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

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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 benefitted 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, Nuremburg, 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

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.

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

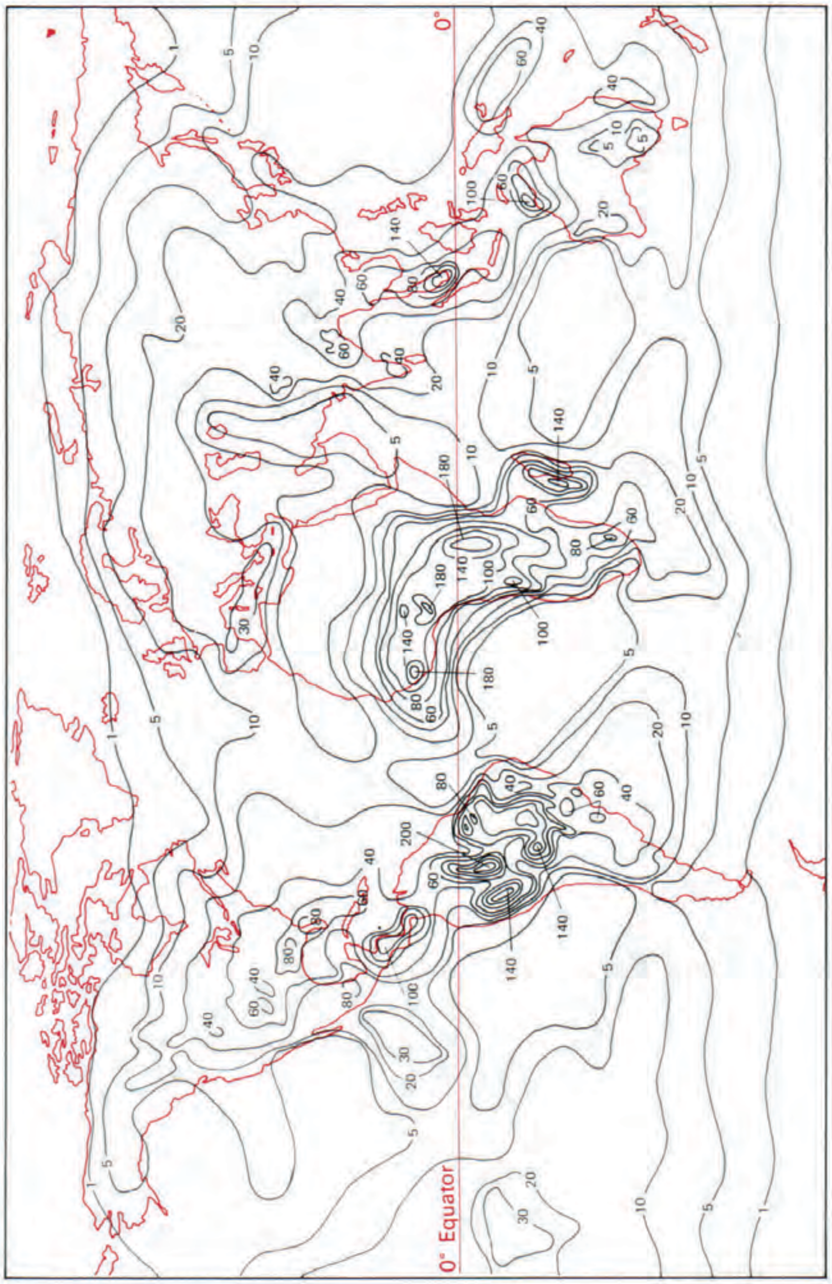


Fig. 1 Annual frequency of thunderstorm days (World Meteorological Organization, 1956)

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

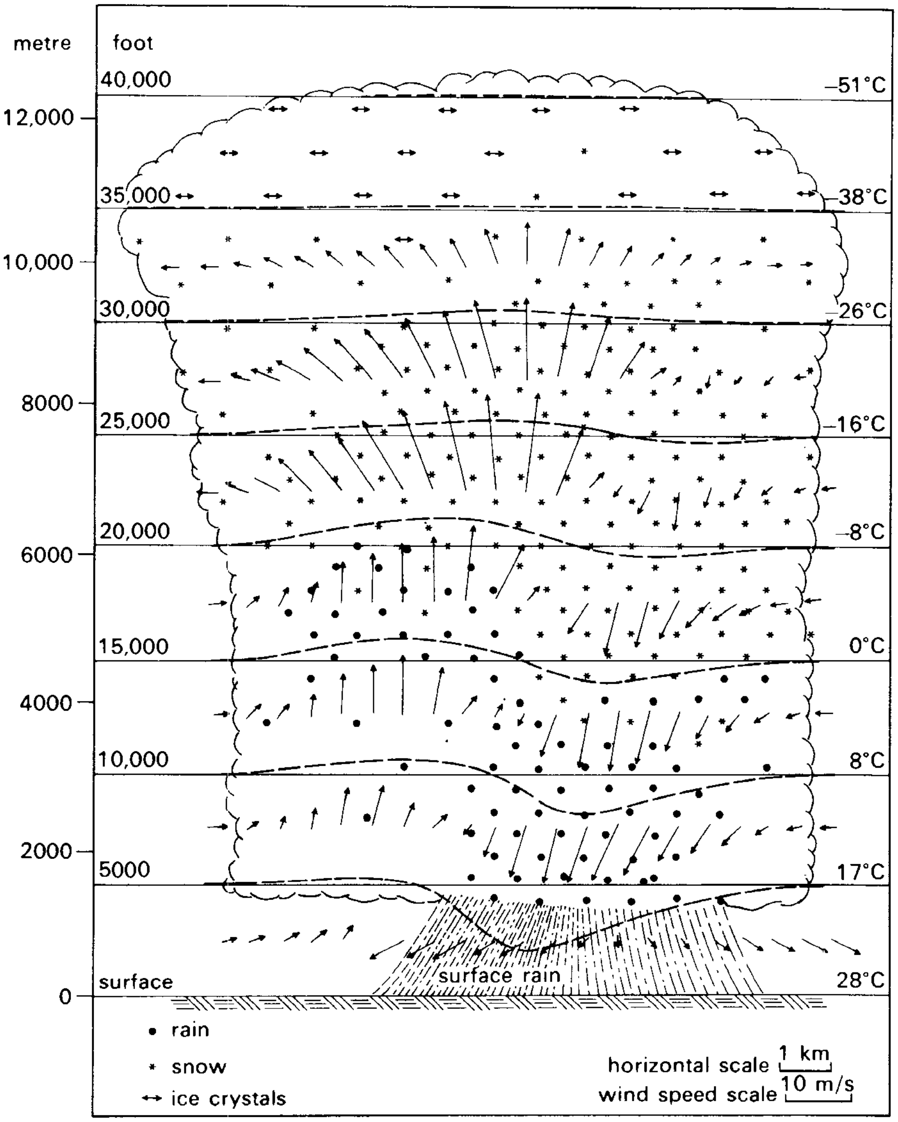


Fig. 2 Thunderstorm cell in mature state (Byers and Braham, 1949)

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 km^3.

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).

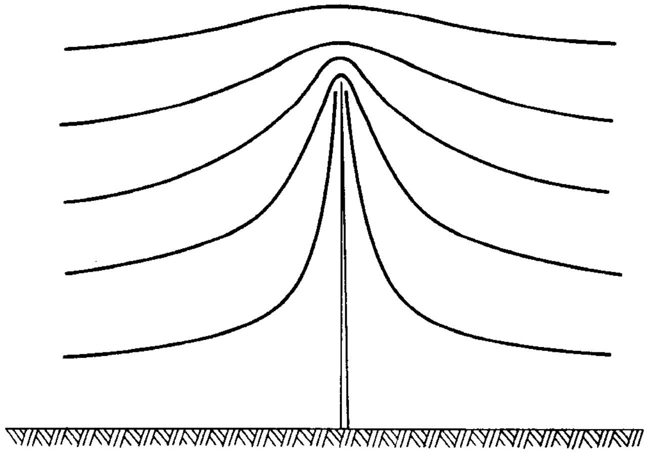


Fig. 3 Electrostatic field distribution about vertical lightning conductor

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

(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 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).

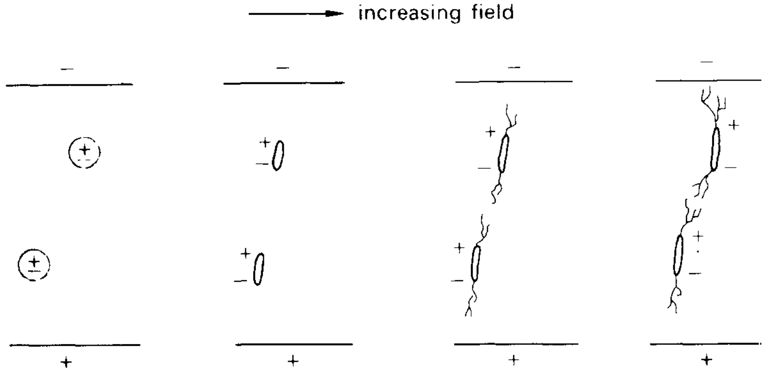
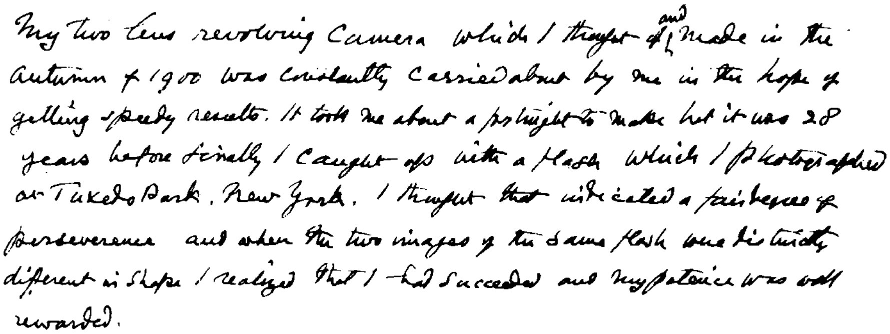


Fig. 4 Induction and deformation of water droplets in increasing electrostatic field

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 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.



My two lens revolving Camera which I thought of and made in the
autumn of 1900 was constantly carried about by me in the hope of
getting speedy results. It took me about a fortnight to make but it was 28
years before finally I caught up with a flash which I photographed
at Tuxedo Park, New York. I thought that indicated a fair degree of
perseverance and when the two images of the same flash were distinctly
different in shape I realized that I had succeeded and my patience was well
rewarded.

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 10^5 and 2×10^5 m/s, that is, less than one thousandth of the speed of light which amounts to 3×10^8 m/s. The cur-

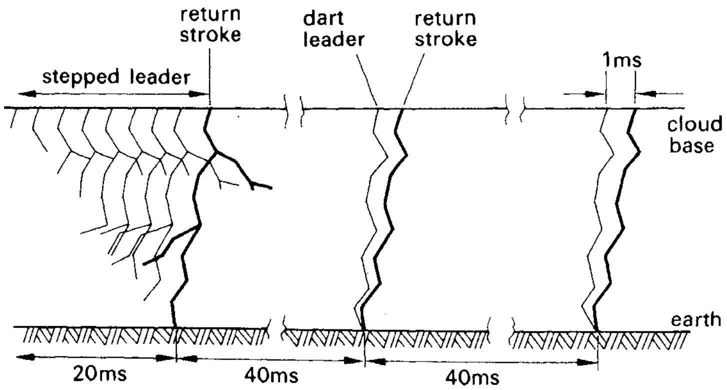


Fig. 5 Temporal development of multiple earth flash as recorded by camera moving from left to right

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 $3{\cdot}5 \times 10^7$ 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

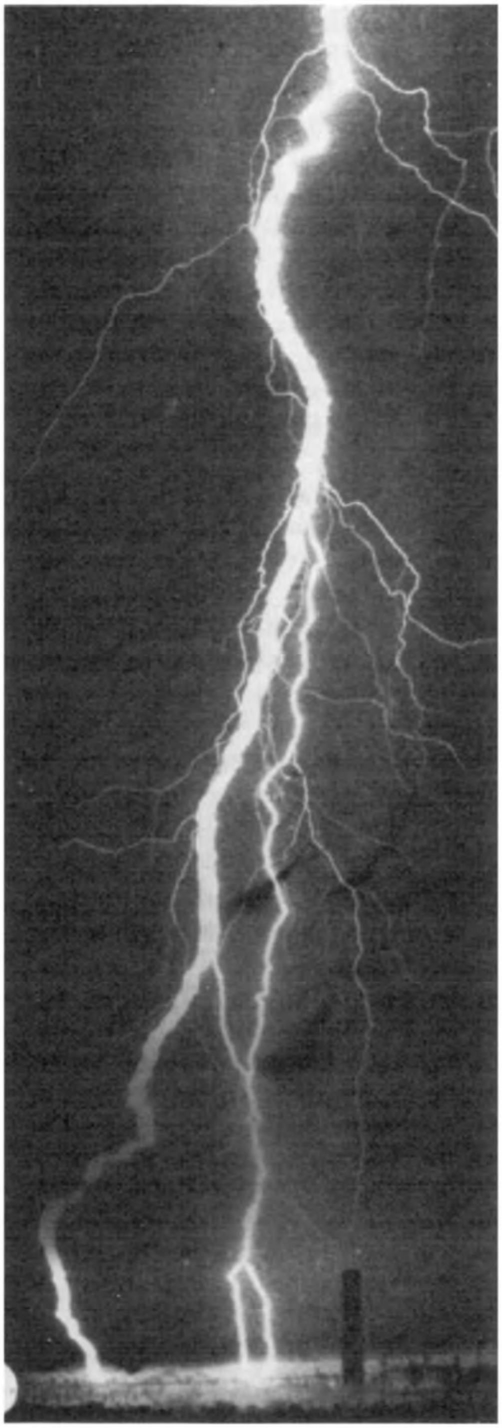


Plate 3 Lightning strike to unprotected chimney (Courtesy Mr. Vesanterä)

Plate 2 Lightning striking at three points 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

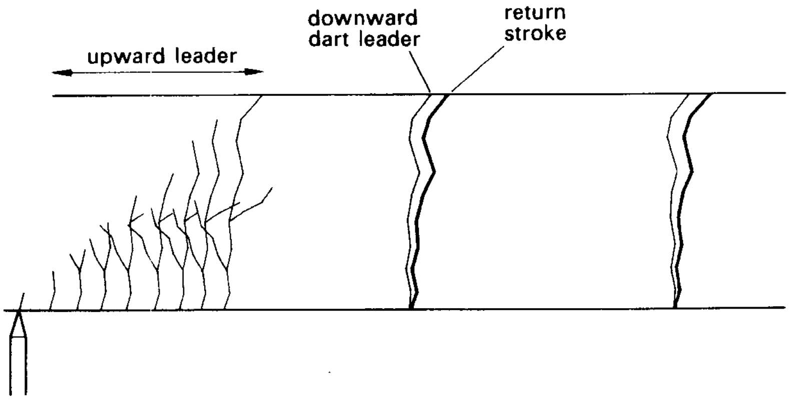


Fig. 6 Temporal development of flash initiated at tip of tall tower as recorded by camera moving from left to right

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