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LIGHTNING PROTECTION REQUIREMENTS FOR AIRCRAFT -
A PROPOSED SPECIFICATION

by

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SUMMARY

This memorandum is the RAE/FS8 recommendation for a specification to define UK MOD requirements for the lightning protection of aircraft. It has been written to be appended to a JAC paper proposing changes to the lightning content of DEF STAN 00-970 and is in five parts covering background and advisory material, certification, design and testing requirements.

Draft Issue B, which was incomplete, formed Annex B of JAC Paper 1213 Issue 1. The sections missing from Issue B have been completed in this issue and minor changes incorporated.

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1 INTRODUCTION

1 This memorandum has been prepared as an essential step in the production of a JAC paper recommending changes to the lightning content of DEF STAN 00-970. The document has been written to the direction of RAE/FS(F)8 and in its final form will give RAE recommendations for a new specification which will define UK MOD requirements (Design, Test and Certification) for the lightning protection of UK Military Aircraft. It is anticipated that an edited version of the final issue of the document will eventually be published as a Defence Standard.

PART A - STATUS BACKGROUND AND RATIONALE

A1 APPLICABILITY AND SCOPE

This specification provides the design and evaluation requirements to ensure that UK Military aircraft comply with the lightning protection requirements of DEF STAN 00-970, Volume 1, Chapter 733 or Volume 2, Chapter 726 (as proposed in JAC paper 1213). It shall apply to all fixed and rotary wing aircraft as decided by the Aircraft Project Director. It does not apply to ground, ship or air launched weapons and weapons systems; the requirements for which are given by STANAG 4327 (in draft) but it does apply to the aircraft pylons and launchers.

Design Requirements are given in Part C and D, with evaluation requirements in Part B and test requirements in Part E.

A2 RELATED DOCUMENTS

Documents related to this specification and which should be read in conjunction with it are:

RAE Technical Memorandum FS(F)457 - Equipment Test Methods for Externally Produced Electromagnetic Transients.

Other documents of interest but which do not need to be read in conjunction with this specification are:

Draft STANAG 4236 - Lightning Environmental Conditions affecting the Design of Materiel for use by the NATO Forces.

Draft STANAG 4327 - Lightning Hazard Assessment and Testing of Munitions and Associated Systems.

A3 DEFINITIONS

For the purpose of this document the definitions of Appendix 1 shall apply.

A4 RELATIONSHIP TO OTHER LIGHTNING SPECIFICATIONS

The following documents have been considered during the preparation of this memorandum:

MIL-STD-1757A - Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware.

DOD-STD-1795 (USAF) - Lightning Protection of Aerospace Vehicles and Hardware.

Draft STANAGS 4236 and 4327

SAE AE4L Report AE4L-87-3 ("Orange Book")

The Multi-burst waveform of the latter document has not been addressed as it is felt that evidence so far from in-flight measurements of lightning parameters does not support the waveform, certainly not in its entirety.

MIL STD-5087 and STANAG 3659 have not been considered as they are completely inadequate.

A5 PROPERTIES OF LIGHTNING AND ITS INTERACTION WITH AIRCRAFT

In order to assist in the understanding of various lightning protection requirements, Appendix 2 briefly describes the relevant properties of lightning and relates them to the hazards experienced by aircraft. It discusses the various effects that lightning may have on the aircraft and its systems, and indicates how aircraft design and test parameters are derived from the physical properties of lightning. A list of references for further reading is also included.

PART B - EVALUATION REQUIREMENTS**B1 LIGHTNING PROTECTION PLAN**

An evaluation of the Lightning Protection afforded to an aircraft, in accordance with the requirements of this specification, shall be made by means of a Lightning Hazard Design Analysis (LHDA) which shall be part of an overall Lightning Protection Plan (LPP) as defined in Appendix 3 of this document. The LPP may be part of an Electromagnetic Hazards (EMH) Control Plan but should be a separate document. It is important that particular systems that affect Flight Safety should be evaluated, as noted in section B2 below.

B2 EVALUATION OF FLIGHT AND MISSION CRITICAL ASPECTS OF LIGHTNING PROTECTION**B2.1 Flight and engine control systems**

The capability of flight and engine control systems to withstand lightning effects without damage or degradation shall be evaluated in accordance with the requirements of Appendix 3 section 4 (vi) and as specifically detailed in section 5 of Appendix 3.

B2.2 Fuel systems

The capability of aircraft fuel systems to withstand lightning effects without the risk of fuel explosion, or electrical occurrences which could provide ignition sources for such explosions, shall be evaluated in accordance with the requirements of Appendix 3 section 4 (vii), and as specifically detailed in section 6 of Appendix 3.

B3 TESTING PHILOSOPHY**B3.1 Need for testing**

The LHDA may or may not identify a need for testing to verify the adequacy of various aspects of Lightning Protection Design but qualification tests on flight safety critical electrical and avionic systems and equipment shall always be made in accordance with section B2 above, unless the MOD(PE) Aircraft Project Director directs otherwise.

B3.2 Selection of tests

When tests are required they shall be selected from those listed in section E2 and made in accordance with the appropriate requirements of Part E of this Memorandum.

B3.3 High voltage testing

- (i) High voltage model tests shall not be used as a means of identifying lightning strike location points.
- (ii) High voltage tests on full scale hardware shall only be used as 'Engineering Tests' when designing protection schemes as they are not normally considered valid qualification tests in isolation.

PART C - GENERAL DESIGN REQUIREMENTS**C1 LIGHTNING DESIGN AIM PARAMETERS**

Unless otherwise agreed with the MOD(PE) Aircraft Project Director aircraft shall be designed to withstand the following parameters for the total flash:

A peak current of 200kA
 A maximum rate of change of current of 10^{11} A/s
 A total action integral of 2.25×10^6 A²s (2.25 MJ/ohm)
 A total charge transfer of 200C

When considering shock excitation effects a maximum rate of change of E field (Edot) of 10^{13} v/m/s shall be assumed.

C2 DESIGN AIM PARAMETERS RELEVANT TO LIGHTNING ZONES

C2.1 Lighting attachment zones are defined in Appendix 1 and discussed in Appendix 2.

C2.2 Parameters relevant to lightning attachment zones shall be as follows:

Zone	Pk I	di/dt	Action Integral	Charge Transfer
1A	200 kA	0.3×10^{11} A/s	2×10^6 A ² s	40C in 50 ms
1B	200 kA	10^{11} A/s	2.25×10^6 A ² s	200C
1C	Full zone 1A parameters unless otherwise agreed with MOD(PE) Aircraft Project Director/see Appendix 2, section 4.1.3			
2A	100 kA	10^{11} A/s	0.25×10^6 A ² s	40C in 50 ms
2B	100 kA	10^{11} A/s	0.25×10^6 A ² s	200C
3	200 kA	10^{11} A/s	2.25×10^6 A ² s	200C

C3 CFC CONSTRUCTION

C3.1 Severe structural damage can occur to CFC structures due to the passage of lightning currents during a lightning strike and the resulting acoustic shock wave. This is caused mainly by the increased ohmic heating resulting from the high bulk resistivity of the material. This effect is compounded by the low thermal tolerance, the low thermal conductivity, and the anisotropic nature of the electrical resistivity, the thermal conductivity, and the thermal expansion of CFC. It is also less malleable than metal and will tend to fracture rather than deform plastically under impact forces. The main areas of hazard are as noted below.

(a) Structural sections of small cross-sectional area which may be required to carry lightning currents where the action integral density exceeds the safe limits.

(b) Glued joints or interfaces either CFC/CFC or CFC/Metal that may be required to carry lightning currents.

In these cases the glue line is usually a dielectric, and the current tends to seek out voids in the glue line, which are then subjected to high current densities and high action integral densities. The hazard is then threefold. First there is the risk of localized high ohmic heating, second there is the risk of explosive expansion in the occluded air in the void, and thirdly there is the possibility of magnetically generated high parting forces.

(c) Bolted joints or interfaces either CFC/CFC or CFC/Metal that may be required to carry lightning currents.

In these cases there is usually a surface layer of surplus resin on the CFC. A good electrical contact is therefore hard to establish and current therefore tends to cross the interface in a few selected places giving rise to high local current densities and high local action integral densities.

(d) Metal inserts moulded into CFC.

Except in the case of very small inserts, these are usually in very good electrical contact with the CFC and do not normally represent a grave hazard.

(e) The region in the CFC immediately adjacent to a joint or interface.

In this region the current is crossing interlamina boundaries while it is redistributing itself in the CFC. Under these conditions the bulk resistivity is difficult to determine, and the voltage/current characteristic is non-linear. The voltage tends to be proportional to $I^{0.85}$. Failure mechanisms therefore tend to become more difficult to predict.

(f) Surface damage and arc root damage.

This is dealt with fully in section C4.

(g) Sparking at joints and interfaces.

There is a tendency for all CFC/CFC and CFC/Metal interfaces and joints to spark when carrying lightning currents. Although both voltage and thermal sparking can occur, the most common form with CFC joints is thermal sparking. Thermal sparking is usually at a lower temperature than voltage sparking, but due to the higher energy content and longer duration, it represents a greater hazard to fuel ignition.

C3.2 At an early stage of development, high current tests must be conducted on samples having the same (or very similar) fibre lay-up and the same resin systems as the various sections of the structure. High current tests shall be conducted on these samples using the methods indicated in Appendix 4 and Appendix 10, to determine the safe action integral density appropriate to that lay-up and resin system. The safe level of action integral shall be defined as that which gives a temperature rise in the test sample of 65°C or less. The Lightning Protection Plan shall include calculations of the probable lightning current distribution through out the CFC structure as related to a total lightning discharge having the parameters of 200 kA peak current with an action integral of $2.25 \times 10^6 \text{ A}^2\text{s}$. The design shall ensure that the safe action integral shall not be exceeded in any part of the CFC structure.

C3.3 All joints and interfaces, whether CFC/CFC or CFC/Metal, and whether glued, bolted, or moulded in, that may be required to carry lightning currents must be considered as potential hazards. Representative samples of each type of joint must be prepared and high current tests conducted as indicated in Appendix 4 and Appendix 10 to determine the safe levels of peak current, and action integral density appropriate to that type of joint. These results may then be used to demonstrate that each joint or interface may be safely used in each particular application. Previous experience or the results of earlier tests may be quoted if it can be demonstrated to the satisfaction of the Project Director that the information arising therefrom is relevant to the application in hand.

C3.4 Tests must be conducted on all fuel tanks having CFC skins or CFC structural parts that have joints or interfaces, whether CFC/CFC or CFC/Metal, and whether glued or bolted, that may carry lightning currents and which are, or may be, in contact with fuel or fuel vapour. The tests shall be conducted as indicated in Appendices 4, 7, 10 & 12 and shall have specific reference to voltage or thermal sparking.

C4 CFC SURFACE PROTECTION

C4.1 Due to the high bulk resistivity of CFC, CFC skins can suffer severe damage in the area immediately surrounding the arc root due to ohmic heating during the high current, high action integral phases of the lightning flash. In addition arc root damage can occur due to the prolonged heating during the intermediate and continuing current phases of the lightning flash. All parts of the aircraft except Zone 3 are therefore subject to possible surface damage in the arc root area during a lightning strike. This damage will take the form of

erosion or volatilization of the resin material over an area up to several centimetres radius, and may also include severe delamination between plies over an even greater distance. There is usually no latent or incipient damage beyond the visibly damaged area. The damage does not normally penetrate more than 3 or 4 plies deep. However the region of delamination can be extended by aerodynamic forces during flight subsequent to the lightning strike. In addition CFC skins are less malleable than metal skins and may fracture rather than deform plastically under impact forces.

C4.2 All CFC surfaces in Zones 1a, 1b, 2a and 2b must be protected against surface damage in the arc root area by a method approved by the MOD(PE) Aircraft Project Director unless it can be shown that:

- (a) there is a low probability of an arc root attachment to the unprotected surface.
- (b) The aircraft will not be endangered by severe surface damage in the arc root area on the unprotected surface.
- (c) The damaged section can be repaired or replaced easily and economically.

C4.3 Tests conducted on test samples of the proposed protection system or systems must be conducted as indicated in Appendix 4 and Appendix 10.

C4.4 Where CFC skins of less than 2 mm thick are used in Zones 1a and 1b it must be demonstrated to the satisfaction of the MOD(PE) Aircraft Project Director that:

- (a) The skin will not suffer impact fracture from the acoustic shock wave associated with the first return stroke.
- (b) That any such damage will not be extended by aerodynamic forces during flight subsequent to the lightning strike, and that the damage will not endanger the aircraft, and that the damaged section can be repaired or replaced easily and economically.

C5 DIELECTRIC SURFACE PROTECTION

C5.1 All Group 1 effects (refer to Appendix 1 section 2.6), other than dielectric skin puncture, arise from the effects of the flow of lightning currents in the aircraft component concerned. As current cannot flow in a dielectric, skin puncture is the only Group 1 damage mechanism applicable to dielectric surfaces. The extent of the immediate damage due to puncture however can be quite severe, particularly in laminated plastics such as Glass Fibre

Reinforced Epoxy Resin plastics. This may take the form of extensive delamination over a wide area (maybe a metre or more across). This may be further extended by aerodynamic forces in subsequent flight, and may also be compounded by secondary damage to equipment under the dielectric surface. Following the puncture of a dielectric skin a long arc may be generated in the space beneath the skin. The rapid heating of the air in the space can generate explosive pressures, which can lead to the loss of part or all of the dielectric skin. Dielectric skin puncture can hazard the aircraft for the various reasons given below:

- (a) It may permit lightning currents to attach to sensitive equipment, or to general aircraft wiring under the skin as in the case of instrument bay covers, radomes etc.
- (b) Severe damage such as extensive delamination to control surfaces eg ailerons, tail fins, rudders, elevators etc, can cause destabilization of the aircraft.
- (c) Severe puncture and possible loss of part or all of a dielectric surface can permit the generation of dangerous aerodynamic forces, such as in the case of the loss of a forward mounted radome particularly during supersonic flight.
- (d) It may cause the ignition of fuel vapours in the case of dielectric skinned fuel tanks or drop tanks.

Dielectric puncture may take place on any dielectric surface in Zones 1a and 1b particularly when conductive stress raisers exist below the surface of the dielectric. These may be aeriels, electronic or electrical instruments, or electric wiring, as in the case of instrument hatch covers, and radomes. They may also be structural metal, or hydraulic or other pipes, as in the case of control surfaces, landing gear covers, or fuel tanks.

C5.2 All dielectric surfaces in Zones 1a and 1b must be shown to be protected against puncture by one of the following methods:

- (a) Small area surfaces such as navigational light lenses may be considered safe without further protection where it can be demonstrated that the puncture voltage is well in excess of the flash over voltage.
- (b) Larger areas which can be opaque to both visible light and radio frequencies, such as control surfaces, may be covered with a thin layer of metal or similar conductive material, if it is necessary to protect the surface against puncture.

(c) Surfaces which can be opaque to visible light must be transparent to radio frequencies such as radomes or aerial fairings, may be protected by lightning protection strips. Such strips must be so designed to give no more than an agreed acceptable amount of degradation of function of the equipment covered by the dielectric. These strips may be of solid aluminium alloy, which have a sufficient cross section area to carry the lightning currents safely, or of strips of light foil which are considered to be expendable, or of expendable small gauge wires. In the case of expendable strips or small gauge wires, it must be demonstrated that no damage will occur to the dielectric surface should these strips fuse explosively when carrying lightning currents.

(d) Surfaces which must remain transparent to visible light such as windscreens may require special attention. In general their position on the aircraft, together with their flashover/puncture voltage ratio means that they are unlikely to suffer puncture, however the tendency of thinner and thinner outer skins over the de-icing layer increases the probability of puncture of the screen by both lightning and electric static voltages.

(e) Dielectric fuel tanks are another special case. Here it must be demonstrated that lightning currents cannot penetrate the skin either by direct puncture or by entering via a metal rivet or fastener.

C5.3 Where tests are required to demonstrate the safety of the protection methods used, these tests shall be conducted as indicated in Appendix 4, 8 and 10.

C6 GROUP 2 EFFECTS BELOW CFC SKINS

C6.1 Because of the high resistivity and the reduced "skin effect" and electromagnetic shielding properties of CFC compared with metal, precautions shall be taken in regions of the aircraft where the skin is of CFC construction to ensure that a lightning strike does not produce voltages or currents of a hazardous nature. Factors to be considered shall include the following:

- (a) The voltage gradient produced on the inside surface of a CFC skin due to lightning current flowing in the skin.
- (b) The amplitude and waveform of voltages induced in wiring due to linking with the magnetic flux that penetrates the CFC skin when lightning current flows in it.

(c) The possibility that a significant proportion of the actual lightning current may penetrate the skin and cause sparking, heating or other effects.

(d) The possibility that even when lightning current does not flow in the CFC skin, the electromagnetic field from lightning current flowing in another part of the aircraft may penetrate the CFC skin and induce internal voltages.

C6.2 Consideration shall be given to the provision of electromagnetic shielding measures on the CFC skin such as a metallic coating; this shall be coordinated with consideration of surface protection against Group 1 effects (section C4) with a view to producing if necessary a protective scheme effective against both Group 1 and Group 2 effects.

C7 SURFACE DAMAGE TO METAL SKINS

C7.1 Surface damage by lightning to metal skins is mainly a function of the duration of dwell of the arc root in any one spot. The high current, short duration phase of the lightning flash does no significant damage to a metal skin in the arc root area. The lower current, long duration phase of the lightning flash can cause appreciable melting, erosion, and even complete burn through of the metal. All parts of the aircraft in Zones 1b, 2a and 2b are therefore subject to possible melting, erosion, or burn through during a lightning strike.

C7.2 Arc root burn through tests must be conducted as indicated in Appendix 4 and Appendix 10, on all metal skins in Zones 1b, 2a, and 2b where:

- (a) There is or could be any fuel, fuel vapour, hydraulic fluid, oil, or any inflammable liquid or gas, or any explosive solid in contact with the skin.
- (b) Where severe melting, erosion or burn through could endanger the aircraft for any reason.

EXCEPT

- (c) In a Zone 2a area where the skin is of standard aircraft aluminium alloy (ie not a high melting point alloy) and is not less than 2 mm thick.
- (d) Where it can be shown to the satisfaction of the MOD(PE) Aircraft Project Director from theoretical considerations or the results of previous experiments that burn through will not occur.

- (e) Where techniques, approved by the MOD(PE) Aircraft Project Director for the prevention of burn through of thin metal skins, have been applied, eg sandwich panel construction or sacrificial layer techniques.

C7.3 In the case of high melting point alloys, eg Titanium alloys, where the metal skin forms part of a 'Wet Skin' fuel tank in Zones 1b, 2a, or 2b, tests must be conducted as indicated in Appendix 4 and Appendix 10 to demonstrate.

- (a) That burn through cannot occur.
- (b) That fuel ignition due to hot spots cannot occur.

EXCEPT

- (c) Where it can be shown to the satisfaction of the MOD(PE) Aircraft Project Director from theoretical considerations or the results of previous experiments that neither burn through nor fuel ignition from hot spots will occur.

C8 INSTALLATION OF CONDUCTORS CARRYING LIGHTNING CURRENT

C8.1 Conductors which may carry lightning current shall be designed to do so without hazard; this applies both to conductors installed for the purpose of carrying lightning current, as for example lightning bonding straps or the lightning diverter strips on a radome, and those, such as a pitot tube, which by reason of their position are likely to be subjected to lightning current. The latter category includes electrical bonds intended for electrostatic, EMC or other purposes but which may be subjected to lightning current. Design requirements for various types of conductor are given below.

C8.2 Bonding straps intended for lightning, or which are likely to be subjected to lightning current.

C8.2.1 These shall be designed so that the temperature rise due to lightning current shall not be sufficient to cause softening, melting, fuel ignition or any other hazard. For a bonding strap of stranded copper subjected to a full lightning discharge this shall be taken to mean that the cross-sectional area shall be not less than 18 mm²; for aluminium the corresponding figure shall be 27 mm².

C8.2.2 In order to minimise the inductance and magnetic forces, bonding straps shall be as short and as straight as possible.

C8.2.3 Soldered connections shall not be used on bonding straps.

C8.3 Other conductors likely to be subjected to lightning current.

C8.3.1 In order to avoid excessive temperature rise, solid conductors shall have a cross-sectional area of not less than 9 mm² for copper or 14 mm² for aluminium.

C8.3.2 The design shall be such that magnetic forces arising from the passage of lightning current shall not cause hazardous damage, such as for example excessive distortion or breaking away from the fasteners, perhaps with consequential damage to other parts or to ingestion into an engine. Consideration of the magnetic forces on a conductor shall include those arising from interaction with its own current (if it is not straight), with the current in other conductors and, where appropriate, with the current in the lightning channel itself.

C9 INSTALLATION OF CABLES AND WIRING

C9.1 Protection of wiring against lightning transients shall be considered in conjunction with EMC requirements generally, and also nuclear EMP protection requirements if applicable. Any conflict between requirements shall be noted and proposals made for resolving the conflict.

C9.2 The level of lightning-injected transients allowed to reach electrical equipment shall not exceed the aircraft transient level of the equipment. Account shall be taken of the different electromagnetic shielding properties of different constructional materials, for example, a dielectric composite provides no shielding, CFC provides some but less than metal, while metal provides the highest degree of shielding.

Note: The aircraft transient level shall be lower than the equipment transient test level by a safety margin of 12 dB.

C9.3 Wherever possible wiring shall be positioned to make maximum use of the shielding properties of the aircraft metallic structure. In aircraft of mainly CFC construction, maximum possible use shall be made of whatever metallic structure exists.

C9.4 Particular attention shall be paid to the protection of wiring associated with systems that are critical to flight safety, such as automatic flight systems, engine control systems and fuel systems.

C9.5 Configuration of signal circuits shall be such as to minimise susceptibility to transients. In particular, the return current connection of each circuit shall be made by means of a separate wire, and the airframe shall not be employed for this purpose. Differential (balanced) circuits shall be employed in preference to single-sided (unbalanced) circuits.

C9.6 Consideration shall be given to the employment of circuit coupling techniques which prevent the transmission of common-mode interference, as for example optical or transformer coupling.

C9.7 Where necessary wiring shall be provided with means of shielding against transients due to lightning. Methods to be considered are the use of screened cable and the placing of wires in grounded metallic conduits or ducts. Conduits and the screens of cables shall be bonded to the airframe at both ends. Where the airframe is mainly constructed of CFC, a continuous metallic conductor may be provided as a power return path. Equipment in a CFC structure that is likely to carry lightning current shall be interconnected such that the equipment cases are grounded, via the screens of the interconnecting cables, at one point only. Individual equipments shall be isolated from airframe with insulation sufficient to withstand the voltage likely to be developed between the equipment concerned and the grounding point.

C10 LIGHTNING SURGE SUPPRESSORS AND DIVERTERS

C10.1 Where lightning current may have a path directly into the aircraft (for example, at an aerial) or there may be high transients in external wiring near a lightning strike point (for example, the heater wiring of a pitot probe) consideration shall be given to fitting a protective device, such as a surge suppressor or diverter, close to the entry point of the wiring into the aircraft in order to block the surge or divert its energy to the airframe.

C10.2 Where the wanted signal is in a restricted frequency band well removed from the frequency spectrum of a lightning current pulse the possibility shall be considered of providing a combination of inductance and capacitance for filtering out the lightning transient.

C10.3 In other cases, consideration shall be given to fitting a device, which switches to a low impedance on the occurrence of a surge.

C10.4 The protective device shall be chosen for high reliability and shall have a most-probable failure mode which is "fail-safe", that is, a shunt component shall fail by becoming permanently open-circuited, not short-circuited.

C10.5 The protective device shall operate on a surge of either polarity and shall be designed safely to withstand the high current to which it will be subjected when operating to suppress the surge.

C10.6 It shall be determined that the effect of the device on the normal operation of the circuit (by reason, for example, of its capacitance or any permanent current consumption), is acceptable.

C10.7 When the device is fitted across a powered circuit, its design shall be such that it switches back to its original high impedance state at the end of the surge.

C11 REQUIREMENTS FOR THE DESIGN AND INSTALLATION OF AVIONIC EQUIPMENT TO WITHSTAND LIGHTNING INDUCED VOLTAGE AND CURRENT TRANSIENTS

C11.1 All flight and mission critical avionic and electrical equipment shall be designed to tolerate without upset or damage the test frequencies and waveforms set out in the latest issue of RAE Technical Memorandum FS(F) 457 (currently at Issue 2), see section A2, at levels which shall be decided by the MOD(PE) Aircraft Project Director, following an analysis of the aircraft installation concerned.

Notes: 1 - For guidance concerning the use of computer modelling, low level swept cw techniques etc in the analysis referred to above, see Appendix 11;

2 - For guidance concerning the correct installation of system wiring to minimise lightning induced effects see section C9, Appendix 2 and Ref 15 of Appendix 2.

C11.2 If it is too early in a project for the analysis referred to in section C11.1 to be made, the highest levels noted in Technical Memorandum 457 shall be assumed (appropriate to the class of equipment under consideration) or at levels which shall be decided by the MOD(PE) Aircraft Project Director.

C11.3 When equipment is installed in a CFC structure due note shall be taken of the requirements of section C9.7.

C12 ENVIRONMENTAL CONDITIONS

All measures taken for protection against lightning shall operate satisfactorily over the full range of environmental conditions (temperature, pressure, climatic, vibration and acceleration etc) specified in the Aircraft Specification unless otherwise agreed by MOD(PE) Aircraft Project Director.

C13 REQUIREMENTS SPECIFIC TO ROTORCRAFT

C13.1 Lightning hazard design analysis

(i) Paragraph B1 of this specification notes a requirement for a Lightning Protection Plan (LPP) and Lightning Hazard Design Analysis (LHDA) to be made when the lightning protection of an aircraft is being developed

and evaluated. Section B2 highlights particular aspects of the evaluations required. When developing an LPP for a helicopter the specific requirements given below in this section (additional to those highlighted in section B2) shall be complied with.

(ii) Likely lightning strike attachment points on the rotor blades and body of the aircraft shall be agreed with the MOD(PE) Aircraft Project Director, together with all likely current paths through the aircraft between those attachment points, paying particular attention to paths through the rotor blades and around the main and tail rotor hubs.

(iii) A Zoning Diagram shall be produced in accordance with Appendix 2, section 4.1.4 of this Memorandum. Full Component A parameters of the lightning test waveform (see Appendix 9, Fig 9.1) shall be assumed for Zone 1C regions of the aircraft unless otherwise agreed with the MOD(PE) Aircraft Project Director.

(iv) If it is thought that the principles outlined in Appendix 2, section 4.1.4 will lead to over and therefore uneconomical protection, a detailed assessment of all possible lightning arc interactions with the vehicle shall be made and agreed with the MOD(PE) Project Director.

C13.2 Particular areas of concern

When considering lightning hazards and the protection required to overcome those hazards, particular attention shall be paid to the following:

- (a) The construction of the main and tail rotors, giving careful thought to the methods of attaching erosion shields and tip caps to composite blades, the use of metallic mass balance weights in composite blades and the installation of electrical de-icing systems. Small area conductors which could carry lightning current and fuse explosively should be avoided.
- (b) Rotor hub actuators, mechanism and control systems.
- (c) Avoidance of any insidious lightning risks (for example, in a blade fold mechanism).

C13.3 Installation of equipment that can influence the lightning strike zoning of the aircraft

Care should be taken that the installation and operation of equipment, such as SAR winches and dunking sonobuoys, does not compromise the lightning protection of the aircraft.

Note: It should be remembered that the deployment of an SAR winch cable or a sonobuoy would significantly alter the Zoning Diagram for the aircraft and could threaten the integrity of protection against lightning induced transients. Such deployment must, therefore, be taken account of in the LPP.

C14 LIFE CYCLE ASPECTS

C14.1 All lightning protection measures shall be chosen with a view to their durability and shall be so designed that they need minimum maintenance and also that expensive repair schemes are not necessary. Protection methods which require a high level of inspection shall be avoided.

C14.2 Care shall be taken to ensure that modifications to equipment and installations, and especially those that are Flight and Mission Critical, shall meet all the relevant requirements of this Memorandum, and that such modifications do not compromise protection of other equipment and installations.

Notes: 1 - Particular care should be taken to avoid surface protection schemes which could be significantly impaired by accidental mechanical damage.

2 - Aircraft maintenance schedules should ensure that all lightning protection measures are regularly inspected and the efficacy of such items as surge suppressors and filter components checked. The bonding and grounding of conduits and screens should not be overlooked and the continued electrical isolation from airframe of equipment in CFC structures should be monitored, as also should the insulation afforded for protection of fuel systems installed in such structures.

PART D - PARTICULAR DESIGN REQUIREMENTS

D1 REQUIREMENTS FOR THE DESIGN AND PROTECTION OF FUEL SYSTEMS

D1.1 Suppression of sparking

Aircraft structure which forms part of a fuel system, and all fuel system components, shall be so designed that sparking cannot occur in areas where fuel or flammable vapour is normally present (or could be present during normal operation of the aircraft).

Note 1 - It must be demonstrated that all sparking has been eliminated down to a level equivalent to 0.04 mJ (see Appendix 3, section 6 (xiv), Note 4 and Appendix 12, section 3.3).

D1.2 Hot spots

Notwithstanding section D1.5 below, aircraft structure inside which there is fuel or fuel/air vapour shall be so designed that hot spot temperatures on an inner surface due to a lightning attachment on the outer surface are limited to a value which cannot cause ignition. Similarly the size of conductors which could carry lightning current shall be such that the temperature rise of any conductor in contact with fuel or fuel/air vapour (notwithstanding D1.3 below) shall be limited to a safe value.

Note 2 - Aluminium structures may be allowed to reach a transient hot spot temperature of 660°C. The temperature of CFC structures shall be limited to 230°C. A safe hot spot temperature for Titanium structures must be agreed with the MOD(PE) Aircraft Project Director, who will generally require a 'Flammable Gas Test' to demonstrate absence of hazard.

D1.3 Lightning current flow inside fuel systems

All reasonable measures shall be taken to prevent the passage of lightning current inside a fuel system structure, or through fuel system components.

D1.4 Position of tanks

Integral fuel tanks shall not be installed in lightning attachment Zones 1B and 2B.

D1.5 Skin thicknesses over fuel tanks

Skin thicknesses over integral fuel tanks shall comply with the following requirements:-

- (i) Aluminium construction - The thickness of solid structural skins below which fuel or fuel air vapour may be present shall not be less than 2 mm, unless it is agreed with the MOD(PE) Aircraft Project Director that suitably protected thinner skins may be used.
- (ii) Titanium construction - When titanium construction is used the acceptable skin thickness shall be agreed with the MOD(PE) Aircraft Project Director.
- (iii) CFC Construction - When CFC construction is used solid skins shall not be less than 5 mm thick unless otherwise agreed with the MOD(PE) Aircraft Project Director.

Note 3 - The above requirements shall apply to bag tanks where there is any risk of flammable vapour accumulating in the structure enclosing the tank.

D1.6 Thin solid skins and sandwich panel skins

When either thin skins or sandwich panel skins are used a suitable protection method shall be agreed with the MOD(E) Aircraft Project Director.

D1.7 Joints and fasteners

- (i) Skin panel joints, access doors and fasteners, must be so designed that sparking, due to lightning attachments to fasteners or Zone 3 current flow through joints, cannot occur in the presence of fuel or fuel/air vapour.

Note: With respect to CFC construction it is unlikely that this requirement can be met without the use of surface protection over joints and fasteners and sealant below fasteners.

- (ii) Co-cured bonded joints shall not be used in CFC 'wet wing' construction when there is any likelihood whatsoever of lightning current crossing the joint.

D1.8 Fuel and air pipes

Fuel and air pipes used in the fuel system shall be so installed that lightning current is unable to flow in them. Alternatively in an aluminium 'wet wing' pipes shall be bonded to structure and across all pipe couplings.

In a CFC structure all pipe work shall be divided into short sections separately bonded to structure and connected one to the other with pipes constructed from material with a conductivity in the range 10^{-5} to 10^{-9} Siemens/m. The insulating sections shall be of sufficient length to prevent the maximum voltage likely to be generated between the conducting sections causing flashover between them.

D1.9 Fuel system wiring

Fuel system wiring shall be so installed that the wiring within a fuel tank (whether in a 'wet wing' or a demountable tank) takes a route to the relevant fuel system component most likely to give minimum voltage coupling. The wiring shall also be installed so that 'aperture flux' and 'diffusion flux' voltages resulting from lightning current flow are below a level where flashover across insulation or breakdown between air gaps (at any ambient pressure) at a fuel system component can occur. All wiring shall be screened by conduit or heavy

duty braid bonded at both ends to the aircraft structure except that such screening shall not penetrate a fuel tank especially where the construction is CFC. Whenever possible twisted pair wiring shall be used.

Cable screens, bonding and cable connectors used in association with carbon fibre structures shall be capable of carrying a worst case lightning current of 10 kA, unless otherwise agreed with the MOD(PE) Aircraft Project Director.

D1.10 Fuel system electrical components

Fuel system electrical components such as probes, level sensors and pumps should be designed to withstand the maximum voltage to ground likely to be generated in the fuel system wiring without flashover or sparking. The electrical components of fuel system equipment when used in CFC structures shall be insulated from the structure.

D1.11 Dump masts and vents

- (i) Unless otherwise agreed with the MOD(PE) Aircraft Project Director, fuel dump masts and vents shall only be installed in areas where lightning strike attachments and corona effects are unlikely to occur.
- (ii) The MOD(PE) Aircraft Project Director may require that dump masts and vent be fitted with flame suppression devices. Such devices shall always be fitted when masts and vents are installed other than as noted above.

D1.12 Fuel filler caps

Fuel filler caps should whenever possible be installed outside lightning strike attachment areas. They shall be so designed that sparking within the ullage space cannot occur as a result of a lightning attachment to the outer surface of the cap. Only non conducting retainer chains or cords shall be used, if such cords are on the fuel side of the seal.

D1.13 Flight refuelling probes

Flight refuelling probes shall be designed and installed so that a lightning attachment to the probe cannot cause lightning current to flow in a part of the probe which is in contact with fuel when the probe is in use, or in fuel pipes from the probe to the fuel system.

D1.14 External fuel tanks

- (i) The requirements of sections D1.1 to D1.3 and D1.5 to D1.9 shall generally apply to external fuel tanks. Guidance concerning the

application of those requirements is given in Appendix 12.
Additional requirements shall apply as noted below.

- (ii) Non-metallic or CFC tanks shall be provided with metallic nose and tail caps for a distance of 150 mm from each end. The fuel space shall not extend into the nose and tail cap areas, which should also exclude fuel vapour. Tail fins (should they be made of metal) shall be engineered in such a way that lightning attachments to them do not cause sparking in the fuel area.
- (iii) Pylon mounted tanks:
 - (a) Shall comply with the requirements of section D2 with regard to lightning current paths between the tank and the pylon, the position of wiring between the tank and the pylon relative to those current paths, and the level of induced voltage generated in that wiring and inside the tank.
 - (b) Lightning current shall be prevented from crossing the fuel/air interface.
- (iv) Tanks constructed with GFRP or other non-conducting material or with CFC:
 - (a) Shall be provided with external protection in accordance with section C4 unless otherwise agreed with the MOD(PE) Aircraft Project Director.
 - (b) All internal metalwork shall be electrically bonded together and to only one of the current paths to airframe or pylon, in such a way that current loops are avoided and lightning current cannot flow in the bonding paths.
 - (c) CFC tanks shall comply with the requirements of D1.8, which shall take precedence over any conflicting requirements in section (b) above.
 - (d) All bolts penetrating skins should have their nuts capped and the caps filled with 'PRC' or equivalent.

D2 REQUIREMENTS FOR THE DESIGN AND PROTECTION OF PYLONS, MISSILE LAUNCH RAILS, AND STORES

D2.1 Definitions

For the purposes of this Memorandum the following terms are defined in Appendix 1:-

- (i) Pylon
- (ii) Store

D2.2 Scope of lightning protection requirements regarding stores

With the exceptions of external fuel tanks, the lightning protection and evaluation requirements for stores shall be in accordance with the specifications governing a particular Store and are not addressed in this Memorandum, except as given in D2.5 below.

D2.3 Zoning and lightning attachment

A zoning diagram of the aircraft with pylons fitted, with and without Stores attached, shall be prepared and all likely lightning attachment points evaluated with respect to possible Group 1 effects damage to the pylon (see Note 1.)

D2.4 Construction of pylon

Unless otherwise agreed with the MOD(PE) Aircraft Project Director pylons shall not be constructed from non-conducting or partially conducting composite material. Where such a construction is agreed suitable surface protection schemes shall be agreed with the MOD(PE) Aircraft Project Director.

The requirements of section D1 shall be adhered to (and particularly D1.1, D1.3 and D1.8) regarding parts of the fuel system within, and associated with, a pylon.

D2.5 Pylon wiring and electrical equipment

- (i) Pylon wiring shall be installed in accordance with section C9 of this Memorandum.
- (ii) Pylon Decoder Units (PDUs), Explosive Release Units (ERUs) and other avionic or electrical equipment installed in the pylon shall be in accordance with section C11 of this Memorandum.

D2.6 Design of stores

- (i) Stores shall be so designed that in the event of a lightning strike to the store, or to the aircraft, the store does not hazard the aircraft or adversely affect its operation.
- (ii) Unless otherwise agreed with the MOD(PE) Aircraft Project Director induced voltage levels generated by a store shall be limited to 125 V (see Note 2).

- (iii) Unless otherwise agreed with the MOD(PE) Aircraft Project Director stores must tolerate the induced voltage level generated by the aircraft/pylon which shall not exceed 425 V (see Note 2.)
- (iv) The above requirements shall be reflected in the Memorandum for a particular store, except that all external fuel tanks shall be in accordance with section D1 of this Memorandum.

D2.7 Aircraft to pylon and pylon to store interfaces

- (i) Lightning current must be excluded from interface wiring and any fuel/airlines. Current paths between a store and a pylon, and a pylon and the aircraft, shall be at well defined places. The normal attachment and suspension points may be used for those current paths provided good non intermittent contact is provided. All intermittent contacts (such as at sway braces) shall be avoided, if necessary with insulating pads.
- (ii) All wiring in the store/pylon and pylon/aircraft interfaces shall be well screened with the screens 360° bonded to the back shell of plug breaks or connectors. All wiring shall cross an interface as close to a main current path as is practically possible. Wiring should not run parallel to the surface of an interface but should cross at right angles to it.
- (iii) Induced voltage levels generated by wiring crossing an interface shall not be greater than:-
 - (a) 125 V at a pylon/aircraft interface.
 - (b) 300 V at a store/pylon interface.

(See Note 3)

D2.8 Missile launch rails

The appropriate requirements of sections D2.1 to D2.7 shall be applied to missile launch rails and their interfaces with an aircraft and store.

Note 1 - Generally speaking lightning attachments can occur to most pylons and stores. However, it should be remembered that even if there is not a lightning attachment to a store, an attachment to another part of an aircraft will cause current to flow from the aircraft onto the pylon and from the pylon onto the store.

Note 2 - The significance of the voltage levels quoted is discussed in Appendix 11. They may be amended in the light of work now being undertaken.

Note 3 - In an interface the wiring layout is extremely important from the point of view of limiting induced voltages. The closer the wiring is to a lightning current path the lower will be the voltage that can be induced on that wiring. This is especially important when there are limitations to the degree of screening that can be provided to the wiring. If the normal attachment hangers are not adequate or are not appropriate current paths, to comply with the requirements of sections D2.7 (i)&(ii) it may be necessary to provide spring loaded plungers between the pylon to give the necessary contact. The correct places for such plungers is as close to the front and the rear of the pylon as is possible.

D3 EXTERNAL PROBES AND EQUIPMENT, INCLUDING DROGUES AND OTHER TRAILED EQUIPMENT

D3.1 All externally mounted probes and equipment shall be protected from Group 1 effects damage, and from causing unacceptable currents to be injected into any wiring connected to the probe (which might cause exploding arcs if the wires fuse), or causing unacceptable induced voltages in aircraft wiring, unless it can be shown that a lightning attachment to the probe is unlikely and that the damage consequent upon such arc attachment is acceptable in terms of flight safety and operational functioning of the aircraft.

D3.2 All metal parts of any external probe or equipment that is located in Zones 1 or 2, shall be adequately bonded to the airframe, except where such bonding would be detrimental to the functional operation of the probe or equipment eg in the case of an externally mounted aerial. The bonding shall be capable of carrying lightning currents having parameters appropriate to the lightning zone in which the probe or equipment is located.

D3.3 All drogues and trailed equipment and their method of deployment and attachment to the aircraft shall be so designed that they do not cause Group 1 effects damage to the aircraft, or unacceptable currents or induced voltages in aircraft wiring, unless the MOD(PE) Aircraft Project Director agrees that those effects are acceptable in terms of flight safety and operational functioning of the aircraft.

Note 4: It should be remembered that the deployment of trailed equipment will significantly alter the zoning diagram for the aircraft and that such equipment will almost certainly form a lightning arc attachment point should a lightning strike occur.

D4 RADOME PROTECTION

D4.1 Due to the need for clear unobstructed radar vision, the radar aerals, and therefore the radomes protecting them, are usually placed in Zone 1 areas. They are therefore in areas where the conditions giving rise to dielectric puncture are the most severe. In addition the surfaces area is often very large, particularly in the case of systems with scanning aerals. Furthermore, in order to reduce parallax problems the dielectric wall is often graded in thickness and therefore it can be very thin in places, or of a sandwich type construction. This type of construction tends to have a relatively low dielectric strength, and it follows that there is a high probability of dielectric puncture.

D4.2 Except for very small area radomes with relatively thick walls, such as for non-scanning weather radar, all radomes must be protected against puncture by lightning currents. The protection shall be in the form of lightning divertors constructed from solid metal strips, foils or wires. The divertor strips should be so placed as to give minimum radar obscuration and an acceptably low level of degradation of the radar performance, while at the same time offering reasonable lightning protection.

D4.3 The efficacy of the protection system must be demonstrated to the satisfaction of the MOD(PE) Aircraft Project Director. This will normally be done by expert assessment of the results of High Voltage tests conducted as indicated in Appendix 8.

D4.4 The protection strips shall be fastened to the exterior surface of the radome wall, and the fasteners must not provide an easy path for lightning currents to penetrate the radome wall. They must also be sealed against moisture ingress.

D4.5 All divertor strips shall be capable of carrying a test impulse having a peak current of 200 kA and an action integral of $2.25 \times 10^6 \text{ A}^2\text{s}$ without causing major damage to the radome wall by virtue of melting or fusing, or from magnetic forces. Where tests are necessary they will be conducted as indicated in Appendix 4 and Appendix 10.

D4.6 All metallic parts of externally mounted instruments or equipment eg pitots, navigation lights etc, shall be adequately bonded back to the airframe.

All electrical cables or wires connected to such instruments or equipments and which pass through the radome wall, shall be contained in metal conduits which are electrically well bonded to the external equipment at one end and the airframe at the other end. The conduits and the bonding shall be capable of carrying a test impulse having a peak current of 200 kA and an action integral of $2.25 \cdot 10^6 \text{ A}^2\text{s}$ together or separately as the case may be.

D5 ANTENNA SYSTEMS

D5.1 As far as other design considerations permit, antennas, shall be installed at locations on the aircraft least likely to receive severe lightning strikes, that is, Zone 3, with Zone 2A the next preference; the worst location in this respect is Zone 1B. The prominence of the antenna, that is, the amount by which it protrudes from the aircraft surface, shall be a minimum consistent with the performance of its function. The design shall take into consideration that a prominent antenna may itself influence the Zone classification, that is, a large prominent antenna in what would normally be Zone 3 could attract a lightning attachment and hence be classified as being in Zone 1 or 2.

D5.2 Protection shall be designed according to the following order of priorities:

- (a) Prevention of damage to other systems, for example by the propagation of transients through the aircraft electrical system.
- (b) Prevention of damage to the antenna system electronics, cables and connectors.
- (c) Prevention of damage to the antenna itself.

Measures shall be taken completely to prevent damage of types (a) and (b), and to minimise damage to type (c).

D5.3 Protective measures shall include precautions against damage to dielectric covers, to conductors by heating or magnetic forces, to cables and connectors and to electrical components both passive and active.

D5.4 For protection of dielectric covers against puncture or shattering, consideration shall be given to the provision of conducting strips to divert lightning currents to the airframe, in so far as such provision is compatible with the operational requirements of the antenna.

D5.5 Conductors shall have an adequate cross-section and method of fixing to prevent damage resulting from the heating effect and the magnetic forces due to the passage of lightning current.

D5.6 Precautions shall be taken against the lightning current, or voltage transients arising from the lightning strike, penetrating further into the system than the antenna itself. Protective measures to be considered shall include shunting transient currents to the airframe and blocking access, by means of shunt and series components respectively. Protective circuits to be considered shall include those dependent on frequency discrimination (filtering, usually employing inductors and capacitors) when the operating frequency of the equipment is well removed from the frequency spectrum of a lightning pulse, and those dependent on amplitude discrimination, as for example a shunt spark gap which breaks down when the voltage across it exceeds a chosen value. Combinations of these methods shall also be considered, such as a shunt spark gap and a series blocking capacitor.

Components fitted for protective purposes shall themselves be designed to be undamaged when operating to suppress a lightning surge. It shall be checked that the effect of protective components on the normal operation of the system is acceptable. Spark gaps or other current diverters shall meet the requirements of section C10.

D5.7 An analysis of lightning induced transients throughout the antenna system shall be carried out as part of the design of protective measures. Special attention shall be paid to the response of Antenna Tuning Units because when stimulated by a lightning transient they can produce high voltage oscillations at the operating frequency of the equipment which therefore cannot be filtered out.

D5.8 Where analysis indicates the need, a test plan shall be drawn up for either direct or indirect effects, or both.

D6 FLIGHT CONTROL SYSTEMS

D6.1 System requirements

D6.1.1 Lightning induced transients in a Flight Control System may produce the following types of fault:

- (a) A transient error with return to normal operation during the flight after a recovery period.
- (b) A deviation from correct functioning, known as an upset or malfunction, which does not correct itself during the flight, but no permanent damage has been done and the system is returned to normal operation after the flight by resetting or by reloading the software.
- (c) Permanent damage to hardware.

The system shall be so designed that type (a) faults are of an acceptable magnitude and duration, and type (b) and (c) faults do not occur.

D6.1.2 In order to increase their reliability, Flight Control Systems usually incorporate a degree of redundancy (multiplexing). However, this is not necessarily effective against a lightning strike, which may affect all channels equally. The design shall therefore incorporate the maximum practicable degree of dissimilar redundancy, such as different wiring routes and methods of coupling for the various channels.

D6.2 System wiring and other interconnections

D6.2.1 In order to reduce the propagation of common-mode transients, maximum practicable use shall be made of optical and/or transformer coupling.

D6.2.2 Wiring shall conform to the requirements of section C9.

D6.3 Sensors and pick-offs

D6.3.1 These shall be situated so that they are protected from direct exposure to lightning.

D6.3.2 Because sensors are usually designed to have a high resistance to airframe compared with that at the Flight Control Unit at the other end of the circuit, a high proportion of the common-mode lightning induced voltage in the circuit will appear as a voltage stressing the sensor insulation. The sensors shall therefore be designed to withstand this stress, the design to be confirmed by an appropriate high voltage insulation test.

D6.4 Control surface

Control surface shall have a bonding strap across each hinge except for installations having a single hinge, in which case at least two straps shall be fitted. The bonding straps shall conform to section C8.2. A piano type hinge may be considered to be self-bonding provided that the resistance across it is less than 0.01 ohms. When a novel type of hinge whose lightning performance is uncertain is to be employed it shall be subjected to Group 1 lightning tests appropriate to the Zone in which it is located, to confirm that binding or welding or excessive pitting does not occur.

D7 ENGINE CONTROL SYSTEMS

Engine control systems are becoming more complex, and more dependent upon electrical and electronic devices, as aircraft design becomes more sophisticated. They are consequently becoming potentially more susceptible to disruption by lightning strike in particular as a result of Group 2 effects.

The system must be considered as a whole with the rest of the aircraft and should be designed to be tolerant to transients from diffuse or resistive coupling, and care must be taken to ensure that the cable runs are well protected from fast flux coupling. (See also Section D6 Flight Control Systems).

D8 ENGINE AND PROPULSION INSTALLATIONS

D8.1 General considerations

Engine and propulsion installations are susceptible to damage during lightning strike from both Group 1 and Group 2 effects. The position on the aircraft is important and where the power unit is mounted external to the main airframe eg in an under wing nacelle, the details of the mounting methods must also be considered. A study of the probable lightning current paths in and around the engine should be made.

D8.2 Propellers and rotors

The methods of protecting composite propellers and rotors are discussed in section D10, and similar methods may be applied to protect wooden blades. For the most part all metal propeller and rotor blades are not at risk from lightning strike except in the case of unusual design eg the use of metal honeycomb sandwich panels. However while lightning currents may pass safely through a well designed blade, there is the danger that serious erosion of bearing surfaces may occur should the lightning currents need to cross bearings in order to get to the main airframe. Designers should address this potential problem.

D8.3 The nacelle

Where the power unit is installed externally in a nacelle, the nacelle becomes the first line of defence against lightning strike.

Those sections of all-metal nacelles situated in Zone 1a or Zone 2 should have a skin of such a thickness as to prevent metal burn through in areas where there is a possibility of the presence of inflammable gases or liquids. Similarly individual panels of the nacelle skin should be in good electrical contact with each other to reduce the risks of thermal sparking in fuel laden areas.

For non-metallic nacelles consideration must be given to the danger of skin puncture and the possibility of delamination and loss of parts of the nacelle skin. In particular the air-intake fairings on jet engines should be protected from the danger of sections breaking away and becoming sucked into the engine.

D8.4 Pipes carrying fuel and other inflammable liquids

Pipes carrying fuel and other inflammable liquids must not be exposed to the possibility of direct lightning attachments to the pipes.

Connections, joints and unions in the pipes must be capable of safely carrying the Zone 3 lightning currents appropriate to their position in the aircraft.

D8.5 Instrumentation

Steps must be taken to prevent malfunction of vital instrumentation eg Fire detectors, during, and subsequent upon, a lightning strike.

D9 DE-ICING SYSTEMS

D9.1 This section refers only to electrically operated de-icing systems.

D9.2 The aircraft can be put in hazard if lightning currents enter directly or by induction into the de-icing heaters. By nature the de-icing systems are installed in regions where severe icing can take place to the detriment of the aircraft performance. This is normally in Zone 1 regions which experience the conditions most likely to cause dielectric puncture, and which experience those components of the lightning flash which contain the highest action integral and the highest di/dt , and the highest peak current. It is in these regions that there is the greatest risk of direct lightning attachment by puncture of the electrical insulation. Any lightning currents flowing in the heater wires will have a high probability of carrying a high action integral. There is therefore a high probability of the heaters melting or fusing explosively, thus causing severe structural damage to the aircraft. Where no direct lightning attachment occurs to the heater, there is still the risk of induced voltages appearing on the heaters from direct flux coupling, diffusion flux coupling, or by resistive coupling. These induced voltages are likely to be high because of the high di/dt , and the high peak current. Apart from the damage that these voltages may do to the heaters themselves, they may also produce potentially disruptive transients on the general aircraft wiring.

D9.3 All electrically operated de-icers in Zones 1 and 2 must be protected against lightning strike. In the case of heaters under a metal erosion strip, the strip shall be so designed as to afford effective protection against the flow of lightning currents in the heaters, either by puncture of the electrical insulation, or by direct electrical contact between the heater and the metal erosion strip. It shall also provide sufficient shielding to prevent induction into the heaters, of unacceptable voltages by direct or diffuse flux coupling.

Where heaters are placed under non-conducting erosion strips, or highly resistant skins, where no protection to Group 2 effects is afforded by shielding, the heater wires must be otherwise protected by use of metal conduits or other approved devices to the same extent as is required for heaters under metal erosion strips or skins.

D10 COMPOSITE ROTOR BLADES

D10.1 This section covers composite rotor blades for both propellers and helicopter rotary wings. It also covers both conducting plastics, such as Carbon Fibre Composites, and non-conducting plastics such as Kevlar and Glass Fibre reinforced plastics. Carbon Fibre Composite rotors are subject to the failure mechanisms described in sections C3 and C4. Dielectric composite rotors are subject to dielectric puncture failure mechanisms due to puncture by lightning currents to underlying metallic structural members.

D10.2 All externally mounted metal work eg rotor blade tip caps, or metallic leading edge erosion strips, shall be provided with a low inductance electrical path to the main frame, capable of carrying a discharge of 200 kA peak current, with an action integral of $2.25 \times 10^6 \text{ A}^2\text{s}$ without damage from ohmic heating or magnetic forces to either the rotor blade, or the bearing on which it turns.

D10.3 All mass balance weight and leading edge weights shall either:

- (a) be protected from carrying lightning currents eg by shielding provided by a metallic leading edge erosion strip;
- (b) be so designed as to be capable of carrying a discharge having a peak current of 200 kA with an action integral of $2.25 \times 10^6 \text{ A}^2\text{s}$ without damage to the weights or the rotor blade from ohmic heating, magnetic forces, or high energy sparking between component parts of the weight.

D10.4 All CFC rotor blades shall be capable of safely carrying a discharge of 200 kA peak current with an action integral of $2.25 \times 10^6 \text{ A}^2\text{s}$ and having an arc root attachment to either the rotor blade tip cap or to the leading edge.

D10.5 All dielectric composite rotor blades shall be protected where necessary, from puncture by lightning currents to electric stress raising metallic structural work inside the blade. Protection can be afforded by using externally mounted metallic shields which conform to the requirements of D10.2 above.

D11 CANOPIES AND PERSONNEL PROTECTION**D11.1 Electric shock and flash blindness**

A lightning strike or a very near flash, especially at night, may cause the crew to experience temporary blindness, usually lasting a few seconds although durations up to 15 or even 30 seconds have been reported.

Crew in the exposed type of canopy may experience electric discharges from their helmets or shoulders due to the high electric field, or may feel mild to severe shocks due to the induced voltage in the loop formed by body, arm, control column, floor and seat when linked with the magnetic fields. Tests with simulated lightning indicate that this loop voltage may be as much as 6 kV. The longer durations of flash blindness mentioned above have usually taken place below such exposed canopies rather than in the more enclosed transport aircraft, suggesting that the blindness may be partly due to a temporary numbing of the brain by electrical effects rather than purely an effect on the eyes. Protection where practicable would take the form of enclosing the crew more nearly in a metal cage by means of one or more overhead conducting bars.

D11.2 Inadvertent ejection by explosives devices

Lightning may cause inadvertent operation of explosive devices, which may include those causing detachment of the canopy and ejection of the seat. These shall therefore be protected from direct lightning attachment and from induced voltages due to field penetration.

PART E - TESTING REQUIREMENTS**E1 INTRODUCTION**

This part of the specification defines the test methods available for use in the Test Plan. Definitions of the interaction effects (Groups 1-4) are given in Appendix 1 and information concerning the damage mechanisms referred to below is given in Appendix 2.

E2 TESTS APPROVED FOR USE

E2.1 When testing is determined to be necessary by the Lightning Hazard Design Analysis (LHDA) (see section B1 and Appendix 3) tests shall be selected from those given in Table E1 below, according to the interaction effects and damage mechanisms under investigation. Appendices give the test methods to be used as follows:

Appendix 4 - Requirements for Group 1 tests (direct effects)

Appendix 5 - Requirements for Group 2 (indirect effects) tests on parts of aircraft

Appendix 6 - Requirements for Group 2 tests on whole aircraft (indirect and nearby effects)

Appendix 7 - Requirements for fuel hazard assessment tests

Appendix 8 - Requirements for Group 4 tests (leader phase effects)

E2.2 Appendix 9 defines the test waveforms that shall be used for the tests.

E2.3 Equipment tests shall be made in accordance with the latest issue of RAE Technical Memorandum FS(F)457.

E3 GENERAL TEST REQUIREMENTS

The following requirements shall apply to all tests:

(i) All tests shall be made at a Test House approved by the MOD(PE) Aircraft Project Director.

(ii) Evidence shall be available to the MOD(PE) Aircraft Project Director that all diagnostic and measuring devices have been calibrated in accordance with recognised engineering practice, or by calculation from basic principles, to a standard of accuracy commensurate with the precision required of the test.

(iii) The test waveforms specified in Appendices 4 to 8 shall be as defined in Appendix 9, unless otherwise agreed with the MOD(PE) Aircraft Project Director.

(iv) The test items shall be arranged in a co-axial or quasi co-axial return conductor system, as detailed in the relevant Test Plan.

Note: Guidance concerning the design of return conductor systems is given in Appendix 10.

(v) The test item shall normally be production or equivalent development hardware. Alternatively an electrically representative simulation of the production configuration may be used if acceptable to the Project Director.

(vi) Variations to the test methods shall only be made by agreement with the MOD(PE) Aircraft Project Director. Such variations shall be recorded in an amendment to the Test Schedule.

E4 REPORTING

All tests conducted as part of an agreed test plan shall be reported to the MOD(PE) Aircraft Project Director and shall contain the following information:

- (i) The aims and objectives of the tests.
- (ii) A description of the test object and identification of the source of the object. The description shall define the nature of the test object (that is production hardware, model, or mock-up). In the case of a model or a mock-up sufficient details shall be given to ensure an unambiguous picture of the object.
- (iii) The test techniques and methods used shall be defined in sufficient detail to enable the tests to be repeated at a later date, and if necessary in a different place.
- (iv) The diagnostic equipment used shall be identified and the method of calibration stated.
- (v) The place, date and time of the tests shall be stated.
- (vi) A schedule of the tests proposed in the approved Test Plan shall be given together with a schedule of the tests actually carried out. An explanation and/or justification shall be given for any deviations made from the original test schedule.
- (vii) Details of all the tests made must be given in the report. Selective reporting is not acceptable. All relevant details, for example test current parameters, damage etc, must be given for each individual test.
- (viii) The results of the test shall be discussed in the report, and the significance of the tests stated. Any unusual or unexpected results shall be highlighted and if possible an explanation should be given.
- (ix) The conclusions arising from the test results shall be stated.
- (x) The report shall end with appropriate conclusions and recommendations.

E5 TEST GUIDANCE

Test guidance is given in Appendices 10, 11 and 12.

Table E1
TESTS APPROVED FOR USE

Effects classification	Test method		
	Title	Appendix No	Test No*
Group 1 (Direct Effects)	Metal burn through	4	1
	Hot spot formation		2
	Arc root damage to CFC skins		3
	Arc root damage to metal sandwich panels with Honeycomb core		4
	Arc root damage to thin metal sandwich panels with ablative layer		5
	Arc root damage to CFC sandwich panels with Honeycomb core		6
	Ohmic heating tests		7
	Magnetic forces		8
	Acoustic shock wave tests		9
Group 2 (Indirect effects on parts of aircraft) (Indirect and nearby effects on whole aircraft)	Induced voltage measurement	5	9
	Voltage flash over		10
	CW injection tests	6	6
	Pulse tests	6	7
Group 3 (Far field effects)	Not applicable to aircraft		
Group 4 (Leader Phase effects)	Dielectric puncture tests	8	1
Fuel hazard tests	Arc root tests	4	1-6
	Sparking tests	7	1
	Flammable gas tests		2
	Flame suppression tests		3

*Test numbers refer to appropriate paragraph numbers in appendices.

Appendix 1

DEFINITIONS

The following definitions apply for the purposes of this document.

1 PROPERTIES OF LIGHTNING

1.1 Flash

The total lightning discharge. A discharge to ground from a region of negative charge is called a negative flash.

1.2 Leader

Each flash begins with a weakly luminous low-current ionised channel known as a leader which usually propagates from the charge centre in the cloud to ground, although sometimes it originates at the ground and propagates upwards (upward-going leader).

1.3 Return stroke

When the leader reaches the ground it initiates the first return stroke which retraces the leader channel with a high current pulse accompanied by high luminosity. A negative flash may discharge several pockets of charge in the cloud in succession, with the result that the flash contains several distinct pulses of current or strokes. All strokes after the first are called subsequent strokes or restrikes. See Fig 2a.

1.4 Intermediate current

This occurs at the end of some of the strokes in a negative flash; it has an amplitude of a few kilo amperes and a duration of several milliseconds. See Fig 2a.

1.5 Continuing current

This occurs after some strokes in a negative flash; it has an amplitude of 100-400 A and a duration of 100-800 ms, so that substantial charge may be transferred. It is particularly common for there to be a continuing current after the last stroke. See Fig 2a.

1.6 Charge

This is the integral $\int i dt$ over the period considered and is measured in coulombs. Thus we may speak of the charge transferred in a particular phase of the flash (eg the continuing current) or in the whole flash.

1.7 Action integral

This is the integral $\int i^2 dt$ over the period considered and is measured in A^2s or Joules/ohm. It gives the energy (Joules) dissipated in each ohm of resistance in the lightning path. We may speak of the action integral in a particular phase of the flash or in the whole flash.

2 INTERACTION WITH AIRCRAFT

2.1 Direct strike

Here the lightning channel attaches to the aircraft, which therefore forms part of the channel and is subjected to the whole lightning current.

2.2 Nearby flash

Here the lightning channel passes near the aircraft but does not contact it, so that the lightning current does not flow in the aircraft. However, the aircraft is near enough to the channel to be within the 'near field' region of its electric and magnetic fields and these may induce voltages and currents in the aircraft.

2.3 Distant or 'far field' flash

In this case the aircraft experiences only the 'far field' electromagnetic radiation from the flash, characterised by a constant ratio between the electric and magnetic components of the field and having an intensity approximately inversely proportional to the distance.

2.4 Attachment point

This is a point on the aircraft surface at which lightning current enters or exits. There must be at least two such points and may be many more due to the sweeping action of the lightning channel (see Swept Stroke).

2.5 Swept stroke

The lightning channel remain substantially stationary relative to the air and therefore as the aircraft moves forward the lightning channel sweeps back along its surface. This is usually called a swept stroke but should more accurately be called a swept flash since the whole of the flash, including all its phases, takes part in the process.

2.6 Classification of lightning effects on aircraft

Group 1 or Direct Effects. These are the effects arising directly from the passage of lightning current and are therefore present only in

direct strikes. An example is burning a hole or forming a hot spot at an attachment point.

Group 2 or indirect effects. These occur in parts of the aircraft not carrying the lightning current and are due to coupling with the magnetic or electric field of the lightning current flowing in other parts of the aircraft or in the lightning channel itself. They can arise therefore as a result of either a direct strike or a nearby flash. An example is transient voltages induced in aircraft wiring which could cause malfunction of equipment or even permanent damage.

Group 3 or far-field effects. These are the effects of exposure to the radiated electromagnetic field of a comparatively distant lightning flash.

Group 4 or leader phase effects. The effects resulting from the attachment of a lightning leader to the aircraft such as corona or dielectric puncture.

2.7 Lightning attachment zones

Because of the sweeping action of the lightning channel, the proportion of the flash experienced by any particular point depends on its location on the aircraft surface and this has led to the concept of dividing the surface into three Zones depending on the probability of initial attachment, sweeping and hang-on, as follows:

- Zone 1 Surfaces for which there is a high probability of initial lightning flash attachment (current entry or exit).
- Zone 2 Surfaces across which there is a high probability of a flash being swept from an initial attachment in Zone 1.
- Zone 3 All other surfaces. Although such surfaces do not experience attachments, they may carry substantial lightning current by conduction between the attachment points situated in Zones 1 and 2.

Zones 1 and 2 may be further divided into A and B regions depending on the probability that the flash will hang on for a protracted period of time, this probability being low for the A region and high for the B region. Further details are given in Appendix 2 section 4.1.

2.8 Corona

The ionisation of a volume of air around a conducting body under high electric field conditions. It occurs particularly at sharp points, edges and protuberances, where the intensity of the electric field is enhanced by the local geometry.

2.9 Streamers

Ionised paths or filaments that emanate from corona regions on a conducting body when the field intensifies still further.

2.10 Arc

An electric discharge between two conductors characterised by high luminosity, temperature and current.

2.11 Thermal sparking

Thermal sparking occurs when a very high current is forced to cross a joint between two conducting materials, which have imperfect mating between their surfaces; it is thus a function of high current density and low mechanical pressure.

2.12 Voltage sparking

Voltage sparking occurs when the voltage difference between two conductors rises to a value high enough to break down the intervening medium, whether this is air or other dielectric. It can arise from the flow of current, either inductively in a loop or bend in a conductor, or from the resistive voltage drop in a high resistance material such as CFC. It is a function of rate of change of current (inductive) or of peak current (resistive voltage gradients).

2.13 Bonding

Bonding is the process of making a firm low-resistance electrical connection between parts or between a part and the airframe.

2.14 Aperture flux (fast flux)

Aperture flux is the magnetic flux of lightning origin inside an aircraft that has penetrated through electromagnetic apertures (non-conducting material) such as a canopy or joints in the skin. Its waveform is that of the external magnetic flux.

2.15 Diffusion flux

Diffusion flux is the magnetic flux that has penetrated by diffusion through a conducting portion of the skin; the diffusion process distorts and

attenuates the external flux. The amplitude depends on the resistivity of the material through which it has diffused, being low for good conductors such as metal and higher for high resistivity materials such as CFC.

2.16 Differential voltage

In a two-wire circuit differential voltage is the voltage difference between the wires.

2.17 Common-mode voltage

In a two-wire circuit common-mode voltage is the difference between the mean voltage of the wires and the airframe.

2.18 CFC

Carbon fibre composite, also known as carbon fibre reinforced plastic (CFRP), is a material constructed of carbon fibres laid in a resin matrix, employed in aircraft mainly for its good strength/weight ratio. It has a resistivity about 1000 times as high as that of aluminium alloy.

3 WAVEFORM PARAMETERS

3.1 Peak or maximum rate-of-rise

The peak or maximum rate of rise of a waveform is the maximum instantaneous rate-of-change of the waveform as it rises to its peak value, that is the peak rate-of-rise is the maximum value of the derivative with respect to time (in a current waveform di/dt (max)).

3.2 Time to reach peak

The time from t to the maximum value of the waveform.

3.3 Total duration

The time from t to 5% of the maximum value taken at the tail of the waveform.

4 GENERAL

4.1 Pylon

A removable structure fixed to the aircraft to which a store may be attached.

4.2 Store

Any munition, pod, fuel tank or dispenser attached to a pylon.

Appendix 2

PROPERTIES OF LIGHTNING AND ITS INTERACTION WITH AIRCRAFT

1 INTRODUCTION

This Appendix describes the relevant properties of lightning and relates them to the hazards experienced by aircraft. It discusses the various effects that lightning interaction may have on the aircraft and its systems and indicates how aircraft protection design and test parameters are derived from the physical properties of lightning. This Appendix is intended as a brief introduction to the subject to provide background information on the design and test requirements.

2 THE LIGHTNING DISCHARGE

Lightning flashes usually originate from charge centres in a cloud, particularly the cumulonimbus thunder cloud, although they can occur in snow storms and sand storms. The charges in clouds are produced by complex processes of freezing and melting and by movements of raindrops and ice crystals involving collisions and splintering. Because freezing and melting take place at different altitudes, and also possibly due to correlation between the mass of a particle and the charge it acquires so that air currents tend to separate the charges, most positive charge accumulate at the top of the cloud, leaving the lower regions negative, although there may be a small positive region near the base. The result is the typical structure of Fig 1 depicted by Malan, who extensively studied thunderstorms in South Africa.

When during their process of development thunder clouds extend vertically over more than 3 km, the strong electric fields can initiate lightning discharges, which may be of three types, namely:

- (a) Discharges between centres of opposite polarity within a cloud (intracloud discharges).
- (b) Discharges between centres of opposite polarity in different clouds (intercloud discharges).
- (c) Discharges to earth from regions of either polarity. Conventionally, a discharge to earth from a positive region is called a positive flash and a discharge from a negative region is a negative flash. It is common for a negative flash to discharge several charge centres in succession, with the result that the flash contains several distinct pulses of current, and these are usually referred to as strokes.

The process that culminates in a lightning discharge begins with the formation of an ionised column called a leader which travels out from a region where the electric field is so high that it initiates progressive breakdown; this critical field is thought to be about 900 kV/m for water droplets or 500 kV/m for ice crystals. For a negative discharge to earth the column advances in zig-zag steps (hence the name stepped leader) each about 50 m long and separated by pauses of 40-100 μ s. The luminous diameter of the leader is between 1 m and 10 m although the current, which is low (about 100 A), is probably concentrated in a small diameter core. The average velocity of propagation is $1.5 \cdot 10^5$ m/s. The leader may form branches on its downward path, most of them fading out before reaching the ground. When a branch is near the ground it causes high fields to form at projections such as trees and buildings and these then send up streamers, one of which will make contact with the tip of the leader. This has the effect of closing a switch; a 'return stroke' is initiated which retraces and discharges the leader channel at a velocity of about $5 \cdot 10^7$ m/s. This initial return stroke is characterised by a current pulse of high amplitude accompanied by high luminosity. After the first return stroke further strokes may occur as higher areas of the negative region are discharged; the leaders for these usually traverse the same path as the first but in one continuous sweep at a velocity of $2 \cdot 10^6$ m/s.

The above description is typical of a negative flash to open ground but over mountains and tall buildings the leader may be of the upward moving type, originating from a high point such as a mountain peak. When such a leader reaches the charge pocket in the cloud a return stroke is initiated and subsequent events (including multiple return strokes) follow the same pattern as for initiation by a downward moving leader. Thus the 'switching point' is near the ground for downward leaders but near the charge pocket in the cloud for upward leaders. This can involve significant differences to the waveform and amplitude of the current experienced by an aircraft that forms part of the lighting path.

Positive flashes to ground are much rarer than negative flashes, the proportion being between 1% and 20% dependent on geographical location, the average being about 10%. Positive flashes are usually initiated by upward moving leaders and more commonly occur over mountains than over flat terrain. They consist of one stroke only, have slower rise times than negative flashes, with higher peak current and charge transfer; the duration is longer than a single stroke of a negative flash but usually shorter than a complete negative flash.

More exact details of the parameters of flashes of both polarities are given in the next section.

3 LIGHTNING CURRENT WAVEFORMS AND PARAMETERS

An example of the return stroke current in a severe negative flash is sketched in Fig 2a. The number of strokes in a negative flash is usually between 1 and 11, the median value being 3; the total duration is between about 20 ms and 1 s, with a median value of 0.2 s. The time interval between strokes is typically about 60 ms. There is some correlation among these parameters, the flashes with the most strokes tending also to be the longest in duration. The rise time of the first stroke is about 2 μ s, with a decay time (to half the peak amplitude) of 45 μ s. Subsequent strokes in the flash tend to have a higher rate of rise although lower peak amplitudes than the initial stroke and they can therefore be significant for inducing voltages in aircraft wiring, where the inductively coupled voltages are proportional to the rate of change of the lightning current.

Near the end of some of the strokes in a negative flash there is often a lower level current of a few kilo amperes persisting for several milliseconds, known as an 'intermediate' current, as shown in Fig 2a. Although each stroke has a high amplitude its duration is short and only a few coulombs of charge are transferred. However, after some strokes a 'continuing' current of 100-400 A flows with a duration of 100-8000 ms, so that there is substantial charge transfer in this phase. It is particularly common for there to be a continuing current after the last stroke. It is generally thought that before a restrike can occur the continuing current must cease, as illustrated after stroke 5 in Fig 2a.

An example of a positive flash is shown in Fig 2b; it is a moderately severe example although not the 'super flash' which occurs occasionally. Typically the rise time of a positive flash is 20 μ s and the total duration 0.1 s. Although positive flashes are far less frequent than negative, they have to be taken into consideration in the selection of design and test parameters because they include some of the most severe flashes in relation to thermal effects and magnetic forces, the governing factors for these effects being peak current, charge transfer and action integral, as discussed in section 6 of this Appendix.

The above discussion relates to flashes of either polarity to ground and indeed most of our knowledge relates to flashes of that type, although in the last few years instrumented aircraft have been employed in USA and France to record the characteristics of cloud flashes. Generally speaking the conclusion

is that cloud flashes are less severe than ground flashes, certainly in respect of peak current, charge transfer and action integral. The only doubt is in respect of rate of rise of current; airborne measurements show some evidence that over a portion of some pulse wavefronts the rate of rise for a short time (less than $0.4 \mu s$) may be higher than the figure hitherto accepted. There are also short pulses of low amplitude but fast rate of rise (called K pulses), which occur also between the strokes of negative ground flashes. It has been argued that a succession of such pulses might induce voltage transients in digital avionic systems of an amplitude and timing to cause upset. This is not generally accepted at present but could eventually be the subject of additional design and test criteria in respect of indirect (induced voltage) effects.

Even if we consider only ground flashes, it is likely that the parameters at the altitude of the aircraft will be different from those measured at stations on the ground, because the lightning channel acts as a transmission line and the return current pulse as it ascends from the ground towards the aircraft experiences changes in both shape and amplitude.

For the present, design parameters will be based on ground flashes measured at ground level, as likely to represent the most severe threat.

An empirical justification is that the actual damage experienced by aircraft roughly corresponds to the damage produced by simulated lightning whose parameters are based on the characteristics of ground flashes measured at ground level.

The parameters of a flash which are significant for the purposes of aircraft protection are listed in Table 2-1. The charge transferred is $\int i dt$ coulomb and governs the energy dissipated at a lightning attachment point since the volt drop at the attachment point is substantially constant. The action integral is $\int i^2 dt$ $A^2 s$ or J/ohm , this gives the energy dissipated in each ohm of resistance in the lightning path. These two parameters together with peak current and maximum rate of current rise are usually the most important to be considered.

The numerical values of the parameters have been determined in measurement programmes extending over many years in several countries, consisting mainly of recording the waveforms of the currents flowing in lightning strikes to towers together with both still and moving photography of the flash. As mentioned, these have been supplemented in more recent years by measurements in aircraft. The numerical values of the parameters vary widely from flash to flash and are therefore best stated in statistical terms. For any given parameter this may

take the form of a curve which indicates the percentage of flashes in which that parameter exceeds any chosen level. For example, in the case of peak current in negative flashes the curve would indicate that 50% of such flashes have a current greater than 20 kA, 2% have a current greater than 200 kA, and so on for any other percentage level of interest. The median level (50% above) may be taken as typical and it is necessary for design purposes to decide what is the maximum level to be considered; usually the 2% level is chosen. Table 2-1 includes the 50% and 2% levels for the listed parameters of negative flashes, as given in NATO STANAG 4236².

Table 2-1 also includes the typical (50%) level for the parameters of positive flashes, which are assumed to consist of single strokes only. Because of the comparative rarity of positive flashes it would give a distorted result to consider the 2% level as the extreme or severe case for positive flashes when devising design criteria which take account of both polarities; the extreme level has therefore been taken to be the 18% level. This figure is based on an assumption that 10% of all flashes are positive, so that the ratio of negative to positive is 9:1 and therefore the 18% (equal to $9 \times 2\%$) level is roughly of the same significance for positive flashes as the 2% level for negative flashes. These levels have not always been strictly adhered to however when arriving at the standard test waveforms, as explained in section 5 below. It is seen that using the extreme levels as defined, negative flashes have higher peak current and rate of rise of current, but that positive flashes have higher action integral; the two polarities are much the same in respect of total charge.

Table 2-1
PARAMETERS OF GROUND FLASHES MEASURED AT GROUND LEVEL

Parameter	Units	Typical	Extreme
NEGATIVE FLASHES		50% above	2% above
Duration of flash	s	0.2	1
Number of strokes		3	11
Time interval between strokes	ms	60	320
Time to reach peak	μ s	1.8	12
Stroke width (at half peak)	μ s	45	170
Peak current, first stroke	kA	20	200
Max rate of rise, first stroke	kA/ μ s	12	40
Peak current, subsequent strokes	kA	10	100
Max rate of rise, all strokes	kA/ μ s	22	100
Continuing current, duration	ms	160	400
Continuing current, amplitude	A	140	500
Continuing current, charge	C	26	110
Charge per stroke	C	5	20
Total charge in flash	C	15	200
Total action integral in flash	MJ/ohm	0.02	0.8
POSITIVE FLASHES		50% above	18% above
Duration of flash	s	0.1	0.25
Time to reach peak	μ s	20	70
Peak current	kA	25	100
Max rate of rise	kA/ μ s	2.5	10
Total charge in flash	C	70	200
Total action integral in flash	MJ/ohm	0.5	3.5

4 LIGHTNING INTERACTION WITH AIRCRAFT

4.1 The mechanism of interaction

4.1.1 General considerations

The most important case of interaction is when the aircraft forms part of the lightning discharge channel, although nearby lightning (the lightning channel passing near the aircraft but not contacting it) can also produce significant effects. In the former case, when an aircraft is near an advancing leader it experiences an increased electric field which is particularly concentrated at the extremities and protuberances; these become electric 'stress raisers' and send out streamers, one or more of which may reach and link with the leader. The leader then passes through the aircraft on its way to the ground where a return stroke is initiated in the usual way and travels up the channel, again passing through the aircraft on its way to the cloud that was the source of the discharge, the return stroke preferentially attaching to the strongest leaders. Thus when an aircraft is struck by lightning there are always at least two attachment points, namely the entry and exit points of the return current.

The above description applies to the situation when an aircraft intercepts an advancing leader and hence becomes part of a natural lightning channel. It is possible however that an aircraft may sometimes 'trigger' a lightning flash, that is, form part of a discharge that would not have occurred if the aircraft had not been present. The mechanism could be similar to the formation of upward moving leaders on the ground. For example, the aircraft might be between two charge centres of opposite polarity either in a cloud or between two clouds; the presence of a conducting body such as an aircraft concentrates the electric field, and streamers of opposite polarity may move out from stress raisers on opposite sides of the aircraft towards the charge centres of appropriate polarity, eventually making contact and initiating a discharge. The mechanism of initiating a ground discharge would be more complicated but it should not be impossible; certainly lightning discharges have been deliberately triggered by firing rockets, both earthed with a trailing wire and electrically isolated, into charged clouds. The question of what proportion, if any, of strikes to aircraft are triggered is important as it is thought that the parameters of triggered flashes are probably different from those of natural ground flashes measured at ground level. The latter will however continue to be the basis of protection design until more is known about triggered flashes, particularly as such a procedure probably errs on the side of safety; triggered flashes are thought to

be less severe than those of natural origin. This document will therefore deal only with natural flashes.

When an aircraft is struck by a natural flash initiated by a downward moving leader, the situation is complicated by the fact that the aircraft has usually moved a significant distance in the interval between the initial leader contact and the arrival of the return stroke from the ground, and indeed it continues to move throughout the duration of the flash. This of course would not apply to a helicopter or a VTOL aircraft that was hovering at the time. The consequences of forward movement are that the initial attachment points (points of return current entry or exit) do not necessarily correspond to the points of leader contact at the extremities (see sweeping leader discussion below) and also that throughout the flash the attachment points are swept backwards along the aircraft since the lightning channel tends to remain static relative to the surrounding air. Except possibly on smooth unpainted surfaces, this movement of the attachment points is not a smooth continuous movement but progresses in a series of discrete irregular steps, the dwell time at any particular step being dependent on the nature of the surface, the velocity of the aircraft and other factors. The movement of the attachment points is known as the 'swept stroke' phenomenon although more accurately it should be called a swept flash, since the whole of the flash, including the fast strokes, the intermediate current phase and the continuing current phase participate in the movement. When the lightning arc has swept back to a trailing edge it can progress no further and will remain there, or 'hang on', for the remainder of the flash.

4.1.2 Zoning concepts - fixed wing aircraft

The sweeping action of the arc channel can have several consequences. For example, inboard areas that are unlikely to be the site of initial attachment and which might be thought to be not at risk will be subject to attachments if they are in the swept path. On the other hand the arc erosion effects of the flash are spread out over a considerable area so that except for hang-on at trailing edges no single point receives the full effect of the flash. The proportion of the flash experienced by any particular point depends on its location on the aircraft surface and this has led to the concept of dividing the surface into Zones depending on the probability of initial attachment, sweeping and hang-on.

Ignoring the sweeping leader effect, the aircraft surface can be divided into three Zones as follows:

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

- Zone 2 Surfaces across which there is a high probability of a flash being swept from an initial attachment in Zone 1.
- Zone 3 All other surfaces. Zone 3 areas have a low probability of flash attachment, although they may carry substantial lightning current by conduction between the attachment points situated in the other Zones.

Zones 1 and 2 may be further divided into A and B regions depending on the probability that the flash will hang on for a protracted period of time, this probability being low for the A region and high for the B region. Some examples of Zones are as follows:

- Zone 1A Likely to have an initial attachment point with low probability of hang-on, such as a wing leading edge.
- Zone 1B Likely to have an initial attachment point with high probability of hang-on, such as a tail-fin trailing edge.
- Zone 2A A swept stroke zone with low probability of hang-on, such as a wing mid-chord.
- Zone 2B A swept stroke zone with high probability of hang-on, such as a wing inboard trailing edge.

NOTE: The 'sweeping leader' effect mentioned earlier, resulting in a transition Zone 1C (between the 1A and 2A regions) is discussed below.

The method of deciding initial attachment points by the use of the 'rolling sphere' concept is not discussed in this Memorandum, although it may be discussed in subsequent issues when there is a more general consensus of opinion concerning application of the method. Meanwhile a description of the method and its application will be found in Ref 6.

4.1.3 The sweeping leader effect and transition zone (Zone 1C)

It has been explained above, considering a cloud to ground strike and a downward going leader, that the leader channel in effect passes through the aircraft structure and continues downward until it is met by an answering streamer from the ground. When that happens a rapid upward return stroke passes back through the aircraft to the cloud from which the downward leader originated. During the time taken for the leader channel streamer to leave the aircraft and the return stroke to arrive back, the aircraft will have moved forward an appreciable distance and the leader channel will have been stretched backwards from its attachment point over the surface of the aircraft. That stretched or

'swept' leader will re-attach to the airframe on the arrival of the return stroke giving an attachment of the initial return stroke aft of the original leader attachment.

It has been shown theoretically^{3,4} that lightning channel parameters change with altitude. For example, for a downward going leader if an aircraft is struck at a significantly high altitude the peak current could be reduced by a factor of 4 and the peak di/dt is likely to be ten to a hundred times less than if it was struck near the ground⁵. Still considering a downward going leader it is obvious that the higher an aircraft is flying the further back will be the initial return stroke attachment due to the sweeping leader effect. However, due to the reduction in parameters with altitude just mentioned, it would be unreasonable to apply the parameters normally associated with Zone 1A to such a swept initial attachment. It is therefore not worth considering return stroke attachments due to swept leaders which are further back from the initial leader attachment (the conventional Zone 1A area) than where the parameters are equal to the Zone 2A parameters. This leads to the definition of a 'transition zone' (Zone 1C) immediately behind Zone 1A regions where the parameters applicable are less than the 1A parameters but greater than the Zone 2A parameters. From Hoole's analysis⁴ it will be found that the two percentile level of action integral falls below the Zone 2A value of $0.25 \times 10^6 \text{ A}^2\text{s}$ at an altitude of 600 metres. Consequently an upper limit for the leader swept time (t_s) that need be considered is given by calculating the longest time taken for a leader to propagate to ground from 600 m and the return stroke to arrive back at that altitude. In practice, as a return stroke is about three orders of magnitude faster than a stepped leader only the leader need be considered and the return stroke may be assumed to be instantaneous. Taking a leader velocity of $1.05 \times 10^5 \text{ m/s}$ (which effectively is the velocity assumed in Ref 6*) gives a sweep time of $5.7 \times 10^{-3} \text{ s}$. The distance the aircraft moves forward in that time ($l_s \text{ m}$), and hence the fore and aft extent of the transition zone, is easily calculated for any aircraft speed from $l_s = 5.7 \times 10^{-3} v$ (where v is the velocity of the aircraft in metres per second)**. Obviously to get a worst case the maximum operating speed of the aircraft should be used in that calculation.

* Ref 6 considers the latest published data for the slowest stepped leader and return strokes.

** l_s is also given by the expression aircraft speed in knots/350, as is noted in Ref 6.

Similar arguments to the above apply when upward going leaders cause the switching point to be near the cloud. However, if the maximum operating speed of the aircraft at any altitude up to say 4,500 m (approximately 15,000 ft) is used in the calculations outlined above, a realistic worst case will be obtained.

Zone 1C may be defined as:- a limited area of the aircraft surface behind Zone 1A into which a leader attachment may be swept and which may therefore experience a first return stroke attachment. The parameters associated with that attachment will be less than the parameters appertaining to Zone 1A but greater than the parameters appertaining to Zone 2A.

Full Zone 1A parameters shall be used in Zone 1C areas, although a worst case for the purposes of design and testing will be obtained if a linear variation from full Zone 1A to full Zone 2A is assumed over the total fore and aft extent of the Zone 1C. Advantage should only be taken of that parameter relaxation in consultation with the MOD(PE) Aircraft Project Director.

4.1.4 Zoning concepts - rotary wing aircraft

(i) General considerations and assumptions

Lightning zoning rules were developed a long time ago and were made by considering theoretical concepts and lightning strike experience to fixed wing aircraft. Although the general concept is still valid, work over the years (and especially lightning strike investigation experience) has shown several shortcomings in the rules, especially when applied by people with little lightning knowledge. For example, the position of initial attachments, the extent of Zone 1A (normally taken as 0.5 m from the extremity under consideration) and whether or not the attachments are leader or return stroke attachments, is arguable. Also no consideration has been given in the past to sweeping leaders. Again the four component test waveform (see section 5 below) applied to the lightning zones for design and test purposes tends to be regarded by those who do not understand lightning as a real lightning event, rather than a worst case compilation of the many variable parameters in all lightning events. All this leads to imprecise zoning and the risk of either under or over protection. More precise zoning is necessary with modern aircraft and especially with composite helicopter rotor blades.

The zoning of helicopters is complex. The problem arises from the difficulty in knowing, or predicting, for all flight modes (hover, forward, sideways and backward flight) exactly where attachments will occur, taking into account the swept leader effect and also the duration of the lightning event. To come up with a set of simplistic rules is therefore very difficult and to take

full advantage of zoning concepts a detailed analysis of each aircraft type must certainly be made. However a realistic worst case can be made, which should cover most helicopter types, by making certain assumptions. These assumptions are that:

only the main rotors of three blades or more are considered;

the rotational speed (N) of the main rotor does not exceed 4 RPS;

the rotor disc effectively screens the rest of the aircraft from a downward coming leader and that initial attachments can always occur to main rotor blade tips, whatever the flight mode;

the lightning event is equivalent to a Component C of 250 ms duration with a corresponding current level of 800 amps.

In the following, n is the number of blades in the main rotor and the blade tip velocity is v_t metres per second, whilst the maximum forward velocity of the aircraft is v metres per second.

A 250 ms duration and 800 A amplitude Component C is justifiable when considering a worst case situation (especially for composite construction) as it will give greater action integral than the longer duration lower amplitude case.

As noted in section 4.1.3 full Zone 1A parameters shall be used in Zone 1C areas unless otherwise agreed with the MOD(PE) Project Director.

It will be noted below that no reference is made to Component B of the composite test waveform (see Appendix 9, Fig 9.1). That is because that component is of somewhat academic interest, as it is seldom necessary to use it in design and is hardly ever used in testing.

(ii) Main rotor

(a) Hover - Leader attachments will occur only to the tips of the blades, and to the hub at a lower probability*. As there is no forward movement of the aircraft the hub automatically becomes a Zone 1B in conventional zoning terms. Also in conventional terms an area of 0.5 m inboard of the tip extremity and behind any leading edge curvature at the tip will be a Zone 1A. That Zone 1A area will be extended backwards by a distance equal to $5.7 v_t \times 10^{-3}$ m to give a Zone 1C which will encompass the trailing edge of the blade (see section 4.1.3). Following blades in the hover can experience

* Mast mounted sights could significantly increase that probability.

a continuing current of duration $1/Nn$ seconds, the majority of which will occur to the trailing edge of the tip. Also subsequent return stroke attachments* could occur to any part of the chord tip area although such an attachment is more likely to occur to the leading or trailing edge or the extreme tip.

(b) Forward flight - As in the hover a leader attachment can occur to a blade tip. On a blade pointing forwards, due to the forward velocity of the aircraft, there will be a Zone 1C extension from the Zone 1A area along the span of the blade towards to hub. The maximum length of that extension will be approximately $5.7 v \times 10^{-3}$ m (see section 4.1.3). It has been noted that above that in the hover there will be a Zone 1C extension towards the back of the blade. Obviously that extension will also occur in forward flight and at the tip may predominate over the spanwise extension just mentioned. In any case the movement of the leader attachment relative to the blade will be the vector sum resulting from the forward and rotational velocity, thus giving a maximum spanwise extension somewhat less than $5.7 v \times 10^{-3}$ m. Although it may be possible to take advantage of this by application to the MOD(PE) Aircraft Project Director, generally a worst case should be considered by assuming a spanwise extension equal to $5.7 v \times 10^{-3}$ m. An initial return stroke attachment can still occur to the tip of a blade and re-attachments can occur anywhere along the span of following blades. The pattern of those re-attachments will depend on whether the blade considered is advancing or retreating relative to the forward motion of the aircraft and whether or not it is in front or behind the hub centre at the time of the attachment. WHL have pointed out, in discussion with RAE, that when the blade initially struck is to the rear of the hub, attachments to advancing blades will tend to sweep from tip to tip, with the likelihood of an early re-attachment to the tail structure. When the first blade to be struck is forward of the hub the attachment patterns will tend to spiral inwards towards the hub and then out again towards the tips. This is taken to the limit when a blade pointing directly forward is struck, so that attachments to the following blades are at points successively inboard along the blade span

* Such an attachment is simulated by 'Component D'.

until the arc passes across the hub and then re-attaches successively outboard until it reached a blade tip. Then, if the duration is sufficiently long, the arc re-attaches to the tail structure. Equivalent Component C durations under these conditions will not exceed $1/Nn$.

Attachments to retreating blades forward of the hub tend to be swept along the blade towards the hub, giving hang on times greater than $1/N$ and re-attachments markedly inboard from the blade tip. The worst case of that is when the re-attachment occurs at a blade radius such that the tangential velocity of the blade at that point approximately equals the forward speed of the aircraft, so that the movement of the blade relative to the (stationary) arc channel is very slow. It is probably reasonable to assume a worst hang on time of $1.4/Nn$ to cover this eventuality.

From the above, the worst case parameters for forward flight may be obtained by considering a Zone 1A at the tips extended chord-wise by a Zone 1C to embrace the trailing edge and along the span by a distance equal to $5.7 V \times 10^{-3}$ m. Also a Component D will be applicable anywhere on the blade (and especially to the leading and trailing edges) together with a Component C anywhere on the trailing edge, of duration given by $1.4/Nn$. The hub can experience parameters equivalent to Component D and a proportion of Component C, say $1/Nn$, together with Component A, should it be an initial attachment point. As is noted above, unless otherwise agreed with the MOD(PE) Aircraft Project Director the parameters applicable to the 1C areas shall be the full Component A values.

(c) Sideways and rearwards flight - The aircraft velocity will always be low in these conditions and cases worse than those given above will not occur. Therefore these flight modes can be ignored from the point of view of zoning.

(d) Worst case for hover and forward flight for main rotor - From the above it will be seen that the worst case parameters for the main rotor are those given at the end of section (b), except that the hub area (0.5 m radius from the centre) must be capable of withstanding the full Component C in addition to Components A and D.

(iii) Tail rotor (non enclosed type)

The tail rotor of a helicopter will be revolving much faster than the main rotor and therefore when it is struck there will be more interactions with the lightning channel to each blade than occur to the main rotor. Initial attachments will obviously occur to the tips of the blades giving a Zone 1A area extending 0.5 m from the tip but due to the relatively small dimensions of tail rotors and the geometry of aircraft in that area, swept leader effects are likely to occur less frequently and be less significant than on the main rotor. When the effect occurs however, as with a main rotor, there will be a spanwise Zone 1A extension from the 1A area given by the vector sum of the rotational motion and the forward motion of the aircraft.

The maximum possible dwell time of the lightning arc on each blade will be $1/(N_t n_t)$ s (where n_t is the number of blades on the rotor and N_t is the rotor speed [RPS]). This means that any blade of a four bladed rotor revolving at 16 RPS can experience an initial attachment followed by approximately 62.5 ms duration of continuing current. Movement of the aircraft can easily sweep any of those attachments down to the hub or the tail structure.

The outcome of the above is that a tail rotor must be designed to withstand Component A parameters to the tip of a blade, $250/N_t$ ms of Component C to anywhere along the trailing edge of a blade, a Component D to anywhere on the rotor disc including the hub and say 150 ms worth of Component C to the hub.

Unless the hub protrudes significantly it is unlikely to be an initial attachment point. When that is so, however, Zone 1B parameters shall be ascribed to it. Also the possibility, discussed above, of a Zone 1C extension from the 1A area at the blade tips shall be taken into account when the construction of the blade in the 1C area is different from that in the 1A area.

(iv) Main body of aircraft

All parts of the aircraft apart from the main and tail rotor discs may be zoned for all flight modes, by considering the usual zoning definitions. Essentially, that means that hover and forward flight must be considered. Due to the hover mode all initial attachment points on the underside of the aircraft must be considered as Zone 1B areas which may have Zone 1C and 2A areas behind them due to forward flight. Zone 1A areas are unlikely to occur anywhere on the aircraft other than at the tip of the tail stabiliser where initial attachments would quickly sweep to the trailing edge of the stabiliser. The rear of the tail structure would be classified as a Zone 1B area from both hover and forward flight considerations.

Therefore, in effect, the majority of the attachment points on the aircraft, other than to the rotor discs, will be classified as Zone 1B. It should be noted however that there could easily be flash over from the main rotor blade cuff area to structure adjacent to the hub and Zone 1A parameters should be ascribed to such regions.

(v) Zoning diagram

A zoning diagram should always be prepared as part of the Lightning Hazard Design Analysis. Areas on the main airframe may be appropriately designated using the conventional zoning definitions discussed in the last section but the main and tail rotor discs should not be described. Instead, the appropriate components of the composite test waveform (see Appendix 9, Fig 9.1) shall be noted.

When the lightning arc has more than one interaction with a rotor blade the Component C duration designated shall be applied during test as a continuous discharge.

4.2 The significance of lightning interaction

There are three possible relationships between a lightning flash and the aircraft with which it interacts, as follows:

Direct strike. Here the lightning channel attaches to the aircraft, which therefore forms part of the channel and is subjected to the whole lightning current.

Nearby flash. Here the lightning channel passes near the aircraft but does not contact it, so that the lightning current does not flow in the aircraft. However, the aircraft is near enough to the discharge for the electric and magnetic fields to induce voltages and currents on the aircraft surface, some proportion of which may penetrate to the interior depending on the electromagnetic shielding properties of the outer surface.

Distant or 'far field' flash. In this case the aircraft experiences only the 'far field' electromagnetic radiation from the flash, characterised by a constant ratio between the electric and magnetic components of the field and having an intensity approximately inversely proportional to the distance. The radiation may cover a wide frequency spectrum. This document does not include protective measures or tests specifically for distant flashes since it is considered that these will be covered if direct strikes and nearby flashes are adequately covered.

Lightning produces a variety of effects on an aircraft and for convenience in formulating protection and test methods it is usual to divide these into three Groups, as follows:

Group 1 or direct effects. These are the effects arising directly from the passage of lightning current and are therefore present only in direct strikes. Examples are burning effects at an attachment point which could puncture the skin or create a hot spot on the inside surface that would be hazardous in say a 'wet wing'; heating in other parts where the lightning current density is high; sparking; and magnetic forces.

Group 2 or indirect effects. These occur in parts of the aircraft not carrying the lightning current and are due to coupling with the magnetic field (inductive coupling) or the electric field (capacitative coupling) of the lightning current flowing in other parts of the aircraft or in the lightning channel itself. These effects can therefore arise as a result of either a direct strike or a nearby flash. For example, voltages and currents may be induced in aircraft wiring which could cause malfunction of equipment or even permanent damage. The induced voltages and currents may contain components related to the shape of the lightning current waveform and also damped high frequency oscillations related to the natural electric resonances of the aircraft and its systems which are shock-excited by the sudden arrival of the lightning pulse.

Group 3 or far-field effects. These are the effects of exposure to the radiated electromagnetic field of a comparatively distant lightning flash. The mechanism of coupling, in which the aircraft acts like a receiving aerial, is the same as for the electromagnetic pulse (EMP) produced by a nuclear explosion⁷ but the intensity is less and falls off more rapidly towards the higher frequency end of the spectrum.

A more detailed account of lightning effects and the various damage mechanisms is given in sections 6 and 7 of this Appendix.

Protection of modern aircraft against the effects of lightning is more important than in the past because of several design and operational trends which tend to make aircraft more vulnerable, namely:

(a) The increased reliance on electronic equipment to perform functions which are critical to flight safety, such as full-authority digital flight and engine controls, so that malfunction due to induced voltages can have disastrous consequences. The susceptibility of modern electronic equipment is increased by the low voltage and power levels employed, although to some

extent this is offset by the fact that the small size of components permits the incorporation of fault-tolerant logic (multiplexing etc) and other protective measures.

(b) The use of non-metallic materials such as glass fibre and carbon fibre composite (CFC) in aircraft construction. These reduce the electromagnetic shielding afforded by the skin, thus tending to increase internal induced voltages. Moreover, because CFC has a much higher resistivity than aluminium alloy it produces much higher voltage gradients and heat generation for a given lightning current. The relevant properties of new materials are discussed in more detail in section 6 of this Appendix.

(c) Aircraft, particularly helicopters, are able to fly in worse weather than previously, because of improved instrument fits, and thus their exposure to lightning is increasing.

5 CURRENT WAVEFORMS AND PARAMETERS FOR DESIGN AND TEST PURPOSES

For the design and testing of lightning protective measures it is necessary to define the threat level in the form of standard simplified current waveforms having the relevant parameters set at a chosen degree of severity. It is considered that the four-component waveform shown in Appendix 9, where the parameters are also listed, will produce effects equivalent to those produced by severe natural lightning. It is based mainly on a negative flash having parameters at the 2% severity level, but with enhanced action integral in order to recognise the occurrence of positive flashes. The four components represent an initial stroke, intermediate current, continuing current, and a restrike. Such a waveform is adequate for Group 1 effects, but for Group 2 effects, which depend largely on the rate of change of current, Component D is specified to have a peak rate of rise of 100 kA/ μ s in addition to the other parameters listed; when employed by itself purely for Group 2 tests it may be designated Component E and the rate of rise defined more exactly, as in Appendix 9.

It is not necessary to employ the whole composite waveform in a test; combinations of the components may be selected according to the Zone in which the test object is situated and the particular damage mechanism being investigated. It is however important for the components employed in a composite waveform to be placed in their correct order in time. Details of the waveforms to be employed in particular cases are given in the Appendices specifying test requirements.

The composite waveform arose out of proposals in USA⁸ and UK⁹; it has been incorporated in the US MIL-STD-1757A¹⁰ for lightning test techniques (with minor

differences in Component E) and the draft NATO STANAG 4327¹¹ for lightning test methods to determine the safety of explosives, electro-explosive devices and associated electronic systems in munitions and weapon systems.

The composite waveform defines the lightning current threat, that is, aircraft are to be designed to withstand the effects of a lightning current of that waveform. The waveforms of induced voltages and currents in parts of the aircraft, such as internal wiring, will however not be copies of the lightning current waveform but will have some components related to that waveform (for example, a component proportional to the rate of change of the lightning current) and others unrelated in shape, being determined by natural electrical resonances of the aircraft and its systems. For the purpose of designing and testing avionic equipment therefore it is necessary to define a second set of standard waveforms based on the probable waveforms and parameters of induced voltages and currents in aircraft wiring. It is necessary to do this because equipment has to be developed simultaneously with the aircraft itself and it is impossible to wait until the aircraft has been constructed and its induced voltages measured before designing the equipment. This subject is not however covered by the present document (except in its procedural aspects, in Part B) but is dealt with in RAE Technical Memorandum FS(F) 457¹². US recommendations on the subject are given in Refs 13 and 14.

6 MECHANISMS OF LIGHTNING EFFECTS: GROUP 1 EFFECTS

6.1 Ohmic Heating

(a) Ohmic heating in all-metal structures

The heat generated in a conductor due to an electrical current is i^2R and the total heat generated by a lightning pulse is $R \int i^2 dt$ ie the total ohmic resistance of the circuit multiplied by the action integral of the pulse. In a lightning discharge the high action integral phases of the lightning flash are too short a duration for any heat generated in an aircraft structure by ohmic heating to disperse significantly. The net heating effect of a lightning discharge to an aircraft is a function of the action integral and the ohmic resistance of the path taken by the lightning currents through the aircraft.

(b) Ohmic heating in carbon fibre structures

The bulk ohmic resistivity of carbon fibre composites will vary with the type of material used, the lay-up, and other factors of manufacture. It will however be between two and three orders of magnitude greater than that of

aluminium alloy. Ohmic heating is therefore a very much more significant factor than it is in an all-metal aircraft.

All CFC components in Zones 1a, 1b and 2b should be critically examined for possible ohmic heating failure mechanisms. In Zones 2a the high concentration of current in the arc root area means that ohmic heating can add significantly to the arc root damage even during the continuing current phase. This is not the case with metal skins.

(c) Exploding conductors (disruptive forces)

Where conductors having a very small cross sectional area are required to carry a substantial part of the lightning current they will fuse explosively. If these conductors are in a confined space this can give rise to major structural damage. Examples of typical danger zones are:

(i) Electric wiring connected to external equipment eg navigation lights, aeri-als, pitot heaters etc. If these are not adequately protected and are confined in or pass through closed compartments in the aircraft, they can present a significant hazard.

(ii) Voids in glue lines; metal honeycomb construction.

6.2 Arc root damage

(a) Metal Burn Through

Metal burn through is a complex function of current and time. It is unlike ohmic heating in that most of the energy is generated at the surface of the metal and not inside the metal itself, and must therefore be dissipated by conduction. The heat energy generated in the arc root is in excess of that which can be absorbed into the metal by conduction, and the excess is used in melting and vapourising the metal in the immediate arc root area, or reradiated.

During the high action integral phases of the lightning strike the current also has a very high di/dt , and tends therefore to flow only on the surface, and so the energy due to ohmic heating is generated there. During the continuing current phase although the di/dt is low, the action integral is also low so ohmic heating is of less significance, and the dominant energy input is due to the arc root voltage drop and is again at the surface in the arc root. The situation therefore is that the total arc root energy keeps the surface molten in the arc root, and usually at or near to the vapourising temperature. The arc root area increases as a function of $t^{0.5}$. Energy is transmitted through the metal from the constantly increasing area of constant temperature by normal conduction. The process is further slowed by the need to supply the energy of

latent heat to the metal for the phase changes that take place at the progressing molten front. There is a minimum current below which burn through cannot occur, and although increasing the current above this level continues for a time to decrease the time to burn through, a level of current will be reached above which there will be no significant decrease in time to burn through. Thus there is a minimum time for any given thickness of any given material below which burn through cannot occur. It is only the continuing current phase of the lightning flash that can satisfy the minimum requirements of both current and duration for metal burn through of any practical thickness of metal aircraft skin.

(b) Arc root damage in CFC

With a resistivity between two and three orders of magnitude greater than that of most metal skins, there is a predictable change in the behaviour of CFC in the arc root. The increased resistivity greatly increases the skin depth even during the high di/dt phases of the stroke, and the ohmic heating effect is not only considerably greater but is also much deeper seated. The CFC composite is anisotropic in its electrical and thermal conductivity, and in its co-efficient of expansion. Arc root damage is usually manifest in two ways:

- (i) There is 'fluffing' of the individual fibres, due to the vapourisation of the bonding material. (Plus of course some loss by vapourisation or oxidation of some of the fibres themselves.)
- (ii) There is some delamination of the composite due to interlaminar stresses from differential expansion between one lamina and the next.

Both action integral and arc duration can each in their separate way lead to failure of the material.

(c) Hot spot formation

Hot spot formation usually occurs on the inner surface of an aircraft skin immediately under an arc root. This may be a fuel ignition hazard for 'wet skin' fuel tanks using high melting point alloys. Fuel ignition is not merely dependent upon the temperature reached, but is also influenced to some degree by the length of time that the temperature is maintained. On high melting point alloys high temperature can be reached on the inner surface of a 'wet skin' at arc currents and durations that would not give rise to metal burn through. These hot spots will persist until the heat has been conducted away. This could be a long time in relation with fuel ignition criteria (viz a time of the order of milliseconds).

6.3 Acoustic shock wave

At the commencement of the first return stroke, there is a rapid pinching of the arc channel due to the increase in the magnetic field surrounding the channel. This produces a radial acoustic shock wave. At the same time the rapid heating of the arc channel itself produces an axial shock wave. The later is probably the most significant in its reaction with the aircraft. The severity of the shock is dependent upon both the peak current value and the rate of rise of the current.

In general the damage due to acoustic shock wave is insignificant on metal skins, but the less malleable CFC skins can rupture, although again only very thin CFC skins appear to be vulnerable. In some rather rare cases it can cause 'flame out' on jet engines.

6.4 Magnetic forces

(a) Magnetic pressure

This force is only significant when the surface current density is in the region of several kilo amperes per millimetre. For example a conductor of 5 mm diameter carrying a pulse of 200 kA peak current would experience a surface pressure of 1000 atmospheres. The pressure is proportional to I^2 and to the inverse square of the diameter. Thus doubling of the diameter or halving the current would reduce the pressure to 250 atmospheres.

High current densities also occur in the arc root. An arc of 200 kA peak current with a fast rise time will have a magnetic pressure of about $0.63 \times 10^9 \text{ N/m}^2$ (ie about 50,000 psi).

In some cases however even relatively small pressures can be significant, such as the case of metal braid bonding strips. These can pinch to near solid conductors leading to metal embrittlement and subsequent mechanical failure.

(b) Magnetic interaction

Considerable magnetic forces can exist from the interaction of the magnetic fields of two current carrying conductors or from two separate sections of the same conductor where the lightning current is forced to change direction. This force can also exist between current in the aircraft and the arc channel. This force is usually only of great significance where the lightning current is confined to small section conductors eg in the radome area. The instantaneous value of the force is proportional to i^2 , but the ultimate effect on the airframe is a complex function of I^2 ; rise time; decay time; action integral; and the mechanical response of the airframe.

6.5 Group 1 effects sparking

Group 1 effects sparking occurs when very high currents are forced to cross a joint between two conducting materials. Sparking normally occurs at points where there is imperfect mating between the two surfaces. Thermal sparking occurs near the edges of high spots on the mating surfaces where the interface pressure is at or close to zero. The primary causes are high current density and poor interface pressure. Thermal sparks generally have a high energy content, and a longer duration than voltage sparks, and are therefore more significant than voltage sparks for fuel ignition hazards inspite of their lower temperature.

6.6 Fuel ignition

Fuel ignition can arise from many causes. These include thermal sparking, hot spot formation, metal burn through or puncture of the tank by lightning currents, Group 2 effects, and ignition by lightning at the fuel vents.

6.7 Dielectric puncture

The process by which conductors become the site of lightning attachment applies also to conductors behind dielectric surfaces such as radomes and antenna covers. The only difference is that the dielectric intervenes between the conductor and the exterior. This does not necessarily prevent the attachment as the dielectric may be punctured or even shattered in the process unless there is a preferred alternative path. It is sometimes possible to protect against puncture by fitting external conducting strips over the dielectric, carefully spaced to preferentially 'attract' the strike; there is obviously a limit to this solution since excessive metal will prevent the radar, antenna etc efficiently performing its function. Again, CFC behaves as a metal rather than a dielectric in relation to high voltage puncture effects.

7 MECHANISMS OF LIGHTNING EFFECTS; GROUP 2 EFFECTS

7.1 Effects on equipment of induced voltages in wiring

Essentially a lightning current pulse flowing through an aircraft, or in a nearby flash, injects a voltage into the wiring and the consequent current that flows depends on the impedance of the circuit. The induced voltage waveforms are often very complex but usually consist of one or more of the following three components:

- (a) A voltage proportional to the lightning current, due to resistive coupling (for example, the voltage gradient on the inner surface of the aircraft skin) or to inductive coupling where the magnetic flux has diffused through a high resistivity skin (such as CFC) and in doing so has

effectively undergone an integrating process. The peak voltage will then be proportional to the peak lightning current.

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

(c) High frequency damped sinusoidal oscillations usually in the range 2 to 50 MHz. These are shock-excited oscillations corresponding to natural resonances (possibly including harmonics) of the aircraft and its electrical systems, and their frequencies and damping (although not their amplitudes) are independent of the shape of the lightning pulse.

The transient induced voltages may affect equipment in various ways. For example, they may cause transient errors with return to normal operation after a short recovery period, or more seriously a malfunction which does not correct itself during a flight but the system may be returned to normal operation by resetting, or by reloading the software for digital systems. In the extreme cases they may cause permanent damage through the breakdown of electronic components. One possible effect, which can be a considerable nuisance, is the spurious operation of warning indicators, such as fire warning lights. Recommendations for installing electrical wiring and equipment in aircraft to minimise induced voltages are given in Ref 15.

7.2 Group 2 sparking and dielectric breakdown

Induced voltages may cause breakdown of insulation in wiring and at connectors, or by breakdown of the air may produce sparking, which would constitute a hazard in a fuel tank or at a fuel vent or near explosive devices.

8 THE FREQUENCY OF LIGHTNING STRIKES TO AIRCRAFT

The frequency with which aircraft are struck depends among other factors on the amount of lightning activity in the area, and this depends on geographical location (including the latitude and the nature of the local terrain) and the season of the year. It has been noted however that a significant proportion of strikes happen when the aircraft is not near an active thunderstorm; some of these may be triggered strikes where the electrical conditions are not quite sufficient to initiate natural lightning but the additional field concentration due to the conducting body is enough to tip the balance.

For given local electrical conditions the probability of an aircraft being struck depends mainly on its altitude and perhaps also on its size and shape. Statistics on strikes to both civil and military aircraft are collected. The figure commonly accepted as average for world-wide operation of civil aircraft is one strike per 4500 flying hours, the figure for Europe being one per 2100 h. The higher incidence of strikes in Europe may be due to shorter flights, with the consequent longer proportion of time spent at the more risky altitudes (many strikes occur at or near the 0°C isotherm, corresponding to 10000 to 15000 ft). As a very rough guide a civil airliner may expect to be struck once every year.

For military aircraft, RAF figures vary from one strike per 2500 h to one per 9000 h, depending on aircraft type and operational role. A fuller account, including an analysis of the types of damage experienced, is given in Ref 1. Statistics for rotorcraft will be published in due course.

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Acknowledgments

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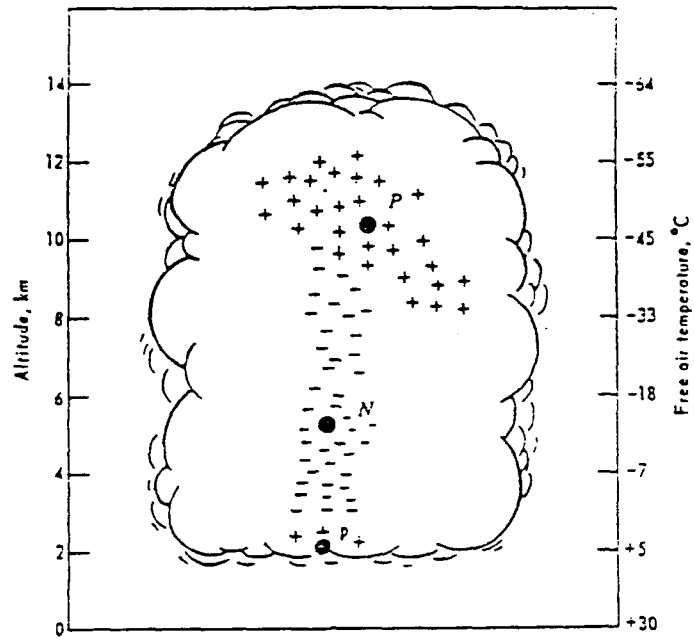


Fig A2-1 Probable distribution of the thunder cloud charges, P, N and p, for a South African thunder cloud according to Malan

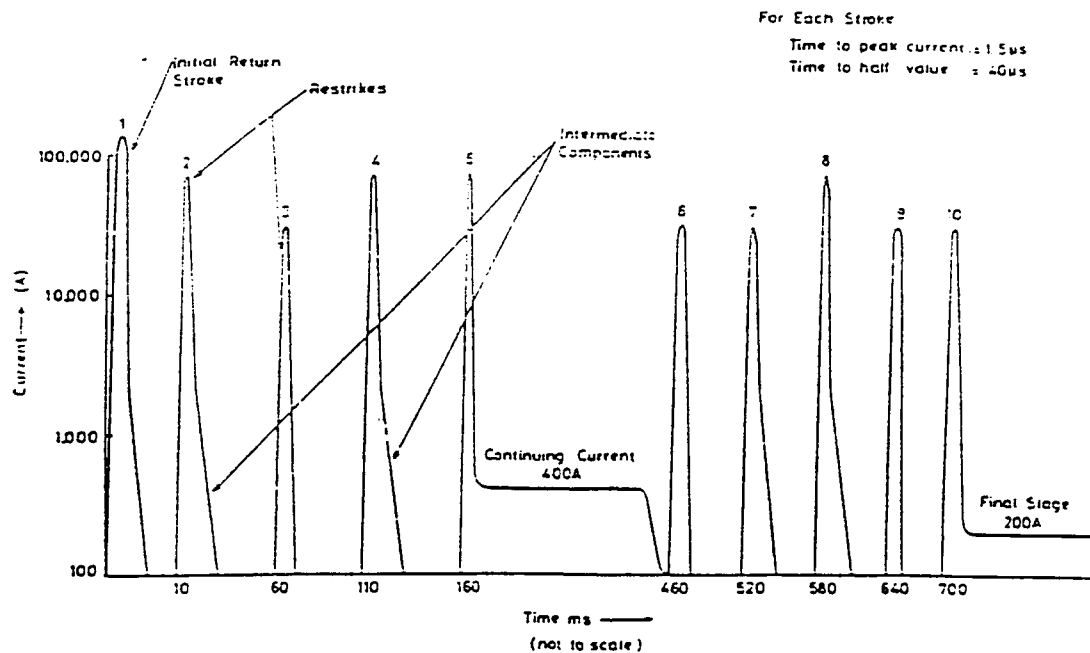


Fig A2-2a Severe Negative lightning flash current waveform

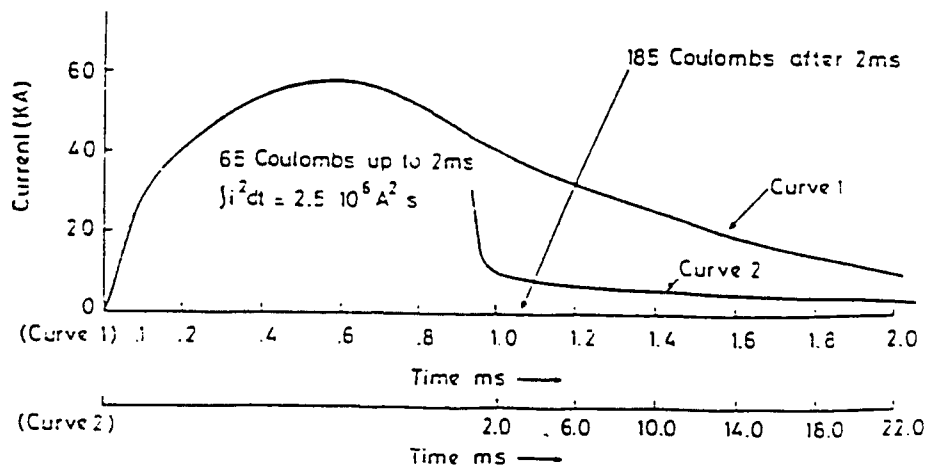


Fig A2-2b Severe Positive lightning flash current waveform

Appendix 3

REQUIREMENTS FOR THE ASSESSMENT OF THE CAPABILITY OF AIRCRAFT TO WITHSTAND LIGHTNING EFFECTS

1 INTRODUCTION

This appendix gives the requirements for the assessment of the capability of aircraft to withstand lightning effects. The assessment shall be made by means of a Lightning Hazard Design Analysis (LHDA) which shall be part of a Lightning Protection Plan (LPP) as described below.

2 AIM OF LIGHTNING PROTECTION PLAN

The purpose of the LPP is to ensure that the lightning hardness of aircraft is adequately addressed and demonstrated.

3 SCOPE OF LIGHTNING PROTECTION DOCUMENT

At the start of a project a LPP shall be prepared and presented to the Project Director. It shall be reviewed and amended as necessary during the life of the project. The LPP shall provide:

- (i) A statement defining the applicability of lightning zoning.
- (ii) A statement defining the lightning design aim/test parameters appropriate to the different parts of the aircraft according to the lightning zones ascribed to it, taking due note of the design aim parameters given in sections C1 and C2.
- (iii) A Lightning Hazard Design Analysis (LHDA).
- (iv) A statement defining the general environmental conditions (climatic, mechanical and electrical) in which any lightning protection devices must be capable of operation.
- (v) The relevant Test Plans (TP), if testing is required.
- (vi) The relevant Test Schedules if Test Plans are prepared.
- (vii) Reports of all tests made with analysis, conclusions and recommendations.

NOTE 1: Guidance regarding the interpretation of zoning rules will be found in section A5 and Appendix 2.

4 SCOPE OF LIGHTNING HAZARD DESIGN ANALYSIS

A Lightning Hazard Design Analysis (LHDA) shall be made and agreed with the MOD(PE) Aircraft Project Director early in the development of a project. It

shall be a continuing process with revisions agreed by the MOD(PE) Aircraft Project Director as they become necessary.

The LHDA shall:

- (i) Outline the general construction of the aircraft, drawing attention to the use of insulating and partially conductive composite materials.
- (ii) Survey the structure and note areas where specific lightning protection is required, making special reference to the protection of those areas made of insulating or partially conductive composite material.
- (iii) Detail wiring runs in relation to 'flux windows' and (in the case of a store) the pylon interfaces, with details of the measures taken to protect Flight Safety Critical wiring (such as enclosure in a conducting conduit).
- (iv) Identify wiring where large common mode voltages could be developed to airframe (for example, pitot heater wiring) and identify insulation which could be at special risk to voltage flash over, detailing measures taken to protect such wiring and prevent such flash over.
- (v) In the case of a store, define the lightning current paths to the pylon.
- (vi) Include a lightning transient assessment which shall:
 - (a) Provide the evaluation detailed in section 5 of this Appendix.
 - (b) Determine the scope of additional Group 2 testing not covered by section 5 below, on parts of aircraft to verify that insulation is not at risk from common-mode flash-over voltages.
- (vii) Include a fuel and explosive vapour hazard assessment which shall:
 - (a) Provide an evaluation of the fuel system as detailed in section 6.
 - (b) Provide a similar evaluation as appropriate for 'dry bays' into which fuel or hydraulic fluid (or other hazardous liquid) may leak.

- (viii) Detail the actions taken to prevent exploding arcs occurring inside dielectric enclosures such as radomes.
- (ix) Draw attention to any specific lightning risks not covered by the above and the actions taken to overcome them, especially noting measures taken to prevent insidious lightning risks that could affect flight safety.
- (x) Provide a criticality list of systems and equipment that might be affected by lightning under headings of Flight and Mission Critical.
- (xi) Determine what testing is necessary (additional to that required in (vi) and (vii) above and justify the reasons why all testing is or is not proposed.

NOTE 2: The additional Group 2 testing referred to in section ((vi)(b)) above can often be combined with the testing required by section 5 below. Guidance concerning this is given in Appendix 11.

5 EVALUATION OF SHOCK EXCITATION AND GROUND VOLTAGE TRANSIENT PROTECTION

An evaluation of shock excitation and ground voltage transient protection shall be made as follows:

(i) A survey shall be made of the installation (or likely installation in the case of new projects) of Flight and Mission Critical Electrical and Avionic Systems and Equipment, in conjunction with the initial analysis of (iii) below, to decide likely Aircraft Transient Levels (ATLs) at all the relevant equipments and cables. Unless otherwise agreed with the MOD(PE) Aircraft Project Director a safety margin of at least 12 dB shall be applied to those levels and Equipment Transient Test Levels (ETTLs) decided. In the case of a new installation, if it is too early in the project to decide test levels, the maximum levels of the latest issue of RAE Technical Memorandum FS(F) 457 shall be used.

(ii) During equipment procurement, equipment tests shall be made in accordance with the latest issue of RAE Technical Memorandum FS(F) 457, using the test levels determined in (i) above. Before such testing is made, due note shall be taken of previous tests made on any 'common user' equipment and the need for retesting decided. Any susceptibility shown by previous EMC testing shall also be taken into account.

(iii) A continuing analysis shall be made as the project develops, using methods acceptable to the MOD(PE) Aircraft Project Director, to predict the

aircraft transient levels (both damped sinewave and ground voltage) at all the equipments and cable bundles defined in the survey of (i).

(iv) 'Whole aircraft tests' shall be made according to Appendix 6 to validate the analysis of (iii) above as follows:

(a) Low level swept CW injection tests, which shall provide -

(1) Frequency domain transfer functions in terms of induced cable bundle current versus current injected into the airframe for each cable bundle and measurement point defined in the test plan.

(2) Using the frequency domain transfer functions time domain responses to a double exponential full threat lightning excitation pulse, for each cable and measurement point defined in the Test Plan, for comparison with the predictions of (iii) and the extrapolated full threat responses obtained in the pulse tests required by the following.

(b) Pulse tests in accordance with section 7 of Appendix 6 to provide by extrapolation full threat responses for each cable and measurement point defined in the Test Plan, for comparison with the responses obtained in section ((iv) (a) (2)) above and predicted in (iii) above. Full threat parameters for dE/dt , di/dt and I_{pk} shall be taken as $10^{13} \text{ V m}^{-1} \text{ s}^{-1}$, 10^{11} A/s and 200 kA respectively.

(v) When of necessity the whole aircraft tests of section (iv) above are made (by agreement with the MOD(PE) Aircraft Project Director) on a non-production aircraft, the CW tests of ((iv) (a) (2)) shall be repeated on a production aircraft, unless otherwise agreed with the MOD(PE) Aircraft Project Director.

(vi) An assessment shall be made of the results of (iii), (iv) and (v) above to confirm that there is linearity in the pulse measurements and reasonable agreement between the latter extrapolated to full threat (see Note 3) and the full threat responses calculated from the CW measurements; and further reasonable agreement between the analytical predictions and both the pulse and CW measurements; in order to:

(a) confirm or correct the aircraft transient level at the equipments of interest,

(b) substantiate the cable resonances used for equipment tests,

(c) confirm that the safety margin between an aircraft transient level and the relevant equipment transient test level used for the equipment tests of (ii) is greater than 12 dB.

(vii) If the safety margin between the equipment transient test levels and the aircraft transient levels and the aircraft transient levels determined in (vi) above should be unacceptable, the relevant equipment shall be retested to the higher levels necessary.

NOTE 3: When calculating full threat responses any $\lambda/4$ resonances shall be taken out and $\lambda/2$ resonances put in assuming a reflection co-efficient of unity (open circuit termination).

Guidance concerning whole aircraft testing is given in Appendix 11.

6 EVALUATION OF FUEL AND EXPLOSIVE VAPOUR HAZARDS

An evaluation of fuel and explosive vapour hazards shall be made as given below. Figures in brackets indicate the relevant requirements in section D1 of Part D of the Memorandum.

(i) A survey shall be made of the fuel system and the following identified:-

- (a) The construction of integral and any external tanks, including a CFC structure the type and location of bolted joints and the location, relative to possible current flow, of any co-cured bonded joints.
- (b) The position of tanks, vents and dump masts relative to lightning strike zones.
- (c) The type and thickness of skins enclosing fuel or fuel vapour.
- (d) The construction of flight refuelling probes.
- (e) The type, location and method of installation of fuel and air pipes, within and external to fuel tanks.
- (f) The location and method of installation of fuel wiring and wiring conduits, within and external to fuel tanks.
- (g) The type and location of fuel sensors.
- (h) The type and location of access doors and covers.
- (i) The type and location of filler caps.

- (j) The size of any conductors which could carry lightning current and which are in contact with fuel.
- (k) The location of all possible sites of thermal and voltage sparking.
- (ii) Identify the measures taken to eliminate unacceptable hot spot temperatures (see section D1.2).
- (iii) Identify the need for, and location of, any solid aluminium structure skin less than 2 mm thick and below which fuel or fuel vapour is present and identify the protection measures used. Determine the minimum thickness allowable for titanium skins. Establish that CFC skins are thicker than 5 mm (section D1.5), or are otherwise protected.
- (iv) Identify the protection methods used for thin solid or sandwich panel skins (D1.6).
- (v) Identify the measures taken to prevent the passage of lightning current inside a fuel system structure or through a fuel system component. Where such current flow cannot reasonably be eliminated, identify the measures taken to prevent a hazard (section D1.3).
- (vi) Identify the measures taken to prevent sparking at joints and fasteners (section D1.7(i)).
- (vii) Establish that current flow cannot occur across co-cured bonded joints (D1.7(ii)).
- (viii) Identify the measures taken to prevent current flow in fuel and air pipes, or alternatively in aluminium structures the bonding used to limit current flow through couplings (section D1.8). In a CFC structure detail the isolation and bonding needed to meet the requirements of section D1.8.
- (ix) Establish that the fuel system wiring is installed according to the requirements of section D1.9 and determine, by analysis and/or test, the value of possible flash-over voltages.
- (x) Establish that fuel system electrical components meet the requirements of section D1.10 and can withstand the voltages determined in (ix) above. Also establish that sparking and flash-over cannot occur in any part of the fuel system wiring in contact with fuel or fuel vapour.
- (xi) Establish the need for flame suppression devices in accordance with the requirements of section D1.11 and determine the scope of testing needed to verify the correct operation of such devices when fitted.

(xii) Establish that fuel filler caps and flight refuelling probes are so designed that they meet the requirements of sections D1.12 and D1.13 respectively.

(xiii) Establish that any external tanks meet the requirements of section D1.14.

(xiv) Determine the testing that is necessary to verify compliance with the above:

(a) on panels, components, and sections of assemblies and structure (additionally to that required in sections (ix) and (xi) above), and

(b) on complete major assemblies, such as fuel tanks and 'wet wings'.

NOTE 4:

From the point of view of sparking, clearance is based on the elimination of all sparking down to an equivalent level of 0.04 mJ.

NOTE 5:

Tests shall be made when it cannot be otherwise demonstrated, by comparison with previously certified safe systems or by analysis, that all sparking, arcing, arc penetration and hotspots have been eliminated. Spark detection methods must be sensitive down to 0.04 mJ (see Appendix 12, section 3.3).

When there is any doubt that sparking tests on panels or sections will be unrepresentative of full scale conditions regarding current density and distribution, and induced voltage levels (and hence the number and position of sites of possible sparking), tests on major assemblies shall be made. Also if there is any doubt that sparking tests (see Appendix 7, Test 7-1) will not not reveal the presence of all the sparking, or that there may be small hot spots not evaluated by Test 4-2 of Appendix 4, flammable gas tests shall be made (see Appendix 7, Test 7-2). Flammable gas tests will not normally be necessary other than on major assemblies, except that titanium skin panel samples shall be so tested.

NOTE 6:

When it is impossible to establish by measurement of induced voltage levels and analysis, or comparison with previously certified safe systems, that sparking and flashover in fuel system wiring will not occur, a test shall be designed to establish that such a hazard is not present.

Unless otherwise agreed with the MOD(PE) Aircraft Project Director the test shall be made on a major assembly and may be either a sparking test (Test 7-1) or a flammable gas test (Test 7-2). When such tests are made care should be taken to simulate the full threat induced voltage values.

7 TEST PLAN

When tests are proposed by the LHDA a Test Plan shall be prepared. The TP shall:

- (i) Detail the tests that are required.
- (ii) Define the objectives for each test.
- (iii) Outline the test methods, which shall include the lightning attachment points, the return conductor system and the lightning test waveforms to be used.
- (iv) Define the number of samples to be tested and the number of shots to be applied to each sample.
- (v) Detail the equipment to be used and the measurements to be made to:
 - (a) Provide evidence that the lightning test waveform is in accordance with E2 and Appendix 11.
 - (b) Record the effects of the lightning simulation.
 - (c) Observe the correct functioning and safety of the installation being tested.

NOTE 7:

When deciding the number of samples to be tested and the number of shots per sample, it should be remembered that the repeated passage of high current across joints reduces the tendency for that joint to spark. If several shots are made on one sample this should be borne in mind. For tests which involve both conduction and attachment shots the conduction should be carried out first.

8 TEST SCHEDULE

A Test Schedule shall be prepared from the Test Plan by the Test House. The Test Schedule shall decide the order in which the tests shall be done and which (if any) shall be combined. The Test Schedule shall be appended to the Test Plan and may be amended as the test proceed.

9 PRESENTATION OF DOCUMENTATION AND RECOMMENDATIONS FOR APPROVAL

The LPP, LHDA, the TP and Test Schedules shall be presented to the MOD(PE) Aircraft Project Director for approval at initial preparation and when significant changes are made. A final submission of the full LPP shall be presented to the MOD(PE) Aircraft Project Director when final approval of the lightning protection is requested.

Appendix 4
GROUP 1 TEST METHODS

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
1	Metal Burn Through	i The general requirements of Paragraph E3 of this document shall apply. ii The test object shall be connected to the lightning current generator by an open arc to the point of test and the test current shall return to the generator via a return conductor configuration which shall be designed to assist in stabilising the arc channel and to produce the correct current distribution for a distance of not less than 400 millimetres from the centre of the arc root. iii The test electrode shall be of the 'jet diverting type' (see Appendix 10). The arc shall be not less than 50 mm long and may be initiated by a fine wire, not exceeding 0.1 mm diameter. The wire may be either metallic (eg copper) or carbon fibre. iv The test arrangement shall be referred to earth potential at one point only v A permanent record shall be made of the arc voltage and the arc current on a common calibrated time base, so that the relationship of voltage and current with respect to time can be determined. vi The moment of penetration shall be detected and recorded on the time base used for voltage and current measurements.	Zone 1B and 2B: Component C immediately followed by component D. Zone 2A: A unipolar pulse of between 400 and 800 A for a duration of 50 ms; immediately followed by component D.

GROUP 1 TEST METHODS (continued)

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
2	Hot Spot Formation	i As for those for test 1 (i)-(v). ii The temperature of the inner surface under the arc root shall be measured by the use of temperature sensitive paints, thermo-couples, thermal imaging cameras, or other forms of temperature measuring systems which can be used without the risk of disturbance by the high electro-magnetic fields created by the test current.	Zone 1B: Component A with duration increased to give an action integral of $2.25 \times 10^6 \text{ A}^2 \text{ s}$, immediately followed by component C. Zone 2A and 2B: As for Test 1.
3	Arc Root Damage Tests for CFC Skins	i As those for test 1 (i)-(v) ii The extent of the damage shall be assessed by methods acceptable to the Project Director.	Zone 1A: Component A. Zone 1B: As for Test 2. Zones 2A and 2B: As for Test 1.

GROUP 1 TEST METHODS (continued)

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
4	Arc Root Damage on Metal Sandwich Panels with honeycomb core	i As for those for test 1 (i)-(v). ii The extent of the damage shall be assessed by methods acceptable to the Project Director.	Zones 1B and 2B: Component C immediately followed by Component D. Zone 2A: As for Test 1.
5	Arc root damage on thin metal Sandwich Panels with ablative layer		All Zones: As for Test 3.
6	Arc root damage on CFC Sandwich Panels with honeycomb core		Zone 1A: Component A. Zone 1B: Component C immediately followed by Component A with duration increased to give an action integral of $2.25 \times 10^6 \text{ A}^2 \text{ s}$. Zone 2A and 2B: As for Test 1.

GROUP 1 TEST METHODS (continued)

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
7	Ohmic Heating Tests	i As for those for Test 1 (i) and (iv). ii Hardwired-connections to the test item shall be used unless tests for arc root problems are also to be investigated, when the test object shall be connected to lightning current generator in accordance with the requirement of 1 (ii). iii When open arc testing is done the return conductor configuration shall also be designed to achieve the correct current distribution in the rest of the test item away from the arc root. The test electrode shall be of the 'jet diverting type'. The arc shall be not less than 50 mm long and may be initiated by a fine wire, as defined in 1 (iii). iv When hard wired connections are used the return conductor configuration shall be designed to produce the correct current distribution in the test object. v A permanent record shall be made of the test currents on a calibrated time base, so that the total action integral of the test current may be determined. The temperature of the test object shall be measured by temperature sensitive paints, thermocouples, thermal imaging cameras, or other forms of measuring temperatures.	Zone 1B and 3: Component A with duration increased to give an action integral of $2.25 \times 10^6 \text{ A}^2 \text{ s}$ Zone 2A and 2B: Component D. Zone 1A: Component A.

GROUP 1 TEST METHODS (continued)

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
8	Magnetic Forces	i As for those of test 1 (i) and (iv). ii The test object shall be connected to the lightning current generator by a hard wire connection to the point of test and the test current shall return to the generator via a return conductor configuration which shall be designed to produce the correct current distribution in the test object. For tests involving magnetic reaction with the arc channel, the arc channel itself shall be represented by a rigid metal conductor. iii A permanent record shall be made of the test current on a calibrated time base, so that both peak current and action integral of the test current can be determined. iv The effects of the magnetic forces on the test object shall be determined by visual inspection or other non-destructive test methods as may be acceptable to the Project Director.	All Zones: As for Test 7.

GROUP 1 TEST METHODS (concluded)

Test No	Title	Test Requirements	Test Waveform (see Appendix 9)
9	Acoustic Shock Wave Tests	i As for those of test 1 (i)-(iv), except that a plain electrode may be used. ii A permanent record shall be made of the test current on a calibrated time base, so that the peak current and action integral can be determined. iii The extent of the damage shall be determined by visual inspection or other non-destructive test methods as may be acceptable to the Project Director.	Zone 1B: Component A with duration increased to give action integral of $2.25 \times 10^6 \text{ A}^2 \text{ s}$ and a rise time to peak of less than 10-5 s. Zone 2B and 2A: Component D with rise time to peak of less than 10-6 s. Zone 1A: Component A with rise time to peak of less than 10-5 s.

Appendix 5**REQUIREMENTS FOR GROUP 2 TESTS ON PARTS OF AIRCRAFT****1 INTRODUCTION**

This Appendix defines the requirements which must be met when Group 2 tests are made on wiring or electrical equipment in parts of aircraft, such as radomes and external probes, or sections of an aircraft, when the 'whole aircraft tests' of Appendix 6 are not appropriate.

2 GENERAL REQUIREMENTS FOR GROUP 2 TESTS

The general requirements of section E3 of this Memorandum shall apply to all the Group 2 tests noted in this Appendix.

3 COMBINATION WITH GROUP 1 TESTS

Group 2 tests may be made at the same time as Group 1 tests provided that all the requirements for both types of test are met and correctly noted in the Test Plan.

4 WAVEFORM

The waveform shall be waveform E defined in Appendix 9, unless Group 1 tests are also being made. In the latter case the waveform shall be that needed for the Group 1 test with a rate of change of current commensurate with the test current component being used, ie for Component A not less than 0.3×10^{11} A/s and for Component D as defined in waveform E.

5 CURRENT PATH

The current shall be applied to the test object through a solid connection, not an arc. The choice of entry and exit locations and the design of the return current conductors shall be such that the current in the test objects flows as nearly as possible in a manner corresponding to that in an actual lightning strike.

6 TEST LEVELS

The tests of section 9 and 10 below shall be conducted at a number of current levels (maintaining the same waveform shape) leading to the full level of waveform E (or components A and D if Group 1 tests are also being made). The measured peak transients shall be plotted against the peak currents to verify that a linear relationship exists.

7 LOAD IMPEDANCES

The wiring forming part of the test object shall be terminated with load impedances simulating over the relevant frequency range those encountered in the actual installation.

8 DATA TO BE RECORDED

For each test shot, calibrated waveforms of the test current and the induced transients shall be recorded in permanent form on a common calibrated time-base so that their relationship in time is known. Consideration shall be given to the possible need to repeat some shots with different recorder time-bases so that records may be obtained of both the whole transient and a suitably expanded initial portion. Repeated shots may also be necessary if the number of recording channels is less than the number of transient monitoring points. When shots are repeated care shall be taken to ensure that all conditions remain the same.

9 INDUCED VOLTAGE MEASUREMENTS

9.1 Common-mode and differential-mode measurements shall be made, according to the requirements of the Test Plan, as noted below.

9.2 The requirements of section 2 to 8 above shall apply.

9.3 Peak induced voltages shall be extrapolated to full threat level as follows:

- (a) Induced voltages dependant on resistive or diffusion-flux coupling shall be extrapolated linearly to a current peak value of 200 kA.
- (b) Induced voltages dependant on aperture-flux coupling shall be extrapolated linearly to a test current rate of change of 10^{11} A/s.

9.4 If a fault such as voltage flashover or sparking is observed, the threshold level of test current at which it occurs shall be recorded, and the measurements repeated at a test current level just below the threshold. The MOD(PE) Aircraft Project Director shall be consulted before proceeding with further tests.

10 VOLTAGE FLASHOVER ASSESSMENT

10.1 When the Test Plan requires voltage flashover assessment tests to be made to satisfy the requirements of Appendix 3, section 4(vi)(b), 'remote earth' induced voltage measurements shall be made as noted below.

10.2 The requirements of sections 2 to 8 above shall apply.

10.3 High impedance measurement equipment shall be connected at one end of the circuit under test, which shall otherwise be open circuit and a temporary connection to airframe shall be made at the remote end. (See Appendix 11, section 5.)

10.4 The measured transient waveform shall be analysed into di/dt and IR components and the amplitude of those components extrapolated to full threat.

NOTE 1: The maximum driving voltage capable of threatening insulation will be given by the sum of the extrapolated components.

NOTE 2: Guidance concerning Group 2 tests on parts of aircraft is given in Appendix 11.

Appendix 6

REQUIREMENTS FOR GROUP 2 TESTS ON WHOLE AIRCRAFT

1 INTRODUCTION

This Appendix defines the requirements which must be met when low level swept CW and pulse tests are made as part of the lightning transient assessment required in the LHDA.

2 GENERAL REQUIREMENTS FOR GROUP 2 TESTS

The general requirements of section E3 of this Memorandum shall apply to all the Group 2 tests noted in this Appendix, except that the test item (section E3(v)) shall be as defined below at section 3.

3 SELECTION AND PREPARATION OF TEST ITEM

3.1 Aircraft standard and configuration

Unless otherwise agreed with the MOD(PE) Aircraft Project Director the aircraft used for test shall be fully representative of a production aircraft with respect to airframe construction, the type and location of access doors and 'flux windows' in relation to the system wiring of interest and the type and installation of equipment, cable runs and wiring relevant to the tests to be made. Consideration shall be given, and agreed with the MOD(PE) Aircraft Project Director, regarding which aircraft configuration shall be tested (position of control surfaces, wing sweep, landing gear up or down, pylons and stores fitted, etc) and the need to change that configuration during the tests.

3.2 Operation of aircraft equipment during the tests

Arrangements shall be made so that the systems of interest can be operated during the tests, preferably using the aircraft's internal power supplies (eg by running the APU if available) or alternatively by using a ground power supply which is independent of 'mains earth' (such as a diesel generating set).

3.3 Modification of aircraft to accommodate diagnostics

The aircraft shall be suitably modified without compromising the requirements of section 3.1 above to allow the fitting of the sensors and diagnostic equipment necessary to make the measurements noted in section 7.2 and if necessary the 'safety earth' as defined in section 4.4 above.

3.4 Fuel system and explosive devices

The fuel system shall be made safe, either by filling the tanks and fuel lines with water, if it is a non-operational aircraft; or by making provision for

continuous purging with an inert gas such as nitrogen, if it is an operational aircraft. When such purging is used, the oxygen content of the effluent gas shall be continuously monitored and tests made only when the content is below the acceptable level.

All explosive devices shall be removed from the aircraft.

4 PULSE TEST CONFIGURATION

4.1 General arrangements

The aircraft shall be supported on jacks so that the landing gear can be operated. The jacks shall be isolated from the aircraft with insulation sufficient to withstand the maximum voltage of the lightning pulse generator. A return conductor system shall be constructed around the aircraft according to the requirements of section 5 below, with provision for simulated lightning excitation between pairs of attachment points as defined in the Test Plan. A hard wire connection shall be made between the aircraft and the return conductors at the end of the system remote from the pulse generator.

4.2 Safety earth and isolation of ground power supply

One connection only shall be taken from the Hanger or Hard Standing earth system to the pulse generator/aircraft/return conductor system to form a safety earth, which shall be a low DC resistance but a high impedance above 0.1 MHz.

If operation of equipment during the tests entails the use of a ground power supply, it shall be isolated from ground with insulation sufficient to withstand the voltage that will appear between the aircraft and earth when the pulse generator is operating.

4.3 Connection of lightning pulse generator

A lightning pulse generator shall be connected to the return conductor system and shall be isolated from earth, with insulation sufficient to withstand the maximum voltage of the generator, and connected to the aircraft and return conductor system with hard wire connections.

5 RETURN CONDUCTOR SYSTEM

5.1 Simulation of the environment

A return conductor system shall be constructed around the aircraft to give, consistent with an acceptable value of inductance, as nearly as possible the free space electromagnetic field pattern around the aircraft and consequently the correct current distribution on the surface of the aircraft. The system should

also be designed to give approximately constant impedance along the transmission line formed by the aircraft and the return conductors.

NOTE 1: It is particularly important to get the correct current density and direction (to a tolerance of $\pm 10\%$) on the aircraft surface and especially at equipment bays or apertures below which cables associated with the systems of interest are routed.

5.2 Inductance value

The system shall also be designed, consistent with section 5.1 above and in conjunction with the design of the lightning pulse generator, to give an inductance value such that the peak value and maximum di/dt of the excitation current specified below at section 7.1 shall be achieved.

5.3 Surface current density

Computer calculations shall be made of the aircraft surface current density and direction at points defined in the Test Plan.

5.4 Termination and current attachment points

The return conductor system shall be designed with a suitable connection from the aircraft to the conductors at the end remote from the pulse generator to enable selection of either the system characteristic impedance from CW testing or a direct connection for high current pulse testing. The return conductors shall also be designed so that they can be modified to allow selection of the current attachment points defined in the Test Plan.

5.5 Isolation

The return conductor system shall be isolated from the aircraft (other than by the special connections noted below) and from earth by insulation sufficient to withstand the full voltage of the lightning pulse generator.

NOTE 2: It is essential that the return conductor system is validated before the system is used for tests by making TDR measurements on each return conductor to confirm symmetry. E field and surface current density measurements should also be made.

6 LOW LEVEL SWEEP CW INJECTION TESTS

6.1 The test configurations shall be as given in sections 4.1 and 4.2, except that the aircraft shall be connected to the return conductors by resistance approximating to the characteristic impedance of the system. A sinusoidal generator shall be connected to the input of the return conductor system, capable

of being swept over a frequency range of 100 Hz to 50 MHz and able to provide minimum output of 1A over that frequency range.

6.2 Current probes shall be placed at the generator input to the aircraft and at each cable bundle measurement point defined in the Test Plan.

6.3 With aircraft equipment operating the generator frequency shall be swept over the range and transfer functions obtained for the drive current to each cable bundle measurement point defined in the Test Plan.

7 PULSE TESTS

7.1 Test waveforms and maximum parameters

The test configuration shall be as given in section 4. The pulse generator shall be capable of providing a double exponential pulse (or equivalent clamped waveform) such that together with the return conductor system the following maximum parameters may be obtained:

$dE/dt > 0.25 \times 10^{13} \text{ V m}^{-1} \text{ s}^{-1}$,
 di/dt of $0.25 \times 10^{11} \text{ A/s}$) with a waveform which shall be as
 I_{pk} of 50 kA) defined in Appendix 9, section 3.2.

7.2 Measurements to be made

Provision shall be made, according to the requirements of the Test Plan, for the measurement of:

dE/dt at the start of the transmission line formed by the return conductors and aircraft arrangement, at a position half way along it, in the cockpit and other apertures.

The generator current waveform.

The current density J at selected points on the exterior surface of the aircraft.

Internal magnetic field at selected points inside the aircraft, especially in the cockpit and equipment bays.

Cable bundle currents on the cables of interest.

Measurement information shall be transmitted to the recording equipment preferably by Fibre Optic Links (FOLs) or by the careful use of hard wire connections to avoid earth loops, as appropriate to a particular measurement. The FOLs shall be capable of making measurements over a frequency band of at least 50 Hz to 100 Mz.

7.3 Test levels

Unless otherwise agreed with the MOD(PE) Aircraft Project Director pulse tests shall be made, with equipment operating, at least three well spaced current levels up to a peak current value of 50 kA, so that it is possible to:-

- (a) Compare the surface current density measurements with the computer predictions of section 5.5, and hence confirm the accuracy of the return conductor system pulse current.
- (b) Confirm the linearity (or otherwise) of the measurements with increasing pulse current.
- (c) To provide by extrapolation the full threat current and voltage responses on the cables and at the equipments specified in the Test Plan for comparison with the responses obtained in section 6.3 (see Appendix 3, section 5(iv)(b) and Appendix 11, Section 4).

7.4 Common mode flashover

As required by Appendix 3, section 4(vi)(b) measurements, as noted in the Test Plan, shall also be made of the common-mode voltage between wires and ground which could result in insulation being stressed to a level at which flashover might occur. Such measurements shall be made by making temporary connections to airframe at one end of the loop under consideration and measuring the open circuit voltage at the other end (REMOTE 'earth' measurements).

Measurements shall be made at the same levels used in section 7.3 either simultaneously with the measurements of section 7.3 or separately. Linearity of the measurements shall be demonstrated and the full threat levels used to assess the danger of flashover.

NOTE 3: When making such an assessment it is necessary to sum the 'IR' and di/dt components of the waveform. This is because in a natural lightning waveform, maximum di/dt occurs at about peak current and not at the start of the waveform.

NOTE 4: If an operational aircraft is used, after Pulse Tests it will be necessary to check that all avionic systems are functioning correctly.

Appendix 7**REQUIREMENTS FOR FUEL HAZARD ASSESSMENT TESTS****1 INTRODUCTION**

This Appendix defines the requirements which must be met when Fuel Hazard Assessment Tests are performed. When such tests are specified as part of the LHDA they will be selected from those listed in Table E1 and noted in the Test Plan.

2 ARC ROOT TESTS

Arc root tests shall be in accordance with the relevant sections of Appendix 4 (Tests 1 to 6).

3 SPARKING FLAMMABLE GAS AND FLAME SUPPRESSION TESTS

The requirements for sparking, flammable gas and flame suppression tests are as follows:

TEST 7-1: SPARKING TESTS**Test Requirement**

- (i) The general requirements of section E3 of this Memorandum shall apply.
- (ii) The test sample may be a wing panel, a fuel system component (such as a fuel filler cap), a section of structure (such as part of a 'wet wing'), or a section of an assembly (such as an external fuel tank) or a complete major assembly (such as a fuel tank or a complete 'wet wing'). When the former are used they shall be mounted in a light tight box so designed to ensure compliance with (iii) below and able to accept the spark detection instrumentation noted in section (vii) below. Modifications to major assemblies for the installation of spark detecting equipment shall also be made in such a way that the requirements in section (iii) below are satisfied.
- (iii) The test current attachment points and the design of the return current conductor configuration shall be as noted in the Test Plan which shall define the lightning current paths through the test object so that the current distribution corresponds as nearly as possible to that which would occur should a lightning strike occur in flight (see Appendix 10). It may be necessary for more than one current path to be tested corresponding to different sets of lightning attachment points on the aircraft, should it be impossible to define a worst case.

The test current connections shall be hard wired to the test object except that an open arc shall be used when localised high current densities are required (eg to a fastener), or when this test is combined with an arc root damage test.

(iv) When an open arc is used it shall not be less than 50 mm long and should be initiated by a fine wire, not exceeding 0.1 mm diameter. The wire may be either metallic (eg copper) or carbon fibre. A Jet Diverting Electrode (see Appendix 10, section 1.2) is not needed unless arc root tests are being made.

(v) The test arrangement shall be referred to earth potential at one point only.

(vi) A permanent record shall be made of the arc voltage and the arc current on a common calibrated time base, so that the relationship of voltage and current with respect to time can be determined.

(vii) Spark detection equipment shall be installed and any sparking that occurs during the tests detected by either method A or B, or a combination of both methods, as defined below in section 6 (see Note 8 and Appendix 12, section 3.3).

Equivalent methods may be used by agreement with the MOD(PE) Aircraft Project Director.

(viii) Test for sparking may be included in tests for other failure mechanisms where test currents with high action integrals are employed provided that all the requirements for all the tests are observed, see section 5, Note 4). Group 1 sparking tests may also be combined with the measurement of induced voltages on wiring inside the test object and the detection of sparking due to those voltages, provided that the special requirements of section 4 of this Appendix are met.

Test Waveform

The test waveform shall be as noted in section 5.

TEST 7-2: FLAMMABLE GAS TEST

Test Requirements

(i) The general requirement of section E3 of this Memorandum shall apply.

(ii) The test sample will generally be a complete major assembly such as a fuel tank or a complete 'wet wing', although panels, fuel system components or sections of an assembly may also be tested. When the latter is so the 'fuel

side' of the sample shall be enclosed in a gas-tight cell provided with 'blow off' panels. Major assemblies shall also be modified to incorporate such panels.

The gas cells or major assembly shall have provision for a continuous flow of the prescribed gas/air mixture (see (iii) below) through it. A test cell, fitted with a calibrated spark source (see (iv) below) to allow the ignitability of the gas/air mixture to be proved, shall be arranged so that both the inflow and outflow test sample mixture can alternatively flow through the cell.

The blow off panels, spark source and gas/air supplies shall be installed in such a way that the requirements of section (v) below are met.

(iii) The explosive mixture shall be ethylene/air in a proportion 1.4 times richer than stoichiometric. There shall be 'continuous flow mixing' of the gas and air and the mixture shall flow through the test sample until the outflowing mixture continuously has the correct composition and is shown to be ignitable.

NOTE 1: The exhaust mixture from the test sample should be collected or safely vented. Areas external to the sample where leakage could occur should be sealed to atmosphere and continuously purged with nitrogen.

(iv) The calibration spark source shall be a gap to give a spark discharging a suitable value capacitor charged to a voltage such that the energy stored immediately before flashover of the gap is 0.04 mJ $\pm 10\%$.

(v) The test current attachment points and the design of the return current conductor configuration shall be as noted in the Test Plan which shall define the lightning current paths through the test object so that the current distribution corresponds as nearly as possible to that which would occur should a lightning strike occur in flight (see Appendix 10). It may be necessary for more than one current path to be tested corresponding to different sets of lightning attachment points on the aircraft should it be impossible to define a worst case.

The test current connections shall be hard wired to the test object except that an open arc shall be used when localised high current densities are required.

(vi) When an open arc is used it shall not be less than 50 mm long and should be initiated by a fine wire, not exceeding 0.1 mm diameter. The wire may be either metallic (eg copper) or carbon fibre. A Jet Diverting Electrode is not needed.

(vii) A permanent record shall be made of the arc voltage and the arc current on a common calibrated time base, so that the relationship of voltage and current with respect to time can be determined.

(viii) Simulated lightning discharges shall be made to the test object. Using the test cell and spark source, both the inflow and outflow mixture shall be checked immediately before and after each shot. Tests shall not be made if the mixture fails to ignite before an intended shot. If it fails to ignite after a shot, that test shall be ignored and repeated.

Test Waveform

The test waveform shall be as noted in section 5.

TEST 7-3: FLAME SUPPRESSION TEST

Test Requirements

(i) Tests shall only be made on a representative example of a fuel dump mast or vent system fitted with flame suppression devices and which shall include a simulated section of the aircraft structure adjacent to the dump or vent outlet.

(ii) The objective of the test shall be to ignite a fuel vapour/air mixture flowing along the jettison or vent system with a simulated lightning strike to the jettison or vent orifice.

NOTE 2: Even though it can be shown theoretically that such an attachment is very unlikely and that only corona effects will occur, the test shall still be made with a simulated lightning waveform.

(iii) Open arc simulated lightning discharges to the dump or vent outlet shall be made with fuel/air vapour discharging until that vapour ignites.

The correct operation of the flame suppression devices shall be monitored.

NOTE 3: It should be remembered that sparking or flammable gas tests may also be needed in a jettison or vent system to establish that there is not a hazard on the fuel side of the suppression device.

4 TEST WAVEFORMS

The test current waveforms shall be selected from those defined in Appendix 9 according to the lightning attachment Zone of the test object, as follows:

- (a) Zone 1a. Component A, with initial rate of rise not less than 0.3×10^{11} A/s.

- (b) Zone 1b and 3. Component A, but with an action integral increased to $2.25 \times 10^6 \text{ A}^2\text{s}$ and an initial rate of rise not less than $0.3 \times 10^{11} \text{ A/s}$.
- (c) Zone 2b. Component D, with initial rate of rise of current and time for which di/dt exceeds $0.25 \times 10^{11} \text{ A/s}$ as defined in Waveform E of Appendix 9.

NOTE 4: When voltage sparking is also being evaluated the initial rate of rise shall be as defined in Waveform E, alternatively a second test shall be made using Component D with di/dt as defined in Waveform E.

NOTE 5: When it can be shown that only voltage sparking will occur, Waveform E shall be used. When it can be shown that voltage sparking will not occur, Components A or D without a specified initial rate of rise shall be used.

NOTE 6: When it can be shown that the test object as a whole will never be subjected to the full current of a lightning strike, the test current amplitudes may be scaled down proportionately.

NOTE 7: When tests for other failure mechanisms are being conducted in the same series of tests, then either the appropriate waveforms for the different mechanisms shall be applied in separate tests or else waveforms shall be chosen, in agreement with the MOD(PE) Aircraft Project Director, which adequately test for all the mechanisms simultaneously.

NOTE 8: When sparking and flashover in fuel system wiring is being evaluated by Test 7-1 or 7-2 (see Appendix 3, Note 5) the lightning current test waveform shall be Component D, with initial rate of rise of current and time for which di/dt exceeds $0.25 \times 10^{11} \text{ A/s}$ as defined in Waveform E.

5 METHODS OF DETECTING SPARKING

5.1 Applicability

The methods of detecting sparking defined below apply to both thermal and voltage sparking. Background and guidance is given in Appendix 12.

NOTE 9: The spark detection methods given below have been developed to detect sparks down to an equivalent energy level of 0.2 mJ and may not be capable of detecting sparks down to 0.04 mJ.

5.2 Method A (photographic)

(i) This relies upon the use of photographic methods with film speeds and exposure times sufficiently sensitive to record voltage sparks down to 0.2 mJ and the equivalent intensity thermal sparks.

(ii) Suitable cameras shall be positioned in the light-tight enclosure in which the sample is mounted, or in the major assembly (if necessary in apertures cut into it, so that all possible sparking sources are viewed. To facilitate that and to limit the number of cameras, a fish eye lens or a system of mirrors may be used, provided due allowance is made for the reduction in sensitivity that will so occur. Alternatively the test may be repeated with the sensors in different positions but this is not recommended (see section 7).

(iii) Film speeds shall not be less than ASA 3000 and lens apertures shall not be less than F 4.7.

(iv) The field of view shall not be wider than one metre and the maximum distance, depending on the focal length of the lens, shall be according to the following table:-

8 mm (fish eye)	-	300 mm
16 mm " "	-	500 mm
28 mm	-	1 mm
50 mm	-	2 mm

(v) The field of vision of each camera shall be completely shielded from all ambient light and a test exposure shall be made with each camera to prove that is so.

(vi) All possible sparking sources shall be temporarily illuminated and each camera carefully focused and a record made of each field of view, to enable any sparking recorded during the test to be referred to its origin.

(vii) A small light source (which can conveniently be provided by a fibre optic cable), which illuminates briefly immediately before or during the application of the test current, shall be provided in the field of view of each camera, to demonstrate that they are capable of recording sparks if they occur. A photographic record shall be made of the position of each of the light sources immediately following the record made in (vii).

NOTE 10: Care must be taken that a light source cannot be confused with a spark and that it does not interfere (eg shield from view) with the recording of any sparks.

Care must also be taken that the cameras do not themselves create a source of sparking.

(viii) When tests are made a procedure shall be followed that locates any sparks as exactly as possible. For example, if sparking is so intense as to

completely over-expose the film, notwithstanding (iii) above the test shall be repeated with the camera aperture adjusted to a lower sensitivity.

5.3 Method B (photomultiplier)

(i) This method relies upon a combination of photomultiplier sensors and supporting cameras - the former to detect and provide a time history of the sparks and the latter to give an indication of the location of the sparks.

(ii) A photomultiplier tube shall be arranged in a remote screened enclosure and linked to all possible sparking sites with fibre optic cables. Each fibre optic cable and photomultiplier combination shall be calibrated to demonstrate sensitivity to at least a 0.2 mJ voltage spark and preferably to 0.04 mJ.

(iii) Cameras sufficient to give general views of the test object shall be installed in general accordance with section 7.2(ii), (iii) and (iv). They may be omitted, by agreement with the MOD(PE) Aircraft Project Director, in areas where they would be unduly difficult to install.

6 CONDITIONING OF TEST SAMPLE BY REPEATED TESTING

It should be noted that the repeated passage of high current through a joint reduces the tendency for that joint to spark. The number of shots applied to each test sample shall therefore be limited to take this into consideration and unless otherwise agreed with the MOD(PE) Aircraft Project Director shall be limited to four shots. For tests which involve both conduction and arc attachment shots, the conduction shots shall be made first.

Appendix 8
GROUP 4 TEST METHODS

Test No	Title	Test Requirements
1	Dielectric Puncture Tests	i A high voltage pulse generator of at least 1.5 MW output shall be used, capable of giving pulses of both polarities with a 1.2/50 μs wave shape. (Wave-form 4. of Appendix 9). ii The generator shall be set to the voltage which will produce breakdown of the gap in 9 out of every 10 discharges (ie 'V_{90}'). iii The test object shall be mounted on an insulating stand not less than 2 metres above the earth plane, in order to reduce earth plane proximity effects. iv The test object and stand shall be placed under the high voltage pulse generator with all conducting structural components and equipment electrically bonded together and connected to the earth plane. v A rod electrode of between 8 mm and 15 mm diameter, connected to the high voltage output terminal of the generator, shall be placed at a distance from the test object such that the gap between the electrode and the dielectric surface under test shall be 1.5 metres, or 1.5 times the maximum flashover distance across the dielectric surface, whichever is the greater. The other side of the generator shall be connected to the earth plane. The electrode shall be capable of being placed in different positions around the test object, or alternatively the test object must be capable of being rotated under a fixed electrode so that different sections of the dielectric surface are presented in turn to the test electrode. vi Between 5 and 10 discharges of both polarities shall be made in each position of the electrode. vii A complete record of all discharges shall be made which shall include: - Oscillograms of the discharge voltage for all discharges, including those which did not break down the gap. - Still photographs of each discharge taken simultaneously from not less than 2 positions

Appendix 9

LIGHTNING TEST WAVEFORMS FOR USE WITH THE TEST METHODS GIVEN IN
APPENDICES 4 TO 8

1 INTRODUCTION

Owing to the complex nature of the various types of lightning discharges, and the limitations of laboratory facilities, it is necessary to define an outline waveforms for test purposes that contains the most important features of both negative and positive discharges to ground. Different components of the waveform are used to represent different aspects of the lightning flash. In addition specific components are selected for the investigation of different failure mechanisms.

2 TEST WAVEFORMS FOR GROUP 1 EFFECTS TESTING

The four test waveform components given in Table 9.1 below contain the important parameters of the four principle phases of the high current part of a lightning flash.

Table 9.1

Test current component parameters

Component	Parameter	Value	Tolerance
Component A (High current)	Peak current	200 kA	±10%
	Action integral	$2 \times 10^6 \text{ A}^2\text{s}$	±10%
	Pulse length	<500 μs	
	Time to peak current	<25 μs	
Component B (Intermediate current) See Note 1	Average current	2 kA	±10%
	Charge transfer	10 C	±10%
Component C (Continuing current)	Current	200-800 A	
	Charge transfer	200 C	±20%
Component D Restrike (Group 1 Effect)	Peak current	100 kA	±10%
	Action integral	$0.25 \times 10^6 \text{ A}^2\text{s}$	±10%

Note 1: Component B is seldom if ever used

The waveforms of Table 9.1 are shown diagrammatically in Fig 9.1 below.

It should be noted that when Component C is combined with Component D the continuing current must fall to near zero before the restrike component commences.

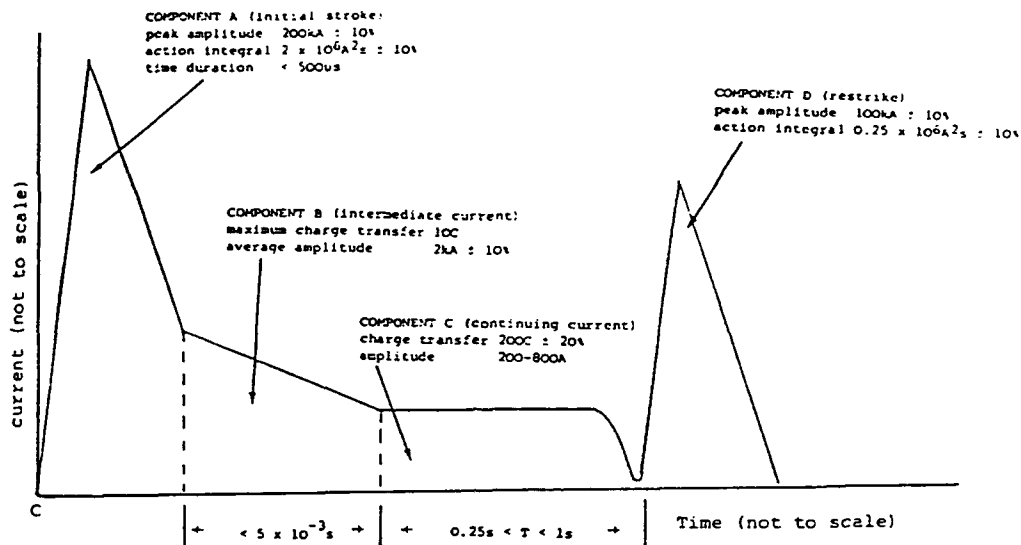


Fig 9.1 Schematic representation of the most important parameters and values considered for lightning tests

In natural lightning the restrike may have a di/dt of 10^{11} A/s in addition to the parameters listed under Component D in Table 11.1. In general this is not required for Group 1 effects testing except for acoustic shock wave test. This rate of rise is however significant for Group 2 effects tests and also when tests are made for both Group 1 and Group 2 effects at the same time. (See section 3 below).

Experiments have been conducted in order to establish some basic rules concerning the action of swept strokes in Zone 2a. So far no method has given any confidence in the ability to predict the probable hang-on time under any particular set of circumstances. It is generally agreed however that a restrike will generate a new attachment point, and that the mean interval between restrikes is of the order of 50 ms. The figure of 50 ms has therefore been accepted as an international test level for dwell time duration.

The test current waveform adopted for metal burn through tests in Zone 2a is defined as:

A unipolar pulse of between 400 A and 800 A lasting for a duration of 50 ms.

The test current waveforms applicable to those parts of the aircraft under investigation according to the Lightning Zone ascribed to it, are shown in Table 9.2 below.

Table 9.2
Currents applicable to the test Zones

Test zone	Current component			
	A	B	C	D
1A	X	X		
1B	X	X	X	X (note 2)
2A		X	X (note 1)	X (note 2)
2B			X	X (note 2)
3 (note 3)	X		X	X

NOTE 1: In this case Component C should be a unipolar discharge of 400 A to 800 A with a duration of 50 ms.

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

NOTE 3: For all Zone 3 tests the test current should be applied through a solid connection, and not through an arc.

3 TEST WAVEFORMS FOR GROUP 2 TESTS

3.1 Waveforms for Tests given in sections 9 and 10 of Appendix 5

In tests for fast flux coupling the important waveform parameter is di/dt , therefore such tests should be conducted with Waveform E which is Component D having additional parameters as follows. The peak current remains at 100 kA $\pm 10\%$, but with an initial peak di/dt of 10^{11} A/s $\pm 10\%$. Also the di/dt must exceed 0.25×10^{11} A/s for a period of not less than 0.5×10^{-6} s. When this waveform is used for combined Group 1 and Group 2 testing it must also have an actional integral of 0.25×10^6 A²s $\pm 10\%$, see Table 9.3.

In the case of diffuse flux or resistive coupling the important parameter is peak current and the tests should be conducted using either Waveform E with appropriate scaling for peak current, or with current Component A. When tests for both diffusion coupling and fast flux coupling are made together, Waveform E should be used with appropriate scaling for peak current recognising the need to add the 'IR' component to the fast flux component of the voltage measured (see Appendix 11).

Table 9.3
Parameters of Waveform E

Component	Parameter	Value	Tolerance
Restrike (Group 2 effects)	Peak current	100 kA	±10%
Component D	Peak initial rate of rise of current	10^{11} A/s	±10%
	Time for which di/dt to exceed 0.25×10^{11} A/s	0.5 μ s	±10%

3.2 Waveforms for pulse tests and lightning transient assessment

(i) The waveform used for the pulse tests in Appendix 6, section 7 shall be either a clamped or a double exponential waveform with the following maximum parameters:

Peak current - 50 kA

Maximum rate of rise - 0.25×10^{11} A/s

The time from t_0 to reach 5% of the maximum current value, on decay, shall be 400 μ s ±10%, and the time to peak from t_0 shall be between 2 and 10 μ s

(ii) For analysis a double exponential waveform shall be used of the form:

$$i = I_0(e^{-at} - e^{-bt}) ,$$

where $I_0 = 218810$ (A)

$a = 8110$ (s^{-1})

$b = 462332$ (s^{-1}).

The above waveform has a peak current of 200 kA and a maximum di/dt of 10^{11} A/s, with a time to peak of 8.8 μ s and a time from t_0 to 5% of peak current of 380 μ s.

4 WAVEFORM FOR GROUP 4 EFFECTS TESTING

The waveform for dielectric puncture tests (Appendix 8) shall be a 1.2/50 μ s waveform defined as follows:

The open circuit voltage of the high voltage generator shall rise to crest from t_0 in 1.2 μ s ($\pm 10\%$) and decay to half of crest amplitude in 50 μ s ($\pm 10\%$).

NOTE: This is the Electrical Industry's standard waveform for impulse dielectric tests.

Appendix 10

TESTING TECHNIQUES

1 SIMULATION OF THE ENVIRONMENT

1.1 Simulation of the correct current distribution

In laboratory tests conditions transmission lines or cables are used to connect the test object to the lightning current generator. The magnetic fields associated with these conductors will influence the current distribution within the test object. The coupling conductor layout will need to be designed in a manner that will satisfy these two main requirements.

(a) First, and most important, the current distribution within the test object must be as close as possible to that which will exist under natural lightning strike conditions.

(b) Secondly the total circuit inductance must be kept as low as possible in order to ease the problem of passing currents of very high di/dt .

One solution to this problem is to have a co-axial or quasi co-axial system of multi-path return conductors. A schematic diagram of such a system is shown in Fig 10.1. This has four equally spaced return conductors, but the principal can be extended to any number as required.

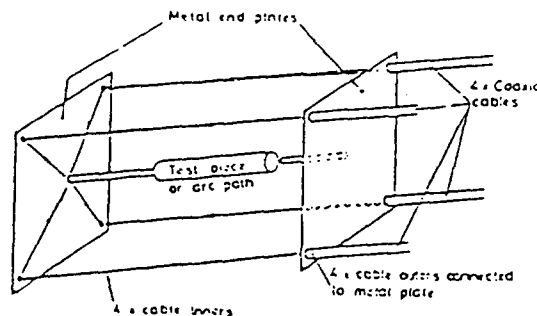


Fig 10.1 A basic Quasi co-axial system

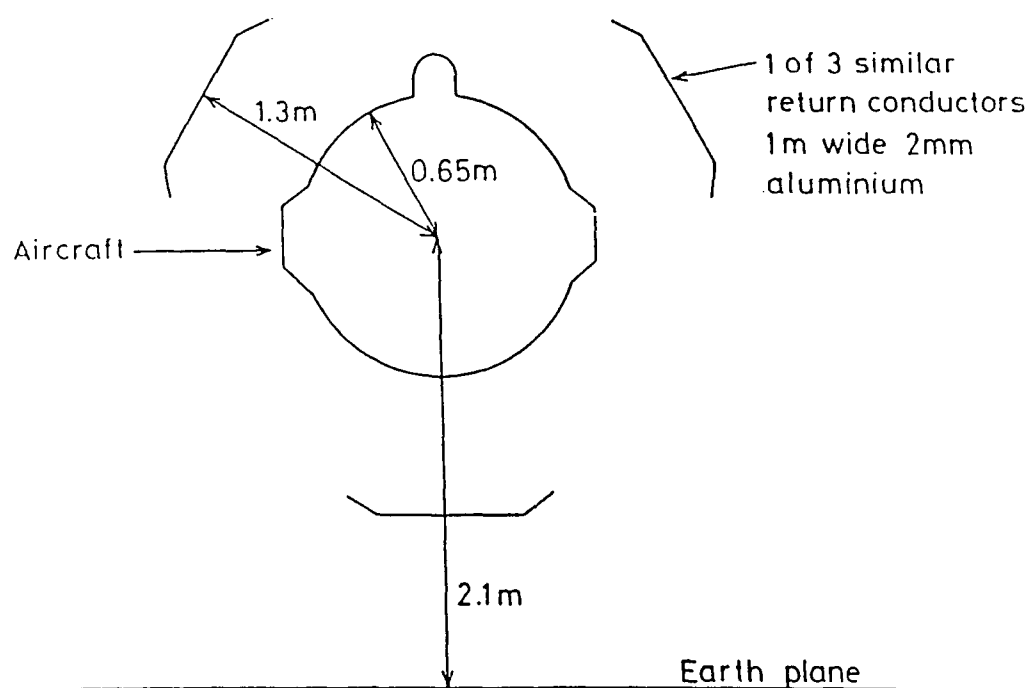


Fig 10.2 Cross section of a three conductor Quasi co-axial system round an aircraft fuselage

The principal has been refined as indicated in Fig 10.2, where three return conductors are used. In this technique the magnetic lines around the test object are plotted, and the three return conductors are placed at a convenient distance from the test object and on the same magnetic surface. The conductors are arranged on this surface in such a way that the value of the function $\int H \cdot dl$ is the same between each conductor and those either side.

Fig 10.3 shows how the correct current distribution can be achieved in a CFC test panel using two return conductors and a metal enclosure to represent a wing box.

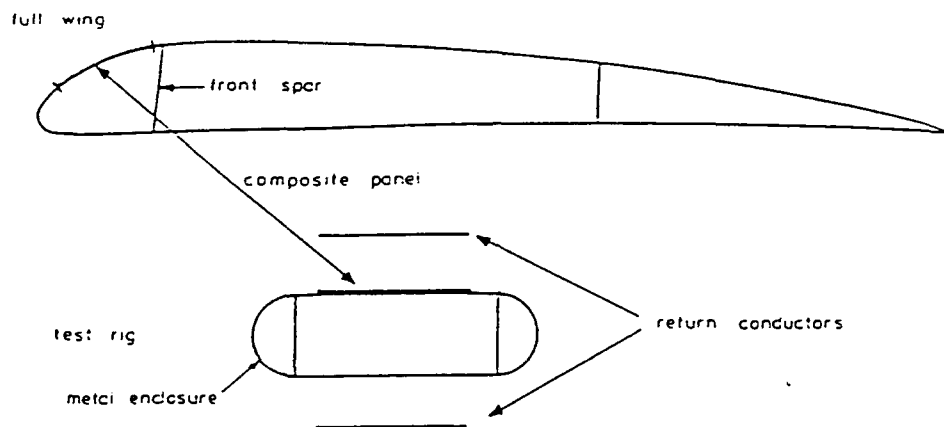


Fig 10.3 A two conductor system to test a composite panel using a metal enclosure to represent the wing box

NOTE: The test current chosen must give the same peak current density in the panel as it would have in the wing, and also the same rise time and decay time.

1.2 The jet diverting electrode

In early work on arc root burn through of metal panels, the results were strongly influenced by the arc length employed in the tests. This was found to be due to the presence of jets of ionised and neutral particles emitted from the arc root on the test object and also on the test electrode. High speed cine film showed these jets to be very active up to 50 mm or so from each arc root. In a natural strike to an aircraft only the jet from the arc root on the aircraft exists and a true simulation requires that the jet emanating from the test electrode in a laboratory test should be eliminated. It has been shown that this

jet is always normal to the surface of the electrode, and so the electrode jet can be separated from the arc channel, and directed away from the test object by redirecting the arc root to an appropriately angled facet of the electrode, by means of a suitable insulator. Fig 10.4 shows a typical jet diverting electrode.

Experiments with this type of electrode has given results sensibly independent of arc length in excess of 15 mm, indicating that the electrode jet effect has been virtually eliminated.

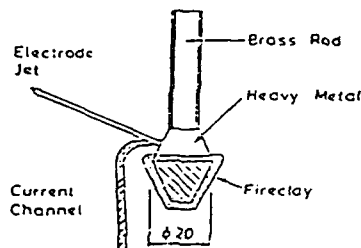


Fig 10.4 A typical jet diverting electrode

1.3 Other environmental considerations

There is no requirement at present to simulate either the effects of forward speed, or the effects of altitude eg reduced atmospheric pressure. The effect of forward speed viz the swept stroke effect is allowed for by defining the dwell time in Zone 2a to be 50 ms for test purposes.

2 TEST CURRENT GENERATION

Because of the very high power rate of the simulated lightning stroke, the generation of lightning simulation currents can only be achieved in practice by storing energy at a lower power rate over a long period, and releasing it at the very high power rate and short duration of the simulated lightning pulse.

Capacitive storage and inductive storage are the two forms most suitable for lightning simulation although heavy duty battery systems have been used for generation of Component C.

In general the capacitive storage system is the most convenient and easiest to control practically, but the inductive system gives the best simulation. A practical solution is the use of the 'clamped' C L R discharge circuit. In this

system energy is stored in a capacitor and discharged into the test object. The initial discharge current will be oscillatory in nature due to the inductance in the load. The first quarter cycle of this discharge will form the 'rise' portion of the test waveform. At the moment of maximum current (zero capacitor voltage) all the energy will have been restored in the load inductance. The clamp switch may then be closed and the energy stored in the inductance will discharge in the load forming the 'tail' part of the required waveform. Extra inductance can be added as required to produce the correct waveform. The basic system is indicated in Fig 10.5.

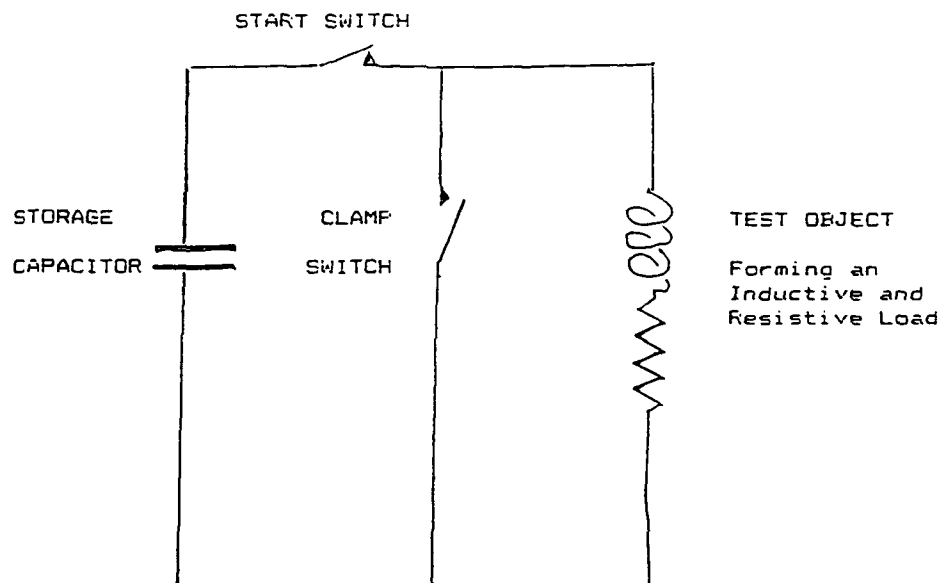


Fig 10.5 The basic 'clamped' circuit

3 REFERENCE TO EARTH POTENTIAL

Diagnostics of high current pulsed circuits can be very difficult, and the first requirements is the elimination of all earth current loops. This can only be achieved successfully if the entire system including the high current circuit, the control circuit, and the diagnostic circuits are reference to earth potential at one point and one point only. This is termed "the experimental earth reference point". For this purpose the screened room will also be considered as part of the diagnostic circuit. Those parts of the control circuit or the

diagnostic circuits which are completely isolated from the system by pneumatic or fibre optic links, may be separately referenced to earth potential for safety reasons, but great care must be taken to ensure that there is no unintentional connection to the experimental earth reference point. Such unintentional connections can occur from many sources such as connection to a recording device in common use with a diagnostic probe that is not isolated from the high current pulse circuit, or through a common mains connection.

Earth loops resulting from multipoint earthing will almost certainly disturb the diagnostics so that what is recorded may not be what is actually happening. In the extreme they can distort the current path through the test object, so that the intended test is not actually conducted. The results of any test conducted under conditions of multi earthing should be considered as unreliable and should be discarded.

4 DIAGNOSTICS

4.1 Voltage and current measurements

Voltage measurements can conveniently be made using suitable potential dividers. The low voltage end of the divider must be connected directly to the experimental earth reference point, and care taken to avoid earth loops.

Current measurements can be made in a number of ways. These include:

- (a) Low inductance resistive shunts.
- (b) Magnetic probes, pick-up coils, and Rogowski coils.
- (c) Other magnetic field effects probes.

Shunts are useful for intermediate and continuing current tests for currents from 100 A to some tens of kilo amperes, where the di/dt is low and the circuit can tolerate the insertion inductance. Calibration is absolute, and the diagnostic is robust consistent, and reliable. The shunt must be capable of carrying the action integral of the pulse without significant temperature rise, and must be introduced at the experimental earth reference point only.

Rogowski coils and magnetic probe coils may be used for the higher currents with di/dt in excess of 5×10^9 A/s. The magnetic probe coil has the better high frequency performance. Neither system need be in metallic contact with the high current circuit, and therefore need not be connected to the experimental earth reference point. They are both susceptible to any high frequency electrical noise. This may best be counteracted by the use of balanced twin cables run in solid copper tubes. The copper tubes must be kept directly against

and in electrical contact with the high current transmission lines from the position of the probe to the experimental earth reference point.

Other magnetic field effects transducers include Hall effects probes and Faraday Rotation Effects Transducers. These are also electrically isolated from the main circuit but any cables to them must be run as described for Rogowski coils.

4.2 Other diagnostic tools

Other diagnostic tools that can be employed include:

- (a) Photographic instruments eg high speed cine cameras for arc root studies; still cameras using high speed film or fibre optics and light sensitive transducers for spark detection.
- (b) Thermocouples, heat sensitive paints, or thermal imaging cameras for hot spot detection or surface temperature measurements.

Appendix 11**GUIDANCE ON GROUP 2 HAZARD ASSESSMENT****1 INTRODUCTION**

This Appendix gives assessment and test guidance concerning the evaluation of measures to protect aircraft against hazards arising from lightning Group 2 effects. It should be read in conjunction with Appendices 3 (sections 4(vi), and 5), 5 and 6.

Section 4 below discusses Group 2 tests as applied to whole aircraft. Those tests are required to satisfy the requirements of section B2.1 and Appendix 3 of this Memorandum, and are needed to evaluate the HF shock excitation discussed in section 2.2 below.

Section 5 gives guidance concerning Group 2 tests to evaluate the resistive and flux penetration voltages discussed in section 2.2. The latter effects are capable of causing gross common mode voltages of several kV, which can severely threaten insulation.

2 SUMMARY OF GROUP 2 EFFECTS MECHANISMS

2.1 A summary of Group 2 effects has already been given in Appendix 2. For convenience that summary is repeated below.

2.2 As noted in section 7 of Appendix 2 Group 2 effects are those due to coupling with the magnetic or electric field of the lightning current flowing in the aircraft or in the lightning channel itself. They can arise therefore as a result of a direct strike, a nearby flash or a distant flash. The principal effect is that voltages and currents are induced on the aircraft surface and in the interior wiring also, the amplitude of the latter depending on the electromagnetic shielding afforded by the surface. Thus avionic equipment is likely to be subjected to transients, which may cause malfunction or possibly permanent damage.

Essentially, a transient voltage is injected into the aircraft wiring and the current that flows depends on the impedance of the circuit. Direct penetration of transient fields into an equipment is usually not important because the grounded case affords good shielding against both magnetic and electric fields. The transient voltage waveforms injected into the wiring are often very complex but usually consist of one or more of the following three components:

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

(b) A voltage proportional to the rate of change of lightning current (di/dt), due to direct coupling with the magnetic field that has penetrated through apertures (non-conducting material). The peak voltage will thus be proportional to the maximum value of di/dt , that is, the greatest slope of the rising front of the current pulse.

(c) High frequency damped sinusoidal oscillations usually in the range 2 MHz to 50 MHz. These are shock-excited oscillations corresponding to natural resonances (possibly including harmonics) of the aircraft and its electrical systems, and their frequency and damping (although not their amplitudes) are independent of the shape of the lightning pulse. In the case of distant lightning, and also NEMP, this is the only form of transient that appears.

The shock excited oscillations referred to in (c) above are initiated when a strike attaches or re-attaches to the aircraft. Most strikes that occur to instrumented aircraft in cloud seem to show bursts of about twenty current pulses within one millisecond, corresponding to the initial attachment, followed by up to 24 bursts or isolated pulses possibly associated with 'K changes' in two seconds¹. This has led SAE Committee AE4L to define a 'Multiple Burst' waveform against which aircraft should be hardened². However as noted in Ref 1 there is controversy about those waveforms and this Memorandum therefore does not, at the moment, address them.

3 AIRCRAFT CLEARANCE

3.1 General considerations

Due to the expense and complication of whole aircraft testing, aircraft clearance must be based on analytical techniques supported and validated by tests. This means that full threat responses must be predicted for all the cables and equipments for all the systems of interest. That analysis must then be substantiated by whole aircraft tests made on selected cables and equipments.

There is a school of thought which says that there should always be a full threat upset test, either on a system rig with multipoint injection, or

preferably during a whole aircraft pulse test. With regard to the latter preference it is argued that only by testing on the aircraft at full threat will the correct environment due to lightning occur, with appropriate amplitude and phase of voltages and currents on cables and electromagnetic fields in equipment bays.

The opposing view is that even such a test cannot reproduce the actual excitation that occurs in the air (for reasons that are too complicated to explain here) and that all the variables and imponderables can be swept up in an adequate safety margin between levels obtained from successfully validated analysis and the bench test levels to which equipment is cleared. This specification adopts the latter position and at the moment requires a safety margin of 12 dB.

3.2 Definition of levels

The following terms are used in this Memorandum to describe aircraft and equipment transient levels:

(a) Aircraft Transient Level (ATL) is the actual level that the transient assessment establishes should exist at the equipment when it is installed on the aircraft.

(b) Equipment Transient Test Level (ETTL) is the level up to which the equipment must operate without malfunction or signs of failure.

As is noted above the specification requires a safety margin of 12 dB between the ATL and ETTL for an equipment.

3.3 Equipment tests

As is noted elsewhere in this Memorandum (section C11) all equipment must be tested to RAE Technical Memorandum FS(F) 457. As is noted above, ideally this should be done in a system rig with multipoint injection but test methods and equipment to do that, although generally feasible in principle, have yet to be developed; hence part of the reason for the 12 dB safety margin referred to above.

Equipment tests, or rather equipment clearance to agreed levels, are both the starting point and finishing point of the Clearance Exercise, as levels have to be specified at equipment procurement, often before the location of the equipment in the aircraft is known. Hence these levels have to be justified or revised at the completion of the evaluation of Lightning Transient Protection, with subsequent retesting if the ATL and safety margin so dictate.

It is important that equipments should be progressively tested up to the ETTL.

4 GROUP 2 TESTS ON WHOLE AIRCRAFT (APPENDIX 6)

4.1 In flight and ground test airframe resonances

As has already been said in section 3.1 clearance must be based on analysis substantiated by whole aircraft testing. Unfortunately such testing cannot completely simulate the lightning environment and reproduce the conditions that will actually occur when an aircraft is struck in flight. There are several reasons for this, one of which is the fact that the lightning channel is a very high impedance compared with that of the aircraft and the aircraft is therefore effectively terminated with an open circuit when it resonates due to the sudden change of E field at a lightning attachment. Therefore there are current nodes at the nose and tail and at each wing tip, implying $\lambda/2$ resonances. It is very difficult to simulate those resonances in whole aircraft testing as the only way to do it is to use open arc terminations at each end of the aircraft return conductor aircraft system, such arcs causing a lot of noise and making measurement very difficult. Terminating with a short circuit however gives a current anti-node at the termination and a node at the generator end and hence $\lambda/4$ resonances. Those resonances can be removed mathematically when calculating the full threat responses and similarly replaced by the $\lambda/2$ resonances which occur in flight.

4.2 Aircraft standard

It is important that an aircraft used for a whole aircraft test is representative of a production aircraft in all the aspects noted in section 3 of Appendix 6. In practise this may be difficult to achieve as such tests often have to be made on prototype or pre-production aircraft where equipment installation and especially wiring layout may be appreciably different from production. Changes to the position of equipments in an equipment bay could make significant differences to the coupling to the wiring to those equipments as could also the type of cover or access door to the bay, for example if the latter was changed from an all metal construction to a partially conducting or insulating composite.

Where changes such have been outlined above are inevitable following an equipment test, the implications on the clearance given to the aircraft shall be assessed and agreed with the MOD(PE) Aircraft Project Director who may require re-testing in certain areas.

4.3 Operation of equipment and safety earth

The preferred method of operating the aircraft equipment is to use the APU. However if the APU is not available, or is unable to be used, then a ground power supply is necessary. A unit which draws its power via a transformer from the 50 Hz mains should not be used however, as such a supply will essentially be earthy and that will complicate the safety earthing arrangements necessary. Instead, an engine driven generator, such as a PE set should be used which can then be isolated from earth. The insulation level used to obtain that isolation will be decided by the position of the safety earth on the system and may need to be sufficient to withstand the full voltage of the pulse generator.

When pulse tests are made a safety earth (the 'experimental earth' of Appendix 10, section 3) must be connected to the system to meet 'Health and Safety' requirements. Such an earth should be used with care to prevent capacitive circulating currents at the higher frequencies and for that reason the earth connection should be a high impedance above say 0.1 MHz. Care must be taken however that the earth lead does not resonate with rig capacitance to ground, although such resonances can be minimised by careful positioning of the earthing point³.

4.4 Return conductors for whole aircraft tests

Computational methods should be used to design a return conductor system to give optimum field distribution around the aircraft consistent with minimum inductance and approximately constant impedance along the transmission line formed by the aircraft and return conductors. Two dimensional computer programmes will normally be sufficient to do this, by taking sections through the airframe to establish the position and spacing of the return conductors relative to the airframe, so that the field pattern around the aircraft approaches that of free space without giving unmanageably high impedance. It is important that surface current density (J) should be computed, especially near access bay doors and 'flux apertures' and compared with the 'free space' values for ' J ' to confirm that the design is acceptable. Further confirmation is then obtained during pulse tests by measuring ' J ' at selected places and comparing the measured values with the computed values.

The lumped series inductance of the return conductor aircraft system must be kept as low as possible as the total series inductance must be taken into account during the design of the pulse generator, so that the required values of peak current and rate of change of current may be obtained.

NOTE: The inductance is minimised and the external field accuracy is optimised if Z_0 of the aircraft return conductor assembly is kept approximately constant along the length of the aircraft at about 42 to 55 ohms giving inductances of 0.15 $\mu\text{H}/\text{m}$ to 0.2 $\mu\text{H}/\text{m}$ (Ref 3).

4.5 Non linearity

When performing pulse tests, non linearity can occur due to voltage or current dependent skin resistance and due to sparking and arcing causing local changes in the current distribution over the surface of the aircraft.

5 GROUP 2 TEST ON PARTS OF AIRCRAFT (APPENDIX 5)

5.1 Applicability

The tests noted in Appendix 5 are intended to be used when measurements are being made of voltages which could cause sparking or stress insulation on the wiring and electrical equipment in parts of aircraft, such as radomes or external probes, and a 'whole aircraft' test is not appropriate. Usually, but not always, if flashover voltages are being assessed, section 10 of Appendix 5 will apply (as required by Appendix 3, section 4(vi)(b)) and the comments of section 6 below are relevant. Such measurements, often referred to as 'remote earth tests', give a worst case situation, giving the maximum open circuit common-mode voltage that can ever be available to drive current around the cable/aircraft skin loop. Hence if all insulation can withstand that voltage there is no problem. Sometimes, however, it may be necessary to find out how that voltage divides between impedances in the loop, or it may be necessary for other reasons (for example, to see if sparking or arcing could occur between two conductors where remote earth tests are not appropriate) to measure the actual voltages generated, either common-mode or differential-mode, or both. When that is so the test of section 9 in Appendix 5 is appropriate.

5.2 Test current waveform

Ideally a test for Group 2 effects should employ a current waveform having the specified full-threat values for both the important parameters, but owing to the limitations of existing test facilities the Waveform E of Appendix 9 which has a lower peak value is generally employed and the magnitude of the measured transients extrapolated to full-threat values.

5.3 Return current conductors

The design of return conductors for whole aircraft tests has been discussed above at section 4.4. For tests on parts of aircraft the return current conductors should be distributed around the test object in cross section and

follow the contours of the object axially, thus forming an approximately co-axial system, as illustrated in Fig 10.2. Depending on the shape of the object, 3 or 4 conductors are usually adequate and they should be placed so that the magnetic contours near the object are as nearly as possible the same as they would be in free space (remote return current). The distance of the conductors from the object is a compromise between distortion of the field (too near) and excessive inductance requiring high driving voltages (too distant).

5.4 Processing of data

Voltages due to resistive or diffusion-flux coupling follow approximately the current waveform although the peak may be reached later (resistive) or earlier (diffusion flux behind high resistance panels). Voltages due to direct flux coupling follow approximately the rate of change of current and they therefore have a steep rise at switch-on and pass through zero at the time of peak current. For large test objects there may be high frequency damped oscillations superimposed on the slower waveform.

5.5 Combination with Group 1 effects

If the Group 1 tests include a Waveform A of Appendix 9, this has one of the requirements for Group 2 tests (200 kA peak) and measurement of induced voltages can often be made provided that the rate of rise of the waveform is at least 0.3×10^9 A/s. If Component D is being used the rate of rise shall be as specified in Waveform E. Depending on which waveform is used either the di/dt component or the IR component must be extrapolated to full threat.

6 ASSESSMENT OF VOLTAGES LIABLE TO STRESS INSULATION OR CAUSE VOLTAGE FLASHOVER

6.1 When evaluating common-mode voltages which are liable to stress insulation or cause voltage flashover (see Appendix 5, section 10 and Appendix 6, section 7.4), it is often convenient, and sometimes necessary, to measure the voltage available to drive current around the loop formed by the conductor carrying the excitation current and the conductors and associated impedances in which the induced current will flow, if there is voltage breakdown. This may be done by connecting one conductor to the other at a convenient place (eg at the connections to a pitot heater) and then measuring the open loop voltage at the other end of the circuit. The di/dt and IR components of the measured waveform must be identified and extrapolated to full threat and then added together to give the maximum voltage which can stress insulation or which could be available to cause flashover. The two components have to be added as in the real lightning waveform peak di/dt occurs at about the same time as peak

current whilst lightning test waveforms give maximum di/dt at the start of the waveform. This will then give a worst case, as a given probability of occurrence of one parameter does not correspond to the same probability for another and therefore there is generally no need for additional safety factors.

6.2 Voltages measured by 'remote earth tests' should not be confused with the 'ground voltage spikes' discussed in RAE Technical Memorandum FS(F) 457, those spikes (used in the 'lightning ground voltages injection test') simulate what is thought to be the worst case value of the IR component (long waveform) and the aperture flux component (short waveform) that would be revealed in a remote earth test.

REFERENCES

No.	Author	Title, etc
1	C.J. Hardwick	The lightning aircraft interaction. Lightning Club Report CLIC/5-1, Oct 1988
2		Protection of aircraft electrical/electronic systems against the indirect effects of lightning. SAE AE4L Report AE4L-87-3, recommended Draft Advisory Circular, February 1987
3		Culham Laboratory short course notes. Lecture 10.1, September 1989

Appendix 12**FUEL HAZARD DESIGN AND ASSESSMENT GUIDANCE****1 INTRODUCTION**

This Appendix gives background to some of the design problems to obviate lightning related fuel hazards and gives some assessment and test guidance.

Over the last twenty years Western Airforces have lost an average of one aircraft per year as the result of lightning strikes, and half of those losses have been the result of fuel explosion. Consequently there is a need for careful design and assessment in the fuel hazard area. The advent of CFC construction underlines that need.

2 HAZARD MECHANISMS

2.1 Fuel hazards can arise in integral fuel tanks (eg 'wet wings'), in external fuel tanks and in other locations, such as fuel vent outlets, where fuel or its vapour may be exposed to the effects of a lightning strike. Fuel ignition can result from burn through of the fuel tank skin; hot spot formation; puncture of a CFC skin by arc root damage, or by acoustic shock wave; puncture of a dielectric tank skin; thermal or voltage sparking; or by ignition at a fuel vent due to streamering or interaction with the lightning channel. Thus the mechanisms of ignition include both Group 1 (Direct) and Group 2 (Indirect) effects and in a fuel tank can vary with the method and material used for its construction.

2.2 Fuel tanks made of dielectric material usually contain metal parts such as brackets, pipes, drain valves, connectors and wiring and these may become centres of electric stresses as a lightning leader approaches. This stress may be sufficient to cause breakdown of the dielectric skin, resulting in puncture or shattering; thus fuel is spilled and may be ignited. Even a nominally empty tank will contain sufficient residual fuel to produce a combustible mixture in the tank. A partially empty tank may also have an explosive fuel/air mixture in the ullage above the fuel and it is necessary that internal pipe work, bonding and electrical wiring be correctly designed and installed so that sparking and arcing does not occur.

Dielectric tanks may be protected from puncture by a thin metal coating, or by a framework of metal strips bonded to the airframe which preferentially 'attract' the lightning discharge and divert it to the airframe. It may be necessary to do a dielectric puncture test (see Appendix 8) when assessing the lightning protection.

2.3 In aluminium alloy tanks situated in Zones 1 or 2 the main hazard (depending on skin thickness) is burn-through of the skin at a lightning attachment point, although hot spots can also be a problem particularly with tanks constructed with high melting point alloys, such as titanium. The sparking hazard in a metal tank is generally low because the good conductivity of metal keeps most of the lightning current on the outside, but the possibility has to be considered, especially for high melting point alloys, which have a lower conductivity than aluminium. Also access doors and complex construction can cause problems.

2.4 CFC tanks present a variety of hazards. Because of the nature of the erosion at the arc root, purely thermal burn-through is less likely than with metal and generally does not penetrate more than 5 plies but a hot-spot hazard is more likely. Moreover the mechanical properties of CFC make it more likely to be damaged by acoustic shock. Above all, the high resistivity of CFC means that its electrical skin effect is low, so that voltage gradients on the inside of the skin are high and a substantial proportion of the skin current can penetrate to the interior, giving a high sparking hazard. Protective measures such as a metal coating on the skin will thus almost certainly be needed and it will be necessary to confirm their effectiveness, probably by testing for all hazards.

3 FUEL CHARACTERISTICS AND CRITERIA FOR EXPLOSION OR COMBUSTION

3.1 Fuel characteristics

All potentially ignitable fluids and vapours including for example oils and hydraulic fluid must be considered when considering lightning strike hazards. Not only must hazardous vapour air mixtures that normally occur be considered (for example the fuel vapour air mixture in the ullage space of a fuel tank) but also where such vapours could form in otherwise dry areas due to seepage and leakage. It is fuel, however, that causes the most problems and the subject of aviation fuel flammability is complex. Complicating parameters are the oxygen enrichment of the fuel/air vapour due to dissolved oxygen in the fuel being released at altitude, and the formation of mist within the tank which may render flammable vapour space which would normally be considered too weak in vapour to ignite.

3.2 Fuel vapour/air explosion limits

The lower explosive limit (LEL) or 'flashpoint' of a fuel occurs when the percentage volume of fuel vapour to air is just sufficient for ignition to occur - about 1.3% for Avtur at ground level pressure¹. The upper explosive limit (UEL) occurs when the fuel vapour air ratio is just sufficient to give an over

rich situation, and prevent combustion - about 7.9% for Avtur at ground level pressure. These limits depend on fuel temperature and air pressure and curves for Avtur (JP1 or F34) and Avtag (JP4 or F40) at Reid Vapour Pressure 3 are given in Fig 12.1. From those curves it is immediately obvious why Avtur is a much safer fuel than Avtag, certainly in temperate climates, as the former cannot form an explosive vapour mixture at temperatures below about 30°C at 10,000 ft and about 35°C at ground level. The curves given in Fig 12.1 relate to steady state conditions in a closed volume without air flow.

Fuel misting, for example due to condensation when a tank is cooled, will lower the LEL. Oxygen enrichment, due to dissolved air in the fuel outgassing as altitude increases, will raise the limits, moving the curves of Fig 12.1 to the right. Operation of booster pumps will also cause oxygen enrichment and normal aircraft vibration can cause misting.

The maximum energy of an explosion occurs when the mixture is stoichiometric (that is a mixture where there is just sufficient air to give complete combustion - for Avtur at ground level about 4% vapour concentration) and gives a maximum over pressure of 7 times the pressure in the vessel before the explosion².

From the above it will be seen that apart from the need for an ignition source there are several factors which will decide whether or not an explosion would occur in a tank, and the strength of that explosion if it occurs.

3.3 Minimum ignition energy levels

Obviously for a fuel vapour mixture to explode it must be ignitable, that is the temperature of the fuel and the pressure of the air above it must be within the explosion limits discussed above. However the spark energy required to ignite such a mixture varies with the mixture strength. It is measured by finding the minimum electric spark energy that will just ignite the mixture.

Minimum ignition energies increase with altitude and decrease with oxygen enrichment. The level varies for different hydrocarbons but usually lies between 0.2 and 0.3 mJ at normal (21%) oxygen concentration. At 35% oxygen, the minimum ignition energy is about 5 times lower,

eg ethane at 21% oxygen = 0.2 mJ
 ethane at 35% oxygen = 0.04 mJ .

The lower value of 0.04 mJ has in the past sometimes been taken in UK for certification of aircraft fuel systems under typical flight conditions but it seems to be a present day consensus that 0.2 mJ should be the clearance figure,

although it also seems that some US sources would like to have a high value. The writer is advised, however, that 0.04 mJ should still be the clearance value unless recent investigations have substantiated the 0.2 figure³. The writer and his adviser are unaware of any such work and it is difficult to believe that it has been done, as it is understood that considerable work was done in RAE by Chemistry and ME Departments in the late 1950s, and subsequently during the development of Concorde, which substantiates the 0.04 figure. A lot of effort, accepted by FAA, CAA (then ARB) and France, was devoted to establishing that figure for Concorde.

Factors which justify the lower figure are:

Oxygen enrichment - due to the operation of booster pumps and decreasing pressure with altitude (which on balance lowers the Minimum Ignition Energy (MIE)).

Pressures above atmospheric in fuel systems - many fuel systems or parts of them, certainly in military aircraft, are pressurised to 3 psi or more - MIE falls with increasing pressure.

The fact that aircraft fuels are very mixed hydrocarbons high in the hydrocarbon series (AVTUR for example is basically a 'C₁₂') and that the MIE falls with ascending value of hydrocarbon.

For the above reasons 0.04 mJ is taken as the MIE clearance level in this Memorandum, although it is realised that at the moment test methods A and B of section 5 of Appendix 7 (and especially method A) for spark detection may only be of use down to 0.2 mJ.

The probability of ignition at the minimum ignition energy is very low. For example the minimum ignition energy of Propane is 0.2 mJ but the probability of a single such spark causing ignition is < 0.1%. Similar figures at 21% oxygen also apply to fuel vapour. The 0.04 mJ figure is likely to correspond to an ignition probability of <0.1% but this needs to be confirmed.

The mixture strength at which minimum ignition energy occurs (that is the most sensitive mixture) varies widely with different hydrocarbons. For example with Methane it is 0.9 stoichiometric and for Hexane it is 1.8 stoichiometric, whilst Ethane and Propane are 1.2 (Ref 4). The most sensitive mixture for aircraft fuels is about 1.04 stoichiometric and for Ethylene is 1.4.

From the above, and from the preceding section, it will be seen that there are several variables which affect the flammability of a fuel vapour air mixture which tend to make aircraft fuel vapour/air explosions a statistical happening.

The low level of 0.04 mJ/0.2 mJ for certification purposes illustrates the need to eliminate essentially all sparking in a fuel system if incendive sparks are to be avoided under all conditions.

3.4 Ignition criteria

As noted above, whether or not an explosive mixture occurs depends on several factors but for the purpose of this Memorandum it is assumed that such a mixture can always occur and that therefore fuel hazard assessment must show that all ignition sources have been avoided. Therefore it is necessary to demonstrate that arc penetration, hot spots, internal arcing and sparking do not occur. Sparking is the most difficult of those mechanisms to eliminate and demonstrate its absence.

The absence of sparking can be demonstrated either by a sparking test (Test 7-1 but note previous comments concerning the sensitivity of this test) or a flammable gas test (Test 7-2). A sparking test is usually preferable, mainly because of the complication of a flammable gas test. Moreover the detection of sparking is a more discriminating test able to provide information on the location of the sparks and therefore assisting in remedial design measures in contrast to the crude pass/fail nature of the flammable gas test. However there will be occasions when the latter test is the only way to demonstrate the absence of sparking.

4 COMMENTS ON DESIGN REQUIREMENTS

Some comments are given below on some of the design requirements in section D1. Figures in brackets indicate the relevant requirement.

4.1 Hot spots (D1.2)

Carbon-fibre hot spots are of long duration which means that internal skin temperatures must not exceed 230°C, the auto ignition temperature of fuel. With metal skins the hot spot is quickly dissipated and temperatures higher than 230°C can be tolerated. There is, however, lack of data to define the temperature /time/area profiles which constitute a hazard but for 2 mm thick Aluminium skins transient hot spots of up to 660°C have been shown not to present an ignition hazard.

There is little data concerning Titanium hot spots and the MOD(PE) Aircraft Project Director will generally require a 'Flammable Gas Test' to demonstrate absence of hazard, if a safe hot spot temperature cannot be established.

4.2 Lightning current flow inside fuel system structures (D1.2 and D1.8)

The LHDA must detail what measures have been taken to prevent the flow of lightning current within a fuel system structure or fuel system component. When such current flow cannot be excluded by reasonable design measures the LHDA must show to the satisfaction of the MOD(PE) Aircraft Project Director what measures have been taken to prevent that current flow being a hazard. Particular attention should be paid to any unavoidable bonding connections to ensure good metal to metal contact. Similarly, the use of fuel sealant (PRC), for example, is a skin joint across which current must flow, must be balanced against the need for good electrical contact of area adequate to limit the current density to a value below which local heating and thermal sparking does not occur.

The MOD(PE) Aircraft Project Director will normally require a careful analysis to show that lightning current cannot flow in the fuel system fuel and air pipes especially with CFC structures and particularly inside fuel tanks. Alternatively in Aluminium structures where full compliance with this requirement would be unreasonable, the correct use of bonding techniques to limit current flow through couplings should be demonstrated. If continuous metal pipes were to be used in CFC structures without the use of insulating sections to prohibit lightning current flow, as is required by section D1.8, very large currents (in the order of 10 kA or more) could flow in them. Ref 5 recommends that isolating sections of pipework should not be longer than 300 mm if they are made from non conducting material, due to the possibility of fuel charging electrostatic hazards. Sections of pipe longer than 300 mm should be made from partially conducting material with conductivity in the range of 10^{-5} to 10^{-9} siemens/m in the bulk material.

4.3 Skin thicknesses (D1.5)

When for structural reasons skins less than 2 mm thick are to be used the LHDA must identify the means of protecting such skins (eg by using an ablating layer). When Titanium construction is used an acceptable skin thickness must be agreed with the MOD(PE) Aircraft Project Director.

4.4 Joints and fasteners (D1.7)

The prevention of sparking at joints and fasteners is often a very difficult task to accomplish, especially with CFC structures. With such structures it is unlikely that sparking can be prevented without the use of surface protection over joints and fasteners and by the use of sealant (PRC) below the fasteners, also special arrangements are sometimes made to share the

current between more than one fastener. The above approach is sometimes called 'multipath protection', as each part of the protection lowers the probability of the occurrence of sparking.

When evaluating sparking at fasteners and joints it should be remembered that the tendency to spark reduces with the repeated passage of current through the joint. This should therefore be borne in mind when deciding how many test samples are required and to what level the test current should be.

Not only can sparking at joints be extremely dangerous from the point of view of fuel vapour ignition but such sparking in CFC structures can also damage the joint as the spark products vent away from the fastener, possibly causing delamination in the immediate area of the fastener. Another problem with CFC construction is that of preventing lightning current crossing adhesively bonded joints. For such a joint to carry current, electrical breakdown of the insulating adhesive must occur and that will be followed by sparking and arcing, which will not only produce an ignition hazard but also explosive forces which are likely to debond the joint.

4.5 Installation of fuel system wiring (D1.9)

It should be remembered that if screens bonded at each end are not used induced voltages of a few hundred volts/metres may be generated when wiring runs along exposed areas, such as between control surfaces and the trailing edge of a wing. The need for screening can be reduced if the wiring route is carefully chosen to take advantage of any inherent screening that may be provided by the structure. However if the structure is largely made from carbon fibre composite or other resistive material, external screens bonded at both ends must always be used, no matter what the wiring route. As the current redistributes out of the carbon fibre such screens will eventually take a large proportion of the lightning current. Hence there is a need for cable connectors, cable screens and bonding to carry current levels of several kiloamps.

4.6 Flame suppression devices (D1.11)

When flame suppression devices are deemed necessary for fuel dump masts and vents, the MOD(PE) Aircraft Project Director will normally require test evidence to show satisfactory operation of the devices when they are subjected to simulated lightning conditions. It should be remembered that under certain flight conditions it may be possible for flight refuelling probes to vent outwards and the need for protection should be considered.

4.7 Fuel filler caps (D1.12)

The implication of requirement section D1.12 is that the cap locking mechanism shall not be on the fuel side of the fuel seal.

4.8 External fuel tanks (D1.14)

It should be remembered that external fuel tanks can be particularly vulnerable to lightning strikes and susceptible to explosion. Metal tanks if incorrectly designed are particularly hazardous and several crashes have occurred as the result of such tanks exploding following lightning strikes to the aircraft.

A lot of problems can arise with external tanks if incorrectly designed. Explosions have fairly frequently occurred in tanks made in non conducting composite. Fuel explosions and fires have undoubtedly occurred but also 'exploding arcs' due to broken bonding straps inside the tanks have ruptured the tank walls without causing fuel explosion. In one incident the writer investigated, such an effect was probably responsible for complete loss of the tank.

It is essential that external tanks constructed from Composite material (both non-conducting and partially conducting) should be so designed as to eliminate all lightning current flow in internal conductors and across the tank/pylon fuel air interfaces. The latter also applies to metallic tanks. An acceptable method of preventing lightning current flow across a fuel/air interface is to insulate the mushroom heads of fuel and air valves with a suitable thickness of nylon or other insulating material to withstand 20 kV at sea level pressure.

An exploding 'plastic' tank is a nuisance and can hazard the aircraft but as noted above an exploding metallic tank can be lethal. The internal pressure at which failure occurs is likely to be considerably greater than that resulting from a plastic tank failure as is also the mass and hence the energy of, the resulting debris; so that when a metallic tank explodes the aircraft will almost certainly crash, as happened in two incidents which the writer helped to investigate.

One approach to metallic external tank design is to ensure that the over-pressure, should an explosion occur, is lower than the proof pressure of the tank. In fact, in some circles, this is even a permissible part of lightning protection for an integral tank. Such an approach however is not favoured and is unlikely ever to be acceptable to MOD(PE). Obviously the correct approach is to eliminate all ignition sources and so prevent an explosion.

5 FUEL HAZARD ASSESSMENT AND TEST

5.1 Assessments

When making fuel hazard assessments it should be remembered that such hazards are not limited to areas where there is obvious current flow between lightning attachment points, as currents decided by the laws of electro-magnetic induction will flow on the remainder of the vehicle. Hence, for example, current would cross the tank pylon interface of a pylon mounted wing tank when there is a lightning attachment to the wing and the tail of the aircraft, without a direct attachment to the tank. Also a voltage sufficient to cause sparking in the contents monitoring system of such a tank could occur due to induction to that part of the fuel system wiring contained in the fuselage, due to lightning current flow in the fuselage.

If the approved test plan includes testing for such a situation the test arrangement will need to include an adjacent conductor through which the test current shall be passed instead of the test object itself.

5.2 Thermal and voltage sparking

Thermal sparking is that phenomena whereby small incandescent particles of material are ejected from the surface of a conductor, due to current concentration forming hot spots together with the resultant magnetic forces acting in the area concerned. Almost certainly small arcs also occur and generate high pressures which tend to blow out the particles. The current concentration may be caused by limited contact areas at the junction of two conductors or by acute changes in geometry in a single conductor.

Because the sparking is thermal, the appropriate test current waveforms are those with high peaks and high action integrals, namely Components A and D. Thermal sparks are usually more significant for fuel ignition as that is the predominant sparking mechanism for Group 1 effects and in practice the sparks which occur within a fuel tank are almost always thermal.

Voltage sparking occurs when the flow of current produces a voltage difference between two conductors which rises to a value high enough to break down the intervening medium, whether this is air or other dielectric. It can arise inductively in a loop or bend in a conductor, by flux coupling to an adjacent conductor, or from the resistive drop in a high resistance material such as CFC. Voltage sparking is a function of rate of change of current (inductive) or of peak current (resistive voltage gradients) and the appropriate test current is therefore Waveform E.

In practice a combination of thermal and voltage sparking will often occur and the test waveform used to investigate such combined sparking must contain the parameters important for both mechanisms. (See section 4 of Appendix 7).

5.3 Sparking tests

As noted above the occurrence of sparking is detected either by a 'sparking test' or by a flammable gas test. The latter is discussed below at section 5.4, this section gives background on the optical methods of detecting sparking. As is noted in section 3.3, at the moment these methods may not be sufficiently sensitive for use below 0.2 mJ.

Sparking may be detected by employing either a still camera or light-sensitive transducers (methods A and B defined in section 5 of Appendix 7). In either case, the detectors shall be positioned so that they cover all possible sparking locations; this may be achieved by the use of a sufficient number of detectors or by a system of mirrors or by repetition of the tests with the detectors in different positions (but see section 7 of Appendix 7). The field of vision shall be completely shielded from all light and tests shall be made to confirm this. Care shall be taken to ensure that the detectors themselves do not create a possible sparking location, if for example they are inside a fuel tank.

Low energy voltage sparks and incandive thermal sparks are very dim and photographic techniques need to be sensitive to detect them. The film speed should be not less than ASA 3000 and the aperture should be not less than F4.7. Also, because of the smallness of the sparks and the fineness of the thermal particle tracks, the actual image size is important and so therefore is the type of lens. This means that shorter focal length lenses have to be closer to the light source for the same sensitivity (see the table in Appendix 7, section 5.2).

Arrangements shall be made to demonstrate that during each test the camera was capable of recording sparks if they had occurred, for example that the shutter had not inadvertently been left shut. This may be achieved by arranging for a low level light source to be in the field of vision, but care shall be taken that this cannot be confused with a spark and that it does not interfere with the recording of any sparks. A procedure shall be followed that locates any sparks as exactly as possible; for example if sparking is so intense as to completely over-expose the film then the test shall be repeated with the camera aperture adjusted to a lower sensitivity.

When light-sensitive transducers (photomultipliers) are used, light from possible sparking sources may be conveyed to the transducers by means of optical fibres (Method B in section 5 of Appendix 7). The sensitivity of the transducers

and the associated optical fibres shall be not less than that specified for still camera systems. A photomultiplier/fibre optic arrangement can provide greater sensitivity than a camera system and may be used as the prime means of detecting sparks. It is very useful when a camera would have a restricted field of view and is sometimes the only method available, for example when looking for sparking inside a fuel pipe.

5.4 Flammable gas tests

As has already been mentioned the flammable gas test is a method of checking for sparking and should not be regarded as an attempt to simulate actual explosive conditions. Explosion tests using an aircraft fuel vapour/air mixture have sometimes been used in the past as a pass/fail test but are unreliable due to the statistical nature of ignition and the difficulty of obtaining the correct mixture strength. As has already been noted, in a fuel air vapour mixture a 0.2 mJ voltage spark corresponds to approximately 0.1% probability of ignition at normal pressure and oxygen concentration but ethylene air in a mixture 1.4 times richer than stoichiometric gives a greater than 50% probability of detecting a 1.6 mm long 0.2 mJ voltage spark. Hence ethylene in that mixture ratio is the preferred gas for spark ignition testing. Propane which has sometimes been used by some test houses only gives a remote probability of detection and therefore is not recommended.

A flammable gas test must always be used when there is any doubt of detecting sparking by other means. The test is usually used on major assemblies although of course it can also be used with part assemblies and panels by constructing a gas cell over the fuel side of the test sample. The test can also detect small hot spots. The mixture should be obtained by continuously mixing the gas and air (as in a welding torch) and should be checked for flammability by passing it through a test cell and containing ignition with a calibrated 0.04 mJ spark source before it is allowed to flow into the test object. When that has been done the mixture should flow through the test sample until ignition of the outflow mixture is consistently obtained in the test cell. Immediately before and after each test shot both the airflow and outflow mixture should again be proved flammable, except that there is obviously no need to prove the outflow mixture if detonation occurred during the test. If ignition of the outflow mixture does not occur after a test, that test is invalid and must be repeated after the mixture has been corrected and the outflow again gives ignition.

5.5 Flame suppression tests

Flame suppression tests are intended to check the correct operation of flame suppression devices in vent and dump mast systems. Such systems should be installed in areas of low probability of lightning attachment (Zone 3) but other design factors may dictate otherwise. When that is so flame suppression devices should always be fitted to guard against flame propagation back to the fuel system should effluent vapour of fuel be ignited by corona or lightning attachments at the vent or dump outlets. It is known that such effects can happen and at least one crash is likely to have been caused by streamering or lightning attachment at a vent outlet.

The test described in section 3 of Appendix 7 (test 7-3) is designed to simulate a worst case ignition of fuel vapour in a suppression system. A lightning discharge is used as the acoustic shock wave from a lightning attachment can influence the flame propagation rate along the vent pipe. A stoichiometric mixture of aircraft fuel vapour/air should be used for the test to give a more representative energy and flame propagation rate.

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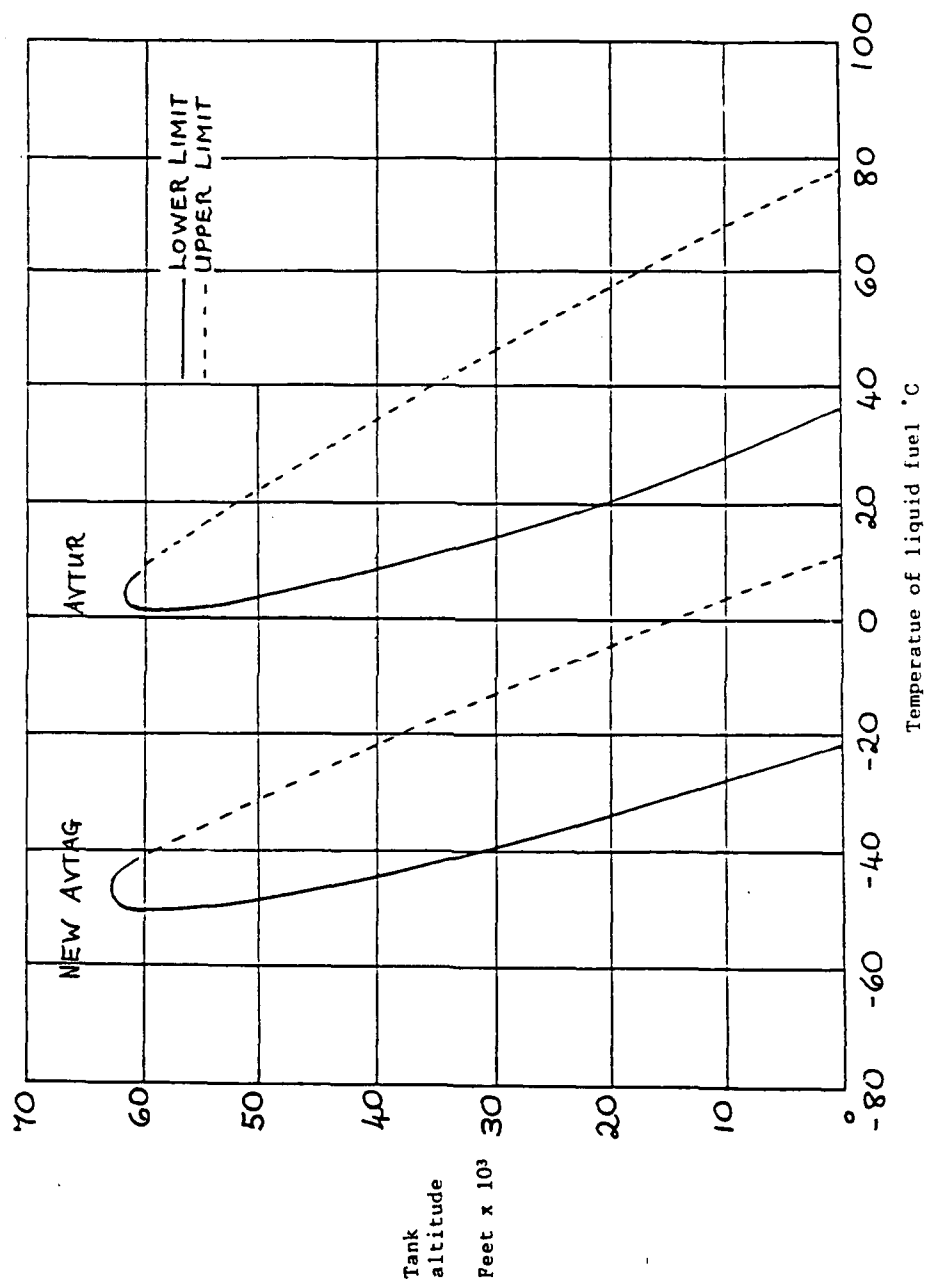


Fig A12-1 Limits of flammability of AVTAG and AVTUR in air