Experimental Validation of Conventional and Non-Conventional Lightning Protection Systems

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Abstract — Three types of lightning protection systems are in common use today: conventional systems, Charge Transfer Systems, and systems based on Early Streamer Emission air terminals. There is a wealth of empirical data validating the effectiveness of conventional lightning protection systems installed in accordance with recognized standards. Field studies of Charge Transfer Systems show that they do not prevent lightning strikes as has been claimed. Studies of Early Streamer Emission air terminals show that their performance in the field is similar to that of conventional sharp-pointed air terminals, and they do not have a greatly enhanced zone of protection as has been claimed.

***Index Terms*—Air Terminals, Charge Transfer Systems, Early Streamer Emission Air Terminals, Lightning, Lightning Protection, Lightning Rods.**

I. Introduction

The purpose of a lightning protection system (LPS) is to prevent or greatly reduce damage from a direct or nearby lightning strike to the protected facility. A conventional LPS is designed to prevent damage by providing a number of preferential strike receptors (air terminals) with low impedance paths to conduct the large lightning current harmlessly to ground. The basic principles of conventional lightning protection systems have been embodied in many national and international standards, such as the National Fire Protection Association Standard 780 in the U.S., and the International Elctrotechnical Commission Standard IEC 1024-1.

There are two widely-used non-conventional lightning protection systems which, according to their proponents, provide protection equal or superior to that provided by a conventional LPS. Charge Transfer Systems (CTS) are claimed to be able to prevent lightning strikes to protected facilities. Early Streamer Emission (ESE) air terminals are claimed to have a much larger zone of protection than conventional lightning air terminals, resulting in an LPS with significantly fewer air terminals and down conductors than a conventional one. In this paper I will discuss these three types of lightning protection systems and look at the experimental evidence supporting the validity of claims for each of them.

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II. Lightning Attachment Phenomenology

In order to discuss LPS technology, it is necessary to have a basic understanding of the phenomenology of the lightning attachment process. More detailed discussion can be found in standard references on lightning (e.g., [31]). Physical processes in a thundercloud separate electrical charge inside the cloud. In a typical thundercloud, there is a main negative charge at about 6 km altitude and an upper positive charge at about 10 km altitude. (Thunderstorm charging is an complicated process, depending on many environmental conditions, and many storms have charge structures different than the typical thunderstorm I describe here.) The negative charge in the lower part of the thundercloud induces a positive charge on the ground beneath it. The electric fields on the ground under a thunderstorm are typically 5 to 20 kV/m. The fields at the ground are intensified at the extremities of exposed objects to such an extent that the fields at the extremities can reach the value needed to break down air (3 MV/m at sea level). When this happens, the object emits corona current, which produces a positive space charge above it. The corona current continues to flow until the space charge reduces the field at the extremities of the object to below the air breakdown threshold. All exposed pointed objects emit corona current – tree leaves, grass blades, antennas, power lines, etc. The space charge produced by objects on the ground limits the fields at the ground to the 5 to 20 kV/m value mentioned above. Without this space charge, the fields at the ground under a thunderstorm would often exceed 100 kV/m.

As the charge separation continues in the thundercloud, electric fields in the vicinity of the cloud intensify. When the fields become strong enough an electrical breakdown (lightning) occurs, which discharges the thundercloud and reduces its electric field. The majority of lightning is intracloud – discharges between the main negative charge and the upper positive charge. A significant fraction of lightning is cloud-to-ground (CG) – between the main negative charge in the thundercloud and the induced positive charge on the ground below. (There are also positive cloud-to-ground discharges, not discussed in this paper, between a positive charge region in a thundercloud and an induced negative charge on the ground.)

A negative CG discharge begins in the negative charge region of the thundercloud. The breakdown propagates downward in a process known as a stepped leader. The stepped leader carries negative charge towards the ground. As the leader nears the ground, the electric fields on the ground intensify to such a level that the field near the tips of objects becomes strong enough to produce positive sparks (called streamers, or counter-leaders) which race upward towards the descending negative leader. If the stepped leader is too far away from the ground, the electric fields between the leader and the streamer are not large enough to sustain the propagation of the streamer, and the streamer dies out. Eventually the leader gets close enough to the ground such that the intervening fields are strong enough to sustain a streamer, and a streamer will propagate to the descending leader. The object which emits the streamer which wins the race – which reaches the stepped leader first – is the object which gets struck by the lightning discharge. The distance from the grounded object to the tip of the descending leader at the time the successful streamer is initially emitted from the object is called the striking distance. The striking distance for a typical lightning strike is about 100 m.

Note that lightning strikes to tall building and towers generally develop differently. Most strikes to such structures are upward-initiated – the initial leader develops from the top of the structure and propagates upward to the thundercloud. This is easily seen by the upward branching channels in such lightning, as opposed to the downward-branching channels in lightning strikes to lower objects. The upward streamer is usually initiated by a sudden large change in the local electric field as a result of a nearby lightning discharge.

III. Conventional Lightning Protection Systems

Most conventional LPSs consist of air terminals (lightning rods) on the top of a structure, a good grounding system, and low-impedance conductors connecting them together. Other essential parts of the LPSs are the bonding of exposed metal parts of the structure to the lightning ground to prevent side flashes, and surge suppression to protect electronics.

Conventional LPSs are claimed to substantially reduce the damage from lightning. Claims for conventional LPSs do not state that they will prevent lightning, or that all lightning will be collected by the strike termination devices. The standards recognize that there is a finite probability that lightning (particularly low-current strikes) will bypass the air terminals, and that the probability of collecting lightning strikes will be increased with a denser spacing of air terminals.

To validate the claims of conventional LPSs it is necessary to show:

A) There is a sound empirical method for determining the location and spacing of the air terminals to collect most of the strikes.

B) Conventional lightning protection systems significantly reduce damage from lightning.

Conventional LPSs are based on Franklin's serendipitous discovery of the lightning rod. Franklin's experiments in electricity in the late 18th century [6] produced two results which led him to the development of the lightning rod: 1) He discovered that thunderstorms are electrically charged, and that lightning is an electrical breakdown – a spark. 2) He found that he could generate a spark from a charged canon ball if he approached it with a blunt grounded object, while a charged ball was discharged "silently", without the development of a spark, when it was approached with a sharp grounded object. (This was, of course, due to corona current from the sharp object.) These results led him to hypothesize that he could use sharp grounded rods to silently discharge a thundercloud and prevent lightning.

To test his hypothesis, Franklin put sharp metal rods (knitting needles) on the roofs of structures, connected to ground with good conductors, in attempts to discharge thunderclouds. He found that the rods were occasionally struck by lightning. When the rods were struck, the building was not damaged – the lightning current followed the grounding conductors to ground, and diverted the high currents away from the structure. While he continued to advocate the use of sharp-pointed lightning rods to discharge thunderclouds, he also noted that, when they failed to prevent lightning, they were still useful for protecting the structure on which they were mounted:

> … pointed rods erected on buildings, and communicating with the moist earth, would either *prevent* a stroke, *or*, if not prevented, would *conduct* it, so as that the building should suffer no damage.

(Over the past two hundred years there has been no evidence that sharp-pointed lightning rods prevent lightning. The sharp-pointed lightning rod traditionally used in the Americas is an historical tradition from Franklin's original misconception that sharp points could discharge a thundercloud.)

After Franklin's discovery of the usefulness of lightning rods, these devices were installed on many structures around the world. There were numerous reports of tall structures with histories of periodic lightning damage which were protected by lightning rods (e.g., [18, 29]). There were system failures due to such factors as insufficient number of air terminals, insufficiently-sized conductors, and conductors made of poorly-conducting materials (e.g., [2, 15]). Analyses of these successes and failures led to a set of guidelines which, when applied, resulted in a high degree of protection. Such guidelines were formally published in 1882 as *The Report of the Lightning Rod Conference* [30]. This Report was the basis of lightning rod standards for many countries, such as the standard issued in 1904 by the National Fire Protection Association in the U.S.: *Specifications for the Protection of Buildings against Lightning* [21], the predecessor of NFPA 780.

Following the establishment of standards for LPSs, many studies were done demonstrating the effectiveness of a properly-installed conventional LPS. An example is data from Ontario [17]. In 1922 the Ontario Legislature passed an act which required that all LPS manufacturers and installers be licensed by the Fire Marshal, and all materials and installations conform to appropriate standards. The Fire Marshal kept records on causes of fires in Ontario. A summary of lightning-caused fires made by the Fire Prevention Engineer from the Office of the Fire Marshal, Toronto, stated that, for a 15-year study period, no rodded buildings inspected by the Fire Marshall had been destroyed by lightning.

More information on the effectiveness of conventional LPSs can be found in two recent reports [11, 27], written in response to a solicitation by the National Fire Protection Association for documentation of the validity of conventional air terminals. As these reports show there are a number of empirical studies which validate the protective effectiveness of conventional LPSs. After reviewing these reports and other material, the NFPA Standards Council concluded [25]:

> … it appears that there is widespread agreement that the basic scientific principles of conventional lightning protection are sound, and that there is sufficient evidence – experimental, experiential, statistical, theoretical and otherwise – to make meaningful consensus judgments about the best way to design and install conventional lightning protection systems.

The only open question for the design of a conventional LPS is the placement of air terminals – how high they should be, and how they should be distributed on a structure. This is partially answered by the electrogeometric model (EGM) [24]. This model is based on the striking distance concept. As discussed in Section II, a streamer emitted by an object on the ground cannot propagate to a descending leader until the electric fields between the object and the leader are sufficiently high. The fields are proportional to the amount of charge carried by the leader. Also, the peak current of a lightning strike is proportional to the leader charge. Thus, the striking distance is related to the lightning current – the striking distance is greater for larger current discharges. This has been verified by numerous studies of lightning discharges to tall objects such as towers and power lines [24]. Use of the EGM and the empirically-derived striking distance provides a method for calculating the placement of air terminals to collect lightning strikes with currents above a desired threshold. A simple method for applying the EGM, the Rolling Sphere Model [20], is incorporated into many LPS standards. This placement of air terminals does not provide 100% protection for several reasons: lightning discharges below the threshold current can bypass the air terminals; the striking distance is a statistical average, so there is a finite probability that a strike with a current higher than the threshold may bypass the air terminals; and the striking distance was derived from studies of strikes to tall objects, so it may not be completely applicable for strikes to air terminals a few tens of centimeters high. Nonetheless it has been convincingly demonstrated that an LPS designed using the Rolling Sphere Model for placement of air terminals provides an excellent degree of protection for a facility.

More complete protection for a facility can be obtained using other conventional techniques – a mesh of overhead shield wires (such as that used to protect the Space Shuttle while it is exposed on the launch pad), or a Faraday cage.

IV. Charge Transfer Systems

A Charge Transfer System typically consists of an array of many sharp conducting points erected over a facility to be protected. Corona current from the points on the array supposedly transfers a significant amount of charge from the array into a region of space above the array [4]. The primary claim made for Charge Transfer Systems is that this space charge above the array prevents lightning discharges to the protected facility. While there are several manufacturers of CTS arrays, the primary advocate for the CTS concept has been Lightning Eliminators and Consultants, Inc. (LEC, previously known as LEA). For that reason, the following discussion will be based primarily on claims made by LEC. Over the years LEC has changed its claims about the mechanism by which a CTS is supposed to prevent lightning strikes, but all the proposed mechanisms depend upon the generation of significantly enhanced corona current from the CTS. Thus, there are two claims which can be investigated for Charge Transfer Systems:

A) Do Charge Transfer Systems produce significantly enhanced corona current?

B) Do Charge Transfer Systems prevent lightning?

A. Corona Current from CTS Arrays

There have been numerous studies of corona current from isolated points under thunderstorms. Some of these results have been summarized by Chalmers [5]. These studies have shown that corona current from an isolated point beneath a thunderstorm ranges from a few tenths of microamperes to a few tens of microamperes. Chalmers also reported that the results from arrays of points vary depending on the conditions under which the measurements were made and on the point spacing. In a laboratory experiment, an array of 8 points gave a current 8 times the current of a single point. In a field experiment, an array of 8 points gave half the current of a single point. The reason for this discrepancy is that laboratory and field conditions are quite different. In the laboratory a nearby electrode is used to create the strong electric field needed to generate corona from the points. As the corona is emitted the electrode collects the space charge ions, so the space charge does not accumulate over the points, and the space charge emitted by one point does not significantly influence the field at the tip of a neighboring point. Under a thunderstorm there is no nearby electrode to collect the emitted space charge. The positive space charge ions migrate slowly towards the negative charge in the thundercloud, so that the space charge emitted by one point can shield and reduce the emission from a neighboring point. Depending upon the spacing of the points, this shielding effect from an array of points often reduces the current from the array to less than that of a single point.

To determine whether a CTS array enhances corona current emission it is necessary to measure the corona current from such an array in the field in response to a thunderstorm. A few such experiments have been performed.

1) After Apollo 15 was struck by lightning while on the launch pad in 1971, NASA instituted a crash program to improve lightning protection at Kennedy Space Center [7]. As part of this program LEA installed several CTS arrays at facilities in Florida, and NASA had contractors monitor the arrays. Corona current was monitored from several arrays, as well as from several isolated points [3]. The data showed that

"the maximum current recorded from a large array at [a height of] 100 feet under a severe storm was under 40 μA", and "[a] single point at 50 feet [height] always gave more corona than a dissipation array at the same height" [3].

2) During the summers of 2001 and 2002, my colleagues and I made measurements on two multipoint arrays at Langmuir Laboratory, New Mexico Tech's mountaintop lightning and thunderstorm research laboratory. One array was a Spline Ball dissipater from LEC – a spherical array of about 100 points with a diameter of about half a meter; the other was an array of barbed wire with about 700 points and an area of about 3 m^2. We found that the current from the Spline Ball was about twice that of a single point of the same height, and that the current from the array of barbed wire was less than the current from a single point of the same height.

There is no evidence that a CTS array under a thunderstorm enhances the emission of corona current.

B. Lightning Strikes to CTS Arrays

The statistic quoted by LEC to back up the claim that a CTS prevents lightning strikes is that their systems are 99.7% effective [4]. To substantiate this claim LEC would have to have installed instrumentation to monitor lightning strikes on a statistically significant fraction of their installations. There is no published evidence that LEC has done this. Instead LEC quotes testimonials from customers who state that, since installation of their array, their lightning problems have been reduced or eliminated. However, **a reduction or elimination of lightning damage is not the same thing as the elimination of lightning strikes**.

There are several documented cases of lightning strikes to LEC arrays [23]. Because LEC does not claim 100% efficiency – occasionally an array may be improperly designed, installed, or maintained, which would make it susceptible to a lightning strike – a few examples of failures to prevent lightning does not necessarily contradict LEC's claim. If, on the other hand, a number of installations were monitored for lightning strikes, and a significant fraction of the monitored installations failed to prevent lightning, the claim of 99.7% effectiveness would not stand. There are four studies I know of where LEC arrays have been monitored for lightning strikes:

1) During the KSC study mentioned above, a 365 m tower at Elgin Air Force Base which had a history of damage from lightning strikes was used [3]. An array installed in 1974 (an upgrade to a poorly functioning array installed in 1972) was monitored for lightning strikes with video recordings and current sensors. In June and July of 1975 this array was struck three times. There was no damage to the tower or associated equipment as a result of these strikes. Later that summer the array was replaced by a well-grounded lightning rod. In September two strikes were documented to the lightning rod, again with no damage to tower or equipment.

(Although not as well monitored as the above case, there were two other documented cases of lightning strikes to LEA arrays at KSC in the early 1970's, and reports of lightning damage to several other facilities equipped with arrays.)

2) In the late 1980's the FAA conducted a study of LPSs at three airports in Florida [9]. CTS arrays were installed at the Tampa and Orlando airports (an LEC array at the Tampa airport and a Verda Industries array at the Orlando airport), while the standard FAA LPS was used at the Sarasota airport. The systems were monitored with current sensors and video recordings. In the summer of 1988, lightning struck the FAA standard LPS at the Sarasota control tower. Equipment within the tower sustained no damage. In the summer of 1989, lightning struck the LEC array on the Tampa control tower. Several systems were damaged from this strike. In 1990 the FAA directed the airports to remove the CTS arrays, and to install FAA standard LPSs in their place. The current FAA lightning protection standard [10] requires use of conventional LPSs (based on NFPA 780), and prohibits the use of CTSs at FAA facilitates.

3) In the late 1980's LEC installed an array on a 150 m meteorological tower at White Sands Missile Range (WSMR) in southern New Mexico. A similar tower, located a few kilometers to the west, did not have an array installed. After installation of the array, WSMR personnel noticed a reduction in lightning damage to the tower with the array. In the summers of 1992 and 1993, I installed video cameras to monitor lightning strikes to the towers. During the following two summers the video recordings documented one strike to each of the towers [28]. Because the lightning density in the deserts of southern New Mexico is much lower than that in central Florida, this low number of strikes is not unexpected.

4) In 1991, equipment was installed on two telecommunications towers in Hakui, Japan, to monitor lightning strikes to them [19]. During the summer of 1994 CTS arrays from LEC were installed on the two towers, at which time the grounding system was improved and surge suppression was installed on equipment at the site. During the four lightning seasons prior to installation of the LPS, 26 lightning strikes (and associated damage) were documented. During the two lightning seasons after the installation of the LPS, 16 strikes were documented to the towers, none of which damaged equipment associated with the towers.

In every case where a CTS was installed on a facility with a history of frequent lightning strikes and monitored for subsequent lightning strikes, the CTS neither eliminated nor reduced the frequency of strikes to the facility. In some cases the LPS reduced lightning-induced damage. However, as observed at the 365 m tower at Elgin AFB and at the control tower at the Sarasota airport, a properly-installed conventional LPS did as effective a job of reducing damage as did a CTS.

V. Early Streamer Emission Air Terminals

An LPS based on ESE air terminals is similar to a conventional LPS. It consists of preferential strike receptors (ESE air terminals), a good grounding system, and low-impedance interconnections between them. The primary difference between an ESE-based LPS and a conventional LPS is that the ESE air terminals are claimed to have a greatly increased zone of protection and thus many fewer air terminals and associated down conductors are required. The claimed radius of protection is typically 100 m for ESE air terminals [13].

A. Streamers from Air Terminals

The claimed mechanism for the functioning of ESE air terminals is that they generate upward streamers significantly earlier than conventional air terminals do [13]. The earlier streamer generation is claimed to effectively increase the height of the air terminal by $\Delta L = v\,\Delta T$, where v is the velocity of the streamer and ΔT is the time advantage of the ESE air terminal. Manufacturers of ESE air terminals measure ΔT through laboratory studies. Typical values of ΔT are 50 to 300 μs, and the value used for v is 10^6 m/s. This results in a claimed height advantage ΔL of tens to hundreds of meters.

Many arguments can be made against the validity of the laboratory measurements: 1) Several studies done at independent laboratories do not support any significant time advantage for ESE air terminals [1, 8]; 2) The velocity v used to calculate ΔL is about a factor of 10 higher than the velocity of positive streamers measured in nature [31]; 3) The scale in the laboratory is orders of magnitude smaller than the scale of natural lightning, which results in overly-optimistic zones of protection [12], and 4) Environmental conditions (wind, rain, humidity, space charge from other objects, waveforms of the electric fields which induce positive streamers, etc.) are far different in the laboratory than under a thunderstorm.

Even if ESE air terminals do generate early streamers, such early streamers will not necessarily result in an increased zone of protection. As discussed in Section II, an attempted streamer emitted before the fields between the object and the descending leader are high enough to sustain its propagation will die out. For the past twelve years my colleagues and I have been investigating the performance of air terminals at Langmuir Laboratory. We instrumented several types of air terminals (including ESE) to measure streamer currents in response to approaching lightning leaders [22]. We found that all of the different types of air terminals we used emitted bursts of current (attempted streamers) well in advance of the successful streamer. Our measurements show that when the descending leader approaches to the striking distance (about 100 m above ground, which is about 100 μs before the return stroke) all of the air terminals were emitting attempted streamers at regular intervals. If an ESE device were to emit an attempted streamer tens of microseconds before the descending leader was within the striking distance, that attempted streamer would simply die out. It is not the generation of attempted streamers at the tip of an air terminal, but rather the conditions away from the tip – the strength of the field between the air terminal and the descending leader – that determines which air terminal will be struck.

B. Zones of Protection of Air Terminals

The main claim made for the superiority of ESE air terminals is that their zones of protection are much larger than those of conventional air terminals. However, it is difficult to find any published information about field tests conducted by ESE manufacturers for their air terminals which validate this claim. There are references to field tests for the Prevectron on the web sites of Prevectron distributors [e.g., 26]. These tests were conducted at three different test sites, and used triggered lightning to guide a leader close to the Prevectron. No technical details are presented, nor are any references to technical reports or papers describing the results of the tests provided. The only reference to results I could find is a rather generic statement: "The Prevectrons used at the various sites have been struck by lightning and found in every instance to be fully operational."

One field test which purports to show the effectiveness of an ESE air terminal was conducted at a wind turbine farm in Nadachi, Japan [16]. Two 51 m tall wind turbines, separated by a distance of 125 m, had a history of lightning damage. A Prevectron ESE air terminal on a 60 m mast was installed between the two turbines (25 m from one and 100 m from the other). Over a monitoring period of two lightning seasons, there were 29 lightning strikes to the ESE air terminal, two strikes to the turbine located closer to the air terminal, and one strike to the turbine located farther from the air terminal. This might lead one to conclude that the ESE air terminal functioned as designed and provided fairly good protection to the turbines. There are two problems with this conclusion:

1) There was no control in the experiment. If a conventional air terminal had been installed instead of an ESE air terminal, would the results have been any different? In fact the results are consistent with the electrogeometric model for conventional air terminals.

2) The strikes to the turbines and to the ESE air terminal were upward-initiated discharges – i.e., the discharge was initiated by the ground object, and the leader propagated upwards to the thundercloud. The Prevectron was designed to generate an early streamer in response to a descending leader from the thundercloud. There is nothing in these results which indicate that the Prevectron would be effective in collecting the more typical downward-propagating, cloud-initiated lightning.

The results from our study of air terminals at Langmuir Laboratory do not support the larger zone of protection claimed for ESE air terminals [22]. In our experiments, we used two different methods to determine whether lightning struck within the claimed zone of protection of ESE air terminals. We installed an array of air terminals of different types near South Baldy Peak, a 3288 meter high peak in the Magdalena Mountains of central New Mexico. The array included conventional sharp-tipped rods, blunt-tipped rods, and three different types of ESE air terminals.

1) For two years we used multiple video cameras to determine the locations of lightning strikes in the vicinity of the array.

2) We instrumented the air terminals in the array with either fuses or lightning counters to determine which, if any, were struck by lightning.

During the twelve years of the study there were no lightning strikes to any of the ESE air terminals. Using the video recordings we documented three lightning strikes within the claimed radius of protection of the ESE devices over the two years. Using the instrumentation on the rods we documented

13 strikes to blunt-tipped air terminals, most of which were located within 6 m of an ESE air terminal. (It is of interest to note that no ESE or sharp-tipped air terminal was struck during this study. This indicates that blunt-tipped air terminals are more effective at collecting lightning strikes than either ESE and conventional sharp-tipped terminals.) Our twelve year study indicates that ESE air terminals function no differently than conventional sharp-pointed air terminals.

In another field study Hartono [14] has documented many instances of lightning strikes to structures in Malaysia and Singapore which bypassed ESE air terminals installed on them, and struck parts with the structures within the zones of protection claimed for the terminals. In over 90% of the cases the lightning which bypassed the ESE terminals struck the corner or the edge of the building.

VI. Conclusions

There are numerous empirical studies which document the effectiveness of conventional lightning protections systems which have been installed in accordance with recognized standards. In four studies designed to determine if CTS arrays were struck by lightning, all of the monitored arrays were struck. While CTS arrays may be effective at preventing damage from lightning, their effectiveness is due to the provision of a low impedance path to ground for the lightning current, not by lightning elimination. In field studies of LPSs using ESE air terminals, there have been many documented lightning strikes within the claimed zone of protection. Field studies show that ESE air terminals are no better at collecting lightning strikes than conventional sharp-pointed ones are.

VII. References

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VIII. Biography

William Rison (M'1990) was born in Silver City, New Mexico. He graduated from the University of Wyoming in 1973 (B.S. Physics) and from the University of California-Berkeley in 1975 (M.A. Physics) and 1980 (Ph.D. Physics) He has been involved in lightning research at the New Mexico Institute of Mining and Technology since 1984, where he is currently Professor in the Department of Electrical Engineering. His area of expertise is the design and use of instrumentation for the study of lightning and thunderstorms. He is a member of technical committees on lightning protection standards for the Underwriters Laboratory and the Canadian Standards Association.