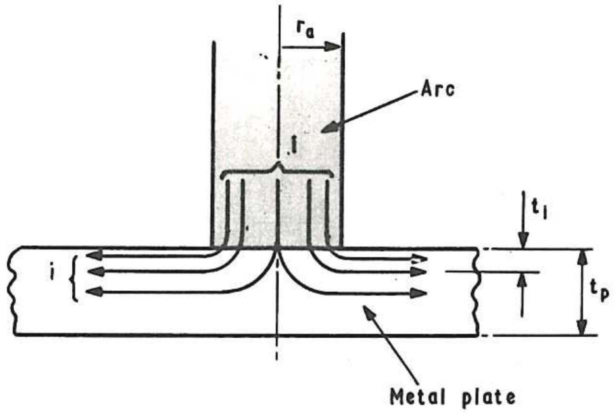
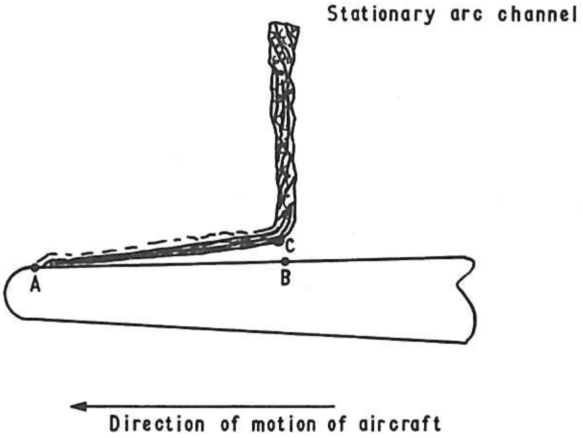

200 kA (t_r = 10μs)
+ 280 AMPS FOR 0·2 SECS
280 AMPS FOR 0·1 SECS
+ 200 kA (t_r = 10μs)
+ 280 AMPS FOR 0·1 SECS
280 AMPS FOR 0·2 SECS
+ 200 kA (t_r = 10μs)

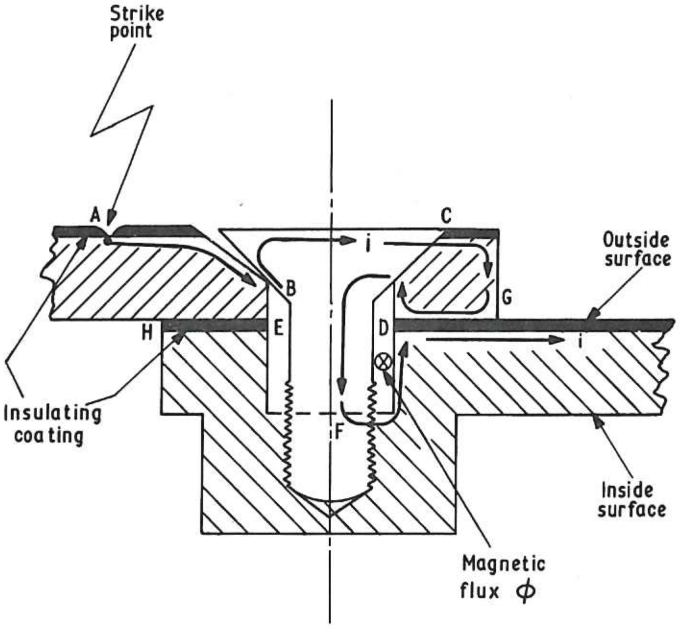
Fig.3.6 Effects of fast pulse timing for constant coulombs


r_a
Arc
I
t_l
i
t_p
Metal plate

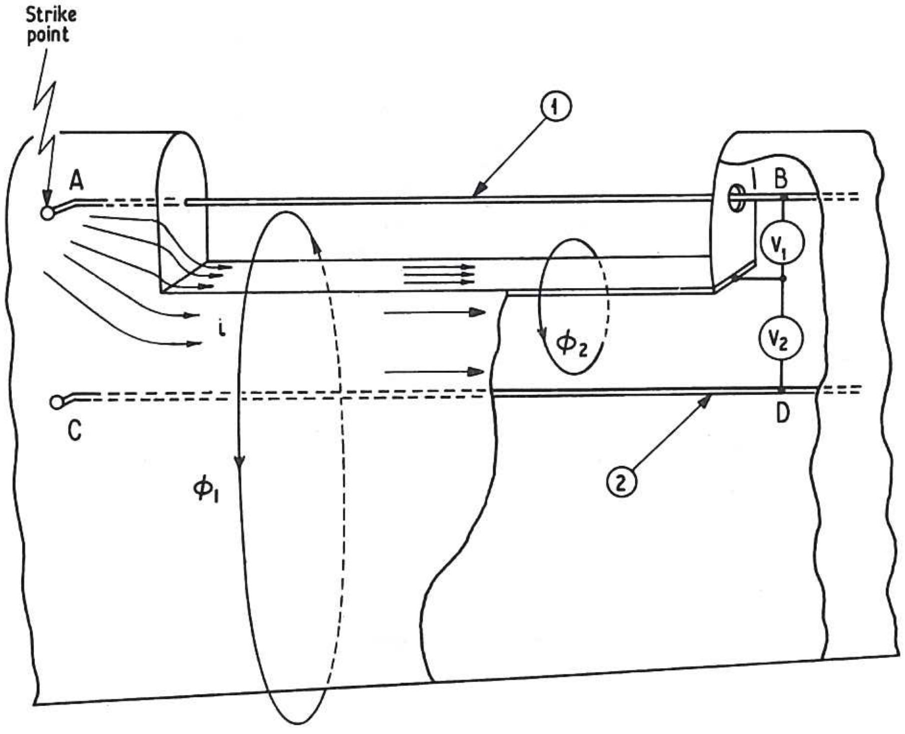
Arc root on metal plate
Fig. 3·7


Stationary arc channel
C
A
B
Direction of motion of aircraft

Swept stroke configuration
Fig. 3·8

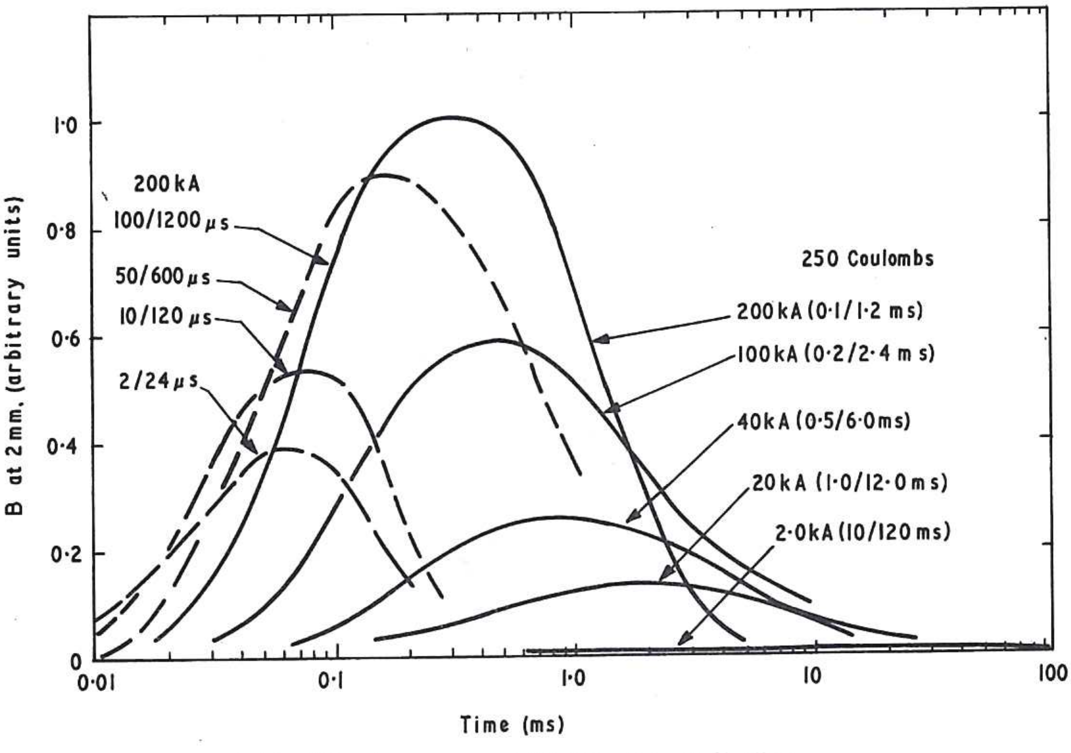

Strike point
A
B
C
i
G
Outside surface
H
E
D
i
Insulating coating
F
Inside surface
Magnetic flux ϕ

Current flow at bolted joint
Fig. 3·9


Strike point
A
B
C
D
1
2
V1
V2
i
I
φ1
φ2

Induced voltages in auxiliary circuits

Fig. 3·10



Field diffusion into an infinite slab of Al. alloy.
Magnetic field B at 2 mm. below surface

Fig. 3·11

Fuel vents are now sited on the very low field regions of the wings, so that many megavolts on the aircraft are required to produce streamering at or near the vent. The design of the vent line and flame arrestors has been studied by Markels (1968).

The phenomenon of fuel charging due to flow through pipes and filters and also the spray effects are well known. It has been usual to pay particular attention to high refuelling rates on the ground. In future the in-flight effects of large quantities of fuel transferred for centre of gravity control or during fuel jettisoning should not be ignored.

These problems could be overcome by earthing all equipment and using conducting pipe lines and hoses; then with the use of fuel anti-static additives, a world-wide increase in safety could be achieved (Perry, 1970).

3.8 Significance to Helicopters

As helicopters are now flown more frequently in adverse weather conditions, the effects of lightning strikes should be considered as the helicopter has a radically different shape from an aircraft. Whilst the predominant number of strikes is likely to occur to the blades, it is unlikely that the blades will capture all the strokes, and consequently some will occur to the helicopter body. The exit point is likely to be from another blade or from the body. The strike point and exit distribution may be significantly modified when the helicopter is carrying large external loads. Under these conditions there is a problem of reducing the potential difference between the helicopter and cargo handler. At the moment of the contact of the load with the ground the hovering helicopter is earthed, thus increasing its strike risk.

The design of the blade and the hub is of paramount importance as the lightning current will flow along the blade into the hub and exit from some point on the body. Present designs use honeycomb and composite structures extensively and hence the discussion on exploding foils and composites is of significance.

4. HIGH CURRENT LABORATORY STUDIES AND TESTS

4.1 Recommended General Studies

From the consideration of the effects of lightning strikes on aircraft given in Section 3, it will be seen that there are a number of general studies that it would be useful to perform in addition to the testing of actual aircraft components to fixed specifications. Some of this work may arise during the development of specific aircraft equipment while remainder will be concerned with the fundamental studies on general experimental assemblies.

The current waveforms considered necessary to study these problems are given in Table 4.1. These are based on maximum values of 300 kA, 100 kA/μs and 500 coulombs (not necessarily together) which are about 50% above the effective parameters given for lightning flashes to ground in Table 2.2. Such waveforms should enable a given problem to be studied at high coulombs over a current range of three orders of magnitude from 0.3 to 300 kA. This approach is considered to be necessary as it appears that previous work in this field has been very limited in the range of parameters studied compared with the wide variations possible in lightning discharges. This may be due to a lack of adequate high coulomb facilities in the intermediate current range.

Most of the general studies are concerned with high current problems whose important aspects are summarised below.

TABLE 4.1

ELECTRICAL PARAMETERS FOR GENERAL HIGH CURRENT STUDIES

Basic Problems	Important Parameter	Maximum Values (current and coulombs may not be required together)
Stationary Arcs Metal skin puncture Hot spot temperature Magnetic forces Composite structures Electrical components	Coulombs I^2 and I^2t	Up to 300 kA and 500 C at lower currents with subsequent strokes
Swept Strokes Metal skin puncture Hot spot temperature Composite structures	Current Dwell time I^2t	500 kV breakdown followed by up to 200 kA for pulse times up to 30 ms with subsequent strokes
Sparking Phenomena Bolted joints Insulation failure	dI/dt I^2t	100 kA at 100 kA/μs followed by up to 300 kA, 500 C.
Electrical Systems Induced effects	dI/dt I	100 kA at 100 kA/μs for direct coupling 40 kA with a rise time of 200 μs for flux penetration problems.

4.1.1. Metal Skin puncture and hot-spots (stationary arcs)

(a) 'Burn through' times for various metals, surface coatings, arc lengths and configurations.

(b) 'Hot-spot' temperatures for conditions as in (a).

(c) Arc parameters (temperature, diameter, movement), if this proves necessary.

4.1.2. Swept Strokes

(a) 'Burn through' times and 'hot-spot' temperatures as in Section 4.1.1 under 'swept stroke' conditions for arc lengths of about 20 cm.

(b) Effect of electric stress raisers due to projecting metal components and screws etc.

(c) Effects of various metals and surface coatings (insulating or conducting).

(d) Relative air velocity.

(e) Subsequent strokes during a lower current period or after original pulse has been chopped.

4.1.3. Magnetic forces

(a) Calculation of magnetic forces and resulting stresses for various configurations and waveforms.

(b) Tests of practical assemblies.

4.1.4. Sparking phenomena

(a) Configurations of bolted or riveted joints and joint surface conditions relevant to fuel ignition by sparking.

(b) Sparking damage to current joint surfaces and resulting from insulation failure.

4.1.5. Composite and glass fibre structures

(a) Arc contact to the surface of a composite with various surface coatings.

(b) Current conduction through composite materials.

(c) Glass fibre panels with internal metal components.

(d) Protective metal strips.

4.1.6. Electrical systems

(a) Induced and resistive voltages for various practical configurations of aircraft structures, wiring and terminating impedances.

(b) External and internal magnetic field waveshapes for various structural configurations.

(c) The effect of the results of (a) on the operation of equipment normally connected to the wiring and on internal sparking.

(d) Direct strikes to external terminal equipment.

4.2 Lightning Simulation Test Specifications for Aircraft Components

4.2.1 Existing test specifications

Production components intended for use in commercial aircraft, which are likely to be damaged by lightning strikes, are tested according to the recommendations of airworthiness authorities such as ARB in the UK and FAA in the USA. These organisations, the US military authorities and the Anglo-French organisation responsible for supersonic transports (TSS) have issued test specifications which include test current waveforms as given in Table 4.2. These waveforms are grouped under fast, intermediate and continuing components though this nomenclature is not used in the specifications. This survey is mainly concerned with the FAA and TSS specifications, (a) and (c) in Table 4.2, since the latter represents ARB's most recent views on lightning protection (Perry, 1968). However, the other specifications are included because natural lightning discharges are more closely represented in terms of dI/dt [100 kA/μs in (e)] and intermediate current components [in (b) and (d)].

TABLE 4.2

CURRENT WAVEFORMS OF LIGHTNING SIMULATION SPECIFICATIONS

Specification	Fast Component 1	Intermediate Component 2	Continuing Component 3	Remarks
(a) FAA (1967) (AC 20-53)	200 kA Peak <15 μs Rise 50 kA at 30 μs	-	2 to 5 s 500 C	Applicable to fuel systems.
(b) ARB (1963) (D4-6)	100 kA Peak 40 μs to I/2 2 C	5 kA peak 10 ms to I/2 30 C	200 A 1s 200 C	Applicable to complete aircraft.
(c) Anglo-French (1969) T.S.S. Standard 8-6	200 kA Peak 15 μs Rise 50 kA at 30 μs 4 C	-	500 A 1s 500 C Rectangular Wave	Based on FAA(AC20-53) Applicable to fuel system. Guide to whole aircraft.
(d) U.S.Mil.Spec. (1969) A9094D (ASG)	100 kA Peak 5 μs Rise 10 μs to 50 kA	2 kA Peak >20 C	1 to 2 s >300 C	Applicable to lightning arresters for antenna systems.
	200 kA Peak 10 μs Rise 20 μs to 100 kA	2 kA Peak >20 C	>500 C	High current test for lightning arresters.
(e) U.S.Mil.Spec. (1964) B5087B (ASG)	200 kA Peak 100 kA/μs 20 μs to 100 kA	-	-	Applicable to aerospace systems.

4.2.2 FAA and TSS specification

The FAA specification is an advisory circular for the protection of fuel systems whereas the TSS specification is more concerned with the complete aircraft. Both specifications include virtually the same current waveforms and also a Table giving methods of protection for parts of the fuel system situated in various zones as given in Table 4.3.

TABLE 4.3

PROTECTION METHODS FOR FUEL SYSTEMS

(FAA and TSS Test Specifications)

Fuel System Part	Zone 1	Zone 2	Zone 3
Tank skin	Al. alloy thicker than 0.080" or equivalent	-	-
Flush or recessed fuel vent outlets	Protect against direct strokes and streamering	Protect against direct strokes and streamering	-
Protruding types of fuel vent outlets	Protect against direct strokes and streamering	Protect against direct strokes and streamering	Protect against streamering
Access doors, filler caps and other semi-insulated parts.	Protect against direct stroke attachments	Protect against direct stroke attachments	-

The following aspects of these two specifications require some comment as follows:-

(a) Fuel tank thickness of 0.080" Al. alloy

Since a 0.080" skin thickness will only withstand about 50 to 100 C, (under test conditions specified for other components) it is not obvious why this is considered to be acceptable in a Zone 1 region and why direct stroke tests are not required.

(b) Fuel access doors etc. - coulomb tests

It could be interpreted that the 0.080" skin thickness also applies to these items which form the tank skin. This would mean that the 500 C test is not required although under specified conditions, tests have shown that this would burn about a 0.75" diameter hole in a plate of such a thickness.

(c) Zone 2 swept stroke

The test specified for such items as access doors in Zone 2 areas are the same as for Zone 1. It is, however, generally agreed that since this is a 'swept stroke' region the present specifications is much too severe (Perry, 1968).

(d) Fast current component - 200 kA in 15 µs

This component has a maximum di/dt of only 20 kA/µs, which is about four times slower than natural lightning discharges. It therefore does not appear to be adequate for use in testing components which may fail due to sparking (e.g. access doors) or induced voltages in wiring.

(e) Continuing current coulombs

500 coulombs is almost twice the value expected in natural lightning discharges. However, in view of the wide variations in damage that are possible with variations of arc length, number of strokes in a flash and geometry of the current connections this margin is probably necessary. These parameters need specifying if 'burn-through' tests are to be meaningful.

(f) General waveform considerations

An important general limitation of this waveform is that its I^2t values (0.4×10^6 and 0.25×10^6 A^2s for fast and continuing components respectively) are much too low to represent damage associated with magnetic forces, arcing and heating of composites. These values are only about 15% of the maximum effective lightning parameters proposed for a positive discharge in Table 2.2 and only 80% of those for the negative discharge. This is mainly due to insufficient coulombs in the fast component, the absence of an intermediate component and the use of low currents and long pulse times of 1 to 5 s for the continuing components compared with a more typical value of 0.2 s for lightning discharges.

4.2.3. Proposed future test specification

It is generally agreed by airworthiness authorities and workers studying high current lightning problems that the present test specifications need revision if they are to adequately simulate natural lightning phenomena. Although in some respects there is not yet enough experimental data on which to decide actual waveform parameters for future test specifications some discussion as to the current waveforms required may be useful. This aspect is in any case the more important factor in deciding what type of equipment a future test facility will require.

In our view a test specification must represent the fundamental characteristics of the lightning discharge relevant to a given failure mechanism. However, it should not be so complex that the test facilities become too sophisticated and expensive to build and operate. To achieve these aims a different current waveform, consisting preferably of one component but not more than two, should be specified to meet the different types of problems likely to be encountered. At present one waveform is used for testing all aspects associated with a specific component. If more than one type of problem exists in a given component it should be tested with different waveforms in separate tests.

A tentative future test specifications to meet three different types of problem is given in Table 4.4. This assumes that such a specification should represent, say, the worst 5% of natural lightning discharges with a safety margin of up to 50% to 100% for coulombs and I^2t so allowing for possible errors in laboratory simulations. Based on Table 2.2 for positive discharges the maximum integrated parameters used in the test specification are therefore 200 kA, 100 kA/μs, 500 C and $\sim 8 \times 10^6$ A^2s for Zone 1 regions and 100 kA, 100 kA/μs, 100 C and $\sim 2 \times 10^6$ A^2s for Zone 2 regions. These actual values will have to be justified by further general studies as discussed above in Section 4.1, especially for Zone 2 regions subject to 'swept strokes'. Apart from this the general basis for the choice of test waveforms given in Table 4.4 (instead of the present FAA and TSS specifications) is as follows:

(a) The continuing current component has been omitted because in a 2-component waveform the required I^2t values can only be obtained with an intermediate component. Otherwise the coulombs in the fast components are very high. The 'burn-through' phenomena and those dependent on the value of I^2t (such as resistive heating and disruptive forces) can be adequately represented at 30 kA.

TABLE 4.4

RECOMMENDED TENTATIVE SPECIFICATION FOR FUTURE COMPONENT TESTS

Type of Test	Recommended Waveform		
	(1) Fast	(2) Intermediate	(3) Continuing
Group (a) (i) Skin puncture (ii) Skin hot spots (iii) Mechanical strength (iv) Resistive heating (v) Lightning arresters	Zone 1		
		30 kA 500 C 7.5×10^6 A^2s Unidirectional	-
	Zone 2		
		30 kA 100 C 1.5×10^6 A^2s Unidirectional	-
Group (b) (i) Fuel ignition internal sparking (ii) Sparking damage at joints (iii) Induced and direct voltage flashover	Zone 1		
	200 kA 100 kA/µs Underdamped	30 kA 500 C 7.5×10^6 A^2s Unidirectional	-
	Zone 2		
	100 kA 100 kA/µs Underdamped	30 kA 100 C 1.5×10^6 A^2s Unidirectional	-
Group (c) (i) Induced voltages in electrical systems	100 kA/µs Underdamped Unidirectional $\frac{\text{Pulse length}}{\text{rise time}} \sim 5$	-	-

(b) The coulombs for Zone 1 regions have been maintained at the high value of 500 C to represent a margin of safety and the uncertainty of simulating the damage due to a multiple stroke flash with a single component waveform. Further experimental data, regarding the effect of surface coatings and arc length may, however, show that this value should be reduced to nearer 350 C if a 1 cm arc, free from the influence of magnetic forces, is used.

(c) The fast component has been omitted from tests in group (a) as it is not likely to result in appreciable additional damage provided the I^2t value of the intermediate component is sufficiently high.

(d) The Zone 2 swept stroke region intermediate component of 30 kA 100 C is based on a 'dwell time' of about 5 ms. The fast component has again been omitted from the tests in group (a) as discussed in (c) above. Since these tests are to be performed with stationary arcs it should have been previously that this waveform is representative of the conditions applicable to a particular surface under swept stroke conditions.

(e) The di/dt for both fuel ignition sparking and induced voltage flashover has been increased to 100 kA/μs at a peak current of 200 kA. The intermediate components are included in case consequential damage results from the fast component. If this is unlikely the latter could be omitted.

(f) The 100 kA/μs specified for induced effects in electrical systems assumes that it is necessary to test equipment in situ at the maximum induced voltage. If this is not so, tests can be performed with the same waveshape but a lower di/dt from which the maximum induced voltage can be calculated.

4.3. High Current Test Facilities

The high current test facilities required to give the performance specified in Table 4.1 for general studies, in Table 4.2 for component tests to existing FAA/TSS specifications, and in Table 4.4 should the specification be accepted, will now be considered.

4.3.1. Fast high current capacitor bank

Peak current	-	200 kA (300 kA for general studies)
Rise time	-	12 to 30 μs
Coulombs/pulse	-	30
Waveshape	-	Half cycle (90% reversal) or damped oscillation (30% reversal)

The bank energy W, voltage V and capacity C required for a specified peak current and rise time are dependent on the total circuit inductance L and the circuit damping factors or voltage reversal. These factors which are functions of $4L/R^2C$ where R is the circuit resistance are given in Fig.4.1. If a half cycle of current is required the voltage reversal should be of the order of 90%. Alternatively a damped circuit with a voltage reversal of only 30% approximates to the required waveform without a complex switching system. Although in this case a higher energy bank is required it may not be any more expensive than for the 90% reversal alternative as discussed below.

Values of W, V and C are plotted in Fig.4.2 as a function of L for a current of 200 kA rising in 12 μs with 90% voltage reversal (full lines) and for a rise time of 15 μs with 30% voltage reversal (dotted lines). These are the parameters required by the FAA/TSS specifications, the two alternative rise times being chosen to give the same voltage for a given inductance.

The circuit inductance L, on which the energy and therefore the cost of the bank depends, is mainly dependent on the size of the component being tested and its connections since the bank inductance can be as low as 0.1 μH if necessary. Typical inductances for various types and sizes of components are given in Table 4.5 and also the bank energy required.

The inductance values chosen represent the limiting inductance that can be used with standard 40 or 50 kV capacitors connected in series-parallel if necessary, for 200 kA with a rise time of 15 μs and are indicated by the encircled numbers (1) to (5) in Fig.4.2. To achieve the lower values of inductance for 15 m and 60 m components a number of return conductors spaced close to the component surface are required where the width of the components is assumed to be more than 5 m.

TABLE 4.5

ESTIMATED VALUES OF L AND W FOR FAST 200 kA BANK

Component	Component Length (m)	Inductance L (μH)	Energy W (kJ)	
			90% Rev.	30% Rev.
Panels Access doors	2	1.5	33	72 (1)*
Small sub-sections Helicopter blade	6	4.0	80 (2)*	180 (3)*
Large sections of wing or fuselage	15	5.0 to 10.0	110 to 240 (4)*	250 to 500
Complete aircraft	60	15.0 to 40.0	340 to 900 (5)*	740 to 2000

*These numbers refer to the encircled numbers in Fig.4.2.

These capacitor banks can be built up from standard units such as the compact low inductance 4-unit capacitor module Fig.4.3 (a). This module, which has been developed for multi-megampere fusion research applications is rated at 40 kJ and 72 kJ for 90% and 30% voltage reversal respectively for a capacitor life of 30,000 shots. A higher rating is obtained at a low reversal because capacitor life is a function of peak to peak voltage.

This 4-unit bank is suitable for alternative (1) in Fig.4.2 and a 1.0/1.8 MJ bank which is large enough to test a complete aircraft (even if the inductance is the maximum value of 40 μH) is shown in Fig.4.3 (b). Reference to Fig.4.2 alternative (5), shows that with a bank of this size a voltage of 1 MV is required to achieve the current rise time with 40 μH inductance. Therefore the capacitor units would need to be connected in series as in impulse generator circuits. Although this is technically possible a specific requirement to test components requiring such a large bank has not yet been identified. It is therefore considered that alternatives (2) and (3) in Fig.4.2 suitable for 4 μH circuits are likely to cover most of the future requirements. These 80 or 180 kJ banks would operate at 100 kV, with two 50 kV sections in series for tests to the FAA/TSS specification (Table 4.2) or at 50 kV for tests to the proposed new specification (Table 4.4). If smaller facilities for exploratory component development work are required (for example at a manufacturer's works) the use of the 72 kJ 4-unit module (alternative 1) would probably be adequate.

A single half-cycle of current can be obtained in the 90% voltage reversal case by the methods shown in Fig.4.4 (a) where the DC supply necessary to give the continuing current is also included. These are as follows:-

(a) Close the clamp switch S_{12} after one half-cycle. If the DC supply is also being used to give a composite waveform, arrangements to avoid S_{12} short circuiting the DC supply are necessary. This circuit has the important advantage that high coulomb unidirectional pulses can also be obtained by closing S_{12} at peak current.

(b) Connect a fuse AB in series with the fast bank C_{11} which is designed to 'blow' after one half-cycle. This has been used successfully in the USA though it introduces extra external inductances into the circuit. Low inductance exploding foil fuses developed for inductive energy storage applications can however overcome this disadvantage.

4.3.2. High di/dt impulse generator

Peak current - 100 kA
di/dt - 100 kA/μs
Rise time - 1.5 μs

As the peak current of this generator is 50% of that of the fast high current bank discussed above its energy will be 25% of the values given in Fig.4.2 for a given inductance. However the faster rise time means that the voltage required will be four to five times higher than given in Fig.4.2. Thus for a component having an inductance of 3.5 μH and allowing 3.5 μH for the generator 28 kJ of stored energy is required. Whereas it is possible to build such a generator with an inductance of 1.0 μH, optimum designs which are a compromise between performance and economic consideration usually have equal generator and load inductances. A 3.5 μH generator inductance could be achieved using low inductance 75 kV capacitors connected in 10 series stages.

The performance of this generator when testing the various components described in Table 4.5 is given in Table 4.6 for oscillatory and critically damped circuits. It will be noted that for the larger components a di/dt value of 100 kA/μs is not achieved so that it will be necessary to scale up the experimental results obtained at lower values as discussed in Section 3.6. To achieve 100 kA and 100 kA/μs for a complete aircraft test would require at least a 2.2 MV 135 kJ generator having an inductance of about 5 μH.

TABLE 4.6

PERFORMANCE OF HIGH di/dt IMPULSE GENERATOR

(28 kJ 750 kV 90% VOLTAGE REVERSAL)

Component	Circuit Inductance (μH)	di/dt (kA/μS)	Peak Current (kA)	
			90% reversal	Critically damped
2 m Panels	5.0	150	100*	38
6 m Subsections	7.5	100	80	30
15 m Aircraft sections	8.5 to 13.5	88 to 55	75 to 60	29 to 23
60 m Complete aircraft	18.5 to 43.5	40 to 17	50 to 33	20 to 13

*For 200 kA, four times the energy would be required.

4.3.3. High coulomb intermediate bank

Peak current	-	100 kA to 0.5 kA
Coulombs/pulse	-	500
Waveshape	-	Unidirectional

To achieve this wide current range, high coulombs, and a unidirectional waveform with the minimum energy, a clamped circuit is the best solution. It may be necessary to use this bank in combination either with the fast high current or the high di/dt banks as shown in Fig.4.4 b. The intermediate bank C_{12} is connected in series with an inductor L_{12} of any desired value to give the peak current required and the clamp switch S_{23} is closed at peak current.

An exponentially decaying current is obtained if the test component circuit is resistive and a linearly decaying current if the arc voltage V_a (which is almost constant) is the dominant factor. Up to currents of 50 kA the arc voltage will dominate and under these conditions the bank energy required is proportional to both coulombs and arc voltage V_a as shown in Fig.4.5 (full lines). The arc voltage which is mainly a function of arc length is plotted against arc length in Fig.4.7 for currents of the order of 10 kA (Phillpott, 1970). These results agree with those previously obtained (Guile, 1969) in a different current regime. This shows that for a 30 cm arc the voltage is less than 500 V in which case a bank energy of about 250 kJ is required for a 500 coulomb pulse. This bank could be built using three modules as in Fig.4.3 each rated at 83 kJ.

Only critically or over-damped circuits seem to have been used previously in lightning simulation studies in the USA to obtain intermediate current pulses. With these circuits the coulombs are limited to those initially stored in the capacitor bank as shown in Fig.4.5 (dotted line). It will be seen that with a critically damped 8 kV 250 kJ bank a pulse of not more than 100 coulombs can be achieved, which is about 20% of that with a clamped circuit.

The performance of a clamped circuit is not dependent on the bank voltage if the correct inductors are chosen. However it is advantageous to keep the voltage below 20 kV so that standard ignitron switches can be used. For currents of 200 to 300 kA the 50 kV 80 kJ fast capacitor bank (alternative 2 in Fig.4.2) would give pulses of about 100 to 200 coulombs with a clamped circuit. At these high currents these coulomb values would be more than adequate.

The intermediate bank performance is also not very dependent on the component inductance (L_{33} in Fig.4.4.b). For example, for a complete aircraft with an inductance of 15 or 40 μH (Table 4.5) peak currents of about 170 kA and 100 kA respectively are obtainable with a 250 kJ bank if the inductor L_{12} is omitted. To achieve a pulse of 500 coulombs with these currents the aircraft resistance would have to be between 5 or 9 mΩ for 15 and 40 μH alternatives respectively. The resistance values of complete aircraft vary from 10 to 50 mΩ (Perry, 1970). With the highest of these two values and a 250 kJ bank a 500 C pulse through the complete aircraft could be achieved at currents up to about 20 kA. Whereas higher energy banks could be used it is envisaged that for complete aircraft tests a portable facility is desirable and for this purpose a 250 kJ bank weighing about 8 tons would be suitable. It would consist of three of the 4-unit modules shown in Fig.4.3, each module being rated at 83 kJ. A portable facility would also enable tests on complete aircraft to be carried out at different locations.

A further significant advantage of the clamped circuit is that if there is any tendency for the arc to become extinguished either when a long arc is used or due to the high resistance of cemented joints an inductive voltage sufficient to maintain the arc will be produced by the changing current in the inductor L_{12}. This therefore closely simulates the natural lightning condition which is in contrast to the situation that exists if a constant voltage DC source is used. A photograph of a 30 cm 10 kA arc supplied from a clamped circuit is shown in Fig.4.6.

4.3.4 Constant continuing current DC supply

Max current - 500 amps
Pulse length - 1 to 5 s
Coulombs - 500

The TSS specification requires a 1.0 s rectangular pulse of 500 C which can most easily be supplied by a DC transformer/rectifier set. The FAA requirements however do not specify constant current so that in principle an intermediate bank could be used with a sufficiently high value of L_{12} (Fig.4.4) to reduce the current to 1.0 kA. The DC set being considered here would therefore not be required if the TSS specification was redrafted in the same way as that of the FAA. The A.R.B. have indicated that an exponentially or linearly decaying waveform of 500 coulombs will be acceptable. It should however be noted that neither waveform is considered to be adequate to simulate all aspects of lightning as discussed in Section 4.2.2.

If the equipment is required, a voltage rating of 5 kV is recommended, to ensure that the current is maintained in long arcs and through cemented joints or composite materials of high resistance. For all-metal components with an arc length of a few millimeters a 500 V battery or rectifier set would be adequate.

4.3.5 Equipment for swept stroke studies

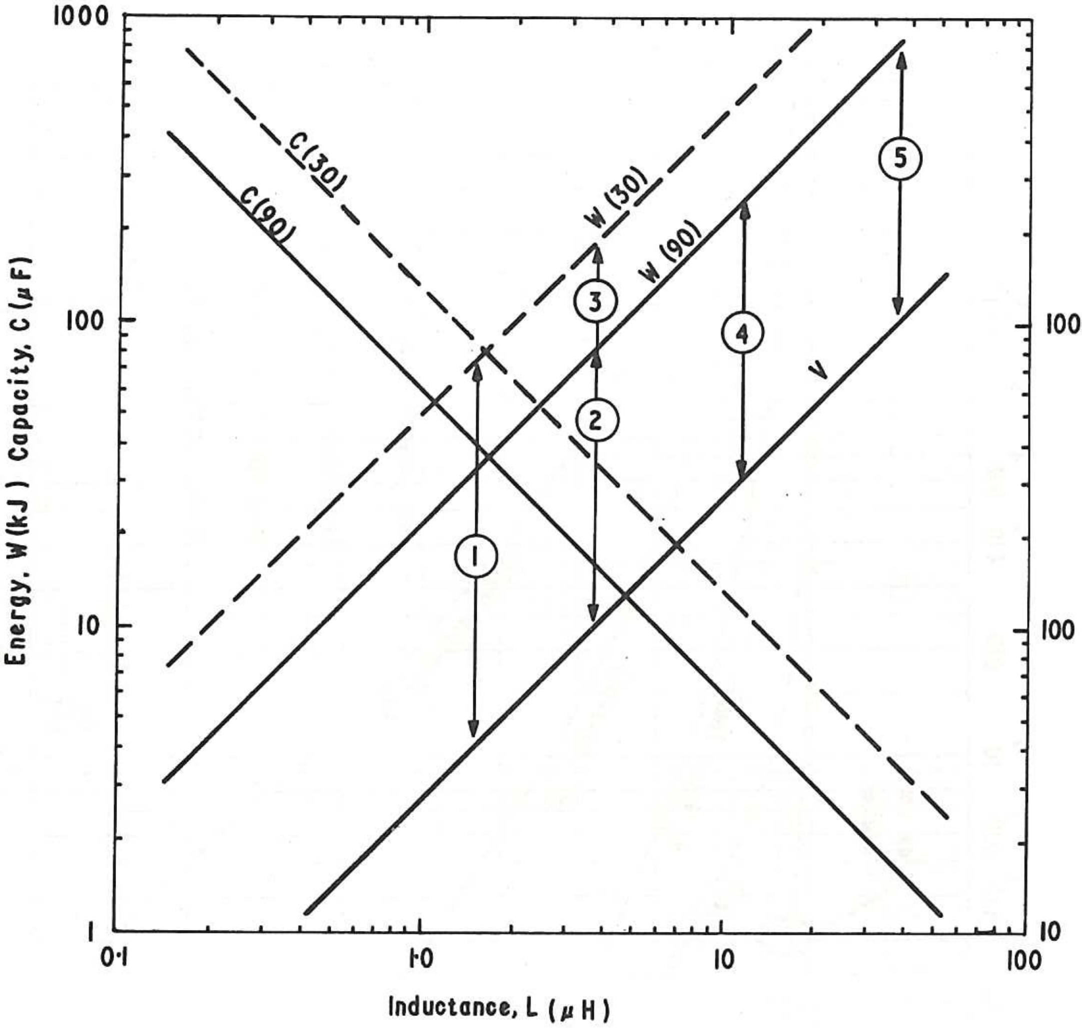
Peak current - 100 kA to 0.5 kA
Coulombs - 100 C
Waveshape - Unidirectional
Breakdown voltage - 500 kV

The high coulomb pulse can be supplied by the intermediate bank and the initial breakdown voltage by the 750 kV impulse generator. The latter can also be used to produce a subsequent stroke to study the influence of inductive effects on the restrike problem.

The actual swept stroke assembly could be one of the following:-

(a) Wind tunnel

Air speed ~ 300 mph
Power ~ 600 kW
Overall size ~ 40 ft × 4 ft



Fast bank parameters
Peak current = 200kA, Rise = 12 to 15μ sec
Fig. 4·2

DAMPING FACTORS FOR R-L-C SERIES CONNECTED CIRCUITS

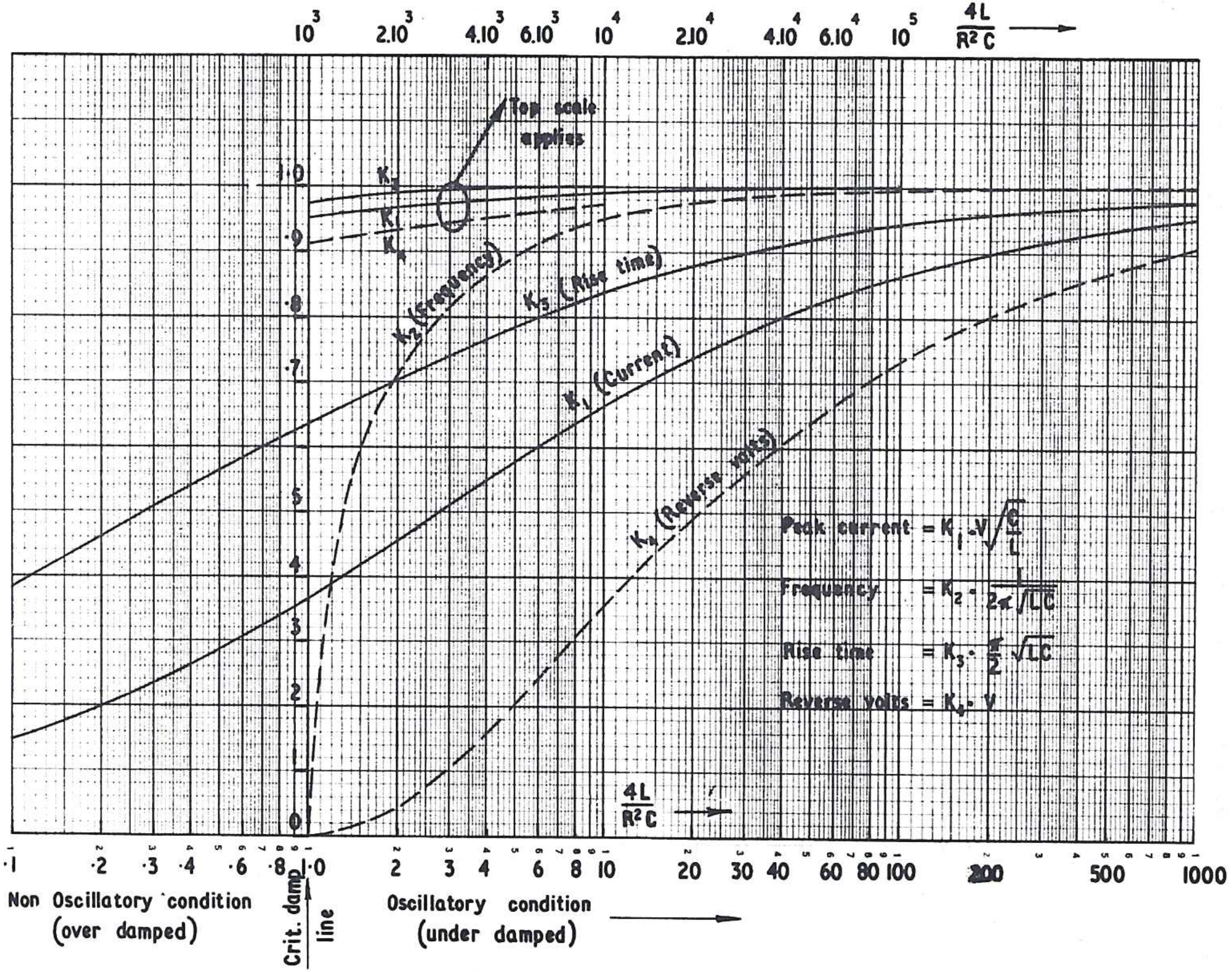
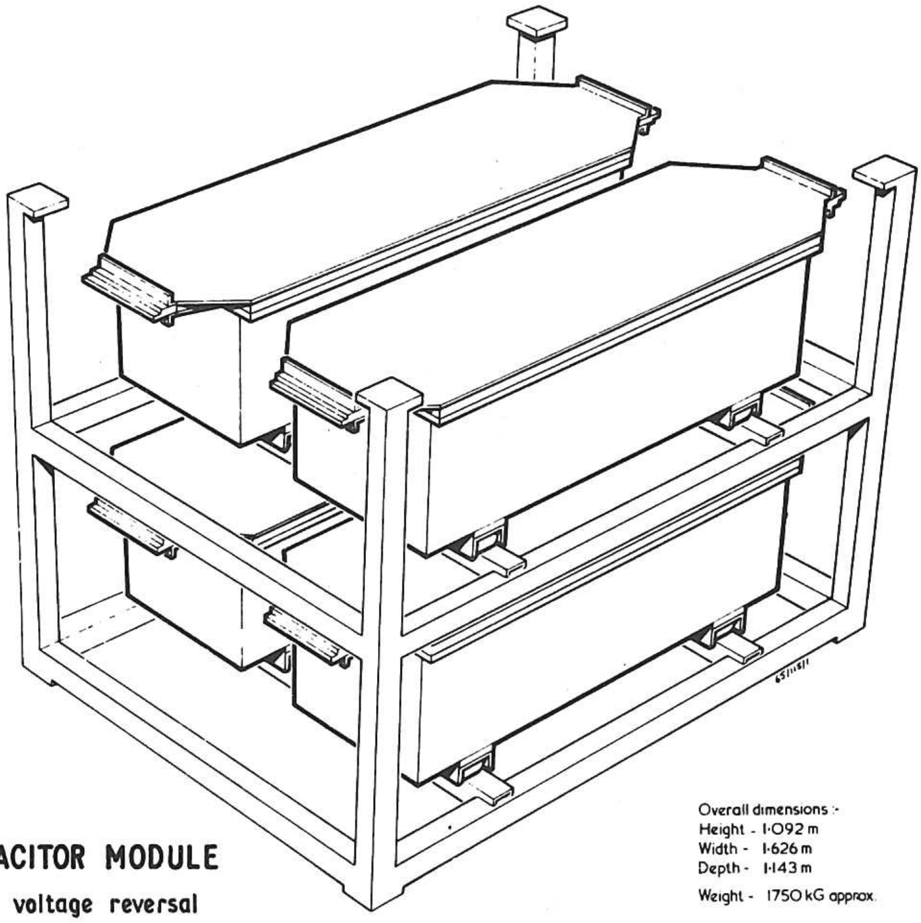


Fig 4·1

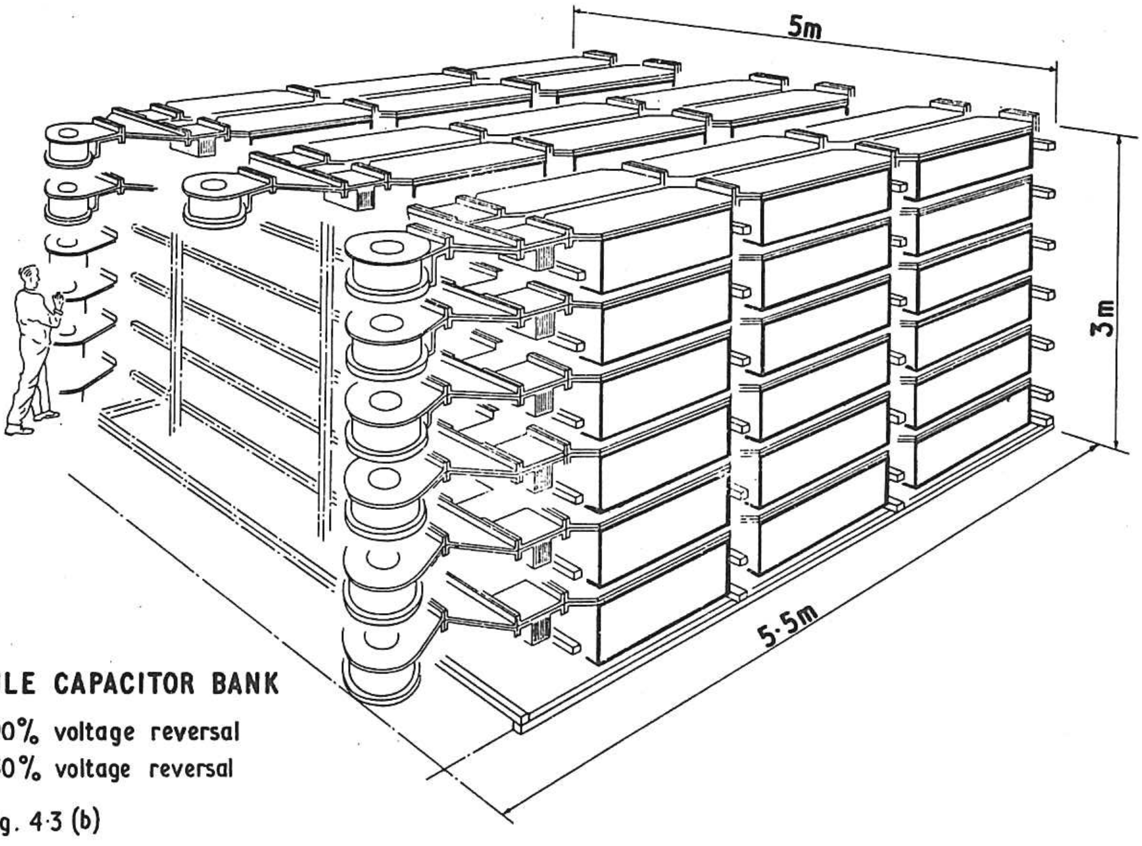


50kV 4 UNIT CAPACITOR MODULE

40kJ at 90% voltage reversal
72kJ at 30% voltage reversal

Overall dimensions :-
Height - 1·092 m
Width - 1·626 m
Depth - 1·143 m
Weight - 1750 kG approx.

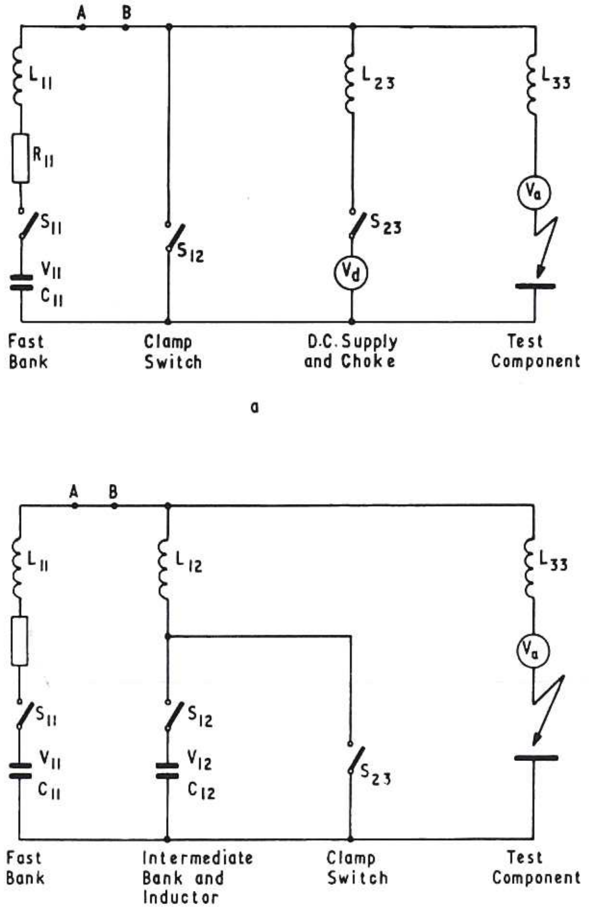
Fig 4·3 (a)



50kV MEGAJOULE CAPACITOR BANK

1·0 MJ at 90% voltage reversal
1·8 MJ at 30% voltage reversal

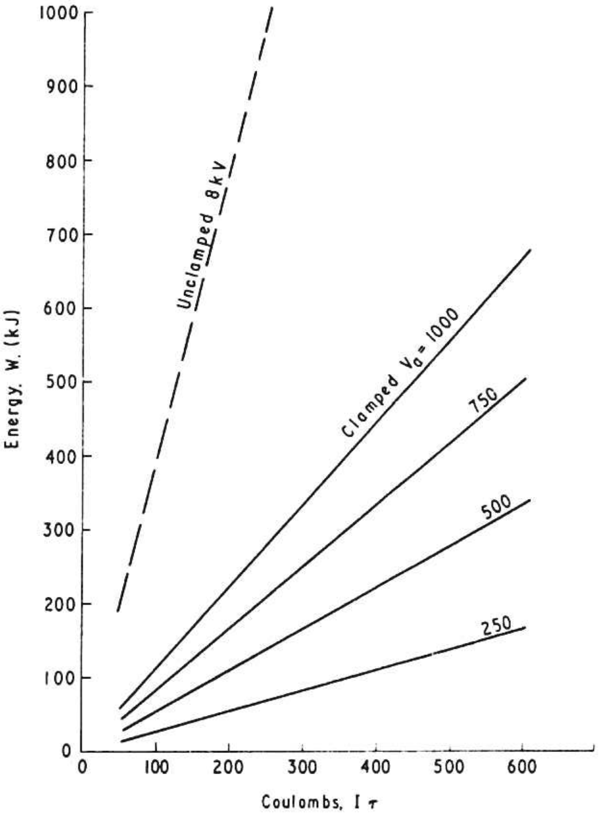
Fig. 4·3 (b)


A
B
L_{11}
R_{11}
S_{11}
V_{11}
C_{11}
S_{12}
L_{23}
S_{23}
V_d
L_{33}
V_a
Fast Bank
Clamp Switch
D.C. Supply and Choke
Test Component
A
B
L_{11}
S_{11}
V_{11}
C_{11}
L_{12}
S_{12}
V_{12}
C_{12}
S_{23}
L_{33}
V_a
Fast Bank
Intermediate Bank and Inductor
Clamp Switch
Test Component

a

b

High current test facilities
Fig. 4·4



Intermediate bank parameters
Fig 4.5

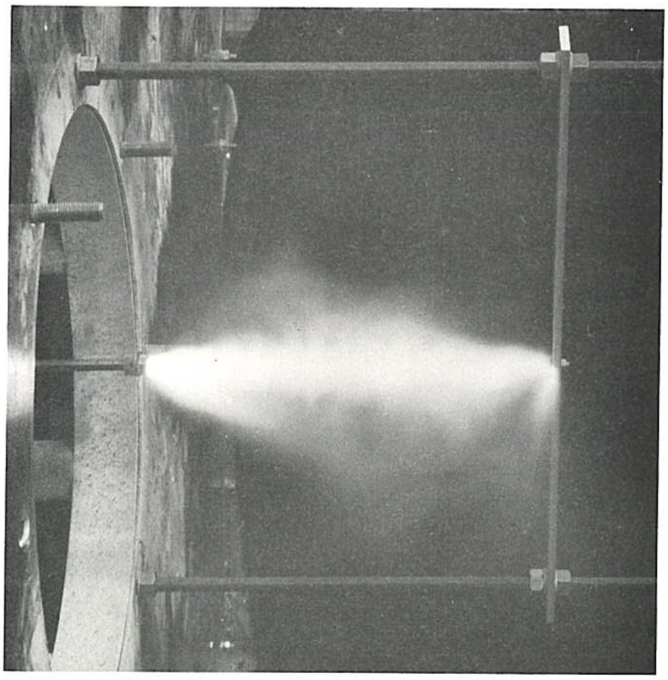


Fig. 4.6 30cm, 10kA arc

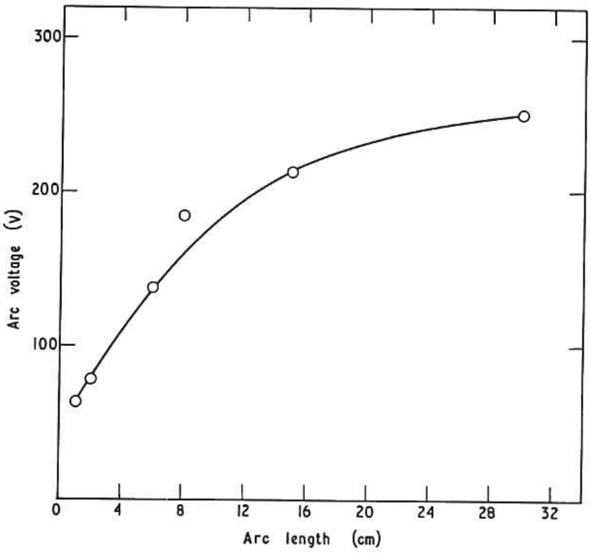


Fig. 4.7 Arc voltage against arc length for unidirectional pulses ≈10kA

(b) Rotating disc

Diameter	~	6 ft
Speed	~	1500 rpm
Linear speed	~	350 mph

(c) Magnetically driven arc

Transverse magnetic field	~ 0.1 to 0.5 Tesla
Peak arc current	~ 1 to 10 kA
Arc speed	~ 200 to 700 mph
Magnetic field bank	~ 10 kJ

Of these three methods the rotating disc most correctly represents the 'swept stroke' phenomena though it would appear to be difficult to study arc movements of more than 2 or 3 feet by this method, The wind tunnel is very difficult to accommodate except in an area especially designed for it due to noise problems and the space required. A further disadvantage of the first two methods is that the relative air speed is limited to about 300 mph. A system incorporating an arc driven by a magnetic field is the simplest equipment to build and a wide range of arc speeds up to about 1000 mph should be obtainable (see Section 3.2). Like the wind tunnel alternative it does not establish a moving metal surface and stationary arc column. However since it is considered that the 'dwell time' is mainly a function of the arc root phenomena and the shape of the arc column it should enable a realistic study of 'swept strokes' to be undertaken. Therefore in view of the above advantages of this method it is recommended for initial studies.

5. STRIKE POINT LOCATION TESTS

5.1 Tests on Models of Complete Aircraft

For commercial aircraft that have been in operation for a number of years, there is considerable information on the position of strike points that have occurred in service as reported by Perry, (1968). These are mainly situated at the nose, tail and wing tips with probably swept strokes along the fuselage. For future aircraft of the same general shape as those for which this data is available, the probable strike points can be predicted with a reasonable degree of certainty. Further laboratory studies to attempt to obtain this information for these conventionally shaped aircraft are therefore probably unnecessary though these studies are very useful for checking the validity of model tests. This however does not apply to aircraft designs with radically different shapes from previous aircraft. For example, supersonic aircraft have a delta-wing shape with a small radius leading edge and it is important to ascertain the strike pattern for such an airframe geometry. To achieve this, voltage breakdown observations can be made on a model of the aircraft, about 1 to 2 m long, placed between the electrode system of an impulse generator of about 5 MV peak voltage. Such tests have been carried out by Reynolds et al (1968) at LTRI on a model of Concorde and also some preliminary work at ERA, Leatherhead (White, 1970).

Model breakdown tests represent a scaling down of the problem dimensionally by a factor of about 50:1 whereas the air pressure is approximately the same within a factor of 2. Under such conditions there is some doubt whether pre-breakdown phenomena and the breakdown process can be accurately simulated. Nevertheless, it is possible that the strike point distribution to a model is similar to that which will occur to the full-scale aircraft. It is claimed that this has in fact been confirmed by tests on models of conventionally shaped aircraft. Robb (1970) states that a general indication of the strike distribution can be obtained by photographing the distribution of streamering round the model. The latter is placed between the electrodes and the impulse generator fired at a voltage below the breakdown value for the electrode system, thus producing intense streamering. With a few shots in varying electrode positions an estimate of the probable strike point distribution may be obtained.

The good agreement between the data from the model tests and actual lightning strikes does not definitely confirm that the breakdown phenomena can be simulated on the laboratory. It probably shows that the strike point distribution in such a very non-uniform field configuration is reasonably well defined and predictable. If this is so, the strike point distribution might be obtained by deducing the field configuration using an electrolytic tank or digital computer techniques, though the computation is very complex in three dimensions. Using a combination of these two techniques the stress distribution near part of the aircraft of particular interest may be studied. It is however considered that model tests, although not completely satisfactory, are at present the best method of obtaining strike point probabilities though eventually analytical methods may replace them. For example if the probability was related to the $(\text{surface electric stress})^m \times (\text{surface area})^n$, computational methods would represent a powerful method of evaluating the low probabilities.

Two additional differences between laboratory and service conditions are due to the aircraft speed (~ 250 m/s) and the variation of air pressure round the airframe. Reference to Table 2.1 shows that the aircraft velocity is only about 0.1% of that of the leader stroke ($\sim 2 \times 10^5$ m/s) so that its effect on the initial strike point location would be negligible

Similarly the distance over which the air pressure varies appreciably is small compared with both the size of the aircraft and the distance travelled by the leader stroke. Variation of air pressure should therefore also have a negligible effect on the initial strike point location.

It has been proposed (Plumer, 1970) that if restrikes in a 'swept stroke' are produced by subsequent strokes in a multiple flash, it may be possible to ascertain these restrike points by bringing up the H.T. rod electrode into various positions close to the fuselage of an aircraft model. It is however considered to be very doubtful whether this method will in fact give the correct restrike points since it does not take into account the existence of a previously ionised channel. The problems of restrike in 'swept strokes' has already been discussed in Section 3.2.

5.2 Test Conditions for Model Tests

5.2.1. Electrode model geometry

The maximum impulse generator voltage in existing UK facilities is about 5.0 MV, which will produce breakdown across a gap of about 7 metres with a positive rod/plane geometry. This maximum voltage and breakdown distance limits the scale of the model. Assuming that it is possible to use a ratio of distance between the model and rod to wing span of 1.5:1 (see Section 5.2.2) and that the distance between rod and model could be 4 m, the model would be about 2.5 m long. This would represent a scaling of about 30:1, so that a 4 metre rod/model gap is equivalent to 120 m or about 2 steps of the approaching leader.

A rod/plane geometry is chosen, as the rod can represent the approaching leader stroke and the plane (or large diameter sphere) will give the more uniform field distribution that will occur in the region away from the leader stroke. Electric field configurations with such an electrode arrangement and two uncharged models having cylindrical symmetry are given in Figs. 5.1 and 5.2 neglecting effects of corona and space charge. These model shapes have been chosen because their field configuration can be deduced using existing two-dimensional digital computer codes (Phillpott, 1970) and represent the maximum and minimum values for the electric field at the nose and tail of the aircraft models.

5.2.2. Leader aircraft field parameters

The potential difference and mean electric stress between a leader and an uncharged aircraft depends mainly on the leader charge/unit length, the effective leader diameter and the distance the leader is from the aircraft. The estimated variation of potential difference and mean electric stress with leader to aircraft distance, is given in Fig.5.5 based on typical leader parameters of 0.5×10^{-3} coulombs/metre length and 5 metres diameter. These results have been deduced from field plots such as those in Figs. 5.1 and 5.2 neglecting the effect of space charge. The aircraft should remain with no net charge on it since its capacity to the leader is only of the order of 100 pf. This capacity could be charged to the potential of the surrounding field in less than 1.0 μs even if the leader inductance is about 10 mH which is equivalent to a leader length of a few kilometres.

As the leader approaches the aircraft, the potential of the latter increases and the potential difference falls from a value of about 33 MV at 500 metres distance. This reduction becomes appreciable at a distance of less than 50 m. The electric stress at the front of the aircraft also rises significantly at a distance of less than 50 m, and depending upon the charge per metre in the leader the front of the aircraft may streamer or corona. The stress at the tip of the leader remains virtually constant until the leader is closer than 50 m; the mean stress increases from a value of about 0.1 MV/m to 1·0 MV/m as the distance decreases from 250 m to 25 m (Fig.5.5). Before this latter distance is reached it is probable that breakdown to the aircraft will have occurred since it approximates to a leader step length, and the electric stress will have produced streamering on the aircraft. The implications from these calculations are that it may be possible to use a ratio of distance between model and rod to wing span of 1.5:1 when performing model tests, since the stress does not rise significantly for distances between leader and aircraft greater than 50 m.

The variations of mean stress, and aircraft stress with time are also given in Fig.5.5, assuming the rate at which the charge is transferred to the advancing leader tip is constant and equivalent to leader velocities of 10^5 or 10^6 m/s. This assumption can be justified from measurements of the magnetic field produced by the leader current (Uman, 1969) which shows that during the rapid movement of the luminous portion of the leader only about 2 per cent of the leader charge is transferred. Since the mean leader velocity and step length will be influenced by the mean electric stress it would be expected that the leader velocity and step length will increase from, say, 10^5 towards 10^6 m/s as the leader nears the aircraft. Thus the time the leader takes to travel the last 200 metres before breakdown would be between 2000 μs (at 10^5 m/s) and 200 μs (at 10^6 m/s) or say about 1000 μs. It would therefore appear advantageous for the voltage on the rod electrode to have a slow rate of rise.

If it is possible for the aircraft to be charged to such a high potential that the electric stress at its extremities is of the order of 3 MV/m, significant streamering will occur from these regions. Under these conditions, the aircraft would be at a potential of about 0.5 MV above its surroundings and its total surface charge would be about a mC. It would be expected that the greater the amount of streamering the more probable would be strike points to the aircraft extremities since here the streamers would be longer than from elsewhere. Thus it is considered that strikes to a charged aircraft will not give rise to such a wide spread in strike point locations as in the case of an uncharged aircraft. Therefore the case of charged aircraft should not require special investigation when performing model breakdown tests.

5.2.3. Impulse breakdown of long gaps

The impulse breakdown of long air gaps is influenced appreciably by the polarity and waveshape of the applied voltage. With a 1/50 μs voltage wave (1 μs rise to peak and 50 μs decay to half peak) the breakdown with a positive rod/plane gap is about 75 per cent of that with a negative rod. With a 250/2500 μs voltage wave (referred to as a switching surge waveform) the positive rod breakdown voltage is only about 50 per cent of that with a negative rod (Legg, 1970). 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 150 μs (Stassinopoulos, 1969).

Another significant difference between positive and negative polarity breakdown which may be very relevant to tests on aircraft models, is the spread in breakdown paths. This is illustrated qualitatively in Fig.5.3 for rod/rod gaps with an earth plane below the lower electrode (adapted from Meek, 1970), a geometry that should approximate closely to that of a leader stroke approaching an aircraft. It will be noted that with a positive HV electrode the breakdown paths are very widely spread and a large proportion of them will be to the plane and not to the lower rod as might be expected. With a negative HV electrode most of the breakdowns terminate on the lower rod because in this case the leader originating at the lower electrode is initiated early in the breakdown period and usually meets the downward moving leader above mid-gap. With a fixed electrode geometry the amount of over-voltage that is applied to the gap and possibly the generator impedance can also influence the breakdown paths. A low over-voltage will give a much wider spread than that obtained with a large over-voltage (Meek, 1970).

Many of the phenomena in long air gaps discussed above are not yet completely understood by workers in this field. However it is generally agreed that breakdown is initiated and propagated by streamers in the high field region followed by a stepped leader (as in the lightning discharge). This develops later into a continuous leader moving at a mean velocity of about 10^4 m/s (Allibone and Meek, 1938; Aleksandrov et al, 1969) which would cause a 4 metre positive rod/plane gap to break down in about 200 μs. Rotating camera photographs of the breakdown process obtained by Allibone and Meek (1938) in 0.76 to 1.83 m gaps are shown in Fig.5.4. The time interval and distance between steps is of the order of 15 to 40 μs and 0.1 to 0.2 m respectively in a 1.4 m gap [Fig.5.4(e)] though these parameters are dependent on voltage waveshape and gap length. In a 10 m gap, measurements made by Aleksandrov et al (1969) with a voltage rise time of 2000 μs suggest that these time and distance intervals are about 200 μs and 0.4 m respectively for positive polarity.

As the leader advances into the inter-electrode space a large number of streamers appear ahead of it in the direction of the electric field. It is possible that for a step length the leader will develop along any of these streamers in a random direction though the axial direction in which the field is greatest has the greatest probability of being followed (Aleksandrov, 1966). The length of the streamers is smaller for low applied voltage and low rates of rise of voltage which means that under these conditions there are are a larger number of smaller steps in the leader stroke (Stassinopoulos, 1969). This is thought to result in more changes of direction giving a larger spread in breakdown paths.

Comparison of the above breakdown parameters for the positive rod/plane gaps of 1.4 m and 10 m length with that of similar parameters for the lightning leader stroke over 200 m (see Section 5.2.2) is given in Table 5.1.

Significantly the range of breakdown times and time/step are of the same order in these two very different situations so that the scaling of the step distances and velocity is very approximately the same as the dimensional scaling of the model (~ 100:1).

Although these estimates are very approximate a rough guide is obtained as to the conditions that have to be simulated in the model tests. They also suggest that the choice of a gap of 2 to 4 m with a 5 MV (nominal) generator, a 250/2500 μs positive voltage wave and a voltage to give 90 per cent probability of breakdown appears to be an acceptable compromise.

TABLE 5.1

COMPARISON OF HV LABORATORY TESTS AND LIGHTNING PARAMETERS

Configuration	Positive rod/plane		Lightning Leader (see Table 2.1)	
			Min. velocity	Max. velocity
Gap length d (m)	1.4	10	200	200
No. of initial steps	~ 5	~ 8	~ 70	~ 2
Time/step (μs)	~ 15	~ 200	30	125
Distance/step (m)	~ 0.15	~ 0.4	3	200
Breakdown times t_b (μs)	125	~ 2000	2000	200
Mean velocity (m/s)	1.1×10^4	0.5×10^4	10^5	10^6
Max. voltage V (MV)	1.1	1.9	25	
Mean field E (= V/d) (MV/m)	0.8	0.19	0.12	
Voltage rise time (μs)	100	2000	Approx. constant voltage	

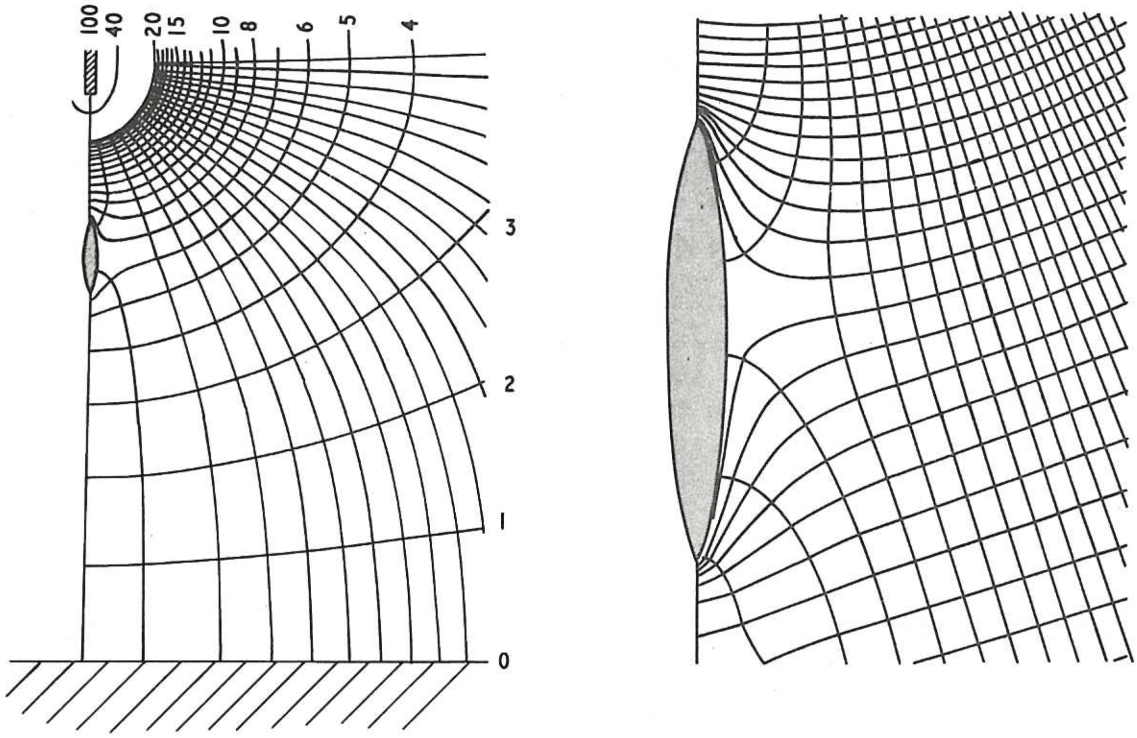
5.3 Recommended Test Procedure

The object of strike point tests is to establish the probability of breakdown to low field regions where this probability is expected to be small. It is therefore necessary to use test conditions that simulate the lightning characteristics which give the greatest spread in breakdown paths as discussed above. Also the rod electrode positions that result in breakdown to low probability regions must be ascertained.

Before a suitable test programme can be proposed it is necessary to know from the airworthiness authorities what probability of breakdown to each region of the aircraft is acceptable. There will of course be a very small probability of breakdown to all external aircraft surfaces. For example for the wing-tips, nose and tail where a 100 per cent breakdown probability is expected from a given rod position, no tests are necessary. Howver, for a region where only one per cent probability of breakdown is acceptable more than, say, 100 tests for each electrode position may be desirable. Alternatively the risk could be defined as the probability of striking a given area from the worst electrode positions for that area. This would reduce the number of tests.**

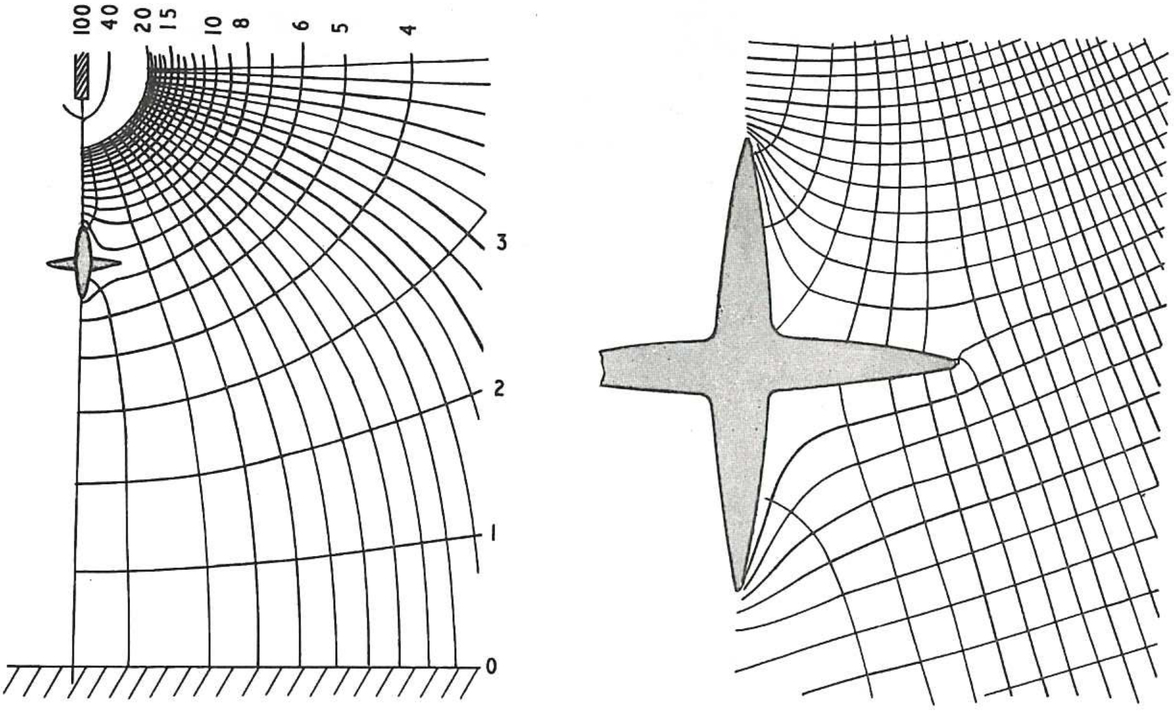
First of all it is necessary to see if the large number of factors influencing breakdown in long air gaps have a marked effect on the strike point location. Exploratory studies are therefore recommended to investigate the effects of polarity, wave front duration, over-voltage, generator impedance and gap length. The need for such studies has been emphasised by Meek (1970) and Plumer (1970). Previous model tests do not seem to have taken these factors into account sufficiently. Some tests have apparently been performed only with a negative 1/50 μs 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 1/50 μs voltage wave for simulating post-breakdown lightning phenomena on ground power transmission equipment by electrical engineers.

**Further discussion on probability is given in the Proceedings of Lightning and Static Electricity Conference, San Diego, 1970 and in the Appendix 9.2.


100
40
20
15
10
8
6
5
4
3
2
1
0

Electric field distribution for a leader approaching an aircraft neglecting the wings.

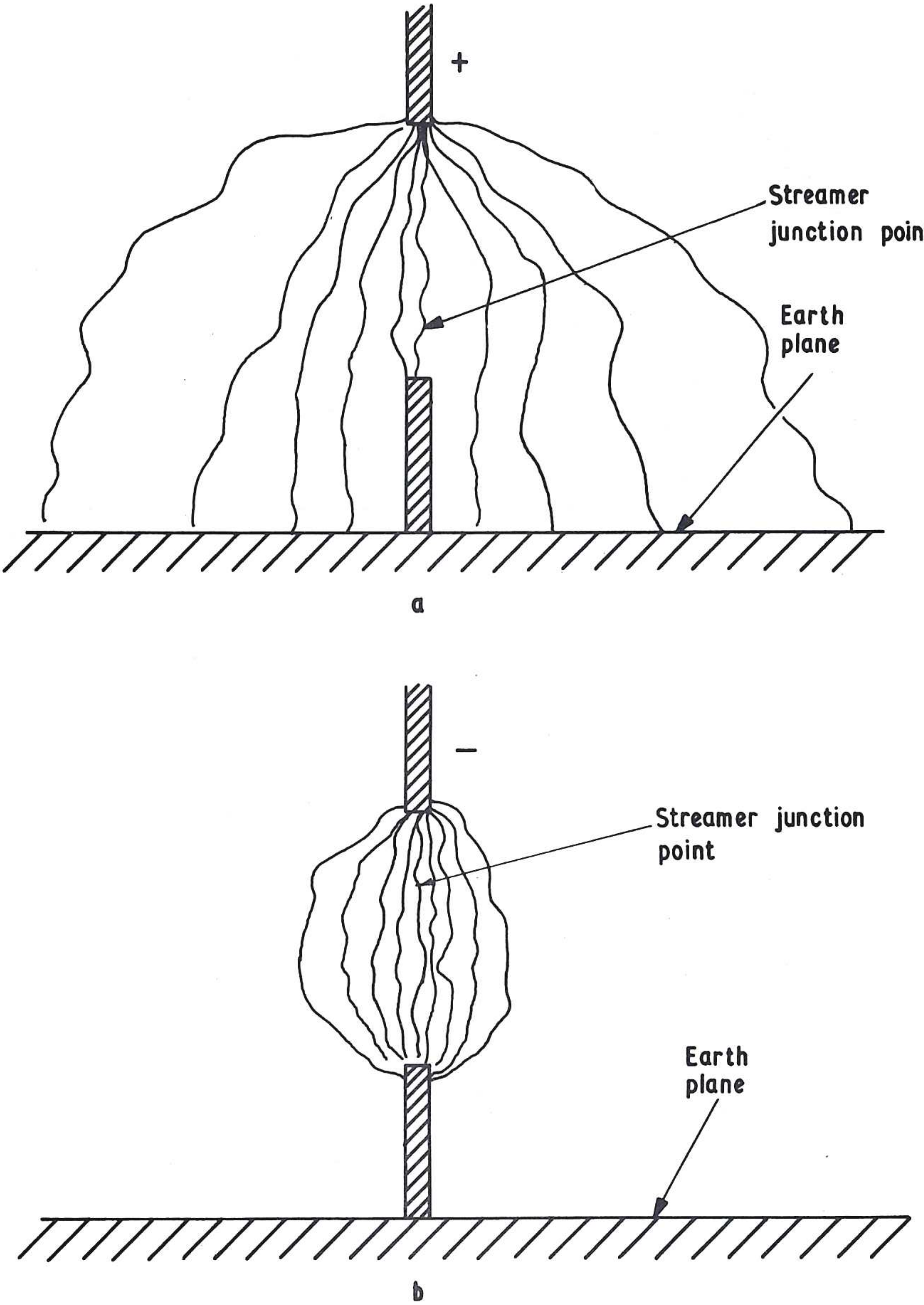
Fig. 5·1


100
40
20
15
10
8
6
5
4
3
2
1
0

a

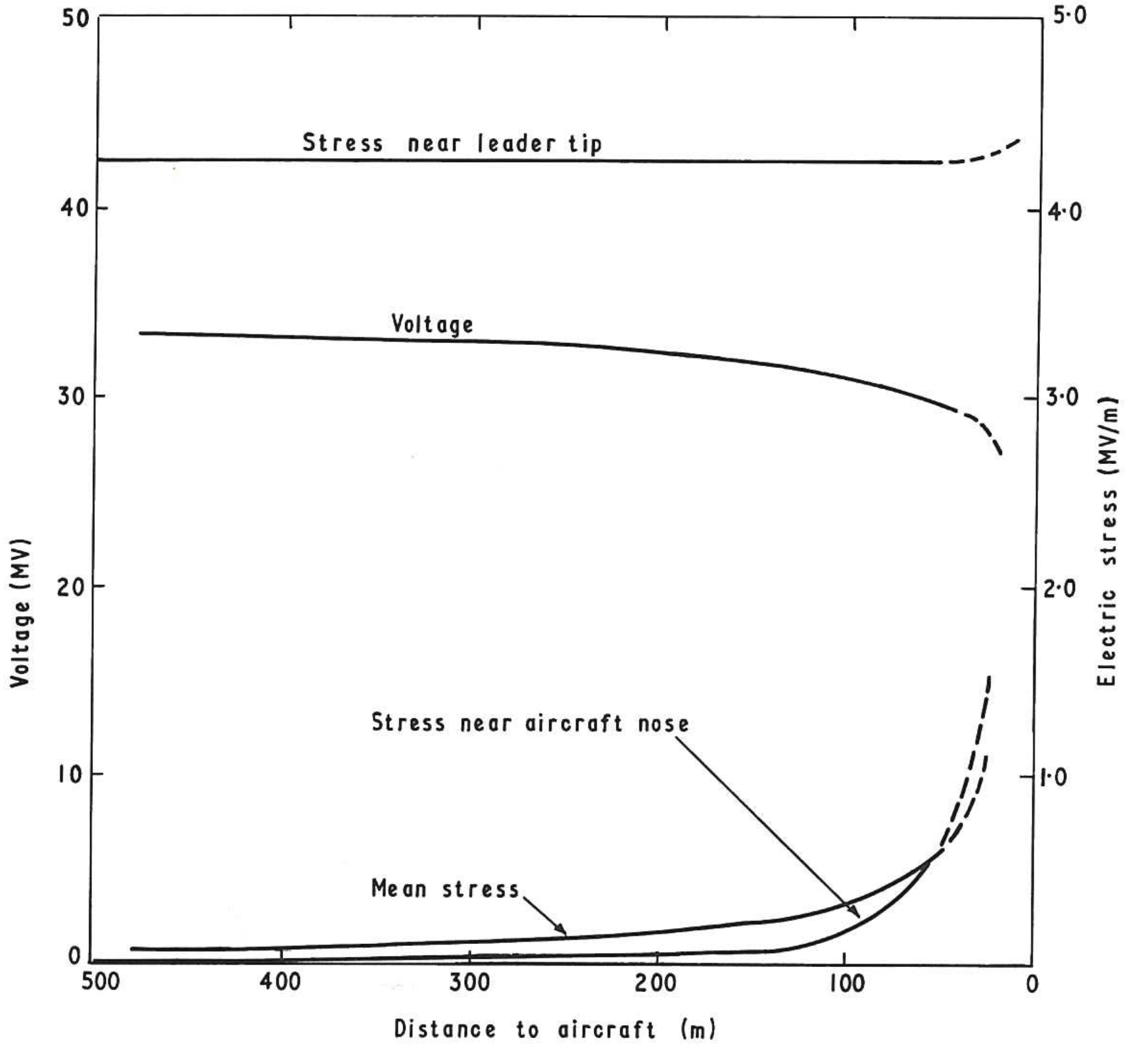
Electric field distribution for a leader approching an aircraft assuming axial symmetry

Fig. 5·2


+
Streamer junction point
Earth plane
a
−
Streamer junction point
Earth plane
b

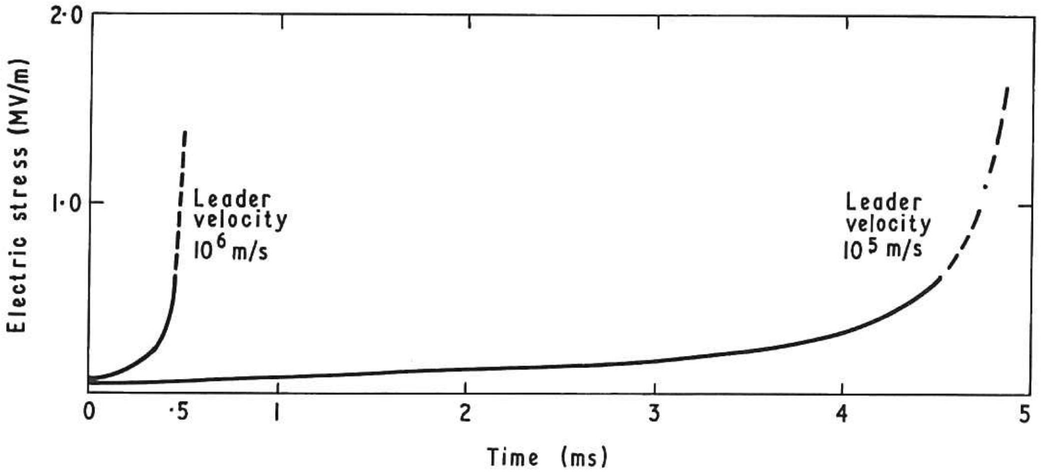
Effect of polarity on breakdown paths of rod/rod gaps (250/2500μ sec wave)

Fig. 5·3



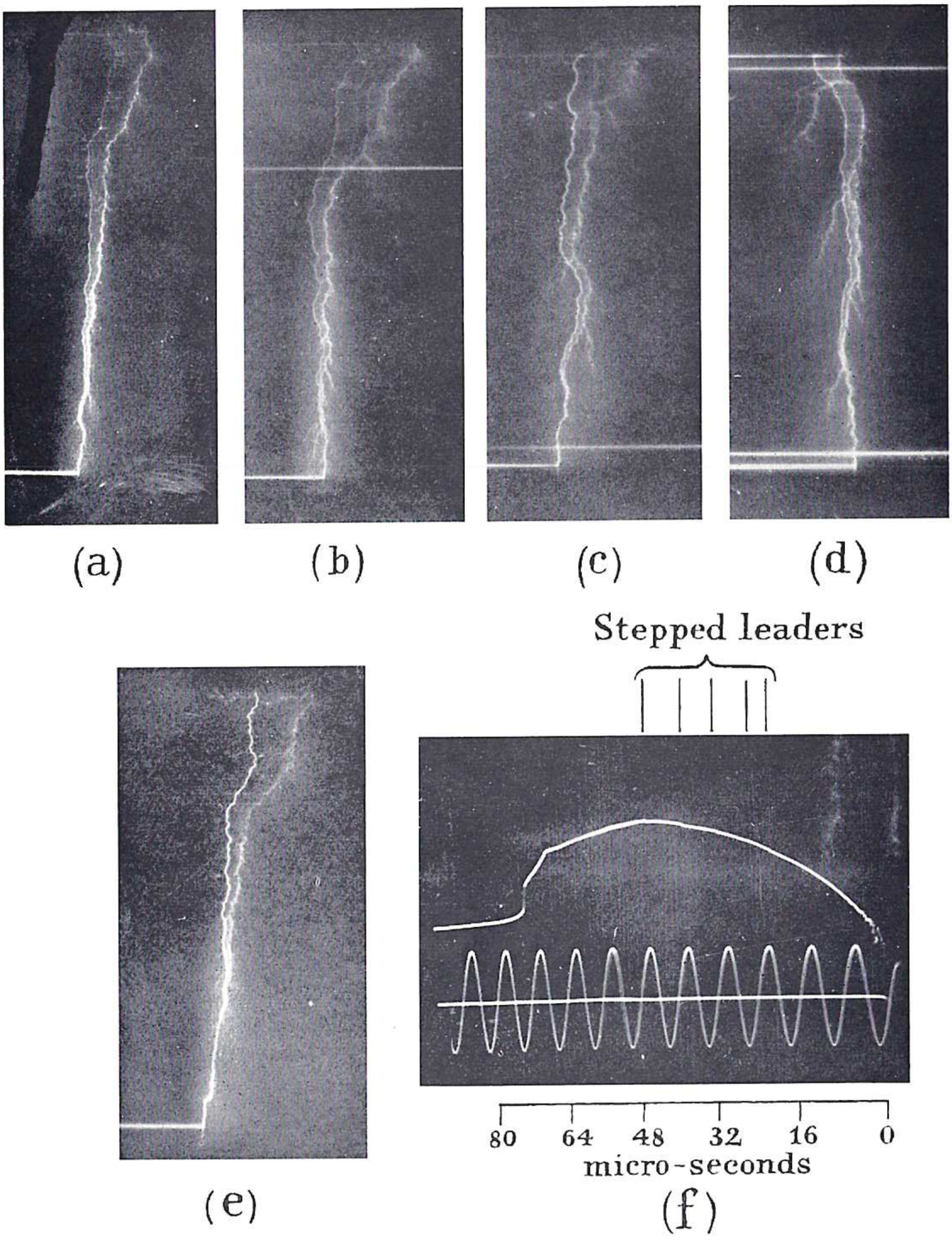
Electric stress and voltage between leader and aircraft against distance

Fig. 5·5 (a)



Mean electric stress against time for various leader velocities

Fig 5·5 (b)


Stepped leaders
80
64
48
32
16
0
micro-seconds

(a) (b) (c) (d) (e) (f)

	Gap length	Series resistance
(*a*)	$d = 183$ cm.;	$R = 1{,}040{,}000$ ohms.
(*b*)	$d = 135$ cm.;	$R = 1{,}040{,}000$ ohms.
(*c*)	$d = 76$ cm.;	$R = 1{,}040{,}000$ ohms.
(*d*)	$d = 76$ cm.;	$R = 1{,}040{,}000$ ohms.
(*e*)	$d = 135$ cm.;	$R = 1{,}040{,}000$ ohms.
(*f*)	$d = 76$ cm.;	$R = 500{,}000$ ohms.

Fig. 5.4 Breakdown of positive point-plane gaps

Based on present evidence the most suitable conditions for model tests are considered to be the following:

Rod polarity	Positive
Waveshape	250/2500 μs
Overvoltage	Voltage giving 90% probability of breakdown
Gap length	Up to 4 m
Peak voltage	3 MV (5 MV nominal)

Having established the operating conditions which give the greatest spread in breakdown paths, the rod electrode and model should be placed in various positions relative to each other. The electrode positions from which breakdown to the region under study occurs can then be found by photographing the breakdown paths to accurately identify the strike point locations. The probability of breakdown to the region is deduced by either carrying out the requisite number of tests from each electrode position or performing the requisite number of tests from the worst electrode position, depending on which definition of probability is accepted (see above).

This general problem has been discussed by Plumer (1970) who has also suggested the use of a 5 m positive rod/plane gap but with a scale factor of only 10:1. Such a large model has obvious advantages though if the relative gap size becomes too small the rod may be placed in a position which a leader stroke may not reach. This suggests the use of a small model to map out breakdown trajectories, followed by a much larger model for local investigations with the rod placed in various positions on the previously deduced trajectories. Alternatively if only one model is available the local investigation could be carried out by moving the rod nearer to the model after the trajectories have been deduced initially with a longer gap spacing.

5.4 Strike Point Location on Full Scale Components

Radomes, canopies and fibre glass panels represent large areas of an aircraft, which do not shield out any electrostatic or magnetic flux and are extremely vulnerable to lightning strikes. These items, if struck, are liable to be destroyed and thereby at best render the equipment behind them inoperable. Under the worst circumstances in the case of canopies, the strike may reach the pilot (Stahmann, 1968).

These items may be protected by attaching metallic strips to the outside of the insulating surface and bonding them at the edge of the component to the airframe. The degree of protection can be established using an impulse generator connected to a rod electrode placed in various positions round the object which is earthed. Breakdown should preferably always be to the protective strips. It is necessary to simulate part of the body of the aircraft to which the panel is attached in order to obtain the correct geometry (White, 1970). A 1.0 to 2.0 MV generator will normally be sufficient to perform meaningful tests on aircraft sections about 3 to 4 m long.

6. CONCLUSIONS

6.1 Lightning Phenomena

The most severe lightning flashes likely to be encountered by aircraft are considered to be positive ground discharges. The maximum parameters that have been measured for this type of discharge are 200 kA (peak current) 300 coulombs (charge transfer) 5×10^6 A^2s (heating, force parameter) and 0.2 s (total duration). The positive flash usually comprises only one stroke and a charge transfer about 50 per cent greater than the negative flash.

However about 80 per cent of the total number of discharges to ground lower negative charge. Each negative flash comprises several strokes occurring approximately every 40 ms, and between each stroke a continuing current of a few hundred amps may flow for several milliseconds. The maximum rate of rise of current (di/dt) of 80 kA/μs occurs in negative flashes, whereas that for positive flashes is about 5 times slower.

6.2 Existing Specification for Component Testing

The most recent specifications proposed by the Federal Aviation Agency, and the Anglo-French Authority for supersonic transport have maximum parameters of 200 kA, 500 C, 0.6×10^6 A^2s and 1 to 5 s with a di/dt of 20 kA/μs. Although these parameters simulate burn-through of metal components reasonably their di/dt and I^2t values are about five times lower than the most severe measured lightning discharge. Thus the specifications are considered to need revision so that they represent the fundamental characteristics of the lightning discharge relevant to the various failure mechanisms that can occur. The recommendation of 0.08" skin thickness for fuel systems and the test conditions required for simulation of swept strokes also appear to need further consideration.

6.3 Recommended General Studies

General experimental studies of problems arising from lightning strikes to aircraft are necessary to provide design data for aircraft manufacturers. The most urgent of these problems are considered to be associated with metal skin puncture (stationary and swept stroke), composite structures, and induced voltages in electrical systems.

6.4 Tentative Future Test Specifications

The above general studies are also necessary if airworthiness authorities are to have the data to formulate improved test specifications. It would however appear from the present information that a future test specification for a fixed strike point region (i.e., zone 1) might consist of a fast component of 200 kA rising at a rate of 100 kA/μs and an intermediate component of about 30 kA, 500 C with a total I^2t of 8×10^6 A^2s. The corresponding values for a swept stroke region (zone 2) would be reduced to about 100 kA, 100 kA/μs, 100 C and 2×10^6 A^2s. A continuing current component of a few hundred amps is not thought to be required since its I^2t contribution is low and its burning effects can adequately be simulated by the intermediate component.

6.5 High Current Test Facilities

The facilities required for high current tests to the existing A.R.B./F.A.A. specifications comprise a fast 200 kA capacitor bank and a continuing current power supply from either a high coulomb capacitor bank or a transformer/rectifier set, or a battery. The high coulomb capacitor bank is considered to be the most satisfactory for the latter duty since it provides the most stable source for driving long arcs. For typical aircraft components about 6 to 10 m long, a standard 80 kJ 100 kV fast capacitor bank having dimensions of 2 m × 1.6 m × 1.2 m (excluding charging equipment) is suitable. For tests at 200 kA on a complete aircraft the energy requirement would be between 500 kJ and 800 kJ at 600 kV to 1.0 MV respectively with bank dimensions of the order of 5 m × 3 m × 5.5 m. Though a definite requirement for complete aircraft tests has not been identified, no technical problems are envisaged in principle in providing the necessary test equipment.

To undertake the work described in the recommended general studies and the tentative future test specification, a 750 kV 100 kA/µs impulse generator and a 250 kJ, 100 kA, 500 C intermediate capacitor bank are required in addition to the 200 kA fast capacitor bank. The 250 kJ bank may however also be used for providing the continuing current supply specified by the existing test specifications.

In view of the large equipment required for existing wind tunnel swept stroke studies, alternative methods for producing moving arcs are considered to be desirable. The most promising of these appears to be a magnetically drive arc, but some preliminary work is necessary to ensure that the boundary layer of air is correctly simulated.

6.6 Strike Point Location Studies

Experiments to establish the probability of lightning strikes to a given location may be performed by placing a model of the aircraft about 1-2 m long between the rod/plane electrodes of an impulse generator of about 3 to 5 MV peak voltage. Digital computational studies suggest that the ratio of the minimum rod/model distance to wing span could be as low as 1.5, and that the electric stress at the aircraft rises in time of about 0.2 to 2.0 ms depending on the leader velocity. The use of a positive rod voltage rising to peak in a time of at least 0.2 ms is recommended, since this polarity and waveform gives the largest spread in breakdown paths. To enable a quantitative assessment and comparison of various model tests to be made there is a need for an agreed test procedure and definition of strike point probability. The values of probability that are considered to be acceptable in the low probability regions can then be specified.

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The authors wish to acknowledge kind permission to reproduce Figs.2.1, 2.2, 2.5, 2.6 (a), (b), (c), (d), from Lightning - M.A. Uman - McGraw Hill, and Figs.2.7 (a), (b), (c) and (d) from Novel Observations on Lightning Discharges - K. Berger, J. Franklin Institute, vol.283, 1967, and Fig.5.4 from Development of the Spark Discharge - T.E. Allibone and J.M. Meek, Proc. Roy. Soc., vol.166A No.924.

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9. APPENDICES

9.1 Organisation and Personnel Consulted

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30. British Rail, Derby.
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31. Liverpool University.
Professor Meek.

32. University of Leeds.
Dr A.E. Guile.

9.2 Lightning and Static Electricity Conference, San Diego, 1970

This conference was held after most of the report on this study had been completed. The following papers give information which is relevant to some of the topics discussed in this report:

The effects of lightning attachment phenomena on aircraft design (Conference Proceedings, pp.139-156)
R.O. Brick, L.L. Oh, S.D. Schneider.

A considerable amount of data is given for 'dwell time' of swept strokes on uncoated titanium and aluminium and with anodised and insulating coatings. On uncoated surfaces the 'dwell time' was about 2 ms and on anodised surfaces about 5 ms. When a subsequent stroke of 20 kA lasting for 35 μs was superimposed on a 400 A pulse it produced a new attachment point through a 0.005 in. of Teflon insulation. Patches of the latter are considered to be promising for the protection of critical components in a swept stroke.

Lightning protective coatings for boron and graphite fibre reinforced plastics
(Conference Proceedings, pp.233-252)
J.G. Breland, J.T. Quinlivan, C.J. Kuo.

Tests on boron and graphite fibre composites at up to 200 kA with various coatings showed that the greatest protection, combined with minimum weight was achieved with aluminium wire fabric and aluminium foil overlays. Other promising coatings were plasma sprayed aluminium, conductive paints used with aluminium foil strips and conductive coatings applied over high dielectric strength films.

Measurements and analysis of lightning-induced voltages in aircraft electrical circuits
(Conference Proceedings, pp.111-138)
P.T. Hacker and J.A. Plumer.

Induced and resistive voltages have been deduced from measurements on circuits positioned inside (mostly) a metal aircraft wing through which a 40 kA, 8 kA/μs current pulse was passed. The maximum induced voltage was about 5 V/m and the effective inductance about 0.5 nH/m. These results are approximately half-way between the values given in Table 3.2 of this report for di/dt values of 80 and 0.3 kA/μs. In view of the approximate assumptions made to obtain the latter results, this close agreement is of course fortuitous. However, it would now appear that the analysis in Section 3.6 gives a more accurate solution to induced voltage problems than would otherwise have been expected.

In the above paper, a so-called mutual inductance M is derived from the open circuit voltage (said to equal M^{di}/dt) measured between the circuit and the end of the wing away from the strike point. However, as pointed out in Section 3.6 of this report, the effective inductance corresponds to the flux linking the loop formed by the circuit and the wing and not to the common flux that links both circuits.

Model studies of stroke probability to selected points on aerospace vehicles
(Conference Proceedings, pp.13-16)
J.R. Stahmann.

Various rod electrode positions are proposed in three planes on a sphere surrounding the model to deduce a surface area S from which a region with a low strike probability such as the wing root can be reached.

It is apparently suggested that the region under study can be reached from only one area S and that only 30 discharges from three different electrode positions are required to deduce a strike probability as low as 10^{-4}. It is suggested that the rod electrode should be positioned sufficiently far away so that the electric stress on the surface of the sphere should not be appreciably influenced by the presence of the model. The proposed distance between model and the electrode of 1.25 m corresponding to an actual distance of 50 m is slightly less than that arrived at independently by the computational studies in Section 5.

It follows from the discussion in 5.3 and Stahmann's paper that there is a need to define the meaning of the probability of lightning strikes to a given area. Two alternatives are outlined below:-

Definitions

1. Define a surface area S on the model as being the area to which a probability value is required.
2. Define a surface area A enclosing the model as the smallest surface where the electric field is not affected by the presence of the model, i.e. all lightning could reach this surface A.
3. There will be m surface areas A_1, A_2, ... A_m on surface A from which lightning can reach surface S.
4. Suppose from the i^{th} area, n_i strikes out of total z_i actually reach surface S.

The probability of reaching S can be defined as

$$\sum_{1}^{m} \left(n_i/z_i\right) \cdot \sum_{1}^{m} \left(A_i/A\right)$$

However if out of these m areas one, say A_r, has a much higher strike rate compared with the other (m-1), then the probability could be defined as:-

$$\frac{n_r}{z_r} \; \frac{A_r}{A}$$

The latter of these two definitions will result in less testing than the former, but the probability with the latter definition will have numerically a larger value than that given by the former. This is of no consequence provided it is understood which definition is being used.

Aircraft and rocket triggered natural lightning discharges (Conference Proceedings, pp.3-7) D.R. Fitzgerald.

Electrostatic fields estimated near an aircraft flying at 2000 ft. are given as about 0.02 MV/m just prior to the triggering of a natural discharge by a wire pulling rocket fired from the LTRI ship. The values of electric field obtained from Fig.5.5 of this report at about 400 m from a leader is in reasonable agreement with these results.

Lightning test facilities measurement techniques (Conference Proceedings, pp.39-46).
J.D. Robb, R.F. Huber, C.J. Kawiecki.

Capacitor bank energies necessary to produce a peak current of 200 kA with various waveforms are quoted. However the information given takes no account of the increased ratings obtainable from capacitors at low voltage reversal and the use of clamp switch circuits to obtain unidirectional waveforms. For example, the energy stated to be necessary to obtain a 1/50 μs waveform (20 MJ for 10 μH inductance) is about 100 times that which is theoretically required with a clamped circuit. Although the latter have not yet been used at the high voltages required with a 1.0 μs rise, their future development would represent a much cheaper solution than the use of multi-megajoule banks costing a few million pounds.

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