Lightning Protection
To the memory of my father,
Dr. M. Golde,
who taught me to think for myself
and
Sir B. F. J. Schonland, K.B.E., F.R.S.
who transmitted to me his passion
for the flight of thunderbolts
Lightning Protection

R. H. Golde, Dipl. Ing., Ph.D., D.Sc. (Eng.), F.I.E.E.
Preface

The scope of a book with so general a title as lightning protection requires some clarification. To begin with the negative aspect, the protection of electrical supply systems and telephone lines is excluded from consideration. Several text books are available on the former subject and an authoritative statement on the latter is being prepared by the Comité Consultatif International Télégraphique et Téléphonique (CCITT).

While the protection of electrical supply and telephone lines is of interest to specialized engineers only, the protection of buildings is not only the concern of architects, building operators and structural engineers but also of the interested layman and it is to all these groups that this book is addressed. To cover the subject adequately, the term building is not confined to dwellings, offices and factories but includes monuments, telecommunication towers and a miscellany of structures for public and private usage. Explosives factories, mining and tunnelling operations, aircraft and boats are also considered.

In the last resort, protection against lightning is not restricted to the preservation of the fabric of a building but should be concerned with safeguarding human life. Insufficient attention seems to have been paid to this subject and I have found myself confronted with the need to clarify my own mind on the medical problems involved. It is hoped that my endeavours in this direction have enabled me to make this intriguing problem reasonably clear to the interested layman by whom death or injury by lightning is regarded as an act of God.

A genius like Benjamin Franklin could establish the nature of lightning and develop the principle of lightning protection in the course of some 6 or 7 years and then dismiss the entire subject from his mind. A lesser man has to spend a considerable part of his professional life on studying the mechanism of the lightning discharge before applying this knowledge to the protection against its effects. I recall with some nostalgia struggling, while bombs were falling on London during World War II, with the physics of lightning, guided by my colleague Dr. C. E. R. Bruce. Later, I was greatly privileged in being able to discuss these problems with such outstanding men as Sir George Simpson, Sir Basil Schonland and Professor David Malan in Britain and South Africa, Drs. K. B. McEachron and C. F. Wagner in the USA and my honoured friend, Professor Karl Berger.
of Switzerland. In more recent years it was my good fortune to continue these discussions with the younger generation of research workers in different parts of the world.

Two subjects are covered in this book on which I can claim little personal experience. The first is the effect of lightning on trees. For valuable information on this subject I am greatly indebted to Mr. Alan R. Taylor of the US Forest Service, Missoula, Montana, who supplied me with several unpublished reports and who looked critically through Section 10.6. Mr. Taylor was also most helpful in clarifying the information on which Fig. 96 is based.

As already indicated, the second subject concerns the effect of electric currents on the human body. Here it is my particular pleasure to thank my son-in-law, Dr. Max Sussman of the Welsh National School of Medicine of the University of Wales, for collecting a large amount of literature, for explaining patiently many medical concepts, for the original of Fig. 87 and for providing critical comments on Section 12.1. Professor Theodore Bernstein of the University of Wisconsin also provided selected literature and supplied valuable information on lightning casualties in the USA; I also benefited from listening on two occasions to his exposition of this subject. My deepest gratitude is due to Professor W. R. Lee of the University of Manchester whose detailed comments induced me to re-write a large part of Section 12.1 and to whose wide knowledge the final form of this difficult section is largely due.

I am greatly indebted to the British Red Cross Society and Miss B. Wade for permission to describe in detail the recommended method for resuscitation of lightning casualties and for permission to reproduce Figs. 97 and 98. If this presentation assists in saving a single human life the entire book is justified.

Sincere thanks are due to the chairmen and secretaries of the National committees on lightning protection listed in the Appendix, who placed their Codes at my disposal. In particular, mention must be made of Mr. van Alphen, Pretoria, who provided the latest unpublished draft of the South African Code and permitted reproduction of Figs. 37 and 54; Professor H. Baatz, Stuttgart, and the VDE Verlag, Berlin, for permission to reproduce Figs. 34 and 53 as well as Table 10 from the German Code 'Blitzschutz'; Mr. J. M. Clayton, Pittsburgh, who clarified the status of several American documents; Professor T. Horváth, Budapest, who kindly arranged for a translation of the Hungarian Code by Mr. Hosserek of Vienna, and who supplied Fig. 22; Professor S. A. Prentice, Brisbane, who obtained permission for the use of Table 5 from the Australian Code and who supplied the original information on which Fig. 94 is based; Professor E. K. Saraoja, Helsinki, who sent me a partial translation of the
Finnish Code; and, last not least, British Standards Institution for permission to use Figs. 31, 41, 46, 55 and Table 4.

A reader of this book may be surprised at the large number of illustrations copied from other sources. The reason for their inclusion is twofold. In the first place credit should be given where it is due and, secondly, many illustrations are taken from sources which are not easily accessible, sometimes even to the expert. Appreciation is therefore expressed to the following organizations or persons for permission to reproduce illustrations.

Mr. Vesanterä of Helsinki for Plate 3; Professor S. Marinatos, Athens, for Plates 5 and 6; the Surveyor of the University of Oxford and Mr. Thomas for Plate 7; The World Meteorological Organization, Geneva, for Fig. 1; the US Department of Commerce for Fig. 2; the Edison Electric Institute, for Fig. 11; General Electric Review for Fig. 15; the Polish Institute of Electrical Engineers for Figs. 20 and 80; the Elektrotechnische Zeitschrift for Fig. 21; Schweizer Elektrotechnischer Verein for Fig. 24; Institute of Electrical and Electronics Engineers for Figs. 25, 48 and 81; Society of Automotive Engineers, Inc. for Figs. 26, 64 and 76; Endeavour and Dr. R. D. Hill for Fig. 27; the late Professor D. Müller-Hillebrand for Fig. 29; Messrs Dehn und Söhne, Nuremberg, for Figs. 38 and 93; Springer Verlag for Fig. 44; Bell Laboratories for Figs. 45 and 47; Das Gas und Wasserfach for Fig. 49; Independent Broadcasting Authority and Mr. J. A. Thomas for Fig. 59; Erdöl und Kohle-Erdgas-Petrochemie for Fig. 69; the South African Institute of Electrical Engineers for Fig. 72; Imperial Chemical Industries for Fig. 73; Mr. C. L. Perry and the Civil Aviation Authority for Fig. 74; BOAC for Fig. 75; CIGRE for Fig. 77; Electrical Times for Fig. 79; Encyclopaedia Britannica for Fig. 86; Elektrotechnik und Maschinenbau for Fig. 88; and Professor T. Kawamura, Tokyo, for the comprehensive report of the tragic lightning incident illustrated in Fig. 92.

It is a pleasure to express my gratitude to the Electrical Research Association for the opportunity to develop many of the ideas expressed in this book while still a member of their staff. I also wish to express my thanks to my colleagues on the code-drafting committee of BSI whose corporate experience contributed notably to the 1965 edition of the British Code of Practice.

Sincere thanks must be acknowledged to my wife who typed and retyped the manuscript. Last not least, I wish to express my sincere thanks to Mr. L. C. Selwood of my publishers who was at all times prepared to listen to my questions and suggestions.

This is the first book on lightning protection of structures and persons in the English language. Undoubtedly it will contain shortcomings. I shall be grateful to any reader who will be good enough to point these out.
# Contents

Preface v

1 Historical survey 1

2 The thunderstorm 3
   2.1 Global distribution of thunderstorms 3
   2.2 The thundercloud 5
   2.3 Point-discharge currents 7

3 The lightning discharge 9
   3.1 Temporal development of flash to ground 9
   3.2 Strokes to tall structures 12
   3.3 Lightning currents and related parameters 15
   3.4 Frequency of lightning discharges 19

4 The lightning conductor 23
   4.1 Mechanism of strike 23
   4.2 Striking distance 26
   4.3 Protective zone 31
   4.4 Radio-active lightning conductors 37
   4.5 Frequency of strikes to a structure 40

5 Principles of protection 43
   5.1 Need for protection 43
   5.2 Design considerations 48
   5.3 Thermal considerations 51
   5.4 Mechanical considerations 55
   5.5 Electrical considerations 56

6 Materials and dimensions 61
   6.1 Conductors for use above ground 61
   6.2 Conductors for use below ground 64
   6.3 Corrosion 65
x  Lightning Protection

7  Protective systems for domestic, industrial and public structures  68
    7.1  Air-termination network  68
    7.2  Down conductors  75
    7.3  Earth-termination network  83
    7.4  Earth electrodes  89
    7.5  Joints  95
    7.6  Metal components on and in buildings  96
    7.7  Sound and television aerials  100
    7.8  Electricity supply and telephone installations  102
    7.9  Structures with flammable roofs and farm buildings  105

8  Protection of tall structures  108
    8.1  High-rise buildings  108
    8.2  Chimneys and cooling towers  111
    8.3  Churches and monuments  113
    8.4  Telecommunication structures  117

9  Protection of danger structures  123
    9.1  General considerations  123
    9.2  Structures above ground  127
    9.3  Structures below ground  132
    9.4  Mining and blasting  133
    9.5  Aircraft  139
    9.6  Warning devices  144

10 Protection of miscellaneous structures  147
    10.1  Temporary structures  147
    10.2  Mobile structures  149
    10.3  Agricultural objects  150
    10.4  Structures on rock  152
    10.5  Playing fields and public highways  153
    10.6  Trees  157
    10.7  Ships and boats  161

11 Maintenance  164
    11.1  General considerations  164
    11.2  Test methods  166
    11.3  Inspection and records  169
Contents

12 Protection of persons and animals 172
   12.1 Effects of lightning currents 172
   12.2 Protection in the open 181
   12.3 Protection indoors 187
   12.4 Lightning casualties and resuscitation 188

13 Postscript 195

Appendix – National Codes considered in text 198

References 199

Author Index 213

Subject Index 216
1 Historical Survey

'It has pleased God in his Goodness to Mankind, at length to discover to them the Means of securing their Habitations and other Buildings from Mischief by Thunder and Lightning.' With these words Benjamin Franklin introduced in 1753 the first description of the lightning rod. His ideas had been evolved from a careful comparison of various manifestations of the natural lightning discharge and the electric spark and from an ingenious application of the primitive methods of experimentation then available.

The lightning rod spread rapidly through the United States and Europe and, for the next century and a quarter, hundreds of papers and books were published without, however, achieving any substantial progress either in the understanding or the practical execution of lightning protection. A notable advance was achieved in 1881 when the 'Lightning Rod Conference' (Symons, 1882) met in London whose authoritative recommendations were published in the following year and, in revised form, in 1905.

Real progress had to await a better knowledge of the lightning discharge itself. This was made possible primarily through the technical development by Sir Charles Vernon Boys of the rotating camera and by Dufour of the high-speed cathode-ray oscillograph. The Boys' camera enabled Sir Basil Schonland to determine the temporal development of the discharge mechanism while oscillographic recording, particularly by Professor Karl Berger in Switzerland, produced vital information on the wave shape of the lightning current.

Progress in a technical field can, in some respect, be assessed by the issue of national and, later, international specifications or Codes of Practice. The first German recommendations on the lightning protection of buildings were published in 1924, followed in 1929 by the first American Handbook. The first British Code of Practice was issued in 1943 and a greatly revised edition appeared in 1965. This latest edition served as a basis for several recent Codes issued in Australia, India, Rhodesia and South Africa. On the continent of Europe many national recommendations have been published in recent years.
2  Lightning Protection

These various documents differ not only in extent and scope but also, to a certain degree, in specific recommendations and no attempt has been made, so far, at obtaining international agreement. This book reviews modern concepts of lightning protection.
2 The Thunderstorm

2.1 Global distribution of thunderstorms

In accordance with international convention, thunderstorm activity is being recorded by Meteorological Offices throughout the world on the basis of days 'with thunder heard'. For anyone who has to reach a decision on whether or not to protect a building against lightning this is a poor guide. In a temperate region, a wide frontal thunderstorm may pass a given district within a few minutes or it may remain stationary for several hours. In tropical areas, thunder emanating from a stationary cloud covering no more than a few square kilometres of country may be heard over 1500 square kilometres, thus giving a grossly exaggerated record of thunderstorm activity.

A reliable assessment of the need for lightning protection requires knowledge of the frequency of lightning flashes to earth. Numerical information available on this value will be seen to be inadequate (Section 3.4). Until more reliable information has been accumulated, the best possible use must, in these circumstances, be made of data from Meteorological Offices.

Fig. 1 shows the global distribution of thunderstorms as prepared by the World Meteorological Organization (1956). The lines which connect places having the same number of thunderstorm days are called isokeraunic lines and the average annual number of thunderstorm days at a given place is called isokeraunic level.

As can be seen from Fig. 1, the number of thunderstorm days is highest about the equatorial belt and decreases towards the poles and it is higher over land masses than over oceans (Sparrow and Ney, 1971). Local thunderstorm activity can vary considerably from year to year but attempts to detect a periodicity have so far been unsuccessful. Long-time statistics are therefore required to establish reliable information on thunderstorm activity at any particular place. Seasonal and diurnal variations are pronounced but these are of no importance for the lightning protection of structures although they may have to be considered in special circumstances, such as the handling of explosive mixtures or underground blasting operations.

Detailed thunderstorm maps are available for many countries and these are usually prepared by Meteorological Offices or sometimes by
Fig. 1 Annual frequency of thunderstorm days (World Meteorological Organization, 1956)
organizations responsible for aviation or research. Such maps are occasionally incorporated in national codes for the lightning protection of structures.

2.2 The thundercloud

Thunderstorms can be conveniently subdivided into two main classes: heat storms and frontal storms. The heat or convective storm predominates in the tropics but also frequently occurs in mountainous areas. It is due to the fact that, on a hot day, warm air rises from patches of ground and is replaced by colder air drifting down. As the hot air rises it is progressively cooled and forms a cloud consisting first of water droplets and, at greater heights, of ice crystals. In this way a single or multiple cloud 'cell' is formed the top of which may reach a height of 12 km.

Frontal storms which predominate in temperate regions are caused by the impact of a front of cold air on a mass of warm moist air which is lifted above the advancing cold front. As the warm air rises the process described above is repeated but the resulting cumulo-nimbus clouds may in this case extend over several tens of kilometres in width and contain a large number of individual cells.

The mechanism by which a cloud becomes electrically charged is not yet fully understood but it can be taken to be associated with the violent updraught of air in the centre of a cell and the resulting impact of super-cooled water droplets on ice crystals (Workman, 1967). Each cell has a diameter of several kilometres and undergoes a life cycle lasting some 30 minutes during which electric charges are generated and lightning activity continues until the charging mechanism is exhausted (Byers and Braham, 1949). In any frontal storm several cells may be active at the same time and the total duration of a thunderstorm can amount to several hours.

The mature state of a typical thunderstorm cell is illustrated in Fig. 2. It shows, in an idealized form, the distribution of rain droplets, snow flakes and ice crystals as well as the strong up- and down-draughts which are conveniently utilized by glider pilots but which have also endangered the lives of early balloonists.

The ice crystals in an active cloud are positively charged while the water droplets usually carry negative charges. A thundercloud thus contains a positive charge centre in its upper region and a negative charge centre in the lower parts. Electrically speaking, this constitutes a dipole, the various consequences of which are discussed in later Sections. Occasionally, but by no means invariably, an additional concentrated region of positive charge is found near the lower leading edge of a moving cloud.

For the purpose of numerical evaluation of the electric field produced
by cloud charges, these can be regarded as concentrated in two points. On this understanding, the centre of the upper positive charge is found to be situated at a height of about 6 km above ground and that of the lower negative charge at about 2.5 km (Bruce and Golde, 1941). These values have been determined for storms in Britain and may be regarded as typical for temperate regions. In the tropics, corresponding values are 10 km and 5 km respectively (Chalmers, 1967).
The total charge in a cell has been estimated at 1000 coulombs, distributed over a space of 50 km³.

2.3 Point-discharge currents

In undisturbed fine weather, the earth which is an electrical conductor carries a negative charge. The corresponding positive charge resides in the upper atmosphere. This layer and the earth thus represent a large spherical condenser. The intermediate atmosphere is subjected to an electric field which is perpendicular to the earth surface. According to convention this fine-weather field has positive polarity and its magnitude is 100 V/m (Malan, 1963).

As shown in the preceding Section, a thundercloud carries, in its lower part, a heavy negative charge. When such a cloud approaches a given point of the earth's surface the polarity of the electric field is reversed and this characteristic feature can be utilized to give a warning of an approaching thundercloud (Section 9.6).

The magnitude of the electric field is highest vertically below the negative charge centre and rapidly decreases with increasing distance. The negative field may reach a value exceeding 20,000 V/m and, even at a distance of 5 km from a cloud centre, it may still amount to 5000 V/m.

A vertical electrical conductor, such as a metallic flagpole or a lightning rod, short circuits part of this electric field so that an intense field concentration is produced at its tip (Fig. 3). If the field strength at the tip is high enough, ionization by collision occurs and this leads to positive ions being transported from the earth through the conductor into the atmosphere. The resulting current is called a point-discharge current.
8 Lightning Protection

(Chalmers, 1967). The ions produced at or near the tip of the earthed conductor move upwards in the prevailing electric field. However, at some small distance above the point, their velocity becomes small compared with that of the high wind speeds below a thundercloud. The ion movement is thus largely governed by the gustiness of the wind so that pockets of positive space charge are formed in the atmosphere. Point-discharge currents and the resulting space charges play an important part in the development of the lightning discharge and in the action of a lightning conductor.

The amplitude of the point-discharge current is a function of the magnitude of the electric field, of the height above ground level of the conductor by which it is produced and of wind velocity. For a conductor of several tens of metres height standing in open country the current amounts to a few microamperes. In mountainous areas where thundercloud fields are intense the currents may reach a few milliamperes (Berger, 1965). They can persist for lengthy periods according to the speed of movement of the thundercloud, a time of half an hour being typical.

Point-discharge currents are also produced by natural growth, such as trees, grass blades or even sharp rocks and stones. They occur furthermore on man-made conducting structures, like buildings, the metal towers of electrical transmission lines or ships' masts. In the last case they were well known to mariners of old by whom they were termed 'St. Elmos' Fire' after the patron saint of Mediterranean sailors (Schonland, 1964). In the high mountains the same type of discharge can be seen in darkness at the tips of mules’ ears or the raised finger tips of men's hands. While harmless in themselves, they are indicative of a highly charged atmosphere and mountaineers are well aware of the risk of sudden lightning strikes once these point-discharge currents have developed.
3 The Lightning Discharge

3.1 Temporal development of flash to ground

As shown in Section 2.2, the typical thundercloud carries positive charges in its upper part and negative charges below. Electric fields thus exist between these charges, as well as below and above them. When a round water droplet is exposed to an electric field it becomes elongated in the direction of the field and, as indicated in Fig. 4, tiny charges of equal and opposite polarity accumulate at its tips according to the principles of electrostatic induction. As the droplet is further elongated point-discharge processes can be initiated at its tips. Millions of water droplets can be subjected to this process more or less simultaneously and the

![Diagram of increasing field and charges](image)

Fig. 4 Induction and deformation of water droplets in increasing electrostatic field resulting tiny discharges can coalesce into larger discharge channels. It is in this way that a lightning discharge is thought to be initiated in a cloud (Malan, 1963).

Detailed knowledge of what happens further is largely due to the invention by Sir Charles Vernon Boys (1926) of the rotating camera. It consists essentially of two lenses rotating at high speed in opposite directions about a horizontal axis. If an object dropping from the sky was photographed with such a camera, the traces of its fall would be deflected sideways in opposite directions by the two lenses respectively and by superposition of the two images the direction of movement of the object and its speed could be determined. As a tribute to the inventor's perseverance and as an encouragement to future research workers a facsimile is
Lightning Protection

shown on Plate 1 of an extract from a letter written by Sir Charles to the author shortly before his death.

The Boys’ camera was first used successfully by Schonland (1933) and his co-workers in South Africa and later by research workers in the USA (Hagenguth, 1940), USSR (Stekolnikov and Valeev, 1937), Switzerland (Berger, 1955) and other countries. From all the available data, it appears that the development and the characteristic parameters of lightning flashes to open ground in different parts of the world are essentially the same although the numerical values of each individual parameter vary over a certain range. The statistical distribution of the frequency of occurrence of most of these parameters is reasonably well established (Uman, 1969) but, for the purposes of lightning protection, representative and maximum values need only be quoted in most cases.

Plate 1 Extract from a letter of Sir Charles Vernon Boys, dated 26 January 1944

A lightning discharge (Schonland, 1956) to open ground starts invariably in the cloud. It becomes visible on penetrating its lower boundary and it then progresses towards earth as a faintly luminous discharge, called the leader stroke. If photographed by a camera the lens of which is moving from left to right, the leader stroke would appear as shown schematically on the left of Fig. 5. It is usually heavily branched and, as the great majority of leaders originate from negatively charged cloud centres and are thus themselves negatively charged, these branches are attracted by positive charge pockets floating in the air as mentioned in Section 2.3.

The leader channel and its branches are extended towards earth in discrete steps of about 20 m length but there is some evidence (Malan, 1963) that these lengthen as the leader approaches the ground. Such discharges are called stepped leaders. The most frequent velocity of movement of the leader tip is between $10^2$ and $2 \times 10^3$ m/s, that is, less than one thousandth of the speed of light which amounts to $3 \times 10^8$ m/s. The cur-
rent in the leader is estimated at several hundred amperes (Bruce, 1944) and the charge deposited along its whole length is likely to vary between a fraction of 1 coulomb and 10 coulombs or slightly more.

When the faint lightning leader channel reaches the ground, intense luminosity is seen to travel upwards along its path towards the cloud and along its branches. This is termed the return stroke. In effect, this constitutes an electric short circuit between the negative charge deposited along the leader and the electrostatically induced positive charge in the ground. The velocity of the return stroke decreases from ground to cloud but initially amounts to $10^8$ m/s, the most frequent average value over its full length being $3.5 \times 10^7$ m/s, which is about one tenth the speed of light or a hundred times faster than that of the leader.

The leader and return-stroke process as described may complete the visible part of the lightning discharge. However, after a certain time interval, a second leader stroke, followed by a return stroke, may occur. This subsequent stroke usually follows the path taken by the first stroke with the exception that it shows no branching. In contrast to the first leader, a subsequent leader is not stepped and is much faster; it is therefore called a dart leader.

The process of dart leader and return stroke can be repeated several times. Each such component is termed a stroke while the complete process of successive strokes is termed a multi-stroke flash, or briefly a lightning flash. A lightning flash can thus consist of a single stroke or a sequence of several discrete strokes. As a rule, all subsequent strokes follow the path blazed by the first stroke but in high wind the entire channel can be blown sideways, thus giving a picture of several parallel luminous ribbons; this is called ribbon lightning. Very occasionally, and
particularly after an unusually long time interval, a later stroke may deviate from the original path near the ground. The same lightning flash then strikes at more than one point. Plate 2 shows a rare case in which lightning strikes at three different points; note also the clear effect of ribbon lightning (Golde, 1949).

The relative frequencies of single-stroke and multi-stroke flashes differ in different parts of the world and there is strong evidence to suggest that, while single-stroke flashes predominate in temperate regions, multi-stroke flashes are much more frequent in tropical storms. Thus the most frequent number of component strokes in Britain is between 1 and 2, but it is 4 in South Africa. The highest value recorded photographically in the USA amounts to no less than 26 component strokes in a single flash (Workman et al, 1960).

Time intervals between component strokes may vary from 3 to 100 ms, with 40 ms constituting a typical value. The total duration of a lightning flash is thus primarily determined by the number of component strokes. Thus the aforementioned flash with 26 strokes lasted 2 s but durations exceeding one second are rare. A representative value may be 200 ms.

Fig. 5 which is not drawn to scale shows a time-resolved picture of a multiple earth flash as seen by a camera moving from left to right. The interested observer will have no difficulty when watching a thunderstorm in recognizing a multiple flash by the flicker of its luminosity while the keen photographer can with luck obtain evidence of multiple lightning flashes by moving his camera with open shutter sideways about a vertical axis.

The account given so far is concerned with negative lightning flashes, that is flashes conveying negative charge from cloud to ground. This comprises some 95 per cent of all earth flashes and even more in tropical storms. Only scanty information is available about the characteristics of positive lightning discharges. Despite differences in the development of the initial leader stroke, the leader-return process is the same in positive and negative discharges to open ground, with the one important difference that positive flashes usually consist of a single stroke and seem to occur towards the end of a storm, when the upper positive cloud charge may be discharged to earth in one stroke which is often of exceptional severity (Berger and Vogelsanger, 1965).

3.2 Strokes to tall structures

The development of the lightning discharge described in the preceding Section refers to the normal flash as it occurs over open ground. A different development was first observed in rotating-camera photographs of
Plate 2 Lightning striking at three points

Plate 3 Lightning strike to unprotected chimney (Courtesy Mr. Vesanterä)
lightning flashes to the Empire State Building in New York which has a height of 380 m (1250 feet) above street level (McEachron, 1939). Later, similar processes were recorded on tall structures in the Alps and in South Africa. This alternative mechanism of a lightning discharge results in a high concentration of strikes to such structures and, having regard to the increasing height of modern buildings and communication or cooling towers, attention must be paid to this phenomenon in lightning protection.

Much of present knowledge on this type of discharge has become available from the work of Berger (1967) on Mount San Salvatore, a conical peak rising to the height of 640 m (2100 feet) above Lake Lugano in Switzerland. Two tall lattice-steel towers, respectively at and near the peak, serve as focal points of the best equipped lightning observatory in the world.

In about one quarter of all lightning strikes to these towers, the development of the discharge process follows the pattern described in Section 3.1 and illustrated in Fig. 5. In the majority of strikes, however, the mechanism is as depicted schematically in Fig. 6. In these cases the discharge is initiated at the tip of the tower in the form of a faintly luminous upward growing leader channel which is heavily branched towards the cloud. In contrast to the normal downward leader stroke, this upward leader is, however, not followed by a return stroke. It may either exhibit gradually diminishing luminosity or it may be followed by one or more subsequent strokes. If such subsequent strokes occur, they revert to the ‘normal’ pattern of downward dart leader, followed by an upward return stroke.

The reversal in the direction of the initiating leader stroke is due to the high field concentration at the tip of a very tall structure such as the

Fig. 6 Temporal development of flash initiated at tip of tall tower as recorded by camera moving from left to right
References


ALLIBONE, T. E. 'Electric breakdown at high voltages.' The University of Strathclyde (1967).


BERNSTEIN, T. 'The effects of lightning and electrical shocks on the human body and animals.' Am. Ass. for the Advancement of Science, Philadelphia (1971).
BERNSTEIN, T. 'Effects of electricity and lightning on man and animals.' J. of Forensic Sciences, in print.
BODLE, D. 'Electrical protection guide for land-based radio facilities.' Joslyn Electronic System, Goleta, California.


BSI (British Standards Institution), Code of Practice, CP 1013, 'Earthing', (1965).

BSI (British Standards Institution), Code of Practice, 'Cathodic protection', (draft).


BÜRKEN, A. 'Blitzschutz bei Seilbahnen.' Int. Blitzschutzkonferenz, Lugano (1967).


COLEMAN, T. H. 'Lightning.' Pennsylvania Medicine, 72, 56–58 (1969).


Golde, R. H. 'The frequency of occurrence and the distribution of lightning flashes to transmission lines.' *Trans. AIEE*, 64, 902–910 (1945).


Hagenguth, J. H. 'Lightning stroke damage to aircraft.' *Trans. AIEE*, 68, 1036–1046 (1949).


HODGKIN, B. C., LANGWORTHY, O. R., KOUWENHOVEN, W. B. ‘Effect on breathing of an electric shock applied to the extremities.’ Trans. AIEE, paper No. T 72 087 (1972).


References 205

KOUWENHOVEN, W. B. and LANGWORTHY, O. R. 'Effect of electric shock.' JAIEE, 49, 381–394 (1930).

LEONARD, G. K. 'Lightning strikes on the job in Apalachia tunnel.' Civil Engineering, 15, 545–547 (1945).
LIEBHART, M. Private communication (1966).
Lightning Protection


PERRY, B. L. 'Lightning strike hazards and requirements.' *Lightning and Static Electr. Conf.*, Miami (1968).


PETROPOULOS, G. M. 'The high-voltage characteristics of earth resistances.' *JIEE*, 95, pt. II, 59–70 (1948).


PIERC'E, E. T. 'Triggered lightning and some unsuspected lightning hazards.' Am. Ass. for the Advancement of Science, Philadelphia (1971).


SAMULA, J. 'The electric strength of concrete and brick under impulse voltages.' (in Polish), Acta Technica Gedanensia, No. 2 (1963 a).


SCHNELL, P. 'Blitzkatastrophe in einem Aussichtsturm.' Dehn & Söhne, Nuremberg (1960).


Schweizerische Unfallversicherungsanstalt 'Unfallverhütung bei Sprengarbeiten unter Anwendung der elektrischen Zündung.' Form. 1708d (1965).


SHIPLEY, J. F. 'The protection of structures against lightning.' JIEE, 90, 501–523 (1943).


SPILSBURY, Sir B., JELLINEK, S., CUMBERBATCH, E. P. 'The pathological
changes produced in those rendered unconscious by electrical shock and the treatment of such cases.' Arch. Radiology and Electrotherapy, 27, 316–319 (1923).


Transvaal and Orange Free State, 'Safety code.' Chamber of Mines (1964).
References


VIEL, G. 'Détermination des zones exposées à la foudre au moyen de mesures de la conductibilité électrique de l'air.' CIGRE, report No. 307 (1935).

WALTER, B. 'Von wo ab steuert der Blitz auf seine Einschlagstelle zu?' Z. für techn Physik, 18, 105–109 (1937).

WEEKS, A. W., ALEXANDER, L., DENNIS, R. M. 'The distribution of electric current in the animal body: an experimental investigation of 60 cycle alternating current.' J. Ind. Hygiene and Toxicology, 21, 517–525 (1939).


WORKMAN, E. J. 'The production of thunderstorm electricity.' J. Franklin Institute, 283, 540–557 (1967).


World Meteorological Organization, 'World distribution of thunderstorm days.' WMO, Geneva, No. 21 (1956).

WORMELL, T. W. 'Effects of thunderstorms and lightning discharges on the earth's electric field.' Phil. Trans., A, 238, 249–303 (1939).

**Author Index**

<table>
<thead>
<tr>
<th>Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akopyan, A. A.</td>
<td>177, 199</td>
</tr>
<tr>
<td>Alexander, L.</td>
<td>211</td>
</tr>
<tr>
<td>Alimamedov, M. S.</td>
<td>90, 211</td>
</tr>
<tr>
<td>Allibone, T. E.</td>
<td>23, 25, 199, 209</td>
</tr>
<tr>
<td>Anderson, J. G.</td>
<td>24, 199, 209</td>
</tr>
<tr>
<td>Anderson, R.</td>
<td>33, 44, 162, 199</td>
</tr>
<tr>
<td>Anderson, R. B.</td>
<td>22, 41, 199</td>
</tr>
<tr>
<td>Arden, G. P.</td>
<td>186, 199</td>
</tr>
<tr>
<td>Armitage, E. R.</td>
<td>199</td>
</tr>
<tr>
<td>Bautz, H.</td>
<td>22, 59, 199</td>
</tr>
<tr>
<td>Baeckmann, von W. G.</td>
<td>94, 95, 199</td>
</tr>
<tr>
<td>Barthum, R. A.</td>
<td>199</td>
</tr>
<tr>
<td>Bartak, A. J. J.</td>
<td>118, 199</td>
</tr>
<tr>
<td>Belluschi, P. L.</td>
<td>89, 199</td>
</tr>
<tr>
<td>Berger, K.</td>
<td>8, 10, 12, 14, 15, 16, 18, 19, 20, 21, 26, 37, 40, 51, 89, 103, 134, 136, 177, 184, 199, 200</td>
</tr>
<tr>
<td>Bergmann, W.</td>
<td>44, 200</td>
</tr>
<tr>
<td>Berko, G.</td>
<td>38, 200</td>
</tr>
<tr>
<td>Bernstein, T.</td>
<td>181, 187, 189, 200</td>
</tr>
<tr>
<td>Bieglmeyer, G.</td>
<td>177, 178, 200</td>
</tr>
<tr>
<td>Birchby, G.</td>
<td>118, 200</td>
</tr>
<tr>
<td>Blümchen, H.-J.</td>
<td>56, 113, 200</td>
</tr>
<tr>
<td>Bodle, D.</td>
<td>121, 200</td>
</tr>
<tr>
<td>Boyce, C. F.</td>
<td>208</td>
</tr>
<tr>
<td>Boys, Sir C. V.</td>
<td>9, 200</td>
</tr>
<tr>
<td>Bragg, K. R.</td>
<td>126, 200</td>
</tr>
<tr>
<td>Brathwaite, R. R.</td>
<td>5, 6, 201</td>
</tr>
<tr>
<td>Bredland, G. J.</td>
<td>142, 201</td>
</tr>
<tr>
<td>Brick, R. O.</td>
<td>54, 201</td>
</tr>
<tr>
<td>Briclley, A. E.</td>
<td>150, 201</td>
</tr>
<tr>
<td>Brighwell, A. H.</td>
<td>180, 201</td>
</tr>
<tr>
<td>Brook, M.</td>
<td>204, 211</td>
</tr>
<tr>
<td>Brown, G. W.</td>
<td>22, 31, 201</td>
</tr>
<tr>
<td>Bruce, C. E. R.</td>
<td>6, 11, 23, 27, 30, 201</td>
</tr>
<tr>
<td>Bruckmann, G.</td>
<td>44, 201</td>
</tr>
<tr>
<td>Bryant, J. M.</td>
<td>143, 201</td>
</tr>
<tr>
<td>Burda, C. D.</td>
<td>174, 201</td>
</tr>
<tr>
<td>Burkhard, G.</td>
<td>73, 201</td>
</tr>
<tr>
<td>Bürkner, A.</td>
<td>150, 201</td>
</tr>
<tr>
<td>Byers, H. R.</td>
<td>5, 6, 201</td>
</tr>
<tr>
<td>Cassie, A. M.</td>
<td>40, 201</td>
</tr>
<tr>
<td>Chalmers, J. A.</td>
<td>6, 8, 139, 201</td>
</tr>
<tr>
<td>Chestnut, R. W.</td>
<td>205</td>
</tr>
<tr>
<td>Coleman, T. H.</td>
<td>191, 201</td>
</tr>
<tr>
<td>Collins, H.</td>
<td>30, 206, 209</td>
</tr>
<tr>
<td>Colton, F. B.</td>
<td>156, 201</td>
</tr>
<tr>
<td>Cumberbatch, E. P.</td>
<td>210</td>
</tr>
<tr>
<td>Dale, R. A.</td>
<td>133, 202</td>
</tr>
<tr>
<td>Dalziel, C. F.</td>
<td>172, 176, 177, 180, 202</td>
</tr>
<tr>
<td>Dauzere, C.</td>
<td>20, 202</td>
</tr>
<tr>
<td>Davis, D.</td>
<td>187, 206</td>
</tr>
<tr>
<td>Davis, R.</td>
<td>144, 202</td>
</tr>
<tr>
<td>Defandorf, F. M.</td>
<td>159, 202</td>
</tr>
<tr>
<td>Dehn, R.</td>
<td>62, 202</td>
</tr>
<tr>
<td>Dennis, R. M.</td>
<td>211</td>
</tr>
<tr>
<td>Dytkowski, E.</td>
<td>210</td>
</tr>
<tr>
<td>Ellis, H. M.</td>
<td>21, 202</td>
</tr>
<tr>
<td>Fagan, E. J.</td>
<td>92, 94, 202</td>
</tr>
<tr>
<td>Fassett, W. M.</td>
<td>141, 202</td>
</tr>
<tr>
<td>Ferris, L. B.</td>
<td>176, 202</td>
</tr>
<tr>
<td>Fisher, C. T.</td>
<td>156, 202</td>
</tr>
<tr>
<td>Fitzgerald, D. R.</td>
<td>139, 202</td>
</tr>
<tr>
<td>Fourestier, J. P.</td>
<td>200</td>
</tr>
<tr>
<td>Franklin, B.</td>
<td>1, 26, 31, 202</td>
</tr>
<tr>
<td>Frischenschlager, J.</td>
<td>137, 202</td>
</tr>
<tr>
<td>Fritsch, V.</td>
<td>44, 93, 202, 203</td>
</tr>
<tr>
<td>Fuquay, D. M.</td>
<td>158, 160, 203</td>
</tr>
<tr>
<td>Geddes, L. A.</td>
<td>177, 203</td>
</tr>
<tr>
<td>Gillespie, P. J.</td>
<td>208</td>
</tr>
<tr>
<td>Golde, R. H.</td>
<td>6, 12, 16, 20, 21, 22, 26, 27, 41, 51, 102, 136, 145, 187, 201, 203, 206</td>
</tr>
<tr>
<td>Goyer, G. G.</td>
<td>160, 203</td>
</tr>
<tr>
<td>Gurvich, N. L.</td>
<td>199</td>
</tr>
<tr>
<td>Haggencuth, J. H.</td>
<td>10, 21, 53, 54, 143, 149, 203, 206</td>
</tr>
<tr>
<td>Harding, G.</td>
<td>93, 204</td>
</tr>
<tr>
<td>Harrington, D.</td>
<td>133, 204</td>
</tr>
<tr>
<td>Harris, C. A.</td>
<td>93, 204</td>
</tr>
<tr>
<td>Harrison, L. H.</td>
<td>204</td>
</tr>
<tr>
<td>Harrison, S. H.</td>
<td>199</td>
</tr>
<tr>
<td>Hauf, R.</td>
<td>174, 204</td>
</tr>
<tr>
<td>Haufe, K.</td>
<td>156, 204</td>
</tr>
<tr>
<td>Hawe, R. G.</td>
<td>203</td>
</tr>
<tr>
<td>Hellmann, G.</td>
<td>188, 204</td>
</tr>
<tr>
<td>Hill, E. L.</td>
<td>208</td>
</tr>
<tr>
<td>Hill, R. D.</td>
<td>55, 56, 204</td>
</tr>
<tr>
<td>Hodgkinson, B. C.</td>
<td>172, 204</td>
</tr>
<tr>
<td>Horvath, T.</td>
<td>42, 204</td>
</tr>
<tr>
<td>Hösl, A.</td>
<td>77, 113, 159, 164, 204</td>
</tr>
<tr>
<td>Howard, J. R.</td>
<td>180, 208</td>
</tr>
<tr>
<td>Irany, J.</td>
<td>174, 204</td>
</tr>
<tr>
<td>Irany, K.</td>
<td>174, 204</td>
</tr>
<tr>
<td>Israel, H.</td>
<td>151, 204</td>
</tr>
<tr>
<td>James, T. E.</td>
<td>54, 204</td>
</tr>
<tr>
<td>Jellinek, S.</td>
<td>210</td>
</tr>
<tr>
<td>Jenner, R. D.</td>
<td>199</td>
</tr>
</tbody>
</table>
Author Index

Johnson, I. B., 209
Jones, P. H., 200

Kay, C. F., 177, 209
Keeley, K. J., 204
Kimmel, C. C., 200
King, B. G., 202
Kinelev, A. P., 176, 204
Kitagawa, N., 17, 204, 211
Klachko, D. M., 204
Kleinot, S., 174, 204
Knickerbocker, G. G., 205, 206
Knowles, P., 208
Koch, W., 64, 87, 205
Koeppen, S., 174, 205
Kouwenhoven, W. B., 172, 176, 191, 204, 205, 206
Kuo, C. J., 201
Kürschner, E., 81, 205

Lane, R., 208
Langworthy, O. R., 172, 204, 205
Laurent, P.-G., 109, 205
Leavitt, P. R., 206
Lee, R. H., 93, 94, 202
Lee, W. R., 172, 176, 177, 180, 202, 205
Lehmann, G., 101, 205
Lemieux, J. E. R., 103, 205
Leonard, G. K., 133, 205
Liebhart, M., 187, 205
Linck, H., 202
Lister, J., 199
Lodge, Sir O. J., 32, 205
Lunquist, S., 82, 205
Lynch, M. J. G., 185, 205

McEachron, K. B., 14, 30, 53, 206
Maclachlan, W., 172, 206
Maksiejewski, J. L., 37, 206
Malan, D. J., 7, 9, 10, 15, 30, 206
Marinatos, S., 114, 206
Markels, M., 127, 206
Marshall, C. A., 135, 206
Matsumoto Fukashi, 186, 206
Maudsley, R. H., 199
Maxwell, J. C., 60, 206
Maxwell Cade, C., 187, 206
Meister, H., 103, 206
Mickwitz, von G., 205
Milnor, W. R., 176, 177, 205, 206
Moore, C. B., 146, 206
Morikawa, S., 172, 206
Morris, W. A., 30, 206
Morris, W. G., 158, 207
Moxon, R. L., 118, 200
Müller-Hillebrand, D., 38, 39, 42, 59, 207

Negovski, V. A., 199
Neuhaus, H., 101, 207
Newman, M. M., 139, 141, 201, 207, 208
Ney, E. P., 3, 209

Orovecz, B., 204
Orville, R. E., 51, 207
Oszypka, P., 176, 177, 205, 207
Otterbein, H., 118, 207

Parker, D. J., 204
Patterson, J. H., 183, 207
Peleska, B., 177, 207
Penton, A. P., 202
Perry, B. L., 139, 140, 143, 207
Peters, G., 175, 207
Petropoulos, G. M., 86, 89, 207
Philpott, J., 54, 204
Pierce, E. T., 19, 140, 145, 207, 208
Plumer, J. A., 202
Popolansky, F., 22, 42, 44, 208
Prentice, S. A., 145, 188, 208
Price, W. S., 209
Prinz, W., 199
Provoost, P. G., 32, 208

Quiniivan, J. T., 201

Ramsey, F. K., 180, 208
Ramsey, I. C., 208
Ramsey, N. W., 208
Ravitch, M. M., 191, 208
Rettel, D. P. J., 102, 103, 208
Roach, C. L., 120, 208
Robb, J. D., 126, 141, 142, 201, 206, 207, 208
Roberts, J. E., 39, 208
Roguski, Z., 110, 208
Rotter, K., 177, 178, 200
Ruedy, R., 20, 151, 208
Ryder, R. W., 155, 208
Ryzko, H., 126, 208

Safar, P., 208
Samula, J., 99, 158, 209, 210
Sass, D. J., 205
Schamroth, L., 174, 209
Schliemann, R. H., 22, 209
Schmid, C. W., 160, 203, 209
Schneider, R., 187, 209
Schnell, P., 183, 188, 209
Schonland, Sir B. F. J., 8, 10, 21, 23, 60, 114, 160, 179, 209
Schwan, H. P., 177, 209
Schwenkhausen, H. F., 75, 200, 209
Screase, F. J., 211
Shears, M., 118, 199
Shipley, J. F., 45, 209
Shorthouse, F. H., 185, 205
Shreeve, L. L., 65, 209
Singer, S., 187, 209
Snowden, A. E., 199
Solak, B. J., 144, 209
Somogyi, E., 204
Sparrow, J. G., 3, 209
Spence, P. W., 202
Spilsbury, Sir B., 172, 210
Spurlock, J. M., 206
<table>
<thead>
<tr>
<th>Author</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stahmann, J. R.</td>
<td>141, 206, 208, 210</td>
</tr>
<tr>
<td>Standring, W. G.</td>
<td>144, 202</td>
</tr>
<tr>
<td>Steen, H.</td>
<td>124, 210</td>
</tr>
<tr>
<td>Steichen, F. M.</td>
<td>172, 206, 208</td>
</tr>
<tr>
<td>Steinseifer, F.</td>
<td>183, 209</td>
</tr>
<tr>
<td>Stekolnikov, I. S.</td>
<td>10, 210</td>
</tr>
<tr>
<td>Suchocki, J.</td>
<td>210</td>
</tr>
<tr>
<td>Sund, E. D.</td>
<td>89, 93, 210</td>
</tr>
<tr>
<td>Symons, G. J.</td>
<td>1, 210</td>
</tr>
<tr>
<td>Szpor, S.</td>
<td>42, 106, 107, 159, 210</td>
</tr>
<tr>
<td>Tacker, W. A.</td>
<td>177, 203</td>
</tr>
<tr>
<td>Tagg, G. F.</td>
<td>89, 210</td>
</tr>
<tr>
<td>Tangen, K. O.</td>
<td>24, 199</td>
</tr>
<tr>
<td>Taussig, H. B.</td>
<td>174, 175, 189, 191, 210</td>
</tr>
<tr>
<td>Taylor, A. R.</td>
<td>158, 160, 203, 210</td>
</tr>
<tr>
<td>Temyachol, S.</td>
<td>205</td>
</tr>
<tr>
<td>Thaden, von H.-W.</td>
<td>131, 210</td>
</tr>
<tr>
<td>Thomas, J. A.</td>
<td>118, 210</td>
</tr>
<tr>
<td>Tomanek, K.</td>
<td>44, 210</td>
</tr>
<tr>
<td>Trueblood, H. M.</td>
<td>21, 210</td>
</tr>
<tr>
<td>Turner, J. W.</td>
<td>183, 207</td>
</tr>
<tr>
<td>Ufer, H. G.</td>
<td>92, 211</td>
</tr>
<tr>
<td>Uman, M. A.</td>
<td>10, 44, 54, 211</td>
</tr>
<tr>
<td>Valev, C.</td>
<td>10, 210</td>
</tr>
<tr>
<td>Viel, G.</td>
<td>20, 211</td>
</tr>
<tr>
<td>Vogelsanger, E.</td>
<td>12, 37, 51, 200</td>
</tr>
<tr>
<td>Vonnegut, B.</td>
<td>206</td>
</tr>
<tr>
<td>Vrablik, E. A.</td>
<td>206</td>
</tr>
<tr>
<td>Walter, B.</td>
<td>33, 211</td>
</tr>
<tr>
<td>Wasielenko, E.</td>
<td>210</td>
</tr>
<tr>
<td>Weeks, A. W.</td>
<td>177, 211</td>
</tr>
<tr>
<td>Weinstock, G. L.</td>
<td>143, 211</td>
</tr>
<tr>
<td>Whipple, F. J. W.</td>
<td>21, 211</td>
</tr>
<tr>
<td>Whitehead, E. R.</td>
<td>51, 201</td>
</tr>
<tr>
<td>Wiener, P.</td>
<td>93, 211</td>
</tr>
<tr>
<td>Wiesinger, J.</td>
<td>183, 211</td>
</tr>
<tr>
<td>Wilhelms, N.</td>
<td>199</td>
</tr>
<tr>
<td>Williams, H. B.</td>
<td>202</td>
</tr>
<tr>
<td>Wlastik, W.</td>
<td>44, 211</td>
</tr>
<tr>
<td>Workman, E. J.</td>
<td>5, 12, 204, 211</td>
</tr>
<tr>
<td>Wormell, T. W.</td>
<td>21, 211</td>
</tr>
<tr>
<td>Yakobs, A. L.</td>
<td>90, 211</td>
</tr>
<tr>
<td>Yonkers, E. H.</td>
<td>207</td>
</tr>
<tr>
<td>Zaborowski, B.</td>
<td>210</td>
</tr>
<tr>
<td>Zhukov, I. A.</td>
<td>199</td>
</tr>
<tr>
<td>Zoledziowski, S.</td>
<td>205</td>
</tr>
</tbody>
</table>
Subject Index

Accidents, prevention of, 50, 59, 60, 144, 148, 181–187, 195
Aerial, 49, 100–102, 111, 120, 130, 143, 149, 162, 169, 187, 195
Agricultural product, 151
Agricultural structure [see Building, farm]
Air conditioning (see Services, metal)
Aircraft, exhaust, 127
  fuel tank, 53, 141, 143
  penetration of skin, 18, 53, 54, 126
  protection, 141–144, 149, 150
  risk of strike to, 19, 127, 139, 141
Air termination, arrangement, 68, 105
  gutter, 68
  material, 61
  mesh, 70, 71, 74, 128, 132
  (see also Lightning rod; Shield wire)
Aluminium, conductor, 52, 61, 64, 113
  corrosion, 64, 65, 81, 141
  sheet, 53, 54, 125, 126
Amnesia, 175, 185
Ancient monument, 114
Animal (see Lightning casualty)
Architect, 48, 80, 169
Artificial respiration (see Resuscitation)
Asphyxia, 172, 176, 189
Attractive effect
  of lightning conductor (see Lightning conductor)
  between parallel conductors, 55, 160
Balcony, 100, 109
Ball bearing, 149, 150, 152
Ball lightning, 187
Banister, 49
Blasting, 3, 133–136
Boat, 47, 181
  internal, 64, 124, 133
  principle, 58, 96
Boys’ camera (see Rotating camera)
Branching (see Lightning discharge)
Brass, 61, 64, 65
Breakdown strength, electrical
  air, 15, 28, 29, 97, 98, 159
  insulant, 79, 97, 99
  soil, 58, 86, 89, 132
  spark gap, 24, 25, 29
Breathing, 172
Bridge, 156
Building, brick, 46, 47, 55, 114
  farm, 60, 70, 106, 107, 150–152, 196
  frequency of strikes to, 40–42
  high-rise, 108–111, 149, 196
  hospital, 39, 40
  industrial, 70, 71, 100, 170
  reinforced concrete, 46, 47, 82, 108, 112, 114, 156, 176
  residential, 68, 69, 71, 106
  rock, on, 121, 152, 153
  steel-frame, 72, 81, 108, 114
  thatched, 44, 55, 105–107, 150, 196
  unprotected, 88, 101, 104, 188, 195
  wooden, 44, 55, 106, 150, 196
  (see also Danger structure)
Building operator, 48, 169
Burn, animal, 180
  human, 175, 185, 186, 187
Camping (see Tent)
Car, 60, 149, 181
Cardiac massage, 191–194
Casting, 62
Casualty (see Lightning casualty)
Catenary (see Shield wire)
Cathodic protection, 66, 67, 94, 95, 131
Charge, electric
  in cloud, 5, 6, 16, 19, 139
  in space, 8, 10, 20, 37, 141
  (see also Lightning current; Lightning flash; Lightning leader; Thunder-cloud)
Chimney, 33, 42, 45, 57, 66, 69, 74, 75, 111–113, 164, 170, 187, 196
Church, 15, 44, 46, 47, 72, 74, 113, 164
Clamp, 62
Clearance
  calculation, 98, 130
  below ground, 85, 88, 132
  practice, 100, 106, 111, 147, 151, 161
  principle, 58, 97, 110
Cloud discharge (see Lightning discharge)
Code of Practice
  Australia, 1, 45, 47, 63, 65, 71, 74, 77, 133, 136, 138, 162, 168, 169
  Austria, 61, 63, 65, 66, 71, 72, 81, 88, 99, 100, 104, 133, 136, 137
  Belgium, 48, 74
  Canada, 63, 91
  Finland, 48, 63, 65, 101
Germany, 1, 36, 40, 48, 61, 62, 63, 65, 69, 70, 73, 74, 76, 81, 88, 93, 99, 100, 104, 113, 118, 148, 151, 152, 154, 168, 170
Great Britain, 1, 36, 40, 45, 46, 61, 62, 63, 64, 65, 71, 75, 77, 79, 91, 97, 99, 100, 106, 107, 114, 133, 147, 155, 161
Holland, 44, 45, 50, 50, 63, 64, 65, 70, 71, 74, 88, 100, 101, 105, 127, 133, 149, 151, 170
Hungary, 48, 63, 70, 71, 74, 77
India, 1, 45
Rhodesia, 1, 45, 136, 139, 162, 170
South Africa, 1, 36, 45, 55, 61, 63, 65, 74, 77, 88, 100, 105, 106, 136
Switzerland, 48, 50, 52, 61, 63, 65, 68, 71, 81, 88, 91, 93, 99, 133, 170
USA, 1, 32, 36, 48, 62, 63, 66, 71, 74, 88, 133, 139, 151, 155, 162
Compass, 163
Concrete, 55, 66, 82, 92, 156
Consultation, 48, 109
Contact resistance, 95, 124, 143
Contact, sliding, 132, 152
Cooling tower, 14, 111–113
Copper
  conductor, 52, 61, 73, 113, 162
  corrosions, 64, 65, 81, 113
sheet, 53
(see also Air termination; Down conductor; Earth electrode)
Corona, 25, 51, 139
shield, 127, 128, 131
(see also Point discharge)
Corrosion, 49, 61–67, 83, 90, 93, 95, 107, 113, 131, 141, 162, 164, 170
Crane, 50, 149
Curtain walling, 49, 61, 80, 108

Damage to boats and ships, 161, 162
to churches, 44, 113, 114
to farm buildings, 44
to houses, 33, 41, 43, 55, 58, 82, 104
insurance against, 43
to monuments, 114
Danger structure, 45, 170
dust/air mixture, 151, 152
explosive factory and store, 35, 128, 129, 161
fuel tank, 126, 128, 131
petro-chemical, 124, 126, 131
vapour/air mixture, 35, 124, 126, 131
(see also Vent)
Durt leader (see Lightning leader)
Death by lightning, 173, 174, 177
(see also Lightning casualty)
Defibrillation, 176, 177
Detonator, 133, 134, 136–138
Down conductor
  arrangement, 49, 76–83, 108, 111, 152
  artificial, 80
  dimensions, 62, 63, 101, 113, 162
  inductance, 49, 57, 76, 81, 96, 111
internal, 81
natural, 80, 81
number, 77, 81, 100, 105, 108, 111, 114, 128
plaster, under, 81, 165
severance, 77, 164, 165
surge impedance, 110, 111
Drawing, 49
Driving (see Thunderstorm, driving in)
Duration, of lightning current (see Lightning current)
of lightning flash (see Lightning flash)
Earth current, 127, 132, 137, 156, 166
Earth electrode
  arrangement, 50, 90
  concrete foundation, 92–94
  dimensions, 65
  material, 64, 65
  plate, 91
  ring, 87, 90, 92, 109, 121, 131, 148, 153, 154, 155, 161, 168, 180, 183
  rod, 65, 89, 90–92, 109, 154, 155, 160, 168
  selection, 90, 196
  steady-state resistance, 57, 89, 90, 92, 93
  strip, 65, 89, 92, 93, 129, 168
  surge impedance, 89
Earth flash (see Lightning flash)
Earthing, of metal components, 50, 72, 81, 82, 83, 89, 93, 138, 139, 148, 149, 150, 153, 181, 195
Earthing resistance
  artificial reduction, 90, 170
  formula, 91
  magnitude, 83, 88, 196
  seasonal variation, 90, 93
(see also Earth electrode)
Earth resistivity (see Resistivity)
Economics of lightning protection (see Lightning-protective installation)
Electric, breakdown (see Breakdown strength)
Electric field
  fine weather, 7, 38
  leader, under, 28, 33, 133, 141, 164
  thundercloud, in and under, 5, 7, 9, 15, 38, 133, 137, 139, 140, 144, 146
Electric field change, 15, 19, 21, 145
Electric shock, 138, 143, 179, 185
Electric spark, 1, 23
(see also Sparking)
Electrical transmission line, 16, 21, 22, 31, 41, 66, 137
Electricity supply installation
  domestic, 49, 56, 59, 85, 88, 101–104, 151, 153, 187
  overhead, 44, 103, 184
  underground, 102, 125, 126, 130, 138, 157
Electrocardiogram, 174
Electromagnetic induction, 138, 143
Empire State Building, 14, 15, 19
Exhaust stack (see Vent)
### Subject Index

Explosive risk, 3, 35, 85, 123, 124, 126, 131, 142, 144, 196  
(see also Danger structure and Vent)

Factory (see Building, industrial)
Fair ground, 148
Fallacy, 20, 40, 51, 180, 187
Faraday cage, 60, 81, 109, 111, 143, 183
Fence, 49, 59, 131, 155, 180, 181
Fine-weather field (see Electric field)
Finial, 70, 74, 75, 112, 117
Fire damage of building, 44, 58, 106, 107
of forest, 157
Fitting, 43, 64, 170
Flagpole, 7, 15, 49, 117, 154, 188
Flammable material (see Building)
Flare lighting (see Lighting installation)
Fuel pipe (see Danger structure, petrochemical)
Funicular railway, 150, 184

Galvanized steel (see Steel)
Gas pipe (see Services)
Geological fault, 121, 133, 138, 153
Glass, 54
Glass fibre, 113, 121, 127, 141
Gilder, 143
Grease, 149
Gunmetal, 62
Gutter, 49, 68, 69, 196  
(see also Air termination)

Heart, 172–174, 176, 177, 180, 191, 194
Heating of lightning conductor (see Lightning conductor)
Helicopter, 144
High-rise building (see Building)
Highway, 156, 157
Hiker, 152, 183
Hospital (see Building, hospital)
Hot spot, 126
Human body  
electric current through, 172, 176–179  
electric resistance, 177, 179

Ignition (see Lightning current, thermal effects)
Impulse breakdown (see Breakdown, electric)
Inductance calculation, 129  
(see also Down conductor)
Inductive loop, 124, 132, 143
Inspection, 70, 77, 165, 169–171
Insulating material, 54, 55, 68, 69
Isokeraunic level (see Thunderstorm frequency)
Isolation, 49, 96, 111

Joint, 52, 66, 95, 96, 105, 113, 125, 162

Lead, 61, 65, 66, 73
Lichtenberg figure, 175, 185

Lighthouse, 152, 153
Lighting installation, 112, 116, 121, 154, 157, 165, 183
Lightning arrester (see Protective device)
Lightning casualty  
animal, 87, 155, 176, 180
human, 59, 87, 88, 133, 136, 144, 162, 172, 174, 177, 185, 186, 188–193

Lightning, cold, 55
Lightning conductor  
artificial, 68
attractive effect, 21, 31, 40
breakage, 61
dimensions, 51, 52, 56, 62, 63, 107, 196
electrical considerations, 56–60
field concentration, 7
inductance, 49, 57
metals used for, 61, 66
natural, 68
protective zone, 31–37
right-angle bend, 56
thermal considerations, 19, 51–55, 107

Lightning current  
amplitude, 16, 17, 19, 28, 29
charge, 18
continuing, 18, 19
duration, 17, 18, 158
mechanical effects, 55, 56, 74, 120, 127, 147, 160, 164
polarity, 16, 18
rate of rise, 18, 57
thermal effects, 51–55, 106, 126, 147, 175, 184

wave shape, 16, 17, 19, 97, 98

Lightning discharge  
branching, 10, 11, 23
cloud-to-cloud, 19, 139
cloud-to-earth, 9–12, 19, 139
frequency, 19–22
initiation, 9, 139, 140
mechanism, 9–12
polarity, 10, 12
pressure, 55, 56, 160, 175
temperature, 19, 139

Lightning expert, 48, 50, 124, 169, 195, 196
Lightning flash  
charge, 18, 19, 40, 53, 139
current strokes, 12
definition, 11
duration, 12, 19
frequency, 3, 19–22

Lightning flash counter, 21, 145, 146
Lightning, hot, 55
Lightning leader  
charge, 11, 27, 28, 30
current, 11, 23
dart, 11
downward, 10, 42
stepped, 10, 23, 25, 26, 29
upward, 14, 15, 18, 19, 42, 179
velocity, 10, 23

Lightning mast (see Lightning rod)
Lightning nest, 20, 30
Lightning photograph, 12, 13, 21, 23, 26, 30, 34
Lightning-protection engineer, 48, 80, 96, 169
Lightning-protection installation economics, 43-45, 71, 76, 81, 82, 84, 85, 87, 94, 97, 104, 107, 123, 151, 155, 168, 195
design, 48
inspection, 50
maintenance, 51
material, 49
Lightning, return stroke
current (see Lightning current)
diameter, 51
first, 11, 98
subsequent, 11, 98
temperature, 51, 74
velocity, 11
Lightning rod
attraction, 33, 42
installation, 1, 31, 32, 74, 105
protective angle, 74, 128, 129
protective zone, 31, 37
radio-active, 37-40, 197
striking distance, 26-31, 32, 33, 36, 37, 40, 42
Lightning Rod Conference, 1
Lightning strike
frequency, 14, 15, 35, 40-42
human body, to, 172-179, 181, 184, 191
mechanism, 14, 23-26, 30, 31
Lightning stroke
charge, 11, 18
definition, 11
(see also Lightning current)
Lungs, 174, 186

Magnetic link, 16, 21, 41, 42
Maintenance (see Lightning-protective installation)
Marquee, 147
Metal cladding, 49, 61, 80, 108
Metal components (see Bonding; Earthing)
Metal service pipes (see Services, metal)
Metal stay wire, 113, 162
Mining, 133-138
Misconception (see Fallacy)
Monument, 114-117, 152, 164, 188
Motorway (see Highway)
Mount San Salvatore, 14, 15, 16, 18, 19, 20, 36, 37
Mountaineer, 8, 152, 178, 183, 186
(see also Lightning casualty)
Need for protection, 3, 43-48
Overvoltage protection (see Protective device)

Paralysis, 175, 179, 185, 186
Penetration of metal, 18, 53, 54, 73, 124, 125, 141
Penthouse, 49
Petro-chemical plant (see Danger structure)
Phosphor bronze, 61, 64
Plastic, 55
(see also Glass fibre)
Playing field, 153, 155
Point discharge, 7, 8, 9, 15, 21, 25, 26, 37, 38, 40, 60, 113, 126, 127, 139, 144, 145, 164
Polarity (see Lightning current; Lightning discharge)
Potential to earth of cloud charge, 23
lightning-protective system, 57, 58, 83, 96, 97, 110, 113, 130, 132
Protective device
general, 120, 153, 156, 162
spark gap, 94, 101, 103, 104
surge diverter (lightning arrester), 85, 94, 103, 112, 121, 125, 130, 149, 151, 157
Protective zone (see Lightning conductor; Lightning rod)
Public safety, 45, 75, 79, 80, 82, 84, 99, 101, 108, 117, 120, 139, 147, 150, 153, 156

Radio-active lightning conductor (see Lightning rod)
Radio activity (see Lightning nest)
Radio installation (see Aerial)
Rail, 49, 122, 133, 134, 136, 138, 149, 156
Railway, 49, 117, 122, 137, 156
Rainwater pipe, 49, 69, 80, 81
Record, 50, 170
Re-entrant loop, 49, 78, 79
Reinforced concrete (see Building)
Reinforcing bars, 82, 83, 93, 118, 156
Resin-bonded glass fibre (see Glass fibre)
Respiration, 172, 186
Resistivity of soil effect on step voltage, 87
measurement, 50, 90, 169
Resuscitation, 172, 174, 186, 191-194, 197
Return stroke (see Lightning, return stroke)
Ribbon lightning, 11, 12
Ring conductor (see Earth electrode)
Rock, 55, 90, 118, 134
(see also Building)
Rocket, 33, 140
Rod electrode (see Earth electrode)
Roof, asphalt, 72
corrugated metal, 52, 73
flammable, 72, 73, 105, 106
metal, 49, 72, 73
metal foil, 52, 74
Roof conductor (see Air termination)
Rotating camera, 1, 9, 10, 12, 30, 37
Rural structure (see Building)
St. Elmo's fire, 8
Scaffolding, 50, 148
Subject Index

Sealing strip, 125, 143
Semi-conductor (see Solid-state device)
Separation (see Clearance)
Services, electricity, 57, 81, 83-87, 109, 149
gas, 81, 83-87
water, 57, 58, 83-88
Shield wire, 129, 132, 147, 150, 155, 161
Ship, 161
Side flash, fuel tank, on, 131, 132
person, to, 75, 148, 154, 172, 187
principle, 57, 58
shield wire, from, 129, 130
structure, in, 44, 49, 60, 72, 76, 77, 80, 81, 83, 90, 99, 108, 109, 124, 128, 142, 151, 162
tree, from, 161, 181, 182
underground, 58, 59, 133
Solid-state device, II8, 143, 149
Space charge (see Charge, space)
Spark gap (see Protective device)
Sparking, 35, 52, 73, 85, 95, 105, 124, 125, 128, 132, 137, 138, 143, 150, 151, 152, 155, 175
Sports ground (see Playing field)
Stairs, 49, 117, 156, 188
Steel, conductor, 52, 53, 62, 107, 113
copper-clad, 61, 64
corrosion, 62, 64, 65, 66, 107, 113
sheet, 53
Step voltage, effect on persons and animals, 92, 111, 147, 152, 154, 172, 179, 180, 182, 183, 185, 186
magnitude, 86, 87, 181
Striking distance (see Lightning rod)
Stroke (see Lightning stroke)
Structure, mobile, 149, 150
telecommunication, 14, 117-122
temporary, 147-149
wooden, 138, 148, 151, 152, 156, 161, 162
(see also Building)
Superstitition (see Fallacy)
Surge diverter (see Protective device)
Surge impedance (see Down conductor; Earth electrode)
Swimmer, 183
Tall structure, 12-15, 36, 37, 42, 63
(see also Building)
Telecommunication tower (see Structure)
Telephone installation, 49, 102-104, 170, 184, 187, 197
Television (see Aerial)
Temperature (see Lightning conductor; Lightning discharge)
Tent, 147, 183
Test joint, 49, 95, 107, 170
Testing, 77, 166-169
Thunder, 55
Thundercloud, 5, 6
charge in, 7
Thunderstorm, driving in, 181
frequency, 3, 4, 45, 162
precaution indoors, 187, 188
precaution outdoors, 183-186
types, 3, 5
Tree, damage, 157, 159, 160
electric properties, 158, 159
lightning casualties under, 180, 181, 182
protection of, 47, 160
structure, near, 49, 59, 131, 160, 161
Tunnel, 133, 134, 144
Upward leader (see Lightning leader)
Upward streamer, 25, 26, 28, 30, 31, 33, 37, 164
Vent, 124, 126, 127, 128, 131, 132
Ventricular fibrillation, 172, 173, 176, 177
Warning device, 138, 144-146
Water pipe (see Services)
Water tank, 57, 58
Wave guide, 120
Windmill, 151, 152
Window frame, 100, 109, 124, 187
Wooden building (see Building)
Wooden structure (see Structure)
World Meteorological Organization, 3, 4
Zinc, 61, 62, 65
Zone of protection (see Protective zone)