The Basis of Conventional Lightning Protection Technology

A review of the scientific development of conventional lightning protection technologies and standards.

Report of the Federal Interagency Lightning Protection User Group
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Federal Interagency Lightning Protection User Group

Participants:

John M. Tobias, P.E.
Chairperson, Federal Interagency Lightning Protection User Group
Electronics Engineer
Department of the Army, Communications Electronics Command
(john.tobias@mail1.monmouth.army.mil)

Charles L. Wakefield
Electrical Safety Team Leader
Naval Ordnance Safety and Security Activity, Indian Head, Maryland

Larry W Strother
Electronics Engineer
HQ Air Force Civil Engineer Support Agency
Technical Support Directorate, Mechanical/Electrical Division
(Larry.Strother@afcesa.af.mil)

Vladislav Mazur, Ph.D.
Physicist
National Oceanic and Atmospheric Administration, National Severe Storms Laboratory
Department of Commerce
(mazur@nssl.noaa.gov)

Josephine Covino, Ph.D.
Chairperson, Lightning Protection Working Group
Department of Defense Explosives Safety Board

John R. Fredlund
Electrical Engineer
National Nuclear Security Administration
Department of Energy
(John.Fredlund@nnsa.doe.gov)

Hugh J. Christian, Jr., Ph.D.
Senior Scientist
Global Hydrology and Climate Center
Marshall Space Flight Center
National Aeronautics and Space Administration

Monte Bateman, Ph.D.
Thunderstorm Scientist (Contractor)
Global Hydrology and Climate Center
Marshall Space Flight Center
National Aeronautics and Space Administration

Warren K. Jordan
Airway Operations Support (AOS)
Federal Aviation Administration
Department of Transportation
(Warren.Jordan@faa.gov)

Greg Heles
U.S. Army Technical Center for Explosives Safety
Department of the Army
(heles@dac-emh2.army.mil)

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1.0 Introduction

This report is a review of the body of literature, theoretical and empirical, that exists to substantiate the methods and practice of lightning protection as embodied in the current National Fire Protection Association's Standard 780, *Standard for the Installation of Lightning Protection Systems*. Development of this report is in direct response to the request embodied in the National Fire Protection Association's Standards Council Decision 00-30 for governmental users to participate in submission of technical substantiation regarding lightning protection systems.

1.1 Notes on the Scope of this Report

We note that the primary emphasis of this effort is to demonstrate the science behind lightning attachment to the strike terminations. We conclude that the effectiveness of down conductors, bonding techniques, grounding methods and practice are well established and need no further exposition. Development of existing lightning protection standards, in the U.S. as well as internationally derive from the same scientific sources. Although we focus on strike terminations (or air terminals) we find that the other components of the lightning protection system received equal attention in the demonstration of their effectiveness.

In this report, we will not address the various methods and practices proposed that deviate significantly from the so-called "traditional" or "conventional" or "Franklin" lightning protection systems. We suffice to let those systems stand on their own merits as put forth in exhaustive studies published to date. Our focus and scope remains on what we find proven to be tried and true.

1.2 Notes on the Federal Interagency Lightning Protection User Group

The Federal Interagency Lightning Protection User Group originally started as an ad hoc committee of Department of Defense representatives to the NFPA Technical Committee on Lightning Protection (initially as part of an NFPA Task Force, since disbanded) assembled for the purpose of responding to the NFPA Standards Committee Decision 00-30, specifically the request for technical substantiation of the lightning protection techniques and practice contained in modern lightning protection standards. Since its original inception, it included representatives from Defense along with other Government agencies such as Department of Defense Explosives Safety Board, Federal Aviation Administration (Department of Transportation), Department of Energy, National Aeronautics and Space Administration, and Department of Commerce as well as advisors from industry and academia. The Government activities participating in this effort contend that the precepts of lightning protection, as codified in NFPA 780 are valid, function to a high degree of effectiveness for the prevention of physical damage from lightning and that these precepts serve as the underlying basis for all of the lightning protection requirements specified by the Governmental departments. Although each department may issue specifications, standards or regulation to augment or detail lightning protection requirements, NFPA 780, Standard for the Installation of Lightning Protection Systems, remains as the basic document for specifying lightning protection.

The agencies represented use this standard extensively and further believe that action to cancel or weaken it would not be in the interest of the Federal Government, nor in the interest of the public good. Nor, as will be demonstrated by the following discourse, is cancellation or weakening in any way justified. Indeed, at the end of this discourse, it will be found that reinstatement of NFPA 780 to code status, as defined by the 2001 NFPA Directory[1] is warranted by the weight of evidence available.

1.3 Development of Lightning Protection Science

The earliest developments in lightning science and lightning protection begins in 1752 with Benjamin Franklin. Our review will encompass his work and the development since.

In citing the older works, we have to note a few points. First, the fact that the observations and even conclusions are old does not invalid them. We shall see that older work is often confirmed when more advanced instrumentation is available. Second, theoretical and empirical work in the field of lightning protection is often inseparable, especially in the earlier efforts. Having no advanced understanding of electromagnetics and electrical theory until the late 1800's, much of the early development of lightning protection technology is based on observation, trial and error.

Last, we must dispel the thought that the development of the lightning protection standard is based solely on "historical" precedents. This is a casual perception, only arrived at if the vast amount of bibliography available is not reviewed. Science in itself, then, is historical in nature because each successive work builds on the prior work. To sum up the scientific method, a theory is formed, tested and conclusions drawn. In that way, previous results and observations are considered as part of forming a theory and used to guide the testing. Without consideration of the prior work, science is doomed to needlessly repeat fruitless efforts and pursuit of fallacious speculation. Indeed, what is largely taught in undergraduate science and engineering programs is the condensed lessons of our predecessors.

The development of the lightning protection principles and techniques used in NFPA 780 and other lightning protection codes throughout the world, is based on solid science. It is easy to demonstrate that the origin of the precepts used is based on old works, works that the casual researcher will not be able to easily find. Like many mature branches of science, the original documents are often no longer referenced. In our effort we quote key papers and books in the area of lightning protection. Despite the daunting amount of literature, the determined researcher can find a trail of literature through time to the present day with relevance and continuity. These key references are the trail left by lightning scientists and engineers as they considered the best available experimental, empirical and theoretical results of their day. We present this trail here.

[1] From NFPA Directory 2001: Code – A standard that is an extensive compilation of provisions covering broad subject matter or that is suitable for adoption into law independently of other codes and standards.

2.0 Origins of Lightning Protection

The earliest literature available that proposes protection from lightning starts in 1752 with Benjamin Franklin. Franklin's original idea was to use a sharp point to draw charges from the cloud to discharge it and thus prevent lightning. Early experiments by Franklin in electrostatics had him arrive at this conclusion. By placing objects with different geometries (sharp and blunt) near a charged object, Franklin found that differing amounts of charge were drawn from the original charged object. (Later researchers would come to understand that electrostatic lines of force concentrate at sharp points, theoretically verifying his electrostatic experiments.) He consequently published the first instruction for protection from lightning:

> "The Method is this: Provide a small iron Rod (it may be made of the Rod-iron used by the Nailers) but of such a Length, that one End being three or four Feet in the moist Ground, the other may be six or eight Feet above the tallest part of the Building. To the upper End of the Rod, fasten about a Foot of Brass Wire, the Size of a common Knitting-needle, sharpened to a fine Point; the Rod may be secured to the House by a few small Staples. If the House be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. A House thus furnished will not be damaged by Lightning, it being attracted by the Points, and passing thro the Metal into the Ground without hurting any Thing. ..."[2]

This news traveled fast, considering the rates of travel in 1752. Within 10 years, we see published accounts of field tests and observations regards the new invention:

> "We had four houses in this city, and a vessel at one of the wharfs, struck and damaged by lightning last summer.... But I have the pleasure to inform you, that your method of preventing such terrible disasters, has, by a fact which had like to have escaped our knowledge, given a very convincing proof of its great utility, and is now in higher repute with us than ever.... Mr. West informed me, that his family and neighbours were all stunned with a very terrible explosion, and that the flash and crack were seen and heard at the same instant. ...
>
> Mr. West further informed me, that a person of undoubted veracity assured him, that, being in the door of an opposite house, on the other side of Water-street, (which you know is but narrow) he saw the lightning diffused over the pavement, which was then very wet with rain, to the distance of two or three yards from the foot of the conductor; and that another person of very good credit told him, that he being a few doors off on the other side of the street, saw the lightning above, darting in such direction that it appeared to him to be directly over that pointed rod. ...Upon receiving this information, and being desirous of further satisfaction, there being no traces of the lightning to be discovered in the conductor, as far as we could examine it below, I proposed to Mr. West our going to the top of the house, to examine the pointed rod, assuring him, that if the lightning had passed through it, the point must have been melted; and, to our great satisfaction, we found it so. ..."[3]

This account is the first published account of an observed strike to an air terminal, with verification by examination of the strike termination. In fact, references exist that indicate very early record keeping of lightning damage that continue past the installation of Franklin rods in the late 1700's. Schonland makes the following statement:

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[2] Franklin, B.: "How to secure Houses, &c from Lightning", *Poor Richard's Almanac*, reproduced in *Benjamin Franklin's Experiments*, edited by I. Bernard Cohen, Harvard University Press, 1941. 453 pp.

[3] Kinnersley, E,: "Letter to Benjamin Franklin, reproduced as Letter XX" (from 1761) in *Benjamin Franklin's Experiments*, edited by I. Bernard Cohen, Harvard University Press, 1941, pp. 348-358.

> "The record of damage to churches, whose elevated steeples attract lightning is voluminous. ... Perhaps the most famous of these structures is the Campanile of St. Mark in Venice. This has had a very bad lightning history. It stands over 340 feet high in an area which, as already mentioned, experiences many thunderstorms. It was severely damaged by a stroke in 1388, at which time it was a wooden structure. In 1417 it was set on fire by lightning and destroyed. In 1489 it was again reduced to ashes. In 1548, 1565, and 1653 it was damaged more or less severely, and in 1745 a stroke of lightning practically ruined the whole tower. Repairs cost 8,000 ducats (3,000 pounds sterling in those days), but in 1761 and 1762 it was again severely damaged. In 1766 a Franklin rod was installed on it and no further trouble from lightning has occurred since."[4]

This statement also sets the tone for much of the lightning protection system record keeping – in many cases if problems do not occur, no report is made. This being the case, we will see much of the evidence for lightning protection systems is statistical in nature.

Faced with empirical results, Franklin published further on the topic in 1767, refining some of the design notes regards grounding in particular. He notes that that his lightning protection system may not work by "silently discharging the cloud.":

> "It is therefore that we elevate the upper end of the rod six or eight feet above the highest part of the building, tapering it gradually to a fine sharp point, which is gilt to prevent its rusting. Thus the pointed rod either prevents a stroke from the cloud, or, if a stroke is made, conducts it to the earth with safety to the building. The lower end of the rod should enter the earth so deep as to come at the moist part, perhaps two or three feet; and if bent when under the surface so as to go in a horizontal line six or eight feet from the wall, and then bent again downwards three or four feet, it will prevent damage to any of the stones of the foundation."

Other confirmations exist of the Franklin lightning protection system from the period (1777) as written by E. Phillip Krider of the University of Arizona:

> "One incident that had a significant impact on public opinion in Italy was a strike that occurred in Siena on 18 April 1777. Lightning rods had been installed on the Torre del Mangia, the 102 m tower of the city hall that dominates the Piazza del Campo, site of the famous Palio, and on the cathedral. A controversy erupted when a Marquis Alessandro Chigi criticized these conductors and claimed that they were dangerous because they would attract lightning and would not work when they did. Domenico Bartaloni and other professors at the University of Siena rallied to the defense of rods, and a hot debate ensued. The matter was settled when a thunderstorm rumbled into the area on 18 April and people gathered in the Piazza to watch the rod on the tower. A contemporary account of the incident reads as follows:
>
> It will not be easy to find a similar observation attested in all its circumstances by a large number of people, who, in a thickly frequented public square, in plain daylight, and with all their attention, had their eyes turned toward an extremely high tower to observe the action of the conductor recently placed upon it, and who, without a long wait, had the fortune to admire, to the glory of Philosophy, the intelligence and genius of the immortal Mr. Franklin, who, extending, so to speak, his prodigious hand over the square of Siena on the 18th of April, took by the hair a horrible lightning bolt and forced it to pass along a route mapped out by his great mind, with express orders not to damage a building on which it has so many times vented its furious strength....
>
> After this, public opposition to the use of grounded rods began to wane, and eventually people began to enjoy a psychological benefit first noted by Franklin in 1762....". " On May 9, 1778, the Senate of Venice issued a decree ordering the erection of lightning rods through the republic. It was the first recognition of the value of conductors by any government ... (Anderson. 1879, p. 48)."[5]

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[4] B. F. J. Schonland's *Flight of Thunderbolts*, Clarendon Press, Oxford, 1950, page 9.

[5] Krider, E. P., 1997 (University of Arizona): "Lightning rods in the 18th Century", *Second International Symposium 0n Lightning and Mountains*, Chamonix Mont Blanc, France, 7 pages

Other churches were not as fortunate to have lightning protection installed. One account of a lightning accident in Italy sets a chain of events that leads to the first overall design revisions to lightning protection systems, that accounts for the overall structure. Viemeister recounts the accident:

> “In 1769 one hundred tons of gunpowder that was stored in the vaults of the Church of St. Nazaire in Breescia, Italy, was exploded when lightning struck the spire. Several thousand people were killed and the city was leveled. As a result, the British government implored the Royal Society to devise some means of protecting their powder magazines at Purfleet.”

3.0 Early Field Trials and Investigation of Failures - Purfleet

Lightning protection was installed at Purfleet and lightning struck there shortly thereafter. Yet the lightning rod was not struck. Investigation revealed another metallic object was struck and lightning conducted to ground. This incident caused the first reconsideration of lightning protection technology and it's techniques. The incident is recounted:

> "Although the House of the Board of Ordnance in the Royal Arsenal at Purfleet, Essex, England was equipped with Franklin rods, lightning struck a iron "cramp" cemented with lead into the copeing stones on the parapet wall at a distance of 46 feet from the tip of the closest lightning rod and caused extensive damage to the masonry. The end of the cramp came "within seven inches of a lead plate ... (which) communicated with the gutter which was the main conductor of the building. At a distance of seven feet and one half from the place stricken, a large leaden pipe went down from the gutter to a cistern of water in the yard".[6]

We now know that the lightning-damaged corner of the Board House at Purfleet would not have been adequately protected by the closest lightning rod, installed above the center of the 44-foot-high building with a tip-height of 27 feet above, and a horizontal distance of 37 feet from the lightning strike point[7]. But this incident drove the first recommendations for lightning protection systems concerning bonding of incidental metal and the first considerations concerning the effective range of strike terminations. It also set off the blunt vs. pointed air terminal arguments which we will not discuss in detail here since it is ancillary to scientific substantiation of the performance of lightning protection systems overall.

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[6] Nickson, E (Store-keeper at Purfleet): *"XV.* Sundry papers relative to an Accident from Lightning at Purfleet, May 15, 1777, Report to the Secretary of the Royal Society", *Phil. Trans.*, *Royal Soc*., **LXVIII**, for 1778, Part 1, pp. 232-235.

[7] Golde, R.H., Lightning, Vol. 2., Academic Press, London, 1977, p. 546, provides a pictorial description of Purfleet.

4.0 Origins of the Protected Zone Concept

Although Franklin is attributed to have proposed the concept of the "cone of protection", detailed inquiry to determine the range of effectiveness of air terminals would wait until 1823. Gay-Lussac proposed a cone of protection with a radius of twice the height of the air terminal[8]. The impact of Gay-Lussac in 1823 is far reaching, quoted by Anderson:

> "In the year 1822, there happened to be in France, and over the greater part of Continental Europe, an extraordinary number of violent thunderstorms ...the almost, continuous thunderstorms caused great alarm among the population; and the priests in many places held processions in and around the churches, with special prayer-meetings, to appease the wrath of heaven.' In consequence of all this excitement, the Minister of the Interior, deeming that something also ought to be done besides the walking in procession to stay the fatal effect of lightning, ordered that all the public buildings in France should be protected immediately by conductors, made on the most perfect model and placed in the best manner."
>
> To get preeminent advice as to the efficiency of lightning conductors, the Minister applied officially to the 'Academie des Sciences,' which learned body thereupon nominated a committee consisting of six of the most celebrated investigators of the phenomena of electricity - MM. Poisson, Lefevre-Gineau, Girard, Dulong, Fresnel, and Gay-Lussac. The committee held many sittings, collecting a vast amount of evidence on the subject, and on April 23, 1823, presented through M. Gay-Lussac its report to the ' Academie des Sciences,' which was adopted and ordered to be printed, being declared a highly important document. The French Government took the same view as the 'Academie des Sciences,' and not only acted upon the recommendations of the report, but issued it to all public functionaries, to the clergy, and others, with directions to make it generally known. In this way hundreds of thousands of copies of the 'Instruction sur les paratonnerres ' found their way all over France, and from thence in translations all over Europe, as the best existing guide for the erection of lightning conductors.[9]"

This is the first codification of a specific protected zone ascribed to the air terminals of a lightning protection system. Further observations leading to the protected zone concept were published in the 1840's by Sir William Snow Harris. His concern (beginning in 1820) was the protection of ships. To some degree, a tall ship provides a very good lightning protection model, since it has less influence from surrounding terrain. The following discussion illustrates the installation and observation of air terminals on ships[10]:

> "...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. ..."

Snow Harris invented a method in 1820 for installing lightning rods and down-conductors on ships but the method was not fully adopted by the Royal Navy until 1847. In the above referenced book, Snow Harris acknowledged the support of Sir George Cockburn, Admiral of

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[8] Gay-Lussac, F. and C. Pouillet: "Introduction sur les paratonneres, adoptee par L'Academie des Sciences."

[9] Anderson, R., *Lightning Conductors - Their History, Nature, and Mode of Application,* E.& F. N. Spohn, 46 Charing Cross, London, p76.

[10] Harris, W. S., (Sir William Snow Harris): *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) 226 p.

the Red, of Snow Harris's efforts to install lightning protection on ships: "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."

Sir Snow Harris' detailed record keeping on lightning strikes to ships is evident in the following excerpt from his 1847 work[11]:

> "It is to be especially observed, that this Record does not profess to comprise all the ships of the Royal Navy damaged by lightning since the commencement of the war about the year 1793, but only such cases as have come to the author's attention ... it is highly probable that almost every ship on the lists of the navy, from the above period upward for full forty years has, at one time or another, suffered in some way from this source of danger. ... The total number of instances of damage done by lightning in the Royal Navy, as given in the record , amounts to two hundred and twenty. They comprise 87 ships of the line. 55 frigates 78 sloops and other vessels. ...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."

This is a direct predecessor to further investigation of lightning protected areas. From these detailed observations, it was clear that the conical 2:1 zone left something to be desired.

In 1880, Preece conducted experiments to measure the actual electric field about a vertical air terminal. Preece concluded:

> "…a lightning rod protects a conic space whose height is the length of the rod, whose base is a circle having its radius equal to the height of the rod, and whose side is the quadrant of a circle whose radius is equal to the height of the rod.[12]"

This concept of the 1:1 protected zone, based on the best measurement available, would pervade lightning protection for many years to come.

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[11] Harris, W. S., (Sir William Snow Harris): *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) 63 p.

[12] Preece, W. H.: "On the space protected by a lightning conductor", Phil. Magazine, **9**, pp. 427-430.

5.0 Lightning Protection Technology Matures – Early Standards

At approximately the same time as Preece's work, Anderson (1879) published a pivotal work on lightning protection entitled *Lightning Conductors - Their History, Nature, and Mode of Application*. This book is essentially the first lightning protection standard. Even today, we follow most of the recommendations of this work. A most important aspect of Anderson's publication is the references. In his book are listed the basic references, from Italy, France, Germany from the 1700's on to his day. We can verify the accuracy and completeness of his work by noting that he references earlier works by Preece, Harris, Gay-Lussac and Franklin. This book summarizes the international literature and empirical observations, the "field trials" of the day into a specification document.

During the period between 1878 and 1882, lightning protection captured the attention of eminent architects, engineers and scientists in Western culture. An essential effort was the harmonization of understanding on lightning protection technology. The Royal Meteorological Society, in May, 1878 resolved to address The Royal Institute of British Architects, The Physical Society and The Society of Telegraph Engineers, to consider issuing a code of rules for the erection of lightning conductors, and to proceed in preparing a code. After lengthy meetings in which all aspects and experiences of lightning protection were addressed, the organizing committee issued the *Report of the Lightning Rod Conference* in 1882[13] that established a set of rules for those who installed lightning protection systems in Britain. At this early time, it was felt that the techniques of lightning protection, as refined to date, was nearly infallible. The conference report summarized:

> "If all these conditions be fulfilled; if the points be high enough to be the most salient features of the building no matter from what direction the storm cloud may come, be of ample dimensions and in thoroughly perfect electrical connection with the earth, the edifice with all that it contains will be safe, and the conductor might even be surrounded by gunpowder in the heaviest storm without risk or danger. All accidents may be said to be due to a neglect of these simple elementary principles. The most frequent sources of failure are conductors deficient either in number, height, or conductivity, bad joints, or bad earth connections. There is no authentic case on record where a properly-constructed conductor failed to do its duty."

In 1904, the National Fire Protection Association essentially adopted the recommendations from the 1882 Conference into *Specifications for Protection of Buildings Against Lightning*. The emphasis of the document was to provide practical recommendations, noting:

> "The treatment of this subject is from an underwriting rather than an electrical standpoint. And for this reason we submit some figures to show approximately the relation the hazard of lightning bears to our business." The losses from fires due to lightning for the five years from 1898 through 1902 were $21,767,185. Of the damage caused by lightning, fires occurred in 3842 dwellings, 9375 barns, 328 churches and 59 ice houses."

> "The study of the phenomenon of lightning in a practical way dates back to about 1747. The first lightning conductor is said to been used by Benjamin Franklin in 1755. ...From what has been learned from then until

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[13] Symons, G. J., editor: *Report of the Lightning Rod Conference*, (with delegates from the following societies, viz,: Meteorological Society, Royal Institute of British Architects, Society of Telegraph and of Electricians, Physical Society, Co-opted members [Prof. W. E. Ayrton, Prof. D. E. Hughes]), E.& F. N. Spon, 16, Charing Cross Road, London, 396 pp.

> now my be briefly stated when we say that a flash of lightning is a passage of electricity between two bodies unequally or oppositely electrified and between which the potential difference is sufficiently strong to break across the air space between. ... "
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> "It has been proved that lightning conductors, properly installed, are a protection, and not withstanding that we are providing against an unknown quantity of current, we believe that there is a limitation which, if provided for by a sufficient metallic surface area properly arranged, may absorb and dissipate any charge likely to occur. At the same time, the protection afforded by a conductor will depend on the relative positions of the electric discharge and the objects it meets in its course. The more any object projects above the general level, the nearer is the cloud and less the resistance offered to the discharge. High objects are therefore more frequently struck, hence need more careful protection….."
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> "Our desire, therefore, in the preparation of the proposed recommendation, is to bring to the notice of the public such methods as we believe, if adopted, afford at least some protection against lightning and to the end that the proportion of fire loss occasioned thereby is materially reduced.[14]"

The first American lightning protection document was based on the culmination of the best lightning science available up to that point. It was quickly followed by other documents to describe implementations of lightning protection systems[15].

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

[15] Hedges, Killingworth: *Modern Lightning Conductors: An illustrated Supplement to the Report of the Lightning Research Committee of 1905 with Notes as to the Methods of Protection & Specifications*, Crosby Lockwood & Son, London, 82 p.

6.0 Early Field Surveys Validating the Performance of Lightning Protection

During the period immediately following the publishing of early standards in the United States, we see an interest in the effectiveness of lightning protection systems. The emphasis is primarily from an underwriting viewpoint and tends to be statistical in nature. This period covers from approximately 1910 – 1950, where there are detailed statistics kept by a variety of organizations.

A statistic often quoted by several researchers is the Iowa Fire Marshal's records. As a preface to these records, the listings are not detailed and do not say if the systems are in a good state of repair or, for that matter, comply with established codes and standards for lightning protection according to the authority having jurisdiction for that region. Despite this, we can use these to provide some useful insight. A first report appears in 1926:

> "THE USE OF METAL CONDUCTORS to protect buildings from lightning damage began with Benjamin Franklin's experiment in 1752, since which time the scientific world generally has advocated the protection of houses, barns, and other property from lightning. Experience has proved conclusively that when the equipment is carefully and intelligently selected and installed the protection afforded is almost complete…..An analysis of the reported losses from lightning fires in Iowa during the years 1919-1924... shows that about 72 per cent of the total fire loss caused by lightning in six years occurred among the farm barns and dwellings, of which 60 per cent was due to fires in barns which were unrodded, whereas about 5 per cent took place in barns supposed to be protected by rods. 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. ... it is estimated that in the rural districts, where most lightning fires take place, about half of the structures are rodded; so that during these six years, out of each 100 fires 5 or 6 occurred in rodded structures; of which a considerable proportion had defective rods.[16]"

Examination of the Iowa statistics continues through the 1940's and is summed up by McEachron in 1950. He sums up that 91% of buildings damaged by lightning were "unrodded," and goes on to say:

> The true percentage for well designed and maintained systems would make a still better showing…15 percent of …dwellings and 44 percent of …barns were reported as defective[17].

These numbers correlate well with the Iowa Fire Marshal's data from 1956 to 1966 which indicates 16% of "rodded" city buildings and 37% of "rodded" rural dwellings struck by lightning were damaged[18]. The relative closeness of the "defective" statistics with the rate of damage for buildings equipped with of lightning protection is a likely indicator that a low rate of damage is being experienced by buildings with lightning protection systems that are up to standards of the day. Other studies support this conclusion.

Underwriter's Laboratories maintains a "Master Label" program for the certification of installations of lightning protection systems under their standard, UL 96A Installation of Lightning Protection Systems. This standard mirrors NFPA 780 very closely. In some years between 1923 and 1950, statistics were kept on the effectiveness of lightning protection systems

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[16] Covert, Roy N. (U.S. Weather Bureau): "*Protection of Buildings And Farm Property From Lightning*" , U. S. Department of Agriculture, Farmers' Bulletin No. 1512.

[17] McEachron, K. B. (General Electric Company): "Lightning Protection Since Franklin's Day", *Jour. Franklin Inst.*, 253, pp. 441-470.

[18] Office of the State Fire Marshal, State of Iowa, Annual Reports for 1956-1966.

certified under the Master Label program. As quoted by Viemeister:

> "In 1923 the National Board of Fire Underwriters inaugurated a system for monitoring the installation of lightning protection systems through Underwriter's Laboratories. A Master Label is granted to a system that meets a stringent set of requirements. Since the start of the Master Label program, more than 240,000 labels have been awarded, and less than one-tenth of 1 per cent have been reported damaged by lightning. Investigators found that in the majority of damage cases the protection system was either in poor condition or the building had been updated without appropriate updating of the system."[19]

The government's experience with lightning protection dates from even earlier, as also indicated by Viemeister:

> "Do modern lightning rods protect a building? When properly installed, lightning rods can provide virtual immunity from direct lightning strokes. The Washington Monument was struck and damaged before rods were installed in 1885. Since that time, it has been struck innumerable times without injury.[18]"

Literature based on further, more recent government statistics also bear out the effectiveness of lightning protection systems:

> "A survey by [Office of the Chief of] Ordinance [U.S. Army] for the period from 1944 through 1948 shows the following: a. Protected structures were struck 330 times; damage negligible. b. Unprotected structures were struck 52 times; damage exceeded $130,000.[20]"

From the bulk of evidence by the 1950's the conclusion was drawn that lightning protection systems, as embodied in the national codes and standards of the day, were greatly effective in preventing damage due to lightning.

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[19] Viemeister, P. E., *The Lightning Book*, MIT Press, Cambridge, MA, p. 202.
[20] McEachron, K. B. (General Electric Company): "Lightning Protection Since Franklin's Day", *Jour. Franklin Inst*., 253, 1952, pp. 441-470.

7.0 Further Development of the Zone of Protection in Lightning Protection Systems

As we reviewed it, discussions of the protected zone resulting from an air terminal in lightning protection systems began in the early 1800's. By 1880 or so, the concept of a protection zone about the lightning terminal at its apex was firmly established in lightning protection standards, it would remain so for nearly another hundred years. Yet this line of inquiry was not exhausted.

In 1892, Sir Oliver Lodge published a review of the various concepts of a protected zone that had been proposed to that date[21]. Wide variation existed in the zones; angles of the conical section from 90 degrees to 30 degrees. A curve similar to the current electrogeometrical concept was apparently proposed by Preece, in a later work. With the bulk of evidence available at the time, cones of protection varying from 45-degrees to 64-degrees were retained as the protected zone concept, with little variation.

Further investigation into this was performed by Larmor & Larmor in their 1914 work[22]. This publication related the zone of protection to electric field lines, using the then available electromagnetic theory of Maxwell. The work was ahead of it's time in the sense it predicted the possibility of oblique strikes, and by extension of their illustration of the electromagnetic field lines in presence of the lightning air terminal, the curved protected zone now used under the electrogeometrical model. Based on this literature review, it also appears to be the first paper to correlate the mechanism of gas ionization to lightning propagation and suggested examining the air terminal in this venue. Following the work of Larmor & Larmor, Schwaiger revisited the problem in 1938, devoting a whole book to it, but ultimately reaching the same conclusions as Preece[23] [24].

It is notable to mention that in the 1920's Peek evaluated the protected zone concept using laboratory testing to determine protected zones of approximately 64 to 76 degrees[25] [26]. Without further elaboration, scale laboratory tests were done on lightning protection concepts beginning in the 1920's most notably by the General Electric Company. An excellent, yet brief, history of this effort is presented by Viemeister[27] with photography illustrating some of the experiments. Any intimation that Franklin lightning protection systems had not been subject to laboratory testing is false. (This topic is discussed in detail in a later section, as well.)

During the period from the 1950's through the 1970's protection for power transmission lines became more of a concern. Consequently a great deal of investigation ensued with significant contributions in the field by authors such as Whitehead, Wagner and Mousa. Although a great deal of work went into the verification of lightning protection techniques for surge suppression, grounding flashover, etc., our primary interest is the establishment that the air terminals associated with lightning protection systems have been proven to intercept the lightning event.

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[21] Lodge, Oliver J., Lightning Conductors and Lightning Guards, Whittaker & Co., London, 1892.
[22] Larmor, Sir J.L. and Larmor, J.S.B., Proceeding of the Royal Society, Vol. 90, pp. 312-317, 1914.
[23] Golde, R.H., Lightning, Vol. 2., Academic Press, London, 1977, p. 547.
[24] Schwaiger, A., Der Schutzbereich von Blitzableitern R. Oldenbourg, Munich, 1938.
[25] Lee, R.H., Protection Zone for Buildings Against Lightning Strikes Using Transmission Line Practice, IEEE Transactions on Industry Applications, Vol. IA-14, No. 6, November/December 1978.
[26] Peek, F.W., Dielectric Phenomena in High-Voltage Engineering, New York, McGraw-Hill, 1929.
[27] Viemeister, P. E., *The Lightning Book*, MIT Press, Cambridge, MA, p. 54, 150-151.

A key paper in this venue, summing up the work of 100 years past, was Lee's paper describing the electrogeometrical model of lightning protection[28]. This model remains in use by not only NFPA 780 but by all U.S. military/government lightning codes and standards, International Electrotechnical Commission lightning protection standards and the lightning protection standards of most countries. The conical zones of protection were superseded by the electrogeometrical model in the 1980 edition of NFPA 78, an example of the NFPA Technical Committee on Lightning Protection keeping up with the current developments in the lightning protection field.

In addition, to give credit where it is due and to provide independent verification of the electrogeometrical model of lightning protection (in the event that its use by the international community is not sufficient), Horvath states that this method was incorporated into Hungarian standards since 1962. He goes on to state that laboratory experiments to formulate and validate the concept were performed as early as 1948. Horvath, having better access to European research, provides an interesting perspective into the development and validation of the electrogeometrical concept at recently as 2000[29]. Extensive work done by Horvath includes verification by computer simulation in 1991[30].

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[28] Lee, R.H., Protection Zone for Buildings Against Lightning Strikes Using Transmission Line Practice, IEEE Transactions on Industry Applications, Vol. IA-14, No. 6, November/December 1978, p.465.
[29] Horvath, T., Rolling Sphere – Theory and Application, Proceedings of the 25th International Conference on Lightning Protection, September 2000.
[30] Horvath, T., Computation of Lightning Protection, John Wiley & Sons, New York, 1991.

8.0 Recent Developments and Literature

Now that we have essentially reviewed the key literature up to 1980 or so and found that there is evidently a solid trail of scientific investigation into lightning protection techniques, we turn to recent key findings. Although the bibliography of recent (i.e., post 1980) literature is quite large, we confine our review again to key documents and sources that have affected lightning protection standards within the scope of “conventional” lightning protection.

8.1 National Lightning Detection Network (NLDN)

A significant recent development in lightning detection technology is the National Lightning Detection Network (NLDN). The NLDN is a networked system of lightning sensors throughout the continental United States originally developed under a Bureau of Land Management contract with the intention of locating potential lightning-initiated forest fires in remote areas. It has since been turned to private ownership and can provide real time data of lightning strikes as well as archived data. Many papers have been published on the methodology and accuracy of this system[31].

Although NLDN is a significant recent development it’s use in conducting scientific studies in the performance of lightning protection systems and specifically the connection of lightning event to air terminals is limited. The accuracy of the system is not usually sufficient for use as a sole means of determining connection of a lightning event to a particular structure. However, this system can be particularly useful in prompting inspections of isolated buildings. As we will see in a later section, field studies have been conducted using NLDN this way.

A significant finding regarding NLDN is that the latest edition of NFPA 780, the not-yet-published 2000 edition, contains NLDN data for the assessment of risk of lightning strike[32]. We conclude that the NFPA 780 standard has clearly kept up with the latest advances in lightning event data for the purposes of risk assessment.

8.2 Optimal Air Terminal Configurations

Recent work by Moore[33] [34] contends that there is an optimal tip radius for air terminals used in lightning protection systems. Interestingly, this work settles a long argument dating back to the origins of lightning protection concerning whether tips of air terminals should be sharp or blunt, Franklin being a proponent of sharp tips. Again, review of the NFPA 780, 2000 edition, reveals that this consideration is incorporated.

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[31] For example: Cummins, Kenneth L., Krider, E. Philip, and Malone, Mark D., *The U.S. National Lightning Detection Network TM and Applications of Cloud-to-GroundLightning Data by Electric Power Utilities*, , IEEE Transactions On Electromagnetic Compatibility, Vol. 40, No. 4, Nov. 1998, p. 465.   Paper has extensive list of 75 references.

[32] NFPA , NFPA 780 Report on Comments, Quincy MA., 2000.

[33] Moore, C. B., W. Rison, J. Mathis and G. D. Aulich, "Lightning Rod Improvement Studies", *Journal of Applied. Meteorology.*, **39**, 2000, pp. 593-609

[34] Moore, C. B. , "Improved Configurations of Lightning Rods and Air Terminals", *Jour. Franklin Inst*., 315, 1982, pp. 61-85.

8.3 From Behind the Iron Curtain

Since the demise of the former Soviet Union, access to Russian literature and research work has increased. A significant work in this regard is the recent publication by Bazelyan and Raizer[35]. This work is noteworthy to this discussion in that it provides, in summary with technical analysis, the results of independent Russian researchers over the past 50 years and more. An overall review of this work reveals that parallel research efforts to determine lightning protection engineering techniques were undertaken in the former Soviet Union. Further, we find that the Russian researchers started with the generally same literature quoted earlier in this report up into the 1930's and continued their efforts independently. Their results generally mirror those of western researchers and is reflected in their standards. An example is their discussion on protected zones:

> " It follows from the foregoing that a lightning-rod has a better chance of intercepting descending lightnings if it has a greater height above the object and is closer to it. Practically, it is important to identify a certain area around a protector, which would be reliably protected. This is the protection zone. Any object located within this cone must be considered protected with a reliability equal to or higher than that used for the calculation of the zone boundary. There is no doubt that this idea is technically constructive. … In Russia, for instance, a single lightning rod zone was usually a circular cone , whose vertex coincided with the rod top. When lightning protection engineers realized that the height of the rod was to exceed that of the object to be protected the cone vertex was placed on the rod axis under its top. The greater the protection reliability required, the more pointed and lower was the zone cone ."

Bazelyan precisely describes protection concepts developed in Russia independently from the same precepts as those used in the U.S. Variation of the conic apex and angle has precisely the same effect as variation of the striking distance of the electrogeometric model, which is the technique employed in NFPA 780. Here was have an independent development of lightning protection engineering techniques arriving at generally the same methods of protection as those used by NFPA 780 and other countries. This newly available resource provides further substantiation and independent verification, using primary literature from Russia generally not examined by western researchers, of the lightning protection techniques embodied in the NFPA 780.

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[35] Bazelyan E.M. and Raizer, Y.P., Lightning Physics and Lightning Protection, Institute of Physics Publishing, Philadelphia, 2000.

9.0 Summary of Literature and Theoretical Results

Review of the key literature, as presented here, leads to the overwhelming conclusion that lightning protection systems have been intensively studied and have been proven effective many times over in the past 250 years. In that time, observations and theoretical developments (notably in electromagnetic theory) have led to system refinements and associated specification changes. Early work validated the effectiveness of these systems leading to lightning protection standards, which were also refined as new findings became available. Evidence demonstrates a solid scientific basis in lightning protection technology from 1904 through the latest edition of the NFPA 780 in 2000. Parallel study of lightning in Russia and their development of similar standards have become available recently to further increase the already substantial weight of evidence.

The next step in our submission of technical substantiation is to examine specific empirical and experimental lightning protection studies, further demonstrating the effectiveness of these systems.

10.0 Systems Analysis and Testing

10.1 Introduction to Systems Analysis and Testing

Standards Council Decision 00-30 requested that the substantiation provided to them include an analysis demonstrating the validity of the basic technology and science underlying traditional lightning protection systems. It goes on to say:

> "The conclusions of the Bryan Panel Report, coming as they do from respected and neutral observers, while not definitive, cannot be overlooked, and that questions about the validity of NFPA 780 should be resolved."

In determining what method would be acceptable in demonstrating the validity of the basic technology, one would assume that the same procedure Bryan et.al., specified for ESE systems would be applicable. Bryan et.al., states:

> "The panel determined this question could only be answered validly with an examination of the laboratory tests (small-scale) and the Field tests (large-scale) provided to it in the submitted documents." [36]

This section provides a brief discussion on laboratory testing and forwards the results of numerous field tests conducted throughout the 1900s. We trust that this discussion will provide substantial validation of the basic technology and science underlying traditional lightning protection systems.

10.2 Laboratory Testing

Testing of air terminals has been conducted in the laboratory. Bryan, et.al.[37] discusses recent comparative testing of air terminals conducted by Chalmers et.al., Berger, ETL, and the Department of Electrical Engineering and Electronics at the University of Manchester Institute of Science and Technology. Although some of this testing was done specifically to evaluate the comparative effectiveness of Early Streamer Emission air terminals, the results are applicable. Consequently, several of these tests focused on comparative time for the initiation of a streamer. However, the true test of the effectiveness of a strike termination device is not in the time required to generate a streamer, but instead in the ability of this streamer to successfully capture the dart leader and provide a termination for the lightning event. To this extent, the most significant of the recent laboratory testing reported is that provided by the University of Manchester Institute of Science and Technology. Bryan, et.al. summarizes the results of this testing on page 12 of his report as follows:

> "With one ESE device the Franklin rod was struck 27 times and the ESE device was struck 22 times. With the second ESE device the Franklin rod was struck 72 times and the ESE device was struck 42 times. The evaluation between the third ESE device and the Franklin rod resulted in each of the devices being struck 101 times, with eight discharges striking neither device. During the entire evaluation program in the laboratory a

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[36] Bryan, John L., Richard G. Biermann, and Glenn A. Erickson, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology*, National Fire Protection Association, 1 September 1999, p.10.

[37] Bryan, John L., Richard G. Biermann, and Glenn A. Erickson, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology*, National Fire Protection Association, 1 September 1999, p. 11-13.

> total of 420 electrical discharges were generated, with 200 of these discharges striking the Franklin rod for 47.6 per cent, 165 discharges striking the ESE device for 39.3 per cent and 55 discharges did not strike either device for 13.1 percent of the discharges."

Mr. W. L. Lloyd of the General Electric Co. High Voltage Engineering Laboratory discussed some of the laboratory testing conducted at the GE High Voltage Engineering Laboratory in a radio address as follows:

> "In the laboratory we can produce the same rate of voltage rise and current rise and the same order of current magnitude as in the natural lightning strokes. With our laboratory lightning we can melt and vaporize metal conductors, split wood, burst bricks and stone and shatter concrete just as natural lightning does. Of course, we can not splinter a whole tree or shatter a whole house for we work with sparks which are only thirty feet long rather than a half mile long. …
>
> … Our tests and field experience indicate that for the protection of a building from damage by lightning , there is nothing more effective than a lightning rod system properly designed, installed and well grounded. Although General Electric does not make or sell lightning rods, we have studied their operation in detail and are convinced of their effectiveness when properly installed. We have also carried on a large number of tests on lightning rods for the various oil companies for the protection of their oil tanks and for the U. S. Government for the protection of their powder and munition warehouses." [38]

One might conclude that laboratory testing proves that Franklin, or conventional, air terminals are quite effective. What we can conclude is that extensive laboratory testing was done in the past concerning air terminals.

Despite these findings, it is generally agreed that there is little correlation between the performance of air terminals in the high voltage laboratory and field test results under natural lightning conditions. Bazelyan and Raizer detail Russian results from laboratory experiments beginning in the 1940's. They detail the conclusion of long experimentation in the following:

> " Laboratory investigations of lightning attraction were initiated in the 1940s….. At that time, experimental researchers expected to derive information necessary for a numerical evaluation of lightning rod effectiveness. The naïve optimism has long since vanished. The measurements showed that the attraction process did not obey similarity laws." [39]

However, laboratory testing can play a role in the development of lightning protection system component parameters, such as conductor sizing requirements and thickness of metal attachment points. Examples are the metal thickness test results discussed by McEachron[40] and recent testing conducted by the U.S. Army[41] that confirms the conductor sizing requirements specified in NFPA 780.

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[38] Lloyd, W.L., *Lightning Protection by One Who Knows, It Pays to Protect*, High Voltage Engineering Laboratory, General Electric Co., Pittsfield, MA, presented on the Farm Forum Program broadcast by WGY Radio Schenectady on 8 July 1937.

[39] Bazelyan E.M. and Y.P. Raizer, *Lightning Physics and Lightning Protection*, Institute of Physics Publishing, Philadelphia, 2000, p233.

[40] McEachron, K.B., General Electric Company letter to Electra Protection Company, Inc. re: *Why Buildings Burn From Lightning With Grounded Metal Roofs*, 12 May 1944.

[41] Tobias, J.M., *"Testing of Ground Conductors with Artificially Generated Lighting Current,"* IEEE Transactions on Industry Applications, Vol. 32, No. 3, May/June 1996.

10.3 System Level Field Testing and Evaluation

Bryan, et.al, states that:

> "It would appear the ultimate evaluation of any complete lightning protection system would be the performance of the systems as installed on buildings."[42]

This sentiment is echoed by Rapp in his submission to the Standards Council for consideration at their July 1995 hearing where he states that "The proof of the pudding is in the eating."

Guthrie, in his 18 September 2000 letter to the Standards Council, provides the following statement as a part of his discussion on the Bryan Panel observation that detailed operational and failure data is lacking for all types of lightning protection systems:

> "Positive feedback on the operation of a lightning protection system is seldom documented and most often not even noticed. Only in some rare cases can it be documented that a lightning protection system has been struck if it works properly and there is no damage. There is sometimes evidence at the strike termination point which can be noted during a careful inspection, but it is seldom cost effective for the owner of a lightning protection system to obtain the expertise necessary to conduct such a careful inspection."[43]

The failure of a lightning protection system is often much easier to document. It most often leaves positive evidence of the failure either in the form of a fire, personnel injury, or damage to the structure or its contents. However, what is difficult is the determination of the cause of the failure. This report will provide data based on both the positive operation of lightning protection systems and techniques and that based on failures. Where the data source provides sufficient information, an attempt will be made to determine the cause of the reported failure. We believe this data will provide clear evidence of the effectiveness of properly installed and maintained lightning protection systems.

10.3.1 Insurance Company Experience

Before discussing the results of testing and analysis of the effectiveness of lightning protection system installations, it is interesting to review the reports of insurance companies on lightning-related losses. There is particular relevance here because the insurance companies are most interested in the bottom line; is the investment worthwhile. The Bureau of Standards, in Bulletin No. 56, provides the following information:

> "The reports of the farmers' mutual fire insurance companies of Iowa at their annual State conventions from 1905 to 1912 show that the total fire losses by lightning for the eight years, on unrodded buildings insured in the companies reporting, amounted to $341,065.52; during the same time the total losses by lightning on rodded buildings insured in these companies amounted to $4,464.30, or 1.31 per cent of the losses by lightning on unrodded buildings. In the cases of some of the companies 60 per cent of the buildings insured were provided with rods; in other companies the percentage of rodded buildings was less. The circular from

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[42]Bryan, John L., Richard G. Biermann, and Glenn A. Erickson, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology*, National Fire Protection Association, Quincy, MA, 1 September 1999, p.23.

[43] Guthrie, Mitchell A., *Letter to Secretary, Standards Council* of 18 September 2000.

which the data were taken states that an average of about 50 per cent of the buildings were rodded. It is also stated that an average of 55 companies reported each year, representing nearly that many counties in Iowa. The foregoing values being taken as correct the efficiency of the lightning rods in this case may be estimated at nearly 99 per cent. As the reports took account of lightning-rod installations of every kind, both new and old, good and bad, these figures give strong support to the use of lightning rods, at least so far as the protection of barns and houses is concerned, since these constitute the greater portion of the risks insured in these companies."

> "During the last few years a great many mutual fire insurance companies have come into existence which make a business of insuring only rodded buildings; other mutual companies, which have been in existence for many years, have commenced the practice of reducing rates on rodded buildings. In both of these cases special reference is had to barns which, if unprotected, are well known to be particularly susceptible to fire by lightning. The assessments of these companies on policies covering rodded barns are, in some cases, but two-thirds of the assessment of companies insuring rodded and unrodded buildings indiscriminently; in other cases the assessments are only half of those in the companies making no distinction between rodded and unrodded risks.[44]"

In his address to the Fifteenth Annual Convention of the Fire Marshal's Association of North America, George F. Lewis, Deputy Fire Marshal of Ontario, provided the following:

> "The Patrons' Mutual Fire Insurance Association of North Western Pennsylvania a number of years ago became alarmed at the great amount of annual losses through lightning, and, as a means of reducing them, approached the situation from a practical viewpoint. About 10 years ago they commenced to give a reduction of 29 per cent in the assessments on policies covering rodded barns. In order to overcome prejudice against lightning rods and encourage their use, the Association purchased 11,000 feet of copper cable lightning rod and installed it on the barns at a number of its patrons at its own expense. The rods put up are inspected by a representative of the Association before the risk is accepted. No damage was paid for by the Association on these rodded buildings covering a period of ten years."

> "The Mutual Fire Prevention Bureau of Oxford, Mich., have informed me that their statistics of losses covering the nine-year period from 1910 to 1918, inclusive, show total number of fires reported caused by lightning: 414. Total amount of loss: $725,454; and their records do not show that any of these risks were protected by a standard lightning rod equipment. They have had no losses reported from lightning where the risk was properly protected. They say, "Our experience has made us firm believers in protection against lightning. Our experience has been that the completely metal clad building sides, roof, and cornice, with this cladding properly grounded is practically immune from lightning."[45]

The experience of the mutual insurance companies as reported in the available literature can best be summed up by the following statement in the United States Department of Agriculture Farmers' Bulletin No. 1512:

> "Experience has proved conclusively that when the equipment is carefully and intelligently selected and installed the protection afforded is almost complete. A number of insurance companies very properly make lower rates for protected buildings, and some companies will not insure an unprotected building."[46]

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[44] Peters, O.S., "Protection of Life and Property Against Lightning", *Technological Papers of the Bureau of Standards: Bulletin No. 56*, Department of Commerce, Washington, DC, 1915, p.26-27.
[45] Lewis, George F., *Lightning: Its Origin and Control*, Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927, p.5-6.
[46] United States Department of Agriculture, "Protection of Building and Farm Property from Lightning", *Farmers' Bulletin No. 1512*, Washington, DC, August 1930, p.II.

10.3.2 Reliability of Data

A major problem in the evaluation of the effectiveness of properly installed lightning protection systems is obtaining the necessary field failure data. At the Fifteenth Annual Convention of the Fire Marshal's Association of North America, George F. Lewis, Deputy Fire Marshal of Ontario presented a paper titled "Lightning, Its Origin and Control." This paper was later printed and distributed by the Ontario Fire Prevention League in an effort to stimulate inquiry and distribute knowledge in an effort "to hasten the day when this destructive natural element shall be brought under proper control." In his presentation, Mr. Lewis states:

> "I have endeavored to obtain reliable data and statistics regarding the waste caused by lightning fires in the United States, and regret to state that it appears to be impossible to obtain this information except through the wildest guesswork. A large proportion of the farm risks in the United States, as well as in Canada, are carried by State, County, and Provincial Farm Mutuals, who have no central organization and probably keep no records. … From the source of my information, I am informed that it is estimated that lightning is responsible for at least 50 per cent. of their number of losses."[47]

Mr. Rapp, in his 12 June 1995 letter to Art Cote regarding the July 1995 Standards Council hearing, is correct in his statement that Underwriters Laboratories (UL) cannot provide field data showing the number of lightning-related incidents associated with Master Labeled systems. (Although, this is true today, at one time in the past such data was available from UL and is quoted by Viemeister as discussed in section 6.0 of this report. Apparently, collection of this data was discontinued between 1945-1950 and the raw data subsequently lost. We can, however find conclusions drawn from UL Master Label data from secondary references, as noted.) We agree that such raw data would be useful in the evaluation of the effectiveness of the existing lightning protection requirements. Even though the Master Label certification does not ensure that the installation will be properly maintained, it at least establishes that the installation and materials used met the UL/NFPA minimum criteria at the time of installation. This would be a great advancement over data, such as the Iowa State Fire Marshal Reports, which make no distinction between a properly installed and maintained system and one that did not meet the requirements of NFPA 780. (In fact, structures described as "rodded" in the Iowa reports may not have met 780 requirements from their initial installation.)

Another major obstacle in the evaluation of the effectiveness of installed lightning protection systems is the predominance of lightning protection system installations that do not meet the requirements of NFPA 780. Lewis, in his December 1920 address to the Fifteenth Annual Convention of the Fire Marshals' Association of North America, provides the following comments:

> "According to the Bureau of Standards it has been estimated that not more than fifteen or twenty per cent of the buildings in the United States, which are liable to damage by lightning, are protected in any manner against it. The lack of lightning protection is charged largely to swindling lightning-rod agents of thirty or forty years ago, who prospered greatly at the expense of a credulous public. Rods of every description were

[47] Lewis, George F., *Lightning: Its Origin and Control*, Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927.

> then erected at excessive cost to the purchaser, and in most cases without much regard for the rules that should be followed in their erection.[48]"

More recently (1952) this point was amplified:

> "In the years which have elapsed [since 1882], many installations of lightning rods have been made. Frequently, they were sold by unscrupulous salesmen, improperly installed or poorly maintained with the result in some quarters that the lightning rod fell into disrepute. Today [1952] the lightning rod, partly at least because of the Code, is regarded as a system with a good record, not perfect, but having probably prevented at least 90 percent of the fires that would have otherwise occurred.[49]"

Unfortunately, this practice has continued over the century and there are still many installers that prey on farmers and homeowners in rural areas by selling installations that do not meet the requirements of NFPA 780. To get an idea of the prevalence of lightning protection system installations that do not meet the existing requirements of NFPA 780 in a rural area with a predominance of farming activity, a general review of a small sample of lightning protection systems in north central North Carolina was performed. From this example, we can see what is included in the "rodded" category in the Iowa reports. The rural area examined is often serviced only by untraceable installers that provide "cookie cutter" installations. None of the property owners or custodians of these systems that were contacted could provide the name of the installer of the system. None of the installations had received any kind of quality control inspection, such as an Underwriters Laboratories Master Label. This was not a large-scale review and was not intended to be a comprehensive study, rather to portray the situation that exists where a standard method of installation is not followed (or if a standard were not to exist!). The review included both occupied and abandoned dwellings ranging from the 1800s through 1990s and assorted farm buildings such as barns, sheds, shops, etc. The vintage of the protection systems installed on these structures ranged over several decades. However, each of the structures reviewed would have been considered "rodded" by the criteria used in some of records kept in the United States, such as the Iowa State Fire Marshal's reports. It is believed that the discrepancies reported as a result of this review would be characteristic of many other rural installations in the United States in those areas where quality control inspections of installed systems are not required.

From this review, only one structure (of approximately 30) was found to meet the existing requirements of NFPA 780. This was a shed used for the storage of farm implements. It was a wood-framed structure with no electrical service provided.

The most common discrepancy found was in the interconnection of grounding systems. The lightning protection grounding system was not bonded to any other grounds (electrical service, telephone, etc.) in any of the installations reviewed. In addition, no other bonding was noted for any of the installations, even though a detailed review was not conducted and no electrical testing was performed. Surge suppression was minimal, and most often, not provided.

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[48] Lewis, George F., *Lightning: Its Origin and Control,* Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927, p.3.

[49] McEachron, K. B. (General Electric Company): "Lightning Protection Since Franklin's Day", *Jour. Franklin Inst*., 253, 1952, pp. 443.

There were two cases found where a single decorative air terminal was installed on a structure with no associated down conductors or grounding electrodes. Figure 1 is a photograph of one such installation on a barn. A second example was found on the cupola of a residence. Other discrepancies were noted due to both initial design/installation errors as well as a lack of proper maintenance. Figures 2 and 3 provide an illustration of a structure where both type of discrepancies can be found. These pictures show the improper placement of air terminals (NFPA 780, 3-6 and 3-8.1), resulting in a prominent section of the structure being left unprotected, and the improper support of primary conductors (NFPA 780, 3-9.6). In addition the support initially provided has failed and no longer supports the cable. Another common design/installation problem noted was the installation of a TV antenna outside of the zone-of-protection of the lightning protection system provided; which is in violation of NFPA 780, 3-6. In most cases, the antenna support straddled the roof conductor with no bonding provided. Figure 4 provides an example of a characteristic installation. Installations were also found where chimneys were not provided with air terminals. In addition to the case shown in Figure 3, Figure 5 forwards an example of a recent installation where the chimney was not protected as required by NFPA 780, 3-8.7. It was also noted that conductor bends were frequently provided which did not meet the requirements of NFPA 780, 3-9.5. Figures 6 and 7 provide an example of an installation with two 180 degree bends in a single down conductor. As an example of the criticality of this aspect of lightning protection, figures 7a – d illustrate a laboratory test performed on a kinked down conductor[50]. An average lightning event can cause catastrophic failure in these cases.

Several examples of poor maintenance were also noted during the review. The most common example of poor maintenance can be seen in the cases where the support for the conductors are broken or pulled out of the structure on which they are mounted. Figure 8 provides a typical example of such cases. Another common example of poor maintenance can be seen in improper air terminal support (as per NFPA 780, 3-6.2), such as that shown in Figure 9, caused by broken air terminal brackets or the brackets being pulled out of the structure on which they are mounted.

10.3.3 Iowa State Fire Marshal's Reports

One of the most commonly referenced records of lightning losses in the United States is the Iowa State Fire Marshal's reports. Data collected by the Iowa State Fire Marshal's office has been both used and misused by various sources over the years. Data concerning fires associated with protected (rodded) and unprotected (unrodded) structures in Iowa during the period 1956-1962 were made available to the Standards Council in hearings packages as early as July 1995. However, the table provided, through no fault of the provider, was incomplete and somewhat misleading. Table 1 provides a complete summary of the losses reported by the Iowa State Fire Marshal's office for this period. The table provided to the Standards Council was incomplete in that it addressed only rural losses. There are a number of citations in the literature that explain why the value of rural losses will be greater than those in more densely populated areas. Briefly, one of the primary reasons is that the response time of the local fire department will be much greater in a rural area and a second reason is that the construction of one of the more costly items in the rural areas, the barn, is such that the structure and its contents burn very rapidly and therefore most incidents result in a complete loss.

[50] Photos courtesy U.S. Army Communications-Electronics Command.

An unsuccessful attempt was made to obtain the entire history from the Iowa State Fire Marshal's Office. However, the current State Fire Marshal of Iowa, Mr. George Howe, was able to forward data that was put together in July 1995 by then Fire Marshal Roy Marshall. Fire Marshal Marshall had an intern compile the total of "rodded" and "unrodded" lightning fires for a 20-year period and forwarded them in the form of a table. Table 2 is this report. Mr. Marshall provides the following history of the Iowa data in his Memorandum:

> "It appears the "rodded/not-rodded" distinction did not start with Fire Marshal Herron, but rather with our first Fire Marshal, Ole Roe. Mr. Roe was a statistician and auditor prior to his appointment, and he went to great statistical detail in his Annual Reports.
>
> Lightning was listed as a fire cause category as early as 1912. For several years there was one lightning category only, but beginning in 1919 these fires are broken down to "rodded" and "not rodded." … A few years later these figures were broken down further, distinguishing between "town" fires and "rural" fires.
>
> Annual reports contained a "rodded" and "not-rodded" breakdown every year from 1919 into the 1970's. I find no indication of a special study or project related to lightning fires during the 1956-1962 period. I have read each of Fire Marshal Herron's Annual Reports, and find no narrative reference to lightning rods or lightning related fires. …"[51]

The data contained in Tables 1 and 2 cover the years 1955-1966 and 1919-1939, respectively. McEachron[52] quotes data provided for the periods 1930-1950 as follows:

> "…Professor Geise has given the following figures for the years 1930 through 1950. Lightning damage of $3,529,670 occurred in a total of 1429 buildings during the 20 year period. 122 of these buildings were equipped with lightning rods while 1307 were unrodded. The data are for "country" dwellings and barns and indicate that 91 per cent of the buildings damaged were unrodded. There is, of course, no record of those rodded buildings which were struck by lightning and which were not damaged. The true percentage for well designed and maintained systems would make a still better showing, since no doubt a considerable number of rodded buildings were not in first class condition. In fact, test reports from the Farmers' Mutual Reinsurance Company of Iowa show that 50 per cent of 10,767 dwellings, and 58 percent of the 11,278 barns were rodded, but 15 per cent of 5416 dwellings and 44 per cent of 6442 barns were reported as defective."

The United States Department of Agriculture Farmers' Bulletin No. 1512 sums up its analysis of the results of the reports covering the years 1919-1924 as follows:

> "The value of rodding is effectively shown. The percentage of total money loss to include all rodded structures is 6.9, and it is estimated that in the rural districts, where most lightning fires take place, about half of the structures are rodded; so that during these six years, out of each 100 fires, 5 or 6 occurred in rodded structures of which a considerable portion had defective rods. Such fires are preventable."[53]

A statistical summary of the data contained in both tables, supplemented by the 20 years of data provided by McEachron would indicate that for the periods 1919-1950 and 1955-1966 (42 years total) there were over 7 lightning-related fires in structures which were "not rodded" for each fire

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[51] Marshall, Roy (Iowa State Fire Marshal) Memorandum to Ben Roy of 14 July 1995 re *Lightning Related Fires.*
[52] McEachron, K. B. (General Electric Company): "Lightning Protection Since Franklin's Day", *Jour. Franklin Inst.*, 253, 1952, pp. 443.
[53] United States Department of Agriculture, "Protection of Building and Farm Property from Lightning", *Farmers' Bulletin No. 1512*, Washington, DC, August 1930, p.2.

associated with a "rodded" structure. Only 11.8 percent of the total 4119 lightning-related fires occurred in "rodded" structures. As discussed in Section 10.3.2 and supplemented by the above McEachron citation, when one takes into consideration the percentage of those rodded structures which were not protected in accordance with approved protection techniques, the true percentage of fires occurring in rodded structures would be expected to be much lower.

10.3.4 Ontario Lightning Rod Act

In January 1922, the Lightning Rod Act of Ontario was implemented by the Fire Marshal's Office. The purpose of this act was to establish some control over the installation of lightning protection systems and reduce the lightning-related losses of insurance companies. The regulations prescribed under the act generally conforms to the Underwriters Laboratories requirement for a Master Label. The act specified that:

> No person or corporation is permitted to sell or offer for sale material or apparatus intended to be used for the protection of buildings from damage by lightning, or to install upon any building any apparatus intended or purporting to be used for the protection of buildings from damage by lightning until authorized to do so by a license obtained from the Provincial Fire Marshal.[54]

Table 3 forwards the results of statistical data on lightning losses recorded in the annual reports of the Ontario Fire Marshal[55] for the periods 1921-1939, supplemented by the pamphlet "Lightning, Its Origin and Control"[56] and a June 1939 radio address by H. C. Keller.[57] During the 22 year period 1918-1939, only 139 of the 17,982 total losses attributed to lightning were associated with rodded structures. Of these 139, at least 14 of the installations were known to be defective and at least 31 were known to have been installed prior to the Lightning Rod Act. Discounting only those installations reported as defective, this results in an efficiency of no less than 99.3 percent. If one were to consider only the losses of those installations complying with the act, only 17 losses were reported in the minimum of 66,282 installations complying with the act. This results in an efficiency of 99.975 percent. It is obvious that as the number of years of data increases, the efficiency should decrease. However, an efficiency of 99.9 percent is certainly feasible. Keller reports that:

> "It should be pointed out that nearly all of the lightning loss to rodded buildings in both periods [1924-1931 and 1932-1938] referred to above 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."[58]

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[54] Lewis, George F., *Lightning: Its Origin and Control,* Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927, p.3
[55] Excerpts of the Ontario Fire Marshal Reports for the periods 1921-1939 forwarded by the Librarian of the Fire Marshal.
[56] Lewis, George F., *Lightning, Its Origin and Control,* Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927.
[57] Keller, H.C., *Results of Modern Lightning Protection in the Province of Ontario,* Farm Paper of the Air, presented on WGY Radio Schenectady, 12 June 1939.
[58] Keller, H.C., *Results of Modern Lightning Protection in the Province of Ontario*, Farm Paper of the Air, presented on WGY Radio Schenectady, 12 June 1939.

This is a significant data point because a total 8,528 installations had been inspected by the Fire Marshal's Office as early as 1932.

Other interesting observations that can be made from the data provided in the table are that within the first 5 years of the implementation of the Act, the percentage of total insurance losses attributed to lightning fell from 51 percent to just over 12 percent and that the percentage of initial inspections meeting the requirements of the Act increased from just under 30 percent to 50 percent.

10.3.5 Explosives Incidents Review

A review of DoD and contractor lightning-related explosives incidents taken from the DoD explosives safety database, the Army ESMAM database, and associated reports and papers providing supplemental information; has been conducted as a part of this effort. The Department of Defense (DoD) requires that all explosives incidents be investigated and their cause reported. In addition, DoD has instituted a maintenance program for their lightning protection systems installed to protect structures used for the handling and storage of explosives materials. Given the rigorous reporting requirements, the maintenance program implemented for the lightning protection systems, and the immense exposure of DoD and associated contractor explosives facilities; we feel that this review will constitute one of the best field tests of lightning protection systems available in the United States.

During the 82 years of records reviewed (1918-2000), a total of 59 incidents were reported as lightning-related, of which only eight were reported as provided with lightning protection systems. Of these eight incidents, subsequent reviews and studies indicate that at least three of the lightning protection systems did not meet existing lightning protection requirements at the time of the incident and lightning protection was likely not a primary cause in another.

One of the reported incidents occurred in 1937 in an aboveground magazine. The data base citation provided no substantiation to justify lightning as a cause of the incident. The investigating board found no problem with the lightning protection system. Unstable propellant was also listed as a possible cause.

A Naval Surface Warfare Center review[59] of the two most recent incidents (Dahlgren 1985 and Lake City 1979) indicated that the lightning protection systems installed for each of these structures did not meet the current lightning protection system and grounding requirements of NFPA 780 and also suggested that arcing associated with the fiberboard containers stored in the structures was likely the primary ignition source in both instances. The Navy recommended that this type of container be stored only in those structures where the radiated electromagnetic pulse can be minimized, such as those which approximate a Faraday cage.

A review of the 3 August 1974 incident at Naval Ordnance Station Indian Head, MD was

[59] Guthrie, Mitchell A., *A Review of Recent Lightning-Related Magazine Deflagrations*, presented at the 22nd DoD Explosives Safety Seminar, Naval Surface Warfare Center, August 1986.

conducted by both the Navy and General Electric Corporation. The General Electric report[60] indicates that a strike with multiple attachment points likely occurred; with attachment points on the 240 volt incoming service, the 120 volt incoming service, and to a ground wire at the edge of the wall around the upper roof. Based on eyewitness reports and damaged sustained, it was concluded that the most likely cause of the incident was arcing in/at the drain pipe for the centrifuge motor. The arc occurred as a result of improper bonding in the structure. The Naval Surface Weapons Center Dahlgren Laboratory concluded that if the incoming power had been run underground for the 50 feet prior to entering the structure and a suitable lightning arrestor had been provided (as was required by NAVSEA OP-5), that the structure would have been saved.[61] Such surge suppression is required by NFPA 780, 3-18 (1977).

The other incident occurring at a DoD site is a toluene tank fire at the Joliet AAP in 9 July 1971 occurring when a storm was in the area. This was reported to be the 6th time in 17 years that toluene tanks at Joliet AAP were ignited by lightning strikes. However, this is the only tank fire occurring after the tank was protected by an overhead mast system until the toluene tanks were taken out of service 8 years later. The installed mast was installed 11 feet 6 inches above the tank. Experts wanted an overhead system 18 feet above the tanks. Documentation to confirm that the installed mast met the requirements of NFPA 780, 6-3.3.1 could not be located.

Of the remaining 3 incidents, one occurred at a fortress in St. Terenzio in 1922, another occurred at a contractor facility containing magnesium in Elkton, MD in 1943, and another at a contractor facility in Camden, AR in 1976. In none of these cases has data been provided to adequately identify the cause of the failure.

The Department of Defense has concluded that a total of 4 lightning-related incidents were reported in the 82-year span of the available data (where it could not be confirmed that there were contributing circumstances affecting the proper operation of the lightning protection system). The time provided for the preparation of this report does not allow for an accurate calculation of the lightning exposure of DoD and contractor facilities. (Consider that a great number of these facilities have been closed or consolidated, especially in post-war years and records of the original installations are not necessarily maintained.) However, with the number of structures utilized for the handling and storage of explosives materials by DoD and our contractor facilities all over the world numbering easily in the thousands, one can assume that during this 82 year period we have received a sufficient number of strikes to confirm the effectiveness of the basic technology used in the specification of lightning protection systems. To put this in perspective, McEachron indicated that the U.S. Army reported that protected structures were struck 330 times during the period from 1944 through 1948 alone.[62]

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[60] Plumer, J.A. (General Electric Environmental Electromagnetics Unit) letter report *Report of Lightning Strike Investigation at US Naval Ordnance Station, Indian Head, MD,* Pittsfield, MA, of 5 September 1974.

[61] Naval Surface Weapons Center Dahlgren Laboratory letter DT-52:RAV:cpe 10550 of 4 March 1976 (NOTAL), paragraph 11.

[62] McEachron, K. B. (General Electric Company): "Lightning Protection Since Franklin's Day", *Jour. Franklin Inst.*, 253, 1952, pp. 441-470.

10.3.6 Kennedy Space Center Results

An evaluation of lightning protection system effectiveness is provided by the STS Lightning Protection and Measuring System (LPMS) installation at NASA/Kennedy Space Center Launch Complex LC-39B. Although this evaluation is less extensive in terms of the number of installations, it is far better instrumented and monitored than many other installations. We understand that more details associated with this installation and the recorded results were provided to the Standards Council by multiple sources for their consideration during the October 2000 Standards Council meeting[63]. The LPMS includes a three video camera/recorder system, which is used to determine the attachment point for the lightning event. It also incorporates a data collection system used to record lightning currents and induced voltages. A detailed description of the installation, a table documenting the lightning damage history at LC-39B, and photographs and a videotape of a strike to the protected complex was provided for Standards Council consideration during their October 2000 meeting. Figure (10) illustrates this event, providing a wide shot of the strike to the air terminal protecting the shuttle on the pad. Mr. Guthrie states in his submission:

> "As can be seen in the table, NASA has incurred no damage since the installation of the catenary lightning protection system with the Franklin rod. This is over 29 years of instrumented exposure in an area which experiences around 100 thunderstorm days per year and 5 to 6 ground strikes per square kilometer per year (among the highest incidence of lightning in the United States)." [63]

In a previous submission to the Standards Council, Mr. Guthrie provided the following:

> "A high profile example that the principles associated with "NFPA 780 type" lightning protection systems have been tested and proven effective under actual thunderstorm conditions is given by the installation of the catenary lightning protection system at Pad 39B at Kennedy Space Center. After an incident in 1975, a catenary lightning protection system was installed (meeting the requirements of NFPA 780, Chapter 6). Since the installation of the lightning protection system at Launch Complex 39B, the "lightning damage that created problems prior to 1975 ceased after the installation of the catenary lightning protection system" according to retired NASA employee Bill Jaffries. As evidence that the lightning system functions properly (has technical merit), it recently took a well-documented lightning strike while the Space Shuttle Atlantis was sitting on the pad. At 5:56pm on 5 September 2000 the "Franklin air terminal" located atop the fiberglas lightning protection mast supporting the catenary lightning protection system, intercepted a 65,000 ampere lightning strike to the launch pad. Subsequent system checks confirmed that the lightning protection system performed as expected with no damage to the shuttle or ground support equipment. In fact, "the countdown clock kept on ticking" according to a CNN report on the incident. NASA test director Stephen Alternus was quoted by the Associated Press as stating "Fortunately, our lightning protection saved us and it doesn't look like it affected any vehicle systems or flight hardware." The Associated Press article appearing in the Houston Chronicle is attached. An attempt is being made to provide a still photo from the video tape which documented the actual strike termination point. This photograph will be provided when available. Obviously, NASA feels that it has clear validation that the lightning protection system technology incorporated in NFPA 780 is technically sound."[64]

The data reported by Mr. Jafferis in his paper of 1987[65] and this well documented strike to the complex provide clear evidence of the effectiveness of conventional lightning protection system installations.

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[63] Guthrie, Mitchell A., *Letter to Secretary*, NFPA Standards Council re: Addendum to 18 September Letter, 22 September 2000.
[64] Guthrie, Mitchell A., *Letter to Secretary*, NFPA Standards Council of 18 September 2000.
[65] Jafferis, William, "Lightning Protection for Launch Complexes LC-39A and LC-39B", *24th Space Congress*, NASA Kennedy Space Center, FL, 24-27 April 1987, p.33-56.

10.3.7 Federal Aviation Administration TDWR Study

Since 1996, the Federal Aviation Administration's Terminal Doppler Weather Radar (TDWR) program has been monitoring failures at 47 TDWR sites and correlating them with ground strike data compiled from the National Lightning Detection Network. The TDWR has an enhanced lightning protection system consisting of air terminals (lightning rods), bonding connections, down conductors and an earth electrode system; as described in NFPA 780 and FAA Standard 019. While **all** FAA facilities are monitored for lightning related failures, the TDWR has the most extensive database which can support, with documentation, the performance of a lightning protection system built on the basic requirements of NFPA 780. All ground strikes are correlated with failure data from each TDWR site. Any malfunctions noted at a site are investigated and evaluated as to the type of occurrence and any correlation to a severe weather event.

While the complete results of all of the data collected as a part of the program are too numerous to discuss in this report (although a complete briefing package can be made available), for the total of all sites in July 2000, a total of over 250,000 strikes were recorded within 20 nautical miles of the site with only 3 radar malfunctions experienced during thunderstorm activity. The 20 nautical mile radius is deemed by the FAA to be the reasonable distance that could generate a lightning-related malfunction.

Two good examples of specific site results would be the results recorded in July 2000 at the Tampa and Orlando sites. Both sites are located in an area that experiences some of the highest incidence of lightning activity in the United States and both consist of a 25 to 30 meter tall tower with sensitive electronics. In each case, the tower is the tallest object visible for a full 360 degrees. The Tampa site experienced approximately 25,000 recorded cloud-to-ground strikes with no equipment failure and the Orlando site experienced approximately 20,000 recorded cloud-to-ground strikes with only one telecom failure (associated with commercial phone service).

10.4 Summary of Field Testing Results

This section provides specific evidence that there was both laboratory testing to support the baseline requirements of NFPA 780 and field studies to quantify the system-level requirements for lightning protection systems. It is generally agreed in the scientific and technical community that conventional lightning protection system technology will not be 100 percent effective in all applications. Bryan, et.al., quotes Allen, et.al., as saying:

> "A simple passive Franklin rod, on the roof of a large building, may not give full protection against a strike to the fabric, since upward corona may be initiated at parts of the structure more favorably placed in relation to the downward leader. "[66]

Van Brunt correctly states in his initial review of ESE technology that:

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[66] Bryan, John L., Richard G. Biermann., and Glenn A. Erickson, *Report of the Third-Party Independent Evaluation Panel on the Early Streamer Emission Lightning Protection Technology*, National Fire Protection Association, Quincy, MA, 1 September 1999, p.9.

> "There is no reason to believe that an air terminal is 100% efficient in attracting lightning, regardless of what kind of ESE device it uses, if any. Considering the wide range of possible atmospheric conditions and types of lightning behavior that have been recorded, it is not surprising that air terminals of all types will sometimes fail. Tall structures are reported to be struck occasionally by lightning at points far below the top, i.e., outside of the "production zone." Any claims of 100% efficiency in the performance of a lightning attractor should be viewed with skepticism."[67]

However, the field data reported in this document provides conclusive evidence that conventional lightning protection systems such as those specified in NFPA 780 can provide substantial reductions in lightning-related incidents. This data clearly demonstrates the validity of the basic technology when the requirements are properly applied.

As discussed in Section 10.1, Bryan, et.al., suggests that the ultimate evaluation of any complete lightning protection system would be the performance of the systems as installed on buildings. This section has reported the results of 5 different data sources providing field test information of complete lightning protection systems. The data ranges from statistics on fire losses with no description of whether the system was properly installed (such as the Iowa Fire Marshal's Reports), to statistics on fire losses where there was some initial control over the installation and a sampling of inspections were conducted (such as the Ontario Lightning Rod Act data), to statistics from a data base of reportable incidents where a maintenance and inspection program has been implemented (such as the Department of Defense explosives incidents data), to data from two sources where the sites were instrumented, located in high lightning incident locations, lightning strike information was carefully documented, and any loss data was closely examined as to determine its cause (such as the Kennedy Space Center and FAA TDWR Enhancement data). It should be noted from the results reported, that the better the data source, the more efficient the lightning protection system is reported to be.

To summarize the results of the data provided, the Iowa State Fire Marshal Reports, which knowingly includes losses known to occur in improperly installed rodded buildings, indicates an efficiency of 88.2% over the entire 42 year period for which data is available. The Iowa Farmers' Mutual Insurance Companies report an efficiency estimated at nearly 99% for the period 1905-1912. Karl T. Klock, an engineer for Underwriters Laboratories, Inc. (UL) provides the following summary of the UL Master Label program during a 1938 radio address:

> "In conclusion, in the 15 years this service has been in operation, some 78,000 buildings have been Master Labeled. The reports of failure that have come back to us have been so few as to be practically negligible, showing an efficiency of about 99.9%. This, my friends, should prove to you that there has now been developed a very effective weapon for your use in combating the ravages of nature's artillery."[68]

The Ontario Fire Marshal Reports, which instituted a program similar to the Underwriters Laboratories Master Label program, provides data that indicates an efficiency of no less than 99.3%, with the 99.9% reported certainly feasible. A most telling summary of the expected

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[67] Van Brunt, Richard J., Thomas L. Nelson, and Samar L. Firebaugh, *Early Streamer Emission Air Terminals Lightning Protection Systems: Literature Review and Technical Analysis*, National Fire Protection Association Research Foundation, Quincy, MA, 31 January 1995, p.25.
[68] Klock, Karl T., *Master Labeled Lightning Protection*, Underwriters' Laboratories, Inc., presented as the Farm Paper of the Air on WGY Radio Schenectady, 26 May 1938.

efficiency of a properly installed system lies in the fact that there are no losses reported to buildings protected by systems which were inspected by the Ontario Fire Marshal's Office. The Patrons Mutual of northwest Pennsylvania also reported no damages paid on rodded buildings that were inspected for correct installation and the Mutual Fire Preventation of Oxford, MI reported no losses for the period 1910-1918 where the risk was properly protected. In a much larger sample of inspected installations, the Department of Defense has reported only 4 incidents in an 82-year period where the efficiency of the lightning protection system was suspect. This certainly reflects an efficiency of greater than 99.99%.

In his summary statement during his address to the Fifteenth Annual Convention of the Fire Marshal's Association of North America, George F. Lewis provided the following statements:[69]

> "In conclusion, let me sum up the whole matter by saying that the cumulative evidence collected appears to be entirely favourable to the lightning rod as a protective device, and gains added significance from the fact that no contrary evidence or opinions are successfully brought forward. No place to which a person may ordinarily retire can be considered absolutely safe from lightning. The place of greatest safety for man and beast as well as for our material assets is a well rodded building.

He goes on to indicate that:

> "France, Austria, Holland, and Germany have also given a considerable amount of official attention to the protection of public buildings against lightning. *School authorities insist upon having lightning rods on all school houses,* and in many cities annual appropriations are made for the specific purpose of keeping the lightning rods on public buildings in repair."

and

> "In Europe the lightning rod was not brought into discredit during the early part of its history to the extent that it was in the United States and Canada, and as a consequence, the European public seems to regard it in a more serious light than do the peoples of these countries. During the century or more that it has been in use in European countries, its performance has been subjected to analysis a great many times, and it seems that if it were not entirely satisfactory, or not even an economical way of insurance against lightning , it would have been discarded many years ago. On the contrary, European governments and scientific societies have given much more attention to the subject of protection against lightning than has heretofore been given under the auspices of what we like to think as being our more progressive governments of the North American continent."

Clearly, the data provided on the field testing seems to indicate that it is not the science behind the requirements that results in the majority of losses due to lightning, but instead in the incorrect application of these requirements. In his presentation, Mr. Lewis also states:

> "A united effort should be made to establish uniform State laws for the standardization and installation of lightning rods and equipment; and propaganda of an educational character should be scattered broadcast in order that people may be enlightened as to the use of the lightning rod as a protective device to life and property. Conditions are somewhat chaotic and tend to bring into disrepute the efficiency of the lightning rod, causing discredit and loss to a business of great scientific and material merit…
>
> "To the Fire Marshals of North America and the N.F.P.A. Committee on Protection against Lightning is allotted the work and responsibility of placing the means of protection in the hands of the farmers, by

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[69] Lewis, George F., *Lightning: Its Origin and Control,* Sixth Edition, Office of the Ontario Fire Marshal, Toronto, 1927.

> strenuous and conscientious educational propaganda. But you mustn't stop there, you must safeguard the farmers by providing constructive legislation so that a perfect, scientific, and mechanical installation of real lightning rod protection is assured."

A review of the field test results reported herein suggests that we in the United States are going the wrong way in our consideration of lightning protection system requirements. We should be considering changing NFPA 780 to a Code so it would be more enforceable instead of making it a Guide or Recommended Practice. The results of the Ontario Lightning Rod Act of 1922 clearly shows that by enforcing the requirements more stringently and implementing fines for non-compliance, the losses decrease and the workmanship increases.

> "With such facts as these presented to you, it seems obvious that two things are essential: *First, that it is absolutely necessary and provident to protect all farm dwellings, barns, and other buildings with properly installed lightning rods. Second, that Fire insurance Companies should allow a suitable discount in every case where a building is properly rodded with standard equipment."*[70]

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[70] Lewis, George F., *Lightning: Its Origin and Control*, Office of the Ontario Fire Marshal, presented at the Fifteenth Annual Convention of the Fire Marshals' Association of North America, New York, NY, 8-10 December 1920.

11.0 Summary

From the time of the first installation of lightning protection systems to the present day, characterization of the effectiveness remains a recurring question. This question has been addressed several times during the past 250 years and answered successively. The consensus of the scientific literature, field testing, etc., is that conventional, or Franklin, lightning protection systems, in the venue of the NFPA 780 standard, are highly effective when properly installed and adequately maintained. We can see a trail of scientific inquiry and engineering practice throughout these years. Indeed, the current lightning protection standards, as embodied in NFPA 780, are the result of a consensus process that spans over a century and has had international participation. In this time, lightning protection systems have been subject to studies invoking the latest evolving theory and experimental technique, from the empirical eyewitness of the 1700's, development of electromagnetic theory in the 1800's, the employment of more advanced instrumentation in the 1900's continuing to rocket-triggered lightning and advanced lightning studies of the present day. Indeed, our knowledge increases daily as researchers build on this trail of effort.

11.1 Discussion

In developing the substantiation of the science and engineering effort as the basis for modern lightning protection standards such as the NFPA 780, several questions and observations arise.

One may ask why, despite this wealth of data and obvious concern about the effectiveness of lightning protection systems, does this question recur? During the development of this report, we see several occasions where effectiveness was clearly demonstrated. Early examples include the citation of UL Master Label Program and the Lightning Rod Act of the Ontario Fire Marshal's Office. From the reading of these citations, used by researchers into the 1960's and 1970's we *believe that the reason why data collection was discontinued under these programs was because the fact that lightning protection systems were highly effective was conclusively answered*. As early as the 1920's, insurance companies had arrived at this conclusion and lightning researchers moved on to other topics in lightning protection. Over time, raw data, such as that collected up until 1945-1950, was lost and is now only to be found in summary by secondary reference (notably by Viemeister, 1972). Recent data proving the effectivenss of lightning protection systems was provided by Federal Aviation Administration and NASA Kennedy Space Center.

In fact, the situation today mirrors that of the 1880's when the Lightning Rod Conference was convened. In 1880, data was available, as we have reviewed, from a variety of sources, notably the French Academy of Sciences (the first "official" lightning protection code), the work of Sir Snow-Harris, Gay-Lussac, Anderson and Preece. From the perspective of that time the recent developments were by Gay-Lussac and Preece in terms of theory work; by Snow-Harris and the French Academy of Sciences in collecting the empirical data and proposing protection schemes; and by Anderson, writing one of the first extensive compilations. Their "historical data" was works of Franklin and others, notably German, French and Italian scientists and engineers. In fact, we propose that the politics of the era (Napoleonic Wars) caused a rift between the efforts in France and England, leading to late consideration of the French efforts. (Consider the lightning protection instructions of the French Academy of Sciences were written in 1854, based on events of the 1820's. It appears this was not considered in England until the 1880's, and possibly not considered in the U.S. at all.)

Today, as in the 1880's, we are driven by the identical questions. What can we do to protect from lightning? What is effective? What is not? A major impetus in the convening of the Lightning Protection Conference of 1882 was substandard installations of lightning protection systems failing consequently leading to questions regards their performance. There is no difference today – from the review presented we can easily see that this has been ongoing from the turn of the century past to the present day.

The result of the Lightning Protection Conference of 1882 was the formulation of a document – *a code* - in an attempt by the eminent authorities of the day to set minimum requirements for lightning protection systems. Reviewing the history of the conference, we find that there was dissent (notably Sir Oliver Lodge), as there often is today, but a consensus on installation requirements prevailed. These requirements were then adopted in the United States in 1904 and promulgated by the NFPA. Within the next two or three decades the question of effectiveness was settled, at least to the satisfaction of the insurance industry. It appears that the loss of the raw data occurred because the industry took for granted that these systems work.

In the venue of settling the question of effectiveness, one major point made by detractors of the Franklin, or conventional, lightning protection systems is that there is no positive tracking - that is, examination of a system after being challenged by lightning when no damage is reported. There are two primary reasons why this was generally not done. First, the technology did not exist for such a study (at least not affordable technology) until fairly recently. Even the crudest methods of determining if a lightning strike had challenged a structure, beyond visual observation) could not be available prior to the 1920's or 30's and methods to conduct such experiments on a large scale basis at a reasonable cost (such as using magnetic strip readers and video technology) was not readily available until the 70's or 80's. (In fact, such a widespread study is in progress in England now, but the results are not yet available.) Even the National Lightning Detection Network, only available in the past ten years, does not necessarily have sufficient accuracy to determine a strike to a specific structure.

Secondly, there was no reason to do the study, at least not a cost-effective reason. The statistical methods, cited herein, served well to determine that these lightning protection systems were highly effective. Governmental users of lightning protection systems, charged with the protection of critical and sensitive assets, continue tracking lightning accidents to facilities. Despite a great deal of exposure to lightning, the number of accidents we suffer is quite low. This is because regulation and directives are in place to protect these assets from lightning by the continued use (and regular maintenance) of Franklin, or conventional lightning protection systems as specified by NFPA 780. In fact, the standards for protection that were recently reviewed and revised, cite the NFPA 780 for guidance with additional requirements as needed for particular applications. We are convinced these systems are highly effective in preventing lightning damage.

11.2 Conclusions

The conclusions of the Federal Interagency Lightning Protection User Group are:
That Franklin, or conventional, lightning protection systems as specified by NFPA 780 are highly effective in preventing lightning damage.

That a great volume of technical substantiation, empirical, experimental and theoretical, exists demonstrating the effectiveness of lightning protection systems. Further, we find that this line of scientific inquiry has been progressively more sophisticated and new findings are being applied to developing new techniques of lightning protection engineering. This is notably manifest in the yet-to-be released the 2000 edition of NFPA 780.

That there is far more than enough evidence available to reinstate the NFPA 780 standard to Code status as defined by the National Fire Protection Association. Effectively it is used as a code on many Federal installations, where use of NFPA 780 standards are mandated by regulation which is as, or more, binding than laws enacted by any other Authority Having Jurisdiction.

In conclusion, we note that here in the year 2001, we are at a critical juncture in lightning protection with precedent in the Lightning Rod Conference of 1882. Recognizing the need for standardization to defeat substandard installations and the need to codify best practice for the protection of the public, our predecessors who where the eminent lightning protection experts of their day, enacted specifications that eventually became NFPA 78, Lightning Protection Code, in 1904. Nearly a hundred years of effort has gone into the maintenance and upkeep of the NFPA Lightning Protection Standard with the assistance of Government, academic and industry experts. Undoing this by abandoning the Lightning Protection Standard and the Project on Lightning Protection returns the situation (at least here in the United States) back to the situation prior to the 1880's. A situation where, in today's language, authorities having jurisdiction and specifying engineers have little or no recourse. The end result will be the lack of lightning protection, resulting in a rise in lightning damage and possible loss of life or substandard protection to the same effect. Government users of lightning protection systems, as charged with the responsibility of authority having jurisdiction for protecting sensitive facilities will continue to use Franklin, or conventional, lightning protection systems in our endeavors. We cannot otherwise risk the consequences. The general public, however, cannot benefit from removal or even weakening of the present lightning protection standard. At present, as illustrated in this report, the public is somewhat susceptible to inadequate lightning protection, whether through design of the unscrupulous vendor or just through lack of awareness. Removal or weakening of the NFPA's hundred-year effort in writing and maintaining lightning protection standards will transfer that fault to the lack of codified, standardized best (or at least minimal) practice. We urge you not to make this possibility a reality.

11.3 Recommendations

Consequently the Federal Interagency Lightning Protection User Group recommends:

Continuance of the Project on Lightning Protection and continued maintenance of the NFPA 780, Standard for the Installation of Lightning Protection Systems.

Immediate release of the NFPA 780, 2000 edition to ensure consistency of lightning protection techniques used in the United States with best available practice and new findings in lightning protection technology.

12.0 Tables

Table 1
Iowa State Fire Marshal's Report
Lightning Fires Summary 1956-1966

Document		**Rodded**			**Not Rodded**		
Year	Page No.	Rural	Town	Total	Rural	Town	Total
1955	p.19	21	1	22	50	38	88
1956	p.15	30	1	31	89	53	142
1957	p.20	10	1	11	41	31	72
1958	p.27	10	3	13	22	16	38
1959	p.?	12	7	19	51	43	94
1960	p.24	14	5	19	26	32	58
1961	p.27	16	5	21	33	29	62
1962	p.27	15	5	50	40	25	65
1963	p.28	18	8	26	39	45	84
1964	p.27	19	11	30	44	39	83
1965	p.28	30	24	54	30	18	48
1966	p.28	30	6	36	27	35	62
Totals		225	77	302	492	404	896

Total reported events = 1198 Total events involving rodded structures = 302

Number of events involving $25,000 or more damage

1955	2	No information on lightning protection
1956	2	Both not rodded
1957	1	No information on lightning protection
1958	4	No information on lightning protection
1959	4	No information on lightning protection
1960	2	Both not rodded
1961	1	No information on lightning protection
1962	1	No information on lightning protection
1963	3	1 Rodded ($38,500/church), 1 not rodded($80,000), 1 not specified
1964	2	1 rodded (barn), 1 not specified
1965	1	Rodded (barn/$30,000)
1966	4	No information on lightning protection

Table 2
BUILDING FIRES INITIATED BY LIGHTNING
(as reported by the Iowa State Fire Marshal)

(Note: The term "RODDED" indicates that the ignited structure had been equipped with one or more lightning rods of some sort)

Year	RODDED	$	NOT RODDED	$
1919	9	28,995	218	414,075
1920	9	26,209	143	362,390
1921	10	32,775	142	284,263
1922	4	11,432	105	292,248
1923	8	41,375	114	265,715
1924	3	9,425	140	328,364
1925	3	6,600	161	518,374
1926	3	16,389	134	339,560
1927	6	44,900	81	152,652
1928	8	14,270	115	242,647
1929	0	0	76	142,662
1930	2	7,300	140	289,486
1931	4	10,530	120	278,857
1932	7	21,725	109	163,149
1933	4	9,811	93	207,424
1934	9	32,200	105	117,341
1935	3	20,550	59	72,184
1936	36	66,723	110	172,141
1937	4	13,775	105	119,452
1938	10	42,134	129	204,081
1939	12	139,264	103	137,097
Totals	154	$596,382	2500	$5,104,162

The ratio of reports of fires in unprotected buildings ignited by lightning due to those in nominally protected buildings is about 16:1.

Comment: While these reports are interesting, in them selves they do not make a definitive case for the protective value of lightning rod because there is no indication as to what fraction of the buildings at risk had lightning rods installed. However, earlier reports from the farmer's mutual insurance companies of Iowa (as quoted in the 1915 "Technologic Papers of the Bureau of Standards, No. 56") indicated that about 50% to 60% of the insured buildings had been equipped with lightning rods. Since "the reports took account of lightning rod installations of every kind, both new and old, good and bad, these figures give strong support to the use of lightning rods …"

Table 3
Lightning Fires Reported as Part of Ontario Lightning Rod Act

Year	Total Fires	Unrodded Losses	Total Rodded Losses	Rodded Prior to 1922	Rodded After 1922	Structures Protected Under Act	Number Inspected	% Comply[a]	% Total Losses[b]
1917	>1600		c						51
1918	1151	1149	2	2					34.5
1919	1104	1102	2	2					44
1920	879	876	3	3					
1921	1270	1267	3	3					
1922	1009	1001	8			5449	710	29.6	
1923	933	923	10[d]			4867		30.5	20
1924	593	587	6			5120	e	38.7	
1925	1032	1013	19			6817	f	42.2	
1926	563	558	5			5840	425	50.0	12.28
1927	681	673	8			6006	g		
1928	983	979	4			5415	h		
1929	1060	1051	9			6194	i		
1930	697	691	6[j]	4[j]		5250			
1931	852	849	3			3108			
1932	539	536	3				k		
1933	766	765	1						
1934	715	715	---						
1935	351	351	---						
1936	607	602	5						
1937	779	771	8						
1938	782	759	23	12	11	m			
1939	636	625	11	5	6				
Total	19,582	17,807	139	31	17	66,282	8,528[k]		

a: Percentage of installations which fully complied with Lightning Rod Act upon initial inspection
b: Percentage of total losses caused by lightning
c: In no case was a damaged building equipped with a properly installed lightning protection system
d: In each case investigated, the system or equipment was found to be defective
e: Inspectors reported on 2,580 installations total since the Act came into effect
f: Inspectors reported on 3,311 installations total since the Act came into effect
g: Inspectors reported on 4,701 installations total since the Act came into effect
h: Inspectors reported on 5,156 + 339 old installations total since Act came into effect
i: Inspectors reported on 6,818 + 490 old installations total since Act came into effect
j: 4 of the 6 fires were associated with barns. Special investigation revealed that all were rodded prior to 1922 and all systems were found to be “imperfect and antiquated.”
k: A total of 8,528 inspections have been made since January 1922.
m: 66,282 installations erected or reconditioned to meet Act by end of 1938.

13.0 Figures

Figure 1. Barn with a decorative air terminal and no associated down conductors or grounding electrodes. If lightning attaches to this air terminal, it will seek a path through the structure. This would have the effect of blowing apart any moist wood or igniting dry wood. If lightning attaches to the thin metal roof, it will most likely cause burnthrough igniting combustible materials within the structure.

Figure 2. South View of Farm House lower level air terminal. Note there is no air terminal provided for the chimney and TV antenna. An attachment to either could prove very damaging. A lightning attachment to the chimney would likely cause it to fracture, while lightning to the antenna would likely be transferred to the structure of the house and enter through the lead in wire.

Figure 3. Detail of conductor installation showing improper conductor support. The conductor span between the upper and lower roof levels did not initially meet the support requirements of NFPA 780, 3-9.6. The support provided has become detached from the roof. Restraining the conductor is important since forces developed during a lightning event could cause it to fail. Environmental factors such as wind can also cause wear and ultimate failure in this case.

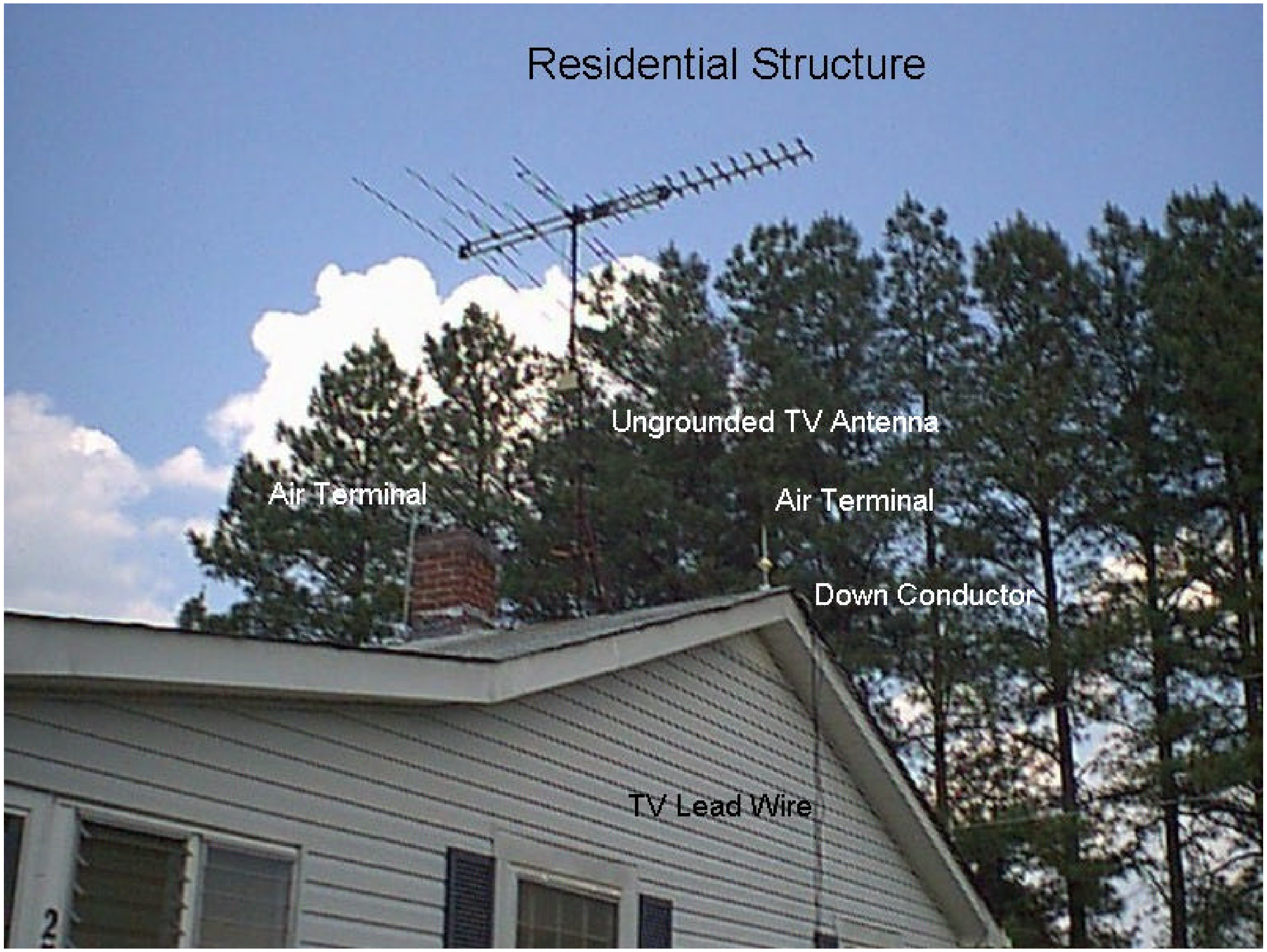
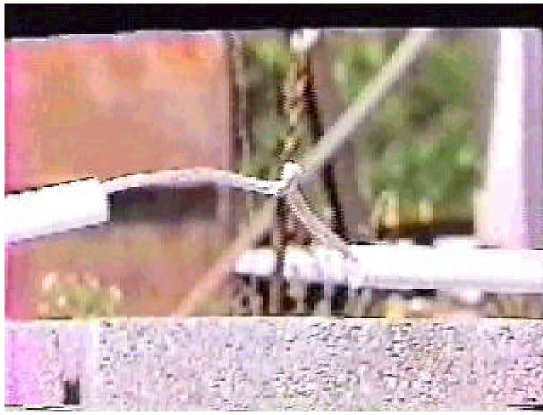


Figure 4. Example of a TV antenna installation outside of the protective area provided by the lightning protection system. There is no bonding of the antenna mast to the lightning protection roof conductor , which would cause a lightning event to be transferred to the structure.

Figure 5. Example of residential installation where chimney was not provided with an air terminal. Also note the installation of Satellite Dish which is not protected by the initial design.

Figure 6. Example of lightning protection system on farm shop structure. Two 180 degree bends were formed in the northern down conductor. Testing and field experience reveals that this will fail during a lightning strike, causing a high temperature spark which could ignite the structure.

Figure 7. Detail of 180 degree bend on farm shop.



7a

7b

7c

7d

Figure 7a-d. A sequence of photographs (captured from high-speed video) illustrating the effect of a simulated average magnitude lightning strike through a downconductor with a mechanical discontinuity (kink). The conductor is violently opened, liberating thermal energy that could easily ignite building materials. This effect illustrates the criticality of bend radii in lightning protection standards.

Figure 8. Example of improper conductor support due to lack of system maintenance.

Figure 9. Example of leaning air terminals due to improper maintenance of air terminal support.

Figure 10. Lightning Strike to Launch Complex 39, Kennedy Space Center, Florida. The air terminal protecting the shuttle on the pad intercepted the strike.

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