CONFERENCE ON LIGHTNING AND STATIC ELECTRICITY,
HELD AT CULHAM LABORATORY, ABINGDON, ENGLAND ON
14-18 APRIL 1975

Marin S. Harris

Office of Naval Research
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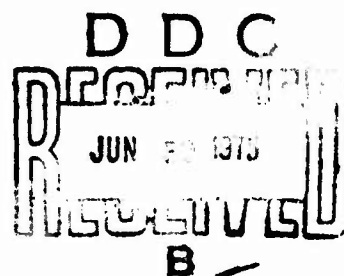
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MAJOR MARIN S. HARRIS (EOARD)

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A four-day international Conference on lightning and static electricity was sponsored by the Royal Aeronautical Society and the U.K. Atomic Energy Agency's Culham Laboratory at Culham on 14-18 April 1975. The meeting was primarily devoted to describing effects of lightning and static electricity on aircraft and components, laboratory simulation of these effects, and methods to prevent aircraft damage. This report discusses some of the European papers presented in the five sessions of

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20. Abstract (Cont)

the conference: Fundamental Aspects and Test Criteria, Fuels,
Structures & Materials, Aircraft Applications, and Missiles and
Spacecraft.

## 1975 CONFERENCE ON LIGHTNING AND STATIC ELECTRICITY
## CULHAM LABORATORY, ABINGDON, ENGLAND
## 14-18 APRIL 1975

The 1975 Conference on Lightning and Static Electricity was held 14-18
April 1975 at Culham Laboratory, Abingdon, England. This was the fourth
meeting on the subject, but the first to be held outside the United
States. The Conference was organized and hosted by the Royal Aero-
nautical Society and Culham Laboratory with support of the Institute
of Electrical Engineers and the Society of Automotive Engineers. It
was attended by about 150 people from thirteen countries with the U.S.
and U.K. dominating. The Conference was divided into five sessions
with some forty papers given. The meeting was primarily devoted to
describing effects of lightning and static electricity on aircraft and
components, laboratory simulation of these effects, and methods to
prevent aircraft damage.

## I.  FUNDAMENTAL ASPECTS AND TEST CRITERIA

Attendees of the Conference were welcomed by Dr. R. S. Pease, Director,
Culham Laboratory, and Lord Boyd-Carpenter, Chairman, U.K. Civil Avi-
ation Authority. The first session, Fundamental Aspects and Test
Criteria, was begun by R. B. Anderson, National Electrical Engineering
Research Institute, Pretaria, South Africa, who described lightning
phenomena in the aerospace environment.

He briefly described a model for lightning discharges which tended to
explain the development of intra-cloud discharges as compared with
cloud-ground discharges, and the basic differences in their character-
istics were emphasized. A mechanism for the lightning discharge to
ground was proposed which assumes a bi-polar structure of the charges
in the leader channel thereby permitting the potential of the leader
tip to fall as it approaches the earth. The return stroke is thought
to take place in two distinct phases when the negative charge has been
lowered by the leader. In the first phase electrons discharge rapidly
from the ionized channel leaving it predominantly positively charged.
In the final phase electrons move more slowly into the channel from
above as a consequence of further penetration of positive streamers
into the negative cloud charge. The base of the channel may become
sufficiently non-conductive to terminate the electrical connection,
otherwise it may persist to allow the flow of continuing currents.
Several such discharges may take place to constitute a multiple stroke
depending upon the rate of charge separation in the cloud and on other
factors tending to maintain the discharge.

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Attention was then focused upon the question of aircraft flying in a
thunderstorm environment. Firstly, there are areas where the electric
field intensities tend to zero and where, electrical breakdown is un-
likely to occur. Other meteorological factors may be more prominent
and constitute a greater danger to aircraft than lightning. On the
other hand, flying in areas where high electric field intensities
occur, introduces the risk of a discharge involving the aircraft in
the discharge path. In the case of the negative discharge, the situa-
tion may not be so critical, but the positive discharge on the other
hand, will involve a continuous discharge the severity of which is
less at the upper extremity of the channel. The importance of de-
termining the position, polarity, and movement of charged volumes in
thunderclouds over airports was therefore stressed, and a plea was
made for more observations.

K. Berger, Switzerland, discussed the development and properties of
positive lightning flashes. The majority of lightning flashes are of
negative polarity and bring negative electric charge from cloud to the
earth. Physical development and qualities of negative flashes (which
generally are composed of several strokes) are well known today. Each
stroke begins with a leader. Downward stroke leaders are connected
to the earth by an upward connecting leader, which bridges the gap
and initiates the return stroke. Negative upward stroke leaders from
a high object produce current impulses only by the subsequent or
following strokes.

Development and qualities of positive flashes to Mount San Salvatore
were described on the base of a special evaluation of 30 flashes,
24 out of them with current amplitudes above 40 kA. The physical
picture of current and field oscillograms is that of an upward leader
as a consequence of a transient electric field caused by an intracloud
discharge. If this upward leader reaches a branch of the intracloud
discharge it causes a heavy impulse discharge of more or less the whole
channel of the intracloud discharge. The leaders of such positive
strokes are in reality very long connecting leaders, which connect the
cloud discharge to the ground.

Systematically the conclusion of the study of positive lightning flashes
is that two classes or four physically different types of flashes could
be distinguished:

First the classical downward progressing leader, (a) from a negatively
charged cloud down to the earth, as a single stroke or a multiple stroke
flash, first impulse less steep current-front than consecutive strokes
(Schonland, "Lightning stroke") - this is the usual lightning flash, and
(b) from a positively charged cloud down to the flat country, one flash
to the lake at Campione, showing a loop near the ground - this case is
very rare.

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Second the positive and negative strokes beginning with upward pro-
gressing leaders from high conducting objects (television tower, mast,
rockets....), caused by the transient field variation during an intra-
cloud flash. The positive stroke with its higher electric field and
higher leader current at the negative tower normally does not show
extinction of the leader before reaching the intracloud discharge:
positive flashes are single stroke flashes therefore. The negative
stroke with its smaller initiating field at the tower tip extinguishes
normally at its ground terminal before reaching the intracloud dis-
charges, hence formation of multiple strokes.

Planes, helicopters and rockets at the earth may be submitted to a
lightning discharge like other objects of similar height.

In the first cases the probability to be struck may be judged by the
number of annual discharges per $km^2$. In the second case probability to
be struck may be many times higher, as is proved by the experience on
Mount San Salvatore. Principally the intensity of electric stress of
the flying object caused by a downward stroke (class 1) is maximum at
the earth and somewhat smaller in the air. Stresses caused in air by
involvement in a class 2 - strokes may differ little with stress at
earth level, as long as the flying object is below cloud base. Above
active clouds there will be little danger from steep impulse currents
but rather from leader-like currents of long duration.

C. Gary, Electricité de France, described a lightning testing station,
erected in the Massif Central, the purpose of which is to study the
response of a tower and its earthing resistance. This involves an
artificial triggering system of lightning strokes: a small rocket,
thrown toward a thundercloud, uncoils a thin conducting wire, the other
extremity of which is fastened on the top of the tower. Under given
conditions, when the rocket reaches an adequate height, the stroke is
triggered. The lightning current flows to earth through the tower and,
in the last part of its path, through the conducting wire, which is
vaporized. This station is cooperated by E.D.F. and the Commissariat
a l'Energie Atomique, the latter studying especially some physical
aspects of lightning, such as the plasmas produced on the ground at
the impact of the stroke.

Lightning strike point location studies on scale models was described
by D. J. Tedford, University of Strathclyde. The work was coopera-
tive with Culham Laboratory, Electrical Research Association, A.
Reyrolle and Co., and the University of Wales Institute of Science and
Technology. Studies of the location of lightning strike points on
aircraft are important in assessing the probability of breakdown to a
specific region of an aircraft, especially regions of low electric
field, and the effect of major changes in aircraft geometry. However,

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in view of the complex mechanisms and wide r~~ge of parameters asso-
ciated with the propagation of lightning lea⟨=rs, some of which are
imperfectly understood, there is a need to consider what factors
affect the validity of laboratory simulation of lightning using scale
models. Preliminary experiments have been made at the Reyrolle Re-
search Laboratories to obtain the breakdown distribution to a simple
model with cylindrical symmetry, placed between the HV electrode of a
5 MV impulse generator and earth. The effect of the following param-
eters was studied: (a) Generator parameters - polarity, waveshape,
and (b) model parameters - floating potential, geometry. It was found
that the voltage waveshape and model potential have a significant
effect on the breakdown distribution, whereas the generator polarity
was not very critical. The highest probability of breakdown to low
electric field regions was obtained with long-fronted waveshapes
(150 µsec rise). Further experiments will be carried out to study
the effect of changes in scale and ratio of model/gap dimensions.
Measurements will also be made of the model "capture radius," which is
defined as the distance by which a model can be displaced from the
direct path to earth and still "capture" the breakdown channel. In
addition, some consideration will be given to the fundamental break-
down mechanisms occurring in a three-electrode system.

In the absence of a general validation, testing at the ERA's HV
Laborato_y using aircraft models has provided supporting evidence on
probable strike distributions in new aircraft designs. No general
superiority of any combination of waveshape and polarity has been
found as far as correlation with service data is concerned. An un-
earthed model is preferred with about 50 m equivalent electrode/model
distance. Logically both spark attachment points should be counted.
Smallscale modelling of minor detail need not be very precise in
present applications.

Tests on full-scale components have also been made. In this case
leader approach is assumed to render a strike inevitable, i.e.
electrode/component distance is much shorter than leader step dis-
tance. The principal aim is to establish preferential attachment
points for the most unfavorable approach directions.

Analysis of the electric field distribution, under ionization-free
conditions, has been made for the above cylindrically symmetric con-
figuration using digital computation methods. This analytical method
has now been extended to simple three-dimensional geometrics and, in
principal can be used with such a complex shape as an aircraft. It
is hoped that such field analysis will enable some correlation between
the electric field and experimental breakdown distribution to be
demonstrated.

J. Phillpot, Culham Laboratory, talked about simulation of lightning currents in relation to measured parameters of natural lightning. The current wave-forms of a lightning discharge are the most important factors in deciding firstly, what damage is sustained by the aircraft, and secondly, what equipment is necessary to simulate the damage in the laboratory. Lightning simulation tests are becoming increasingly important due to the increased use of (a) fiber reinforced structures, (b) solid state circuitry for aircraft system control, and (c) thinner high strength metal skins. Furthermore, the requirement to meet existing lightning specifications is now becoming the limiting factor in the design of some components. Therefore, a knowledge of the characteristics of natural lightning and realistic simulation methods are required in order to ascertain the level of confidence that can be attached to a component or aircraft's ability to withstand a severe strike.

For some time, it has been acknowledged that the existing specifications are inadequate, and opinions differ markedly on the significance of the relevant parameters of natural lightning. It is generally agreed that the worst strike an aircraft can encounter is a strike to ground, and therefore, since there is some considerable data on ground strikes, it should be possible to resolve the differences between the various views, most markedly demonstrated by the U.S. proposed waveform replacement for Mil Spec 5087B and the waveforms contained in the NAMMA specification.

Positive discharges which have been measured have been initiated either by upward or downward going leaders to mountain tops. The significance between the two types of initiation related to the aircraft situation was discussed, since this has a major bearing on the differences between various specifications. An attempt was then made to define for both positive and negative discharges, an equivalent waveform in terms of fast, intermediate and continuing current components. A lightning simulation waveform was recommended which will cover the major parameters and takes into account limitations imposed by capacitor and battery banks.

E. S. Hotston, also of Culham Laboratory, presented some preliminary investigations into the screening of electrical charges of thundercloud. The electric field of thundercloud has been assumed to be maintained by the convection of charge in a predominantly vertical direction which balances the dissipation of the charge separation by the electric conductivity of the cloud and its surrounding atmosphere. Calculations have been made of the electric field distribution around such a convection current system, assuming the conductivities of the atmosphere and the cloud to be functions of altitude, and it was

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shown that it is possible by a plausible choice of convection current to obtain an electric field distribution in reasonable agreement with the measured parameters of natural lightning. The charges inside the cloud are greater than those deduced from the simple electrostatic model by a factor which varies between unity and three (depending on the geometry of the cloud) and are closer to measured values in flashes to ground. The charges are concentrated near the axis of the cloud. There is no evidence of a substantial surface charge on the cloud associated with the change of electrical conductivity at the edge of the cloud.

Papers in this first session by U.S. scientists included:

1. Advances in Lightning Triggering Experiments, M. M. Newman, Lightning and Oceanics Institute, given by J. D. Robb.

2. Scale Model Lightning Attach Point Testing, D. W. Clifford, McDonnell Aircraft Co.

3. Natural Lightning Parameters and Their Simulation in Laboratory Tests, E. T. Pierce, Stanford Research Institute, given by J. E. Nanevicz.

4. Aerospace Recommended Practice: Lightning Effects Tests on Aerospace Vehicles and Hardware, J. D. Robb of Lightning and Transients Research Institute and J. A. Plumer of General Electric.

5. Lightning Flash Densities and Calculation of Strike Probabilities to Certain Vulnerable Installations at the Nevada Test Site, K. Buset, Los Alamos Scientific Laboratory, and K. W. Price, Lawrence Livermore Laboratory, given by Buset.

6. Flight Test Studies of Static Electrification on Supersonic Aircraft, J. E. Nanevicz, Stanford Research Institute.

## II. FUELS

A. Lewis, Shell Research Ltd., U.K., began the second session with a paper on static electrification with liquid aviation fuels. Recent results in the research into the development of electrostatic charging during the high speed pumping of hydrocarbon fuels were reviewed. The degree of charging generated in a hydrocarbon fuel is dependent upon the presence in the fuel of trace quantities of impurity. Work on the behavior of some impurities in non-aviation applications was described and its relevance to the aviation scene discussed. One remedy for high charging is to speed the relaxation of charges, and the favored way of achieving this is to increase the conductivity of the fuel, by the aid of an antistatic additive. Recent progress in the adoption of this additive was reviewed.

Monitoring of fuel supplies is facilitated by the development of in-line conductivity monitors. The experience with these in operational service was described. Constant watch for any side effects of the additive is being exerted. No significant effects have been detected from airline service, so that the overall conclusion can be drawn that the static electricity hazard in fuelling aircraft at high speeds can be overcome effectively by means of a conductivity improving additive.

The development of electronic field meters for use in automatic systems for control of electrostatic charge in fuel tanks was described by A. W. Bright, University of Southampton. The present approach to fuelling ships and aircraft is based on the establishment of a code of practice controlling fuelling rates, such as the I.O.T.T.S. safety guide for tanker loading. Charge densities and electric fields are sometimes reduced by using antistatic additives such as ASA 3. Prediction of charge densities produced during fuelling is difficult if uncontrolled parameters such as fuel contaminants, foaming, filter contamination are involved. An alternative approach would be to use instruments which could indicate density or electric field at an appropriate point in the fuelling system. Electronic instrumentation could be used either to indicate the approach to a predetermined threshold (as a warning system) or in conjunction with a control loop to provide an equilibrium situation with a low level of static charge. Early work in the U.S. and also at Southampton and RAE showed that the principle of a control loop system involving a field mill and active discharger system could be used to maintain helicopters at low levels of static charge. From 1970 a major investigation in conjunction with Shell on tanker cleaning hazards resulted in further work on instrumentation. This also showed the potential value of instruments to indicate charge density and electric field in fuel tanks.

Electric field meters can be used to indicate the approach to a discharge condition. Existing instruments are mainly of the rotating vane type (field mills). Field mill sensors are somewhat bulky, being metal vanes driven by electric motors; and this, coupled with possible spark hazard consideration, has made them rather unsuitable for incorporation into operational fuelling systems, although the A.O. Smith charge density meter operating in liquid fuel has been successful. There is clearly a need for measurement of electric fields within the vapor space of a fuel tank by means of an electrically safe field meter with no moving parts. The authors have therefore developed some prototype electronic field meters for this purpose. The basic design criteria involved in meters of this type, including the relationship between probe size and the specification of the dc amplifier used was explained. A satisfactory specification can be met

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with relatively simple electronic circuits provided care is taken to minimize certain leakage currents. The paper described some prototype meters developed at Southampton University during the last three years, capable of measuring fields in the range from $<10^3$ V/m up to $5 \times 10^5$ V/m. A field of $5 \times 10^5$ V/m can be measured, in one example, using a probe having an area of 2 $cm^2$, with a drift rate $<1\%$ per hour. Since the probe is virtually at earth potential and the hermetically sealed amplifier energized by a low voltage supply, the instrument itself should not present an ignition risk. Work has now begun in conjunction with Admiralty Oil Laboratory on a general study of fuelling phenomena with plastic and metal tanks having capacities of 2,800 gallons.

J. Thompson, de Havilland Aircraft of Canada, presented a paper by Walton and Bootsma summarizing the technique developed at de Havilland for measuring the inner skin surface temperatures of aluminum honeycomb panels using the Aga Thermovision System 680 in conjunction with closed circuit television equipment. The inner skin temperature distribution resulting from a simulated lightning strike on the outer skin is displayed by the Aga equipment in real time. A Color Monitor attachment is used to display the temperature distribution of the inner skin as a series of discrete bands. This display is recorded on magnetic tape via a black and white closed circuit television system. The recording can be played back in real time, slow motion or stop frame on a standard television screen for later evaluation and detail analysis. Two separate reference temperature sources are included in the display. The results following conversion from display units to temperature units can be presented in a number of graphical forms.

Development of the technique was carried out in conjunction with static skin penetration tests using the de Havilland Canada Lightning Strike Simulation facility. Rental of the infrared system was expensive, but the other equipment was on hand. The technique permitted over 150 temperature distributions to be taken in a period of two weeks, thus minimizing rental costs. In these high charge transfer tests on aluminum honeycomb access panels, the maximum temperature reached directly under the strike was usually about 400°C. However in a few test cases the temperature did exceed 600°C. Melting of aluminum skins and hence penetration is required before fuel ignition will occur. The measurement technique was useful to de Havilland in assessing the available temperature margin against penetration of the inner honeycomb skin and hence fuel ignition. The same technique could be applied in the case of single skin construction and for other materials such as titanium and stainless steel. In structures which utilize a titanium or stainless steel skin the procedure should be even more

useful because in such materials the melting point is higher than the
fuel ignition temperature. A fuel explosion can occur without pene-
tration, and it is therefore important to have a reasonably accurate
temperature distribution on the inner surface of the tank during a
lightning strike.

About 10-15% of deaths arising from aircraft accidents are due to fire.
Some years ago a program aimed at producing aircraft fuels which would
resist fire under crash conditions was started in the Materials Depart-
ment, RAE, Farnborough, and was described by S. P. Wilford. It was
assumed that in a "typical" aircraft crash involving fire, fuel tanks
or lines would be ruptured while the aircraft was still moving for-
ward, thereby spilling fuel into a fast moving airstream. Under
these conditions fine mists are formed which are readily ignitable
and may result in large areas of the aircraft being enveloped in flame.
While such mist fires are relatively short lived, they promote con-
tact between major fuel spillages and stray ignition sources even
though these may originally have been relatively remote from one
another. Suppression of mist should therefore markedly reduce the
chance of fire. Other possiblities which were considered were the
reduction of fuel mobility, as in the gels and high-internal-phase
ratio emulsions studied in the U.S., and the reduction of the rate of
flame spread across fuel pools. A number of fuels were developed by
Ministry contractors embodying some of these properties, and it soon
became apparent that a series of antimisting kerosenes developed by
ICI Ltd., Paints Division, offered outstanding fire resistance and
moreover appeared to give rise to fewer handling problems than con-
ventional thickened fuels.

To test the fire resistance of these fuels a ten gallon fuel tank
mounted on a rocket sled is used. The sled is sent down a track at
high speed and decelerated by means of an aircraft arrester wire giving
decelerations of 10-12g. Approximately half the fuel is spilled out
during the deceleration phase onto a series of ignition sources of
various sorts. Conditions in the test have been chosen to be similar
to those in a severe but potentially survivable aircraft crash. A
number of mist-suppressing additives, code named FM4-FM9, all completely
inhibit ignition at concentrations of 0.3% in kerosene. By contrast,
aviation kerosene produces a large fire under these conditions. Less
volatile fuels such as gas oil also produce fires similar to kerosene,
and it is interesting that all the conventional thickened fuels which
have been tested also produce large fires. Even small quantities of
antimisting additives produce large effects on fuel properties and,
as would be expected, give rise to certain problems in engine and
fuel systems. Early fuels were difficult to pump at low temperatures,
but this has been improved until, with FM9, the efficiency of a

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miniature centrifugal pump is nearly 90% as high as with Avtur at
-35°C. Under engine idling conditions deposits have been observed in
combustion chambers, and engine fuel system problems have occurred.
One possible solution to these problems is the controlled degrada-
tion of the additive causing a breakdown in the high molecular weight
polymers of which it consists. Care must be taken, however, to avoid
degradation of safety fuel in the tank since this would result in a
loss of fire resistance. A further problem with certain additives is
the formation of deposits in the presence of water. All these prob-
lems are currently being investigated at RAE and elsewhere.

U.S. papers in the Fuels Session were:

1. Charge Generation by U.S. Commercial Aircraft Fuels and Filter-
Separators, given by W. G. Dukek, Exxon Research and Engineering Co.,
and co-authored by K. H. Strauss, Texaco, and J. T. Leonard, Naval
Research Laboratory.

2. Variables which Influence Spark Production Due to Static Electricity
in Tank Truck Loading, K. C. Bachman, Exxon.

3. Development of Requirements for Aircraft Fuel Tank Explosion
Prevention, R. J. Auburn, FAA.

Also during this session a USAF training film, "Great Balls of Fire,"
was shown. It very dramatically demonstrated the results of static
electricity when combined with careless fuel handling.

## III. STRUCTURES AND MATERIALS

In this session A. W. Hanson, Culham Laboratory, discussed some tech-
niques of strike tests. Due to the nature of the problem, it is not
practical to conduct lightning strike tests on structures, components
and materials by using natural lightning strikes to aircraft in flight.
A series of simulated lightning current tests must therefore be con-
ducted. Clearly the simulated current waveform used should reproduce
the parameters of natural lightning as closely as possible within the
practical limitations of a laboratory test. The various parameters of
natural lightning, namely peak current, maximum di/dt, the total
charge transferred, and $I^2dt$, must be considered separately as each
can be responsible for a different failure mechanism within the speci-
men under test.

Composite waveforms intended to represent a broad spectrum of natural
lightning have been defined by various organizing bodies. Where these
composite waveforms are used, either for experimental or for statutory
reasons, it is frequently useful to conduct additional tests employing

one part only of the composite waveform, or an alternative non-composite waveform. This permits the critical investigation of a suspected weakness, or alternatively, assists in the diagnosis of the nature of the failure mechanism. Examples of this type of application were cited from work conducted at Culham Laboratory.

In specifying the waveforms, and designing the test rigs for a series of tests, consideration must be given to the relevance of: (a) the particular waveform chosen, with respect to the failure mechanism anticipated, (b) the manner in which the test is applied, and (c) the environmental differences between a laboratory test and an aircraft in flight. The high cost of aircraft components and materials often limits the number of tests possible, sometimes to the stringent limit of one test only. It is important therefore that the maximum possible information be obtained from the one shot: the testing equipment must be very reliable as a misfire under these conditions spells disaster. Further problems arise in devising representative dummy loads for ranging shots, or when using new materials with electrical characteristics which may vary under simulated lightning current conditions. Some of the problems encountered in choosing and generating the test currents, simulating a valid environment, and conducting the tests were discussed.

L. N. Phillips, RAE, Farnborough, presented a paper on the effect of simulated lightning strikes on the mechanical strength of carbon fiber reinforced plastic (CFRP) laminates and sandwich panels. It was co-authored by A. C. Cornwell, RAE, and E. L. White and E. N. Jones, Electrical Research Association. Some 150 test panels, consisting of carbon fiber reinforced laminates or sandwich constructions having CFR skins with different metallic or non-metallic cores, were subjected to simulated lightning currents. Variations included type and orientation of fiber, and type of matrix resin used. In some cases various protective metallic layers were added. In general, the lighter protective schemes were metal meshes, with a fine aluminum mesh being the most effective.

Panels were subjected to test currents entering the front surface by a short unswept arc and collected by a metallic contact strip along one edge. Impulsive currents having a duration of 15 μsec and amplitude up to 40 kA caused little apparent damage. Test currents having a duration of 15 msec and peak amplitude of 5 kA and test currents having a duration of 1 sec and amplitude of about 230 A rms, supplied from a 6.6-kV 50-Hz source, were generally more destructive. The amplitudes were chosen with a view to detecting mechanisms of loss of mechanical strength and failure of protective coatings rather than estimating the possible extent of damage by the highest lightning

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currents. From superficial inspection, damaged areas were estimated and subdivided into areas of eroded resin, exposed fibers, lifted fibers, eroded protective coating, etc., a classification which would be applied to a real lightning strike situation.

In the case of solid CFRP panels the damage consisted of a larger or smaller area in which resin degradation and volatilization effectively removed the matrix from the surface layers only. The flexural strength was little reduced by this surface damage. With sandwich panels having thin skins of CFRP the damage extended into the glue-line and adjacent core. Mechanical tests in both compression and bending were designed to estimate the reduction in skin stiffness as the result of lightning strikes by measuring both E and G.

Test techniques in use at Culham were quoted, and included those used for investigation into the effects of arc length, arc root damage, and skin puncture; resistive heating in metallic and non-metallic conductors; magnetic forces; swept stroke effects; and induced voltage effects including sparking.

The U.S. papers in this session were:

1. Lightning Strike Performance of Thin Metal Skin, L. L. Oh and S. D. Schneider, Boeing Co., given by R. O. Brick.

2. Swept Lightning Stroke Effects on Painted Surfaces and Composites of Helicopters and Fixed Wing Aircraft, J. D. Robb, J. R. Stahman, T. Chen, Lightning and Transients Research Institute, and C. P. Mudd, U.S. Army Aviation Systems Command, given by Robb.

3. Electrical Current Flow Damage to Advanced Composites and Integral Protective Composite Concepts, J. L. Perry, Philco Ford Co., given by P. Little of Culham Laboratory.

IV. AIRCRAFT APPLICATIONS

In this session, S. T. M. Reynolds, British Aircraft Corporation, talked about lightning protection of supersonic transport aircraft. The special features of supersonic transport aircraft which govern vulnerability to lightning strikes were discussed in general and with particular reference to the Concorde supersonic transport. This study embraces the flight environment, aircraft shape and the special need to protect flammable systems; it also considers the relationship between the location of vulnerable zones in SST aircraft and the selection of the relevant test parameters.

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The paper described in engineering terms the nature of the design problems and the techniques and results of tests which have contributed to the evolution of solutions on Concorde aircraft. These aspects were explained in relation to fuel storage arrangements, fuel venting and jettison, radome antennae and other excrescences and flying control surfaces. The measures taken to minimize penetration of transient distrubances into electrical wiring were described. Details were also given of the nature and effects of lightning strikes and static discharges which have so far been encountered by Concorde aircraft during the course of development flying.

A. Alric, Aerospatiale, France, presented a summary of studies on bonding requirements and techniques. The word "bonding" is commonly used whenever an electrical path is considered between two parts, but it might be interesting to know that it also applies to an almost insulated joint, yet allowing a very low electrical leak, as well as a good copper braid specially designed for draining an important electrical flow. It is strange enough to discover that very often the right reasons for bonding such or such part are completely unknown. The good old tradition is often the unique rule. In fact, the first instruction, and one of the most important, is not to spend any time, or money, in bonding parts which do not require to be bonded. Some typical examples were discussed, as well as some occasions where unnecessary bonds lead to possible dangerous situations. It was interesting to note here that there are sometimes good reasons for avoiding electrical contact between parts, when galvanic corrosion is suspected for example, or when the intention of the designer is precisely to "discourage" the lightning strike transfer from using certain paths which might be unable to sustain such a stress safely. Two essential qualities are required: (1) achieving the designed conductivity value, and (2) keeping it during the totality of the aircraft life. Surely, the cheapest price and the lowest possible weight are also two important aspects to be considered. For each family of parts, each type of bonding, and each case where bonding is required, the maximum value of the electrical joing must be quoted in a realistic mode. It was therefore proposed that a table listing the values found from experience to achieve and easily maintain throughout the totality of the aircraft life, be established.

With the modern concept of protection against galvanic corrosion and the general use of titanium rivets and bolts for the assembly of light alloy structural parts, the conductivity of the main frame becomes a serious problem. Some typical examples were given, as well as the results of investigations. The introduction of new materials such as carbon fiber composite were also discussed from the bonding aspect.

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O. K. Trunov, National Research Institute for Civil Aviation, USSR,
presented some statistics on damages caused to Aeroflot aircraft by
electrical discharges and gave a comparison between the rate and
intensity of static electricity effects on aircraft with different
aerodynamic geometries. An analysis of 258 cases of lightning effects
on Aeroflot aircraft was made indicating strike distribution accor-
ing to years and type of aircraft.

One of the main signs of lightning strike danger is an area of radar
reflectivity in clouds. It is noteworthy that only 4% of the hazards
occurred with flare spot signal on the airborne radar screen. Flare
spot was registered in only 46% of the cases. In 13% flare spots had
no bearing on thunderstorms and 37% of lightning flare spots indi-
cated thunderstorms at over 10 km off route. The absence of extreme
or even moderate turbulence in the majority of cases when aircraft
were struck by lightning is also typical. Thus, most strikes were
outside thunderstorm clouds.

B. J..C. Burrows, Culham Laboratory, discussed induced voltages,
measurement techniques and typical values. Solid state circuitry is
being increasingly used for aircraft system control, with the conse-
quent low tolerance to large amplitude pulses within the system. It
has been felt for some time that the lightning current flowing in an
aircraft skin can induce voltage pulses of sufficient amplitude to
cause concern. In order to have a better understanding of the complex
nature of the problem, Culham has set up some simple "perfect"
geometries, on which experimental measurements could be made, and
related to mathematical models. Experimental measurements have been
made, using the Culham Lightning Studies Unit facilities, on a circu-
lar cylinder, and on wing shapes. The circular cylinder represents
the ideal case of uniform current distribution with both fast and slow
pulses which results in the simplest mathematical model. A wing has
the biggest difference between fast and slow pulse current distri-
bution and, therefore, represents the worst magnetically enclosed
geometry. The Unit's facilities allow simulation of lightning param-
eter over a very wide range of up to the most severe, e.g., peak
current I = 200 kA, peak di/dt of >100 kA/$\mu$sec, and single pulse charge
transfer of 500 C.

Induced voltage measurements have been made over a wide range of cur-
rent amplitudes and duration, enabling the scaling and time dependence
of induced voltages to be established, including the transitional
stage between the fast pulse current distribution and the "dc" distri-
bution. The penetration or diffusion of magnetic flux through this
skin metal into the interior of the wing has been measured, and also
flux access via a longitudinal opening. In all cases the theoretical
models now available compare satisfactorily with measurements.

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P. J. Sharp, Lucas Aerospace Ltd., five years ago in an article published in the journal, Aircraft Engineering suggested that a number of problems associated with aircraft operation could be due to windscreen static electrification. Laboratory tests had shown that extremely high voltages could be induced in aircraft circuits by electical discharges from windscreen surfaces. More recent tests have demonstrated the manner in which charging of the windscreen surface may take place. These tests have been carried out in a low temperature wind tunnel in which ice crystals have been introduced into the airstream.

Although air crew sometimes have difficulty in differentiating between a lightning strike and a windscreen static discharge, there are flight reports of the latter which vary from visual distraction only to the loss of vital navigation and control equipment in IFR conditions. Because of the susceptibility of modern electrical equipment to high energy transients, the static discharge can present a greater hazard than the direct lightning strike. There are also reports of air crew and ground personnel being severely shocked from static retained by large windscreen and canopy surfaces.

Sharp's paper reviewed the basic problem and the supporting evidence, particularly the wind tunnel tests, during which typical static discharges have been photographed and surface glasses penetrated. The types of failure which can occur are considered in relation to (1) the windscreen, (2) the windscreen circuit, and (3) circuits not associated with the windscreen. Actual examples were detailed. These include an instance when all electrical power was lost and another when the flight deck filled with smoke and an emergency declared. Consideration is also given to a number of instances which were attributed to other phenomena but could, in fact, have been the result of windscreen static electrification. Of the solutions proposed, the two currently in use have electrical conducting coatings applied to the windscreen outer surface and electrical suppression devices connected to the windscreen heating circuits. The advantages and limitations of these solutions were discussed. The possible alternatives to electrical windscreen heating were considered. The conclusion was drawn that for the modern aeroplane, there is none. Research into the phenomenon, particularly the acquisition of flight data, was therefore recommended. If quantitative values can be established for a particular windscreen configuration, realistic test requirements can be formulated for all aircraft electrical equipment likely to be affected.

D. A. Conti, British Aircraft Corporation, presented a paper on radome protection techniques co-authored by R. H. J. Cary, Royal Radar

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Establishment. Lightning strikes to aircraft usually occur at the air-
craft extremities, such as its nose, wing tips, tail and fin tips.
These places are usually the chosen sites for antennas enclosed in
dielectric structures such as radomes, as they often give the best
radiation patterns. Thus radomes are in high risk areas for lightning
strikes, which result in damage to them and the enclosed antenna and
its associated equipment.

Protective measures such as to enclose the radome in a metallic cage
can result in severe radiation degradation. Some degree of compro-
mise is therefore necessary, which gives an acceptable equipment degrada-
tion while maintaining adequate lightning protection. Certain varia-
bles exist in the design of protection techniques to radomes, which
are: (1) the type and dimensions of the protection elements, (2) the
number of these elements, and (3) the distribution of these elements.
The paper discussed these variables and the various types of protec-
tion elements, such as metallic conductors of solid or foil strips,
wires and meshes, or segmented conductors. The behavior of these was
given under simulated tests, on various radome constructions, to the
FAA waveform.

The number and distribution of the elements is critically dependent
upon the electrical strength of the radome. A solid laminate radome
construction has a greater resistance to puncture and will require
fewer protection elements than a thin skin sandwich. Also, a foam
filled sandwich will be better than one honeycomb spaced. The seg-
mented conductor was described with its marked advantage of small
antenna radiation interference but with certain disadvantages. Methods
were described of fixture of lightning protective elements to the
radome which need to be structurally acceptable, without introducing
aerodynamic drag, erosion, and electrical static problems, as well
as acceptable radiation interference. Radome protection against light-
ning is therefore a compromise where a large number of factors must
be considered before a final design is arrived at.

There were three U.S. papers in this session:

1. S.3A Lightning Protection Program: Lightning Effects Analysis,
H. Knoller, Lockheed Aircraft, and J. A. Plumer, General Electric,
given by Plumer.

2. Passive Potential Equalization Between the Cargo Handler and a
Hovering Helicopter, D. G. Douglas and H. E. Nanevicz, SRI, and S. J.
Solak, Boeing, given by Douglas.

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3. Aircraft Applications of Segmented-Strip Lightning Protection Systems, M. P. Amason, G. J. Cassell, J. T. Kung, Douglas Aircraft, given by Cassell.

## V. MISSILES AND SPACECRAFT

Session V was dominated by five U.S. papers to only two European papers. R. J. L. Grard, ESRO-ESTEC, Holland, discussed the effect of ambient medium upon the electric properties of spacecraft surfaces and environment. The electrical properties of the spacecraft environment in the magnetosphere and solar wind are strongly influenced by photon and particle interactions with its surface. Photoemission, and also secondary emission, plays a particular role where the ambient plasma density is reduced to a few particles per $cm^3$. Space and laboratory measurements of electron emission from surfaces were presented followed by a review of the present understanding of the spacecraft sheath profile based on theoretical studies, computer simulation and satellite measurements. The consequences of photoemission and secondary emission for satellite experiments were considered and practical solutions, which could possibly remedy the resulting interferences, were discussed. It was concluded that wave and particle measurements presently made on geostationary and highly eccentric orbits must sometimes be interpreted with caution. It was also emphasized that certain experiments to be performed outside the plasmasphere must be designed with great care when they are likely to be more influenced by the perturbation caused by the spacecraft itself than by the ambient medium which they are intended to probe.

J. Taillet, ONERA, France, talked about the methods for reducing electrostatic hazards in space launches. During the first phase of the flight of a space launcher, electrostatic charges can be produced by a variety of physical mechanism, among which the most important is the charge separation in ionized exhaust gases. In some configurations (highly insulating fairings, staging) these charges can be transferred to an insulated conductor, sometimes after being stored on the surface of a dielectric. This can cause sparking to occur with possibility of jeopardizing the electronic systems - including the guidance computer - and of triggering the pyrotechnic devices. One of the most spectacular accidents of this kind, the failure of the F11 flight of the Europa II launcher, led to the demise of ELDO. A detailed study of that failure was presented. The findings have been incorporated in France's Diamant-BP4 launchers to preclude another catastrophe due to electrostatic charging.

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The usual rules for reducing electrostatic hazards in space launchers
have to be applied also in the case of launchers having insulating
surfaces. These rules comprise a careful shielding and filtering of
the sensitive electronic hardware, and a careful grounding of all the
launcher subsystems. In particular no casing, mechanical stiffener,
metallic socket, connector, screen or winding shall be left un-
grounded. The terminals and the wiring of the internal power supplies
shall be sufficiently insulated for avoiding electrostatic charging by
the onboard equipment.

As a second step, the particular danger revealed by the F11 accident,
i.e., the release of electrostatic energy by internal corona--its
storage on insulating surfaces and its transfer to a possibly over-
looked insulated subsystem--has to be avoided. With this end in view,
the reduction of the time constant relative to the discharge by con-
duction of the insulating surfaces is of prime importance.

The U.S. papers were as follows:

1. Recent Developments in Electrostatics of Spacecraft, R. W. Ellison,
Martin Marietta Aerospace.

2. Electrical Discharges Caused by Satellite Charging at Synchronous
Orbit Altitudes, R. R. Shaw, Aerojet Electrosystems, and J. E. Nanevicz
and R. C. Adamo, SRI, given by Nanevicz.

3. Laboratory Simulation - Study of the Electrostatic Properties of
Liquid Vented from Space Vehicles, Adamo and Nanevicz, SRI, given by
Adamo.

4. Lightning Protection for the Space Shuttle, F. A. Fisher, G.E.

Proceedings of the conference can be obtained for about $32.00 from
The Royal Aeronautical Society, 4 Hamilton Place, London WlV OBQ,
England.