The Scientific Basis for Traditional Lightning Protection Systems

Report of

The Committee on Atmospheric and Space Electricity

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1. INTRODUCTION

In 1998 the National Fire Protection Association (NFPA) appointed an independent panel to evaluate Early Streamer Emission (ESE) lightning protection technology. The panel members were John L. Bryan, Richard G. Biermann, and Glenn A. Erickson, hereinafter referred to as the Bryan Panel. After a public solicitation for information related to their study, the Bryan Panel issued their report based on a review of 377 submitted documents, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology*. In addition to their conclusions regarding ESE technology, the Brian Panel presented a conclusion concerning NFPA 780, *Standard for the Installation of Lightning Protection Systems*:

> It appears to the panel the NFPA 780 document does not meet the NFPA criteria for a standard since the recommended lightning protection system has never been scientifically or technically validated and the Franklin rod air terminals have not been validated in field tests under thunderstorm conditions.

Based upon that conclusion the NFPA issued Decision D#00-30 in which it stated its intention to terminate its lightning protection standard unless it is presented with “an adequate substantiation" of the technology, and “that such substantiation should include, at a minimum, an independent literature review and analysis from a reliable source demonstrating the validity of the basic technology and science underlying traditional lightning protection systems”. This report provides such a substantiation. It also represents a distilled consensus view of a significant fraction of the established lightning researchers and specialists working in the U.S. on the issue of traditional lightning protection.

The American Geophysical Union (AGU) is an international scientific society with more than 39,000 members in 115 countries dedicated to advancing the understanding of Earth and its environment in space, including atmospheric electricity and lightning, and is the leading scientific society in the United States for researchers involved in the science of lightning. Its journals *The Journal of Geophysical Research* and *Geophysical Research Letters* are the premier journals for the publication of basic research results on lightning and its effects. A large number of lightning researchers attend and present papers at the Fall Annual Meeting of the AGU. The Committee on Atmospheric and Space Electricity (CASE) is a committee of the AGU devoted to the study of electrical phenomena in the atmosphere and in space. Lightning is a fundamental area of interest for CASE members. CASE holds its annual meeting in conjunction with the Fall Annual Meeting of the AGU. At the December 2000 meeting of CASE, the NFPA Decision D#00-30 was discussed, and CASE formed a working group to prepare this report in response to that NFPA decision.

This report examines the seminal literature related to the development and effectiveness of traditional lightning protection technology, and discusses those aspects of the basic science of lightning which pertain to lightning protection technology. It should be noted that none of the literature about these subjects examined for this report was included in the 377 references listed in the Bryan Panel Report.

2. THE DEFINITION OF A TRADITIONAL LIGHTNING PROTECTION SYSTEM

Traditional lightning protection systems are described in Appendix L of the 1997 Edition of NFPA 780 [National Fire Protection Association, 1997]. Appendix L describes a system which provides a low-impedance path to carry the large currents of lightning discharges to ground, preventing damage to the protected structure.

> **L-2 Lightning Protection Systems.**
>
> **L-2.1** Lightning protection systems consist of the following three basic parts that provide the low impedance metal path required:
>
> (a) A system of strike termination devices on the roof and other elevated locations
> (b) A system of ground terminals
> (c) A conductor system connecting the strike termination devices to the ground terminals
>
> Properly located and installed, these basic components improve the likelihood that the lightning discharge will be conducted harmlessly between the strike termination devices and the ground terminals.

In addition, Appendix L specifies that metal bodies on protected structures are to be interconnected to the above lightning protection system "to ensure that such metal bodies are maintained at the same electrical potential so as to prevent sideflashes or spark-over."

Chapter 2 of NFPA 780 has definitions related to lightning protection systems. Three definitions are pertinent to this report:

> **Strike Termination Device**. A component of a lightning protection system that is intended to intercept lightning flashes and connect them to a path to ground. Strike termination devices include air terminals, metal masts, permanent metal parts of structures as described in Section 3-9, and overhead ground wires installed in catenary lightning protection systems.
>
> **Air Terminal.** A strike termination device that is essentially a point receptor for attachment of flashes to the lightning protection system and is listed for the purpose.

> Typical air terminals are formed of a tube or solid rod. Air terminals are sometimes called lightning rods.
>
> **Zone of Protection**. The space adjacent to a lightning protection system that is substantially immune to direct lightning flashes.

Although the Bryan panel did not define specifically what it meant by a Franklin rod, it appeared to use the definition of a Franklin rod as a sharp-pointed rod, similar to the lightning rod originally proposed by Benjamin Franklin to try to discharge thunderclouds to prevent lightning. It is important to note that neither the 1997 edition nor the proposed 2000 edition of NFPA 780 refers specifically to Franklin rods. In fact, in an Appendix to the proposed 2000 edition reference is made to recent research findings that blunt-tipped rods are probably better for air terminals than are sharp-tipped rods. While Franklin rods are often used as strike termination devices in traditional lightning protection systems, their use is neither required nor encouraged by NFPA 780. Any of the above strike termination devices may be used.

3. HISTORICAL DEVELOPMENT OF LIGHTNING PROTECTION SYSTEMS

The development of the modern lightning protection system began with Benjamin Franklin. Franklin found that he could generate a 3 inch long spark when he discharged a capacitor by bringing a blunt iron bolt up to it. By using a sharp needle, the capacitor was silently discharged without a spark (at a distance of 12 inches) [paper to Peter Collinson, July 29, 1750, in Cohen, 1941]. Franklin also demonstrated for the first time that lightning is an electrical discharge, a fact well accepted today. Putting the two together, Franklin proposed using sharp-pointed rods to discharge clouds, similar to the way a needle could be used to discharge a capacitor.

In 1750 Franklin wrote [Cohen, 1941, p. 221]:

> ... houses, churches and ships [should be provided] on the highest parts of those edifices, upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of those rods a wire down the outside of the building into the ground, or down round one of the shrouds of a ship, and down her side till it reaches the water.

Thus, Franklin early on described what has become the traditional lightning protection system with its three components: a strike termination device, a grounding system, and a conductor between the strike termination device and the grounding system. Although Franklin mistakenly proposed this system as a means to prevent lightning, it was soon demonstrated that the system was quite effective at preventing damage from lightning when the lightning rod was struck. Experiments in France first showed this [Cohen, 1941, p. 131]: "The French demonstration of his hypothesis showed that the rods could do more; they could conduct a stroke to the ground safely."

By 1755 Franklin wrote of the two uses for his lightning rods [Cohen, 1941, p. 307]:

> I have mentioned in several of my letters, and except once, always in the *alternative*, *viz*, that pointed rods erected on buildings, and communicating with the moist earth, would either *prevent* a stroke, *or*, if not prevented, would *conduct* it, so as that the building should suffer no damage.

Following Franklin's suggestion for the use of lightning rods, the first lightning conductor was installed in 1752. More were installed over the next few years. By 1760 there were three reports of houses which were struck by lightning, but undamaged, using Franklin's system [Cohen, 1941].

(a) In Charlestown a thin brass wire was completely destroyed when lightning struck the house of Mr. Kraven. The house was protected.

(b) Lightning struck the house of Mr. West in Philadelphia. The point of the Franklin rod melted; but there was no damage to the house.

(c) In Indiana the lightning conductor on the house of Mr. Maine was struck.

Over the next hundred years it became well established that lightning conductors worked well in protecting structures from lightning. There were numerous reports of structures which had a history of lightning damage, with an end to the damage after the installation of a lightning protection system [*e.g*, Schonland, 1950; Krider, 1997]. There were reports on failures of lightning protection systems due to several factors: insufficiently-sized conductors, conductors made of the wrong materials, metal bodies not being bonded to the lightning protection system, and an insufficient number of strike termination devices [*e.g*., Henley *et al*., 1778; Anderson, 1879].

Based on the developing knowledge about the effectiveness of lightning protection systems, and on studies of system failures, national standards for lightning protection systems were initiated. The earliest was in Venice in 1778, when the Senate of Venice issued a decree ordering the erection of lightning rods throughout the republic [Anderson, 1879, p. 48]. In 1823 the French Academy of Sciences, under the chairmanship of Gay-Lussac, issued instructions for lightning conductors [Gay-Lussac and Pouillet, 1823]. This was revised in 1854 and 1867 [Anderson, 1879]. In 1878 several British societies (the Meteorological Society, the Royal Society of British Architects, the Society of Telegraph Engineers, and the Physical Society) organized a conference on lightning protection. They issued their report in 1882, *Report of the Lightning Rod Conference*, which laid out a code of rules for those who installed lightning protection systems in Britain [Symons, 1882].

The NFPA issued its first document on lightning protection in 1904, *Specifications for Protection of Buildings Against Lightning* [Lemmon *et al*., 1904]. They modeled their specifications closely after those developed in the 1882 *Report of the Lightning Rod Conference*. In their preface they stated:

> Since our knowledge of the nature of the lightning flash is so limited, the best that we can do is to accept the results of years of practice and observation by the best known authorities on the subject.

These specifications, later identified as NFPA 78, became the first lightning protection standard in America.

Both the 1882 Lightning Rod Conference report and the 1904 NFPA report specified the use of sharp-pointed air terminals. At that time it was still thought that sharp-pointed rods could be useful in discharging thunderclouds, and the following was included in both reports:

> A lightning conductor fulfills two functions; it facilitates the progress of the electricity to the earth, carrying it off harmlessly, and tends to prevent disruptive discharge by neutralizing the conditions which determine such discharge in the vicinity of the conductor. … The second object is accomplished by the conductor being surmounted by a point or points.

As stated in this initial American standard, there was very limited knowledge of the science of lightning, so standards at that time were based on many years of observations about what worked and why systems failed, the way many other standards have been developed and updated. As described later in this report, lightning protection technology was quite effective in preventing fires from lightning. As equipment became available to allow scientists to make more detailed studies of lightning, NFPA 78 (renamed NFPA 780 in 1992) was periodically updated to reflect more current scientific findings. In particular, the idea that sharp points can be used to discharge a thunderstorm has been shown to be incorrect, so the specification of the use of sharp-pointed lightning rods was dropped many years ago from then-NFPA 78.

4. STUDIES OF EFFECTIVENESS OF TRADITIONAL LIGHTNING PROTECTION SYSTEMS

While the technology that was developed in the 18th and 19th centuries, and used in the early lightning protection standards, was based on “the results of years of practice and observation by the best known authorities on the subject” [Lemmon *et al*., 1904], several studies were conducted to establish the effectiveness of such technology.

One of the earliest studies was of lightning damage to ships in the British Royal Navy. Lightning was a major source of damage to Royal Navy ships in the first part of the 19th century [Harris, 1843]:

> … in the British Navy the effects of lightning have been most disastrous. Since the commencement of the war in 1793, more than two hundred and fifty ships are known to have suffered in thunderstorms…. In one hundred and fifty cases, the majority of which occurred between the years 1799 and 1815, nearly one hundred lower masts of line-of-battle ships and frigates, with a corresponding number of topmasts and smaller spars, together with various stores were wholly or partially destroyed.

In 1820 Harris invented a method for installing lightning rods and down-conductors on ships. The method was adopted by the Royal Navy in 1847. In a letter to Admiral Sir George Cockburn, Harris writes :

> That your opinion of the propriety of giving my method of fixing conductors in ships an adequate trial was not erroneous, is fully shown by the uniform success which has attended its adoption in about thirty vessels of Her Majesty's Navy, which during the last twelve years have been exposed to heavy storms of lightning in various latitudes, without experiencing the slightest inconvenience or damage.

From 1905 through 1930 a large amount of data were collected in Iowa by various farmers' mutual fire insurance companies. Several reports examined this data over different periods of time [University of Missouri, 1912; Peters, 1915; Covert, 1926; Lewis, 1952]. The conclusions of all the reports were similar — that farm buildings protected by lightning rods had far fewer fires than those without such protection: "The foregoing values being taken as correct the efficiency of the lightning rods in this case may therefore be estimated at nearly 99 per cent" [Peters, 1915].

In many of the cases where lightning did cause fires to protected buildings it was found that the protection system was defective: "Nearly one-third of these so-called rodded barns, however, are known to have had defective rods. Lightning running in on wires is stated to have caused 10 fires" [Covert, 1926].

Another study showing similar effectiveness was conducted in Ontario, Canada. Keller [1939] reports from an address by J. E. Ritchie, the Fire Prevention Engineer from the Office of the Fire Marshal, Toronto:

> The Ontario Legislature passed a Lightning Rod Act which became effective in January, 1922. The Act requires that all Lightning Rod Agents and Manufacturers must be licensed by the Fire Marshal before selling, offering for sale or installing lightning protection equipment. The Regulations prescribed under the act specify the standard of materials that shall be used and the manner in which installations shall be made, and in general conform to the Underwriters' requirements for Master Label Service. Prior to the enactment of this legislation there had not been any established standards in the Province, and much of the work was therefore improper and incomplete. Since then there has been a very marked improvement and a corresponding reduction in lightning losses. … It should be pointed out that nearly all of the lightning loss to rodded buildings … resulted where the installations were erected prior to 1922 and had not been brought up to standard. During the 15 years from 1924 to 1938 the rodded buildings damaged by lightning included less than an average of one per year of those that were rodded since 1922. In no case has a building rodded under the Lightning Rod Act been destroyed by lightning after having been inspected by the Fire Marshal's Office.

McEachron and Patrick [1940] write of the Ontario study:

> A 10-year survey in the Province of Ontario, in Canada, disclosed that during the period covered, 10,079 lightning fires took place in structures not equipped with lightning rods, while only 60 such fires occurred in buildings with lightning rod systems of protection. Of these sixty fires, it was found that many were started in structures equipped with improper lightning rods, or rods in bad condition because of poor maintenance. It is safe to say today that a lightning rod system practically eliminates the chance of damage from a stroke, although it will not prevent the stroke itself….

A study in Poland by Szpor [1959] (reported in English by Müller-Hillebrand [1962]) showed that there were about 6 fires per 10,000 houses from lightning for unprotected houses in Poland. Between 1956 and 1960, there was a 97% lower probability of lightning-caused fires in houses with lightning protection systems than in houses without such protection.

The studies discussed above show that there is overwhelming statistical proof that traditional lightning protection systems prevent fires from direct lightning strikes. In many cases of fires to protected structures it was found that the protection system was improperly installed. Because the American standard at the time specified the use of sharp-pointed Franklin rods, the Iowa and Ontario studies proved the efficiency of Franklin rods under thunderstorm conditions.

In addition to the statistical studies there are numerous reports of structures with a history of lightning damage where the damage was eliminated with the installation of lightning protection systems. Such examples are the Campanile of St. Mark in Venice [Schonland, 1950], the Torre del Mangia in Sienna, Italy [Krider, 1997], and the Washington Monument in Washington, D.C. [Viemeister, 1972].

5. SCIENTIFIC BASIS FOR TRADITIONAL LIGHTNING PROTECTION SYSTEMS

There have been many scientific studies of cloud-to-ground lightning discharges, and of the attachment process to an object on the ground. Uman [1987] reviews much of this work, and is a reference for the general discussion which follows.

Cloud-to-ground lightning strikes begin in thunderclouds as a result of very strong electric fields which cause the formation of low-current electrical breakdown called streamers. Under the influence of the strong electric fields, these streamers develop into higher-current self-propagating leaders that often propagate toward the earth. As a leader approaches the ground, the leader greatly intensifies the electric fields at ground level, causing upward-going discharges from well-exposed objects; one of these upward discharges connects to the approaching, descending leader and provides a path to ground for the lightning. When this connection is made, peak currents of several tens of thousand amperes flow between ground and the thundercloud. This high current passing through an object with sufficiently high electrical resistance (such as an unprotected building) can generate sufficient heat to start fires.

The rate of current increase in a lightning discharge often exceeds 10^{10} amperes per second. The large currents and high rates of current increase produce large voltage differences across the parts of the current path which have high resistances and/or inductances. The potential differences between the current carrier and the surrounding objects can exceed several hundred thousand volts, causing "side flashes" to objects nearby, which can result in injury or death to people, and damage to electrical equipment.

As the noted physicist J. C. Maxwell suggested [Maxwell, 1876], complete protection against lightning damage can be obtained by totally enclosing the structure at risk within a thick-walled, metal shell, which is now called a Faraday cage. Application of such a method for protection, however, is impractical for most structures. As discussed above, traditional lightning protection systems have been proven to be a highly effective means for protecting structures against direct lightning strikes.

The scientific basis for NFPA 780 and its predecessor NFPA 78 that has been maintained through all of the revisions is that:

1. Cloud-to-ground lightning preferentially strikes well-exposed, tall, conducting objects that are connected to the Earth; it does not strike bodies that are shielded from strong atmospheric electric fields.

2. Sufficiently large diameter wires, suitably connected, can convey lightning discharges from the strike receptor to ground, without damage to the structures on which they are mounted.

Item (1) concerns the use of strike-termination devices, the subject of the Bryan Panel Report. Item (2) appears to be non-controversial and was not a topic in the Bryan Panel Report. There is a substantial body of literature on how to design downconductors and grounding systems (e.g., Golde [1977]), which is incorporated into NFPA 780. Since Item (1) was the topic of the Bryan Panel Report, its scientific validity is discussed below.

The fact that lightning preferentially strikes well-exposed, tall, conducting objects that are connected to the ground is apparent to anyone who has observed lightning from a thunderstorm. The pioneering lightning researcher Schonland [1950] remarks on the damage to elevated structures in the 1700's: "The record of damage to churches, whose elevated steeples attract lightning, is voluminous." Sir William Snow Harris [1848] observed that lightning preferentially struck the elevated parts of naval ships:

> By a careful analysis of the phenomenon, it may be further shown —
>
> 1st. — That in two out of three times lightning strikes upon the top-gallant & or highest masts.
> 2d. — in about one in five times upon the topmasts, or on the next highest points.
> 3d. — in about one in seven time upon the lower masts, or next highest points.
> 4th. — in about one in fifty times upon the hull directly.

Several more recent studies demonstrate the preference of lightning to strike elevated, conductive objects. Eriksson [1987] summarized his own and many other long-term studies of lightning attachment to elevated objects such as towers and power lines (including studies by Berger [1967], Popolansky [1970], Eriksson [1978] and Gorin *et al*., [1977]).

The need for strike receptors to protect a structure is undisputed. The primary question in the design of a lightning protection system is the placement of the strike termination devices to achieve a sufficiently low probability of a strike bypassing them. It was realized early on that a single lightning rod on a structure may not provide complete protection. The first well-known case of lightning bypassing a lightning rod to strike a structure was in 1777, when lightning struck a parapet of the House of the Board of Ordnance at Purfleet in London. The strike point was 14 m from, and 7.3 m below, the tip of the lightning rod installed at the high point of the structure [Nickson, 1778]. From this, and other such incidences of lightning striking near a lightning rod, the idea of a zone of protection for lightning rods was developed.

In the 1930s Schonland and co-workers in South Africa used streak-photographic measurements to show how a cloud-to-ground lightning discharge attaches to an object on the ground [Schonland and Collens, 1934; Schonland, 1938; Schonland *et al*., 1938a,b]. The distance between the tip of the downward leader and the strike termination point at the time the upward-going leader is initiated is called the striking distance. Studies of the striking distance show that it depends on the charge in the leader, which is related to the peak current of the lightning discharge [*e.g.*, Eriksson, 1978]. The field strength of a stepped leader is proportional to the leader charge, and inversely proportional to the square of the distance from the leader; hence the distance from the stepped leader to the ground at which the critical field for the initiation of an upward leader will be reached is larger for leaders having more charge.

With knowledge of the striking distance several methods can be used to determine the placement of air terminals to reduce the probability of a strike bypassing the strike termination system. Bazelyan and Raizer [2000] have an extensive discussion of these methods; one of the methods they discuss, the electrogeometric method, is the one used by NFPA 780. Analyses of the probability of lightning bypassing a properly-designed strike termination system [e.g., Mousa and Srivastava, 1988; Bazelyan and Raizer, 2000] conclude that, with proper placement of air terminals, the probability of a strike to a structure cannot be eliminated, but can be reduced to a desired level (e.g., 1% or 0.1% probability of lightning bypassing the strike termination system). Higher levels of protection require more extensive (and hence more expensive) strike termination systems.

The 1997 edition of NFPA 780 and the revised edition for issue in 2000 both specify, in detail, the methods to be used in meeting the essential requirements for lightning protection that uses strike receptors and down conductors. While revisions to the current standard will continue as more is learned about lightning processes and as the industrial technologies advance, the 2000 edition of NFPA 780 contains the current, informed consensus as to the best methods for protection against lightning with the use of lightning rods and elevated, grounded wires.

6. ATTEMPTS TO IMPROVE TRADITIONAL LIGHTNING PROTECTION SYSTEMS

There have been many attempts to improve traditional lightning protection systems. While this report does not try to assess the effectiveness of any of these proposed modifications to traditional systems, it is useful to examine the methods used by these non-traditional systems.

Non-traditional lightning protection systems fall into two categories — those which attempt to prevent lightning strikes to the protected structure, and those which claim to provide an improved air terminal which has a much greater zone of protection than do the traditional strike termination devices specified in NFPA 780.

Enhanced Protection Zone Devices. These devices include the commercial ESE devices which were the subject of the Bryan Panel Report. There are also experimental devices such as laser lightning rods [*e.g.*, Diels *et al*., 1997] and energized Franklin rods [*e.g.*, Abdel-Salam and Al-Abdul-Latif, 1997]. Systems based on these devices contain the three components of traditional lightning protection systems — strike termination devices, a grounding system, and low-impedance conductors to connect the two together. The main difference in the design of a system using enhanced protection zone devices is the claim that one enhanced air terminal protects a much larger area than does one traditional air terminal of the same height.

Lightning Elimination Devices. These devices (currently being called Charge Transfer Systems, or CTSs) claim to prevent lightning from striking a protected area by the release of space charge into a region above the area to be protected. These devices are based on Franklin's original idea for preventing lightning strikes, and consist of an array of sharp-pointed air terminals, a grounding system, and low-impedance conductors to connect the air terminals to the grounding system. While claiming to have a different function than a traditional lightning protection system, these systems contain the three essential features of an NFPA 780 style system. In fact, according to a recent article by Zipse [2001]:

> Should the design of the CTS generate a space charge that is less than the charge on the downward leader, the CTS reverts to a Franklin-rod-type collector.

It is interesting to note that ESE and CTS proponents, many of whom recommend termination of the NFPA lightning protection standard, use the basic principles set out in NFPA 780 in the design of systems for their products. All these alternative technologies recognize the validity of the basic elements of traditional lightning protection systems, and incorporate these elements into their designs.

7. CONCLUSIONS

The effectiveness of traditional lightning protection systems was well established by the mid-19th century, and statistical studies verified their effectiveness in the 20th century. With increased scientific knowledge about lightning and the lightning attachment process, the reasons for the high degree of effectiveness of these systems have become understood. Many updates to the original NFPA lightning protection standard of 1904 have been made to incorporate new scientific findings into the current edition. Some of these updates were the replacement of a conical zone of protection for lightning rods with a rolling sphere model for the placement of strike termination devices (based on the electrogeometric method); the removal of the requirement for sharp-pointed air terminals; and the specification of the use of surge suppressors to protect electrical and electronic equipment.

If traditional lightning protection systems are so well founded on science, how could the Bryan Panel have reached their erroneous conclusion that "the recommended lightning protection system has never been scientifically or technically validated"? This is easy to understand when one looks at the literature reviewed by the Bryan panel. The Bryan Panel issued the following request for literature [Bryan *et al*., 1999]:

> The panel will review the following issues, and any other issues it deems relevant: 1) whether ESE lightning protection technology is scientifically and technically sound; and 2) whether the ESE lightning protection technology is supported by an adequate scientific theoretical basis and laboratory testing. The panel is inviting anyone with information which may be relevant to its inquiry, to submit it for the panel's consideration.

Almost all of the 377 references in the Bryan Panel Report dealt with ESE technology. Of those documents with dates, 92% were from 1990 or later, well after the effectiveness and validity of traditional lightning protection systems were established. Forty nine percent of the documents were personal communications, and 14% were publications (often sales literature) from industries involved in manufacturing and installing lightning protection systems — there is no control over the scientific merit of such documents. Nine percent of the documents were unrefereed conference proceedings, and only 2% were articles published in refereed scientific journals. Because the Panel did not request information on lightning or traditional lightning protection systems, it did not receive the hundreds of articles and books which have been published on the subjects. (Golde's 1973 book, *Lightning Protection*, lists 234 references, most of which were refereed articles, relating to lightning protection. Many more articles relevant to lightning protection have been published since then.)

There is no indication that the Bryan Panel reviewed any of the literature which has established the validity and the scientific basis for traditional lightning protection technology. Most of the literature reviewed by the Bryan Panel that dealt with any aspect of traditional lightning protection systems concerned studies which compared Franklin rods to other types of air terminals. Most of the discussion in these documents concerned modifications to Franklin rods in attempts to increase their zone of protection. The discussion about attempts to improve the Franklin rod could have led the Bryan Panel to conclude that the Franklin rod is ineffective, and may have been the basis for their statement "the Franklin rod air terminals have not been validated in field tests under thunderstorm conditions". However, the statistical studies showing the effectiveness of traditional technology were done in an era when Franklin rods were specified by then-NFPA 78, so lightning protection systems using Franklin rods have been validated under thunderstorm conditions.

In the original NFPA 78, it was thought that sharp-pointed rods could prevent lightning strikes, and hence Franklin rods were specified. After it was realized that lightning strikes could not be prevented, the required use of Franklin rods was long ago removed from NFPA 78. An Appendix to the proposed 2000 edition of NFPA 780 discusses new findings which indicate that blunt-tipped rods are more effective lightning receptors than are sharp tipped rods. If this result is confirmed, future editions of NFPA 780 will probably specify blunt-tipped rods, as the standard is updated to reflect current scientific findings. It is unfortunate that the Bryan Panel proposed the downgrading of NFPA 780 for something which was removed from its predecessor many years back.

The evidence is clear and overwhelming that lightning protection systems as provided for in NFPA 780 are both needed and effective in reducing lightning-caused fires and damage to buildings and structures. The Standard has evolved over time to reflect our improved knowledge and understanding of lightning processes and will continue to evolve in the future. The Bryan Panel reviewed essentially none of the studies and literature on the effectiveness and scientific basis of traditional lightning protection systems and was erroneous in its conclusion that there was no basis for the Standard.

8. REFERENCES

Abdel-Salam, M. and U. S. Al-Abdul-Latif, Simulation of energized Franklin rods for lightning protection, *IEEE Trans. on Industry Applications, 33*, 651-659, 1997.

Anderson, R., *Lightning Conductors — Their History, Nature and Mode of Application*, E. & F. N. Spohn, 16 Charing Cross Road, London, 1879.

Bazelyan, E. M. and Y. P. Raizer, *Lightning Physics and Lightning Protection*, Institute of Physics Publishing, Bristol, England. 2000.

Berger, K., Novel observations of lightning discharges: Results of research on Mount San Salvatore, *Jour. Franklin Institute, 283*, 1967.

Bryan, J. L., R. G. Biermann and G. A. Erickson, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology,* National Fire Protection Association, Quincy, MA, 1999.

Cohen, I. B., *Benjamin Franklin's Experiments, A New Edition of Franklin's Experiments and Observations on Electricity*, Harvard University Press, Cambridge, 1941.

Covert, R. N., Protection of Buildings And Farm Property From Lightning, *Farmers' Bulletin No. 1512*, U. S. Department of Agriculture, 1926.

Diels, J.-C., R. Bernstein, K. E. Stahlkopf, and X. M. Zhao, Lightning control with lasers, *Scientific American*, pp. 50-55, Aug., 1997.

Eriksson, A. J., Lightning and Tall Structures, *Transactions, South African Institute of Electrical Engineers, 69*, 238-253, 1978.

Eriksson, A. J., The incidence of lightning strikes to power lines, *IEEE Trans. Power Delivery, PWRD-2*, 871-886, 1987.

Gay-Lussac, F. and C. Pouillet, *Introduction sur les paratonneres, adoptee par L'Academie des Sciences*, French Academy of Sciences, 1823.

Golde, R. H., *Lightning Protection*, Edward Arnold (Publishers) Ltd., London, 1973.

Gorin, B. N., V. I. Levitov, and A. V. Shkilev, Lightning strokes to Ostankino TV tower in Moscow, *Electric Technology USSR, 3*, 45-55, 1977.

Harris, W. S., *On the Nature of Thunderstorms and on the Means of Protecting Buildings and Shipping against the Destructive Effects of Lightning*, John W. Parker, West Strand, London (reproduced by Xerox University Microfilms, Ann Arbor, MI, 1972) 1843.

Harris, W. S., *Protection of Ships from Lightning*, compiled by R. B. Forbes and printed in America by Sleeper and Forbes, Boston (reproduced by Xerox University Microfilms, Ann Arbor, MI, 1974) 1848.

Henley, W., T. Lane, E. Nairne and J. Planta, Report of the Committee appointed by the Royal Society, for examining the Effect of Lightning, May 15, 1777, on the Parapet wall of the House of the Board of Ordnance, at Purfleet in Essex, *Phil. Trans. Royal Soc., LXVIII Part 1*, 236-238, 1777.

Keller, H. C., Results of modern lightning protection in the Province of Ontario, *Farm Paper of the AIR WGY*, Schenectady, NY, June 12, 1939.

Krider, E. P., Lightning rods in the 18th century, *Second International Symposium on Lightning and Mountains*, Chamois Mont Blanc, France, 1997.

Lemmon, W. S., B. H. Loomis and R. P. Barbour, *Specifications for Protection of Buildings Against Lightning*, National Fire Protection Association, Quincy, MA, 1904.

Maxwell, J. C., On the protection of buildings from lightning report, *British Ass'n. Advance. Science*, London, 1876.

McEachron, K. B. and K. G. Patrick, *Playing with Lightning*, Random House, New York, 1940.

Mousa, A. M. and K. D. Srivastava, A Revised Electrogeometric Model for the Termination of Lightning Strokes on Ground Objects, *Proc. Inter. Aerospace and Ground Conference on Lightning and Static Electricity*, Oklahoma City, OK, 342-352, 1988.

Müller-Hillebrand, D., The protection of houses by lightning conductors — An historical review, *J. Franklin Institute, 273*, 35-44, 1962.

National Fire Protection Association, *NFPA 780, Standard for the Installation of Lightning Protection Systems, 1997 Edition*, National Fire Protection Association, Quincy, MA, 1997.

Nickson, E., XV, Sundry papers relative of an Accident from Lightning at Purfleet, May 15, 1777, Report to the Secretary of the Royal Society, *Phil. Trans. Royal Soc., LXVIII Part 1*, 232-235, 1777.

Peters, O. S., *Protection of Life and Property against Lightning*, Technologic Papers of the Bureau of Standards, Dept. Of Commerce, Government Printing Office, No. 56, 1915.

Popolansky, F., Measurements of lightning currents in Czechoslovakia and the application of obtained parameters in the prediction of lightning outages of EHV transmission lines, *CIGRE Paper No. 33-03*, 1970.

Schonland, B. F. J., *Flight of Thunderbolts*, Clarendon Press, Oxford, 1950.

Schonland, B. F. J., Progressive lightning, Pt. 4, *Proc. R. Soc. London Ser. A, 164*, 132-150, 1938.

Schonland, B. F. J., and H. Collens, Progressive lightning, *Proc. R. Soc. London Ser. A, 143*, 654-674, 1934.

Schonland, B. F. J., D. B. Hodges, and H. Collens, Progressive lightning, Pt. 5, A comparison of photographic and electrical studies of the discharge process, *Proc. R. Soc. London Ser. A, 166*, 56-75, 1938a.

Schonland, B. F. J., D. J. Malan, and H. Collens, Progressive lightning, Pt. 6, *Proc. R. Soc. London Ser. A*, *168*, 455-469, 1938b.

Symons, G. J., editor, *Report of the Lightning Rod Conference*, E. & F. N. Spohn, 16 Charing Cross Road, London, 1882.

Szpor, St., Paratonnerres ruraux de type léger, *Revue Générale de lÉlectricité*, 263-270, 1959.

Uman, M. A., *The Lightning Discharge*, Academic Press, Inc., Orlando, 1987.

University of Missouri, *The use of Metal Conductors To Protect Buildings Against Lightning*, University of Missouri Engineering Experiment Station Bulletin Number 7, 1912.

Viemeister, P. E., *The Lightning Book*, MIT Press, Cambridge, MA, 1972.

Zipse, D. W., Lightning protection methods: An update and a discredited system vindicated, *IEEE Trans. on Industry Applications*, *37*, 407-414, 2001.