LIGHTNING PROTECTION AT PETROCHEMICAL FACILITIES – PART 3 ALTERNATIVE PROTECTION SYSTEMS, FACTS AND MYTHS

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Abstract – Development of lightning protection standards for petrochemical processing and storage facilities has progressed significantly over the past 20 years. Standard requirements have become more stringent and prescriptive. Understanding of development and propagation of lightning has grown with the advent of 3-D detection systems. This is Part 3 of a 3-part primer on lightning protection systems for petrochemical production, storage, and processing facilities. Part 1 - basic science and history. Part 2 - current requirements of national and international standards for protection systems at petrochemical facilities. Part 3 - alternative protection systems. The purpose of this paper, and the primer series, is to update the design and operating engineer's knowledge of lightning protection at petrochemical facilities, and to increase the safety of these facilities to workers and equipment.

Index Terms – Lightning, Lightning Protection, Petroleum, Flammable, Hazardous, Tanks, Tank Battery, Standards, Refinery, Production, Grounding

I. INTRODUCTION

Conventional lightning protection systems (LPS) follow the principles established in the 1750s to intercept the stroke, conduct the energy to earth, and dissipate the energy into earth. These systems are described in detail in Part II of this Primer.[1] The history of lightning protection is rife with attempts to develop lightning schemes, methodologies or products that deviate from this basic approach.

Even before Dr. Benjamin Franklin's famous kite experiment, Franklin theorized that pointed rods could be used to dissipate the energy in thunderstorm. "Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?" [3] Franklin's subsequent research, along with that of Dalibard, Delor and others demonstrated that pointed rods could, in fact, protect structures from damage from lighting. However, it was a far cry from drawing the electrical energy "silently" from the cloud. Over the intervening 270 years since Franklin developed his hypothesis, there have been multiple attempts to harness the "power of points" to dissipate lightning energy from clouds.

Alternative systems take the opposite approach. These systems artificially increase the emission of ions from a strike termination device (STD) in an attempt to influence the lightning stroke from a further distance away than a traditional Franklin rod. In theory, this larger area of influence would extend the zone of protection provided by the STD, allowing for fewer rods, and at greater spacing.

This paper addresses both of these alternative LPS concepts and designs, explains the history and theory behind these alternative approaches and provides a technical analysis of some of the claims made by proponents of these devices.

II. REVIEW OF LIGHTNING CHARACTERISTICS

A quick overview of the characteristics of lightning is appropriate. A more detailed description was in Part 1 of this Primer [2] with its references. It is strongly suggested that both [1] and [2] be reviewed to further the reader's understanding of the discussion contained in this treatise.

Lightning is a high-power, high voltage, high current, high frequency electrical signal, but intriguingly low energy. A typical lightning cloud is bipolar, with positive charge at the top of the cloud and negative charge at the bottom of the cloud. During a storm, the electrical field inside the cloud increases due to storm forces such as friction of rain droplets, cloud ice, or high velocity convection. In most cases, the air between the positive and negatively charged layers breaks down and intra-cloud lightning occurs. In other cases, the air between the charged layers of two adjacent clouds breaks down and inter-cloud lightning occurs.

Under some circumstances, a local breakdown of the field inside the lower charged layer occurs, resulting in the development of a mildly ionized channel approximately 50m in length. Energy transfers along this ionized path, resulting in another localized breakdown, and the extension of the path another ~50m. This "stepped downward leader" travels toward the oppositely charged earth at a speed of between 1.5 – 2 x 10^5m/s.

At the same time, as the electric field near the earth intensifies, a positively charged "upward leader" develops from grounded objects. These leaders are more likely to develop on objects that elevate the ground plane (are tall) and concentrate the electrical field (e.g., pointed objects). As the charge on each of the two leaders is of opposite polarity, an attractive force develops, and the stepped downward channel tends to divert toward the upward leader. When these two leaders are within ~100m of each other, the ionized pathways join, completing the path from cloud to ground, and a high current lightning stroke occurs, further ionizing the path.

The likelihood is that there will be subsequent strokes along this same ionized path between the cloud and the grounding path. This creates the characteristic strobe or flicker affect observed during lightning events. Current flows in pulses until the ionized channel is disrupted due to wind, cloud movement, or other events, or the charges are equalized.

Several characteristic lightning signals have been developed. Generally speaking, however, each individual lightning signal has a rise time of ~10μs, with a duration of 20-350μs. The rise times generate harmonics in the megahertz range. Follow-on current can continue for several seconds. Lightning current generally ranges between 10kA and 200kA for each stroke. Voltages developed are typically between 100kV – 1 MV. The amount of charge contained in a typical cloud is on the range of 10 – 40 Coulomb (C). Due to the extremely short duration, the total amount of energy is relatively low, in the neighborhood of tens of Joules. The power generated, however, is tremendous, in the range of several hundred megawatts to gigawatts. The high power is what causes physical damage to structures.

III. REVIEW OF CONVENTIONAL LPS

Conventional LPS systems, the approaches used, and the principles behind such systems are discussed in detail in [1]. A quick overview follows.

Conventional systems use a conductor connected to earth. This conductor (rod, wire, other STD) is elevated above the structure to be protected. The STD initiates the upward leader which would then intercept the downward leader and causes the ionized channel to terminate at the STD. The STD is connected via at least two low impedance paths to the earthing system. The earthing (grounding) system is designed to dissipate energy from the lightning stroke into the earth in a safe manner.

For petrochemical facilities, the earthing system consists of, at a minimum, a ring around the entire facility, and sufficient grounding electrodes (ground rods) to dissipate the energy without a dangerous buildup of potential difference. In many cases, the ring is supplemented with horizontal cross conductors, creating a ground grid.

Spacing of STDs is governed by the electrogeometric method (EGM). The EGM states that the area protected by an STD is defined as an arc with a radius of 150 ft (45.7m). A “rolling sphere” with a radius of 150 ft, which touches either two STDs or an STD and ground, is used analytically to place STDs. The STDs are spaced so that none of the structure being protected by the LPS intercepts this sphere. Formulae for the placement and spacing of STDs, based on the EGM are in [1].

IV. CHARGE TRANSFER SYSTEMS

The first type of alternative LPS examined is systems broadly referred to as lightning arrays. These systems, in one form or another, rely on “power of points” to dissipate, divert, delay or otherwise affect the connection between the upward and downward leaders. These systems go by several names including Dissipation Array Systems (DAS), Charge Transfer Systems (CTS), Multipoint Discharge Systems, Multipoint Corona Systems, Streamer Delay Systems (SDS) and other names. For simplicity purposes, the term CTS will be used in this discussion.

Fig. 1 CTS Devices Installed

As discussed above, Franklin was the first to propose such a system. Franklin later discarded this approach in favor of the intercept, conduct, dissipate conventional approach. In 1881 LeConte criticized other lightning researchers for not considering “neutralization due to the power of points” [6]. LeConte developed a theme that would be stated and restated over the past 140 years when describing array systems “the whole subject of the power of points, although one of the best-established and most conspicuous phenomena in electricity is sadly in need of experimental investigation”.

A. Cage and Wilcox

By 1926, J.M. Cage filed an application for a U.S. Patent for Lightning Protection. [7] Cage’s system, in his view, was designed to improve on traditional lightning rods which “have been practically ineffectual for the dissipation or transfer of the flash-causing charge”. Cage’s invention was intended specifically for “protecting oil storage tanks and reservoirs against the influences of lightning”.

In describing the method by which the system protects oil tanks, Cage states that the system would increase the local electric field around the protected tank so the field acts “to dissipate or transfer the charge at a total rate sufficient to keep the charge on the protected area or object from building up to the danger point.” In Cage’s view, such a system would dissipate the charge from the protected object into the atmosphere so that the upward leaders would never form, and thus the ionizing channel would not attach to the protected object.

Cage stated that not only could a structure be protected, but also an entire area (such as an oil reservoir), by connecting his device to the earth through ground connections. Interestingly, Cage’s CTS would not necessarily be above the protected structure or area but could be at some other location and connected “by direct conductor connections between the area or body and the charge-transferring element.”

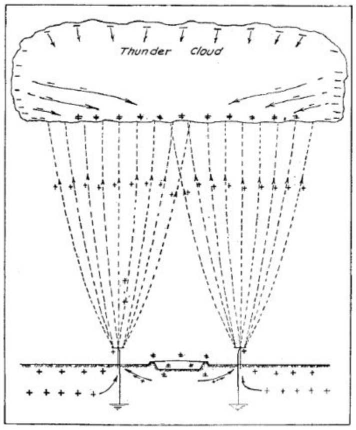

Fig. 2 Cage / Wilcox Dissipation System Courtesy of JSTOR

E.H. Wilcox further describes Cage's claims as "gathering into itself the ground charges which would have existed within the protected area and returning them to the charged thundercloud by ionic discharge, so distributed in time and in space that no destructive discharge can take place over, or within, the protected area." [8] Wilcox described the practical construction of such a system as "erecting steel towers of suitable height, completely surrounding the area to be protected, these towers being connected at the top by a cordon or ring of wires arranged in a horizontal plane and carrying frequent points [< 6 inches] from which discharges take place, all properly grounded and interconnected electrically with the reservoir or other object which it is desired to protect." The system described and shown in the figures of Wilcox' article greatly resemble a conventional catenary type of system, as described in [1].

As seen in Fig. 2, Cage and Wilcox had a basic misunderstanding of the nature of the ground charge. Fig. 2 shows the lower cloud layer as being the same polarity as the ground charge. The scientific community now know that the ground charge is of opposite polarity to the lower cloud layer. Neither Wilcox nor Cage provided any mathematical or formulaic principles on which the system worked.

Wilcox documented laboratory experiments that he understood verified the effectiveness. In each case, a metal "cloud" was conducted of mesh wire and charged. A Cage system was put in place over the protected area and grounded. Wilcox observed "A cloud thus charged would spark across six to eight inches of air to the unprotected reservoir or tank, while the same cloud could only spark across ¼ inch with the protective system in place, this spark invariably being to the protective system, never to the oil." [8] In other words, the system worked exactly as a conventional catenary system with sharp point rods.

Despite Cage's claims, in practice, this system was nothing more than a conventional system with the addition of points on the catenary wire.

Cage's system largely fell out of use when large, open oil reservoirs stopped being used for oil production. By the 1940s, oil was contained in enclosed open top steel tanks, and were either self-protected or protected by conventional LPS systems, as described in NFPA 78 (now NFPA 780) [[28].

B. Carpenter, NASA and FAA

In the 1970s, new companies began marketing CTS systems. A 1977 US Patent application by Roy B. Carpenter Jr. describes a "System and Equipment for Atmospherics Conditioning". [9] Carpenter describes the "foremost objective of the invention is to reduce the electrostatic potential between the area or facility of concern and the passing cloud cells to a level where the ongoing atmospherics induce no deleterious effects into the facilities of concern…by significantly reducing and suppressing, respectively, the electrostatic field and conducting the charge away from the area of concern."

Carpenter's system used a "space charge generator" to "produce an abundance of air ions through use of a point discharge effect…without encouraging the formation of an upward going leader". The space charge, thus generated, would suppress the development of an electric field around the protective device by providing a large, similarly charged "blanket" above the protected structure. Carpenter included a figure in the patent application showing the zone of protection around such a space charge generator. This figure is duplicated in Fig. 3.

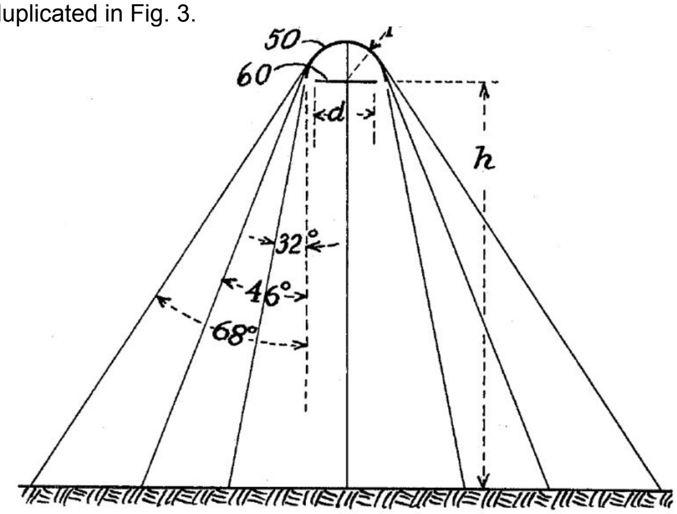

Fig. 3 Carpenter's Zone of Protection

Carpenter describes the different angles as allowing for different levels of protection ranging from 99.9% for the 32° cone to 95% for the 68° cone. Those familiar with conventional lighting protection systems will recognize this as Gay Lussac's cone of protection first proposed in 1823, which has since been supplanted by the EGM. [2] Despite the claims, it is clear that the system described by Carpenter is nothing more than a conventional system with multiple points on the Strike Termination Device (STD). Carpenter and Auer discuss this system in some depth in [10], though most of the description is a rehash of the patent application.

By 1975, the Office of Naval Research (ONR), National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA) and the US Air Force (USAF) commissioned a study regarding lightning protection for tall structures. This study including input from Carpenter, civilian and military personnel, as well as industry experts such as C.B. Moore, S.K. Llewellyn, R.H. Golde and M.F. Stringfellow examined the effectiveness and efficacy of CTS type systems in protecting structures against lightning. The results of this study indicate several problems with CTS, most significantly that the amount of charge dissipated by even a massively large dissipation array system is trivial when compared to the cloud's own charging rate.

As part of this study, NASA reported on CTS installations at four different locations at Kennedy Space Center. NASA documents strikes to the protected structures both before and after installation of the CTS. NASA reported "we can detect no significant difference in strike frequency to the tower after the…installation. On this basis, we must conclude that the…array did not prevent strokes." [11]

Further, NASA measured the amount of charge dissipated through the arrays and found "the charging rate in the storm clouds were order of magnitude greater than the discharge rate" of the dissipation array". The amount of discharge current during a storm was ~150μA. For a minimal lightning stroke containing ~10 Coulomb of charge, it would take ~18.5 hours for the array to dissipate the charge. Effectively, even the minimum amount of charge in a lightning stroke cannot be dissipated.

An interesting outcome of the ONR study was the observations that blunt conventional rods often outperformed sharp conventional rods in protection. This led to additional work and verification by Rison, Moore and Rizk about the effectiveness of blunt rods [12],[13],[14]. The difference between blunt and sharp rods is discussed in more detail in Part 2 of this Primer [1].

As a follow on to the 1975 ONR study, the FAA installed and monitored CTS type systems at two air traffic control (ATC) towers in South Florida (Orlando and Tampa) and compared the resulting protection to a conventional system installed at Sarasota, FL ATC tower. NASA observed lightning stroke attachments to the CTS protected systems, with associated outages to electrical and electronic equipment with the dissipation array installations, while the conventional system at Sarasota, FL intercepted a stroke with no damage to associated electronics. As a result, the test was terminated in early 1990 and the dissipation systems removed and replaced with conventional systems.[15]

C. Zipse

Zipse published two papers in the 1990s relating to dissipation systems. In his 1993 paper, Zipse broadly outlined general parameters of lightning and some advantages and disadvantages of conventional and dissipation type systems. Zipse concluded that CTS systems functioned "like an inexpensive Franklin Rod system". Zipse attributed any functionality of the CTS to the "extremely low resistance connection to earth" constructed at CTS installations. Further, Zipse stated "the claims of being able to dissipate any and all lightning strokes have been shown to be untrue".[16]

In 1999, Zipse published what he claimed to be an "update of, and correction to" version of his 1993 paper. In this paper, Zipse addresses charge transfer systems (CTS). Zipse claims that CTS systems had been "vindicated". He states that the correct theory for the effectiveness of the CTS is not neutralization of the cloud, as was originally thought, but the development of a "charged space cloud" above the CTS location that blankets the location and prevents development of upward leaders. If the space cloud does not prevent development of leaders and there is attachment, then the CTS acts as a conventional Franklin rod.

Zipse bases his conclusions on the "more than 33 installations in oil facilities worldwide". Additionally, Zipse places great reliance on the "Memphis hole" above one portion of the Memphis, Tennessee airport where a CTS was installed.

In one annual map (1998) of National Lightning Detection Network (NLDN) detected strikes, ninety-four percent of the Memphis airport shows a flash density of 8-12 strokes/km^2 per year. One 2km^2 area on the west side of the airport shows 2-4 strokes/km^2 per year, while the extreme NE corner of the Memphis airport shows 8-16 strokes/km^2 per year.

A CTS system is located in the northeast of the Memphis airport. Zipse, and others, interpret this to mean that the CTS is preventing lightning attachments at the airport, despite the fact that the area with the CTS has a *higher* flash density, and the area with lower flash density is on the opposite side of the airport. This is difficult to reconcile. Examination of NLDN maps compiling 10 years of data show that the single year showing the "hole" at the Memphis airport was an aberration. Multi-year data suggests that the actual flash density for the Memphis airport varies between 12 and 16 strokes/km^2 per year, with no particular or consistent "holes" at the airport.

Zipse does, however, provide some mathematical analysis of the number of points required to dissipate the charge. Equation (1) purports to provide calculation for the number of points.

$$N = \frac{Q}{I_p t} k \quad (1)$$

Where

- N Number of points required
- Q Charge to dissipate
- I_p dissipation current per point
- t time between strokes
- k *efficiency of the system*

This equation, by its very nature, assumes a linear relationship between the number of points and the current dissipated. The nature of space charges makes this an incorrect assumption. Further analysis into this relationship is addressed in subsequent sections.

Further, Zipse points to Technical Committees formed by NFPA and working groups formed by IEEE to investigate standards developments for alternative lightning protection systems as evidence of the validity of such systems. The current status of such standards activities, along with the status of alternative systems relative to active standards, is also addressed in later sections.

Other authors have referred to these systems as streamer delay systems or streamer retarding air terminals. Hossam-Eldin and Houssin describe laboratory analysis of such systems. [18] This series of tests compared the flashover voltage for Franklin rods and for CTS systems and found that the CTS systems had a higher flashover voltage. Others have performed somewhat similar studies. [19],[20] Proponents of CTS installations have pointed to this as an indicator that initiation of the upward streamer is delayed for some period of time, presumably until the thundercloud has moved past the facility to be protected.

V. TECHNICAL CHALLENGES OF CTS

Regardless of the assumed theory behind CTS installations, whether it is neutralization of the thunder cloud, dissipation of the ground charge, or creation of a “space charge cloud”, all of this family of systems rely on the dissipation of charge from the CTS to some portion of the atmosphere. This transfer is the result of corona formation at the tip of the rod or STD. This corona “leaks” electrons into the space above the point, and generates a dissipation current, allowing charge to flow from the grounded object into space.

As discussed above, it is often assumed that there is a linear relationship between the number of points and the dissipation current. Further, it is assumed that this process continues linearly until all charge is dissipated. The physics behind corona development in electrical fields shows that neither relationship is linear.

A. Space Charge

The development of space charge above a pointed object under a thundercloud is a function of the electric force developed from the lower charged layer (mostly negatively charged) in the cloud. [21],[22],[23] This develops an electrical field near the ground that typically ranges between 2,000 and 5,000 V/meter (N/C). Rison reports observation of fields as strong as 30,000 V/meter (N/C), but that these are rare.[21] Corona develops on pointed objects when the electric field around the object is above ~1,000 V/meter. Thus, there is some level of ion leakage, and charge dissipation, anytime the field around the pointed object exceeds ~1,000 V/meter.

Charged ions in fields of around 5,000 V/meter travel at about 10 meter/S. Taking 10 seconds as the time between strokes, as proposed by Chauzey and Soula [24], the distance that the charged ions leaked by the Corona can travel is calculated as near 100 meters. These ions would create an E field based on Coulombs’ law, with a polarity opposite of that of the electric field surrounding the pointed object.

$$E = \frac{Q}{4\pi\epsilon_0 R^2} \quad (2)$$

Where

E	E-field generated
Q	Amount of charge
ϵ_0	permittivity of free space
R	radius of field of charge

When this generated field exceeds ~4,000 V/meter, then corona extinguishes and charge dissipation ceases. From (2), it is easy to determine that a charge dissipation of 4.4×10^{-3} C would create a field of 4,000 V/meter at a radius of 100m. When this amount of charge has been leaked from a point, then the space charge would suppress any further leakage. As the space charge is moved by wind, some additional leakage would occur.

Assuming a 25 m/s (~56 MPH) average wind under a thunderstorm, 4.4×10^{-3} C of charge could be generated about every 4 seconds. The amount of time necessary to dissipate 10C to prevent a single strike would be in the neighborhood of 18,000 seconds, approximately 180 times the amount of time necessary for a cloud to charge for the next stroke.

It can be observed that, as the downward leader approaches earth, the E-field intensifies until it reaches 100-200 kV/meter. As this occurs, the amount of dissipation current increases proportionately. However, as the speed of the downward leader is ~2.5×10^5 meter/s, the time available for dissipation is on the order of 400 μs, and significant charge cannot be dissipated.

It should also be clear that, given the assumptions above, space charge generated by point would influence charge dissipation on other points surrounding it as far as 100m away. As only one example, research at New Mexico Tech’s Langmuir Laboratory’s mountain top (South Baldy Peak) thunderstorm research center indicates that, during storm conditions, an 80-point array emits a corona current about twice the value of that from a single isolated point. [27]

B. Size of Array Necessary

Measurements of the actual dissipation current generated by both single point and multi-point STDs has been made in both laboratory and field conditions. Chalmers stated that the maximum current dissipated by a single point in a multipoint array is 20μA. [25] Rison states that maximum dissipation is 10 μA. [21] Bent & Llewellyn measured 0-20μA dissipation current, with peak currents lasting very short periods of time. [26] Bent & Llewellyn also observed that a multi-point array never emitted more dissipation current than a single point.

Taking 10 seconds as the time between strikes, 10 C as the minimum charge dissipated by a single stroke, 20 μA as the current dissipated by a single point, and assuming 100% efficiency, the number of points necessary to prevent a single stroke can be calculated from (1) as 50,000 points. From descriptions in [7] and [9], points are spaced ~ 6 inches (~0.15 m apart). This would necessitate a field of closely packed points ~25,000 ft^2 (~2320 m^2) in size. For comparison, this is approximately the size of one-half of an American football field.

The above calculation assumes a linear relationship between the number of points and the dissipation current. However, as discussed above, the space charge would self-limit the dissipation current. This would necessitate a much larger array than even calculated above.

C. Grounding

Proponents of CTS installations point to the “many” installations where these systems have been installed and “no strikes have occurred”. It should be observed that, in contrast, strikes have been observed on facilities that have CTS installed. In addition to those reported in the literature (NASA, FAA, etc.), the author has personally observed security camera footage, eyewitness accounts and other recorded data of stroke attachment to facilities supposedly protected by CTS. Why do some installations work and some installations fail?

Some of the “success” gained from such installations can be attributed to mere statistics. Both NFPA 780 and IEC 62305 contain techniques to determine the risk of lightning damage to a particular location. [28],[29] Consider a petroleum production facility located in eastern New Mexico. The facility is 54m X 20m x 11.5m high. Without any protection, the facility has a risk of ~0.12 events per year, or one attachment every ~8.3 years. As the life of many such facilities is less than 8 years, many facilities do not suffer lightning damage simply because they are not in place long enough. This does not explain the lack of damage to longer term facilities.

For those facilities, the most reasonable explanation can be observed in the descriptions of CTS installations. Cage, Carpenter, Zipse and others have included a large "ground connections", "ground current collector circuit" or "improved grounding" in the design for installations. As discussed in Part 2 of this Primer, excellent ground design is a key component in the dissipation of lightning energy from stroke attachment. [1]

In those locations observed by the authors to have lightning damage, the ground system did not meet the requirements of NFPA 780 or IEC 62305. Anecdotal reports of the FAA indicate that the "existing" ground system was used" at those facilities where damage occurred. [11] Zipse even comments on the value of the improved ground in preventing damage when the "blanket" collapses and attachment occurs. [16],[17]. It is posited that the benefit to such installations comes from improved grounding and ground connections, rather than any improvement in performance from charge dissipation.

VI. EARLY STREAMER EMISSIONS SYSTEMS

In contrast to charge transfer systems, which attempt to dissipate or blanket a facility to prevent lightning attachment, early streamer emissions (ESE) systems take the opposite approach. ESE systems use some form of an ionizing mechanism to create an "early" or stronger upward leader, as compared to traditional Franklin rods. Proponents of these type systems maintain that such an early leader increases the attraction of the downward leader to the ESE terminal. The upward leader formed by the ionization activity is believed to add to the height of the ESE terminal, thus creating a rod that has an "effective height" greater than the actual height. This higher effective height purportedly increases the zone of protection beyond that of a traditional rod.[30]

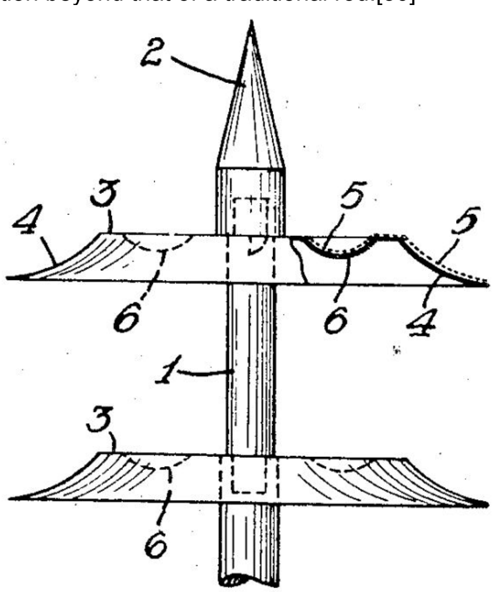

Fig. 4 A. Capart's ESE

The concept of an ionizing mechanism being used is traced to the early 20th century. Some authors attribute the concept to Leo Szilard, better known as one of the authors of Einstein's Nassau Point letter to Roosevelt.[16] However, no primary source material can be found to substantiate such a claim.

G.P. Capart filed a US patent application for a "Lightning Arrestor with Ionization Chamber" in 1931, which patent was granted in 1935. [31] According to Capart, the "functioning is based on the use of an ionization chamber which, in a manner, artificially creates a corona effect". In Fig. 4, the ionization chamber is depicted by the rectangle identified as "1".

The chamber caused "the efflux of electric charges due to supertension" to ionize the air around the terminal. This pre-ionized air, it was theorized, would create a path more suitable to the development of leaders than non-ionized air.

In the 1950s, A. Capart filed additional family of patents, including a US patent regarding additional ESE systems. The intent of A. Capart's "Radioactive Lightning Arrester" was to "produce an increase in the conductivity of the air by ionization". The function of the device was to prevent lightning by increasing "the exchange of electricity between the storm cloud and the earth" to create a "path of lowest resistance for the lightning". A. Capart directed ionized particles upward through the use of wind deflectors, identified as items 3 – 6 in Fig. 4. In this way, A. Capart claims, the ionizing effect could be extended beyond the 3.33 cm that the ionized particle could travel naturally. [32]

Two different types of ionization chambers have been used for ESE terminals. The earliest types use a long half-life radioactive isotope such as Americium 241 (^{241}Am), Radium 226 (^{226}Ra), or Cobalt 60 (^{60}CO). [36] These isotopes ionize the air in the vicinity of an ESE terminal by the production of ion-pairs due to alpha decay. As decay occurs, the alpha particles are passed through an ionization chamber, which is simply an air-filled space between two electrodes. The resultant increase in conductivity allows for current to flow between the electrodes and releases free ions.

In many ways, the radioactive ESE acts in a similar method to an ionization type smoke detector. The difference is that the smoke detector measures current through the ionization (interrupted by smoke), while the ESE drives current through the ionization chamber with the intent of developing free ion pairs.

After concerns about the health effects of radioactive air terminals, electrical triggered ESE terminals were developed. One such device uses a capacitor to collect charge from the atmosphere while the electrical field around the terminal increases as the result of an approaching downward leader. When the voltage across the capacitor is charged to a sufficiently high level, the energy in the capacitor is released across an air gap, generating ions. [37]

Another type of terminal senses the electric field increase due to an approaching downward leader and starts a plasma generator. The plasma is then directed to the tip(s) of the air terminal and blown into the space around the terminal using air. This plasma ostensibly either (1) disturbs the electric field around the terminal and object to be protected, which prevents attachment or (2) alternatively, creates an ionized path that preferentially causes attachment to the ESE terminal. [38]

Still another type of design uses actively energized biasing circuits to affect the polarity of neighboring lightning terminals. This biasing is below the corona discharge limit in clear air. However, as a thunderstorm or downward leader approaches, the E-field increases, reducing the level of biasing needed to create corona discharge. The terminals then discharge between two oppositely biased terminals, releasing ions and modifying the E-fields above the terminals. The system then uses devices such as lasers or charge guns to generate ionized path segments in the atmosphere and either dissipate the leader or create an ionized path to encourage attachment to the ESE terminal.[39]

VII. TECHNICAL CHALLENGES OF ESE

ESE systems were largely unstudied by the scientific community until the 1960s. Roberts determined that the amount of charge release from an ESE system increased background ionization by only 0.5% at 100 m. [34] This increase in ionization is unlikely to divert a downward leader by any significant amount.

Cassie evaluated ESE rods and stated that the ionization will only travel up to 10 cm away from the point, even with varied deflection patterns. Since downward leaders move in 50 m steps, the increased ionization will have a minimal impact on the direction of a downward leader. [35]

Laboratory tests have purported to show the efficacy of ionizing air terminals (ESE) over traditional Franklin rod terminals. One set of experiments, widely quoted as being supportive of increased ESE efficacy, compared ionizing and non-ionizing air terminals under a metal screen simulated cloud. The terminals were protected from wind. The metal cloud was energized with a step waveform, and discharge observed.

The conclusion of the reporting publication state that the ionizing terminal was the preferred attachment point more often than the Franklin rod. The experimenters found, however, that the difference in effective height was less than 0.25” (6 mm). [40]

It is reasonable to conclude that if exposed to horizontal winds such as those occurring during a storm, the effective height would be reduced below the 6 mm difference as the ions would be distributed horizontally by the wind. Regardless, a 6 mm difference in effective height would cause a negligible change in the zone of protection.

Another set of experiments subjected a Franklin rod and an ESE terminal to an electric field generated by a sphere and then applied a 1.2 x 50 μs impulse voltage to both air terminals. Values measured were time to corona, time to breakdown and breakdown voltage. The results of these tests show that there is a possible time to breakdown advantage of ~40 μs for the ESE terminal. The investigators point out, however, that this advantage was well within the standard deviation of the collected data. The speed of the upward leader was determined to be ~$2x10^4$ m/s. [41] These results have been used to attempt to prove that the ESE has an advantage in effective zone of protection over a Franklin rod.

Assuming that the time difference is actual present, and is not a statistical anomaly, as the authors suggest, the increase in effective height can be determined. Based on the speed of the upward leader, the difference in effective heigh is 0.8 meters. This is ignoring the fact that wind would distribute the ions released by the ESE in actual field conditions. Regardless, an effective height difference of 0.8 meters has an insignificant impact on the zone of protection.

For the most realistic conditions, ESE terminals and Franklin rods were placed in the open air and exposed to thunderstorms. The rods were monitored for lightning attachment by both electrical and video means. [42],[43] These studies showed that lightning had no preferential attachment to the ESE terminals over Franklin rods. In fact, lightning attachment fell within the supposed zone of protection of the ESE terminals on multiple instances.

It can be observed, then, that whatever advantage on upward streamer initiation that an ESE provides is negligible when considering the overall size and speed of the lightning event.

VIII. ALTERNATIVE PROTECTION SCHEMES AND STANDARDS

The status of alternative lightning protection schemes in the world of standards has been a contentious topic since the late 1980s. In 1988 a proposal was made to include CTS systems in NFPA 780 (then NFPA 78) by creating a new chapter for the standard. The NFPA 78 committees rejected the proposal as there was a “lack of sufficient technical justification for the concept”.[44] Further efforts by proponents of alternative protection systems led the NFPA Standards Council to approve a new standards project for ESE system (NFPA 781) in October of 1991. At the same meeting, the Council voted to not approve a standards project for CTS systems.

A Draft of NFPA 781 was published in September 1993 and submitted for public review. The draft was rejected and returned to the NFPA 781 Technical Committee at the NFPA Fall meeting in October 1993 by “overwhelming vote”. This vote was appealed to the NFPA Standards Council, which ultimately upheld the vote and returned the standard.[46],[47] NFPA commissioned the National Institute of Standards and Technology (NIST) to conduct an “independent third party review” of ESE technology. [30]

The results of this NIST review were published and public comments requested. After review of the report and the comments from both proponents and skeptics of ESE technology, NFPA discharged the NFPA 781 Technical Committee as a “sound technical basis for proposed 781 has not been demonstrated”.[48]

Proponents of ESE systems decided to file a US Federal Court lawsuit against the NFPA, and other parties involved in the 781 decisions, claiming antitrust and false advertising. This is the lawsuit identified by Zipse.[17] The court found that the claims that ESE systems provided a measurable zone of protection and protect against lightning strikes were “literally false”. [49]

Additionally, plaintiffs were prohibited from making any advertising claims that ESE systems had a zone of protection larger than a NFPA 780 compliant system; were improved, more efficient or enhanced above an NFPA 780 compliant system; or is able to protect open spaces.[50] Further efforts to include ESE systems in NFPA 780 continue to be made, at least as recently as the 2017 Edition. To date, these efforts have not been successful.[51]

Similarly, ESE systems are not recognized by IEC 62305. Some national adoptions of 62305 recognize ESE systems.

After the rejection of a CST or dissipation array standard by NFPA in what became the NFPA 781 Technical Committee, additional efforts were made to constitute a CST standard. Additional requests were made to NFPA in 2005. NFPA found that the request did provide “ample support in the scientific and technical literature to support meaningful standards development for DAS/CTS lightning protection systems".[52]

Efforts were also made to develop an IEEE standard for DAS/CTS systems. In 2000, PCIC rejected a proposed working group to develop such a standard. In a similar timeframe, a working group was established by the IEEE Power Engineering Society to investigate such a standard. (IEEE 1576). After 5 years, the IEEE SA denied extension of the working group and efforts to develop an IEEE standard ceased.

UL Standard 96 contains a provision that specifically excludes attachments such as those typically used for CTS systems from air terminals for type 1 systems, the systems most often installed in petrochemical facilities.[53] Additionally, stainless steel is often used for CTS components. Stainless steel is not a material allowed by NFPA 780 or UL 96, as such these terminals could not be used for NFPA 780 compliant systems.

IX. CONCLUSION

Dr. Benjamin Franklin, physicist, diplomat, and creative thinker developed his namesake lightning protection system in 1752. Improvements have come on only three points: rounding the end of the rod, improving grounding systems, and determination of the zone of protection. Alternative approaches such as the CTS and ESE are not effective in extending the zone of protection beyond that of a Franklin type system.

The installation of CTS and ESE systems often involves expanding or improving the grounding systems. Based on the data available at this time at best such systems act as traditional air terminals, with the same zone of protection. Several researchers have questioned whether the "delay" of the development of upward streamers from CTS systems may actually decrease the zone of protection in those systems.

The development of upward streamer and the subsequent attachment to the downward leader is best described as a race. With the passage of a thundercloud, upward streamers are developed from multiple locations. In a properly designed and installed lightning protection system, the streamers from the air terminals "win" the race and get close enough to the downward leader to attach. Current research shows that neither CTS nor ESE systems affect the starting point of this race in any significant manner.

X. REFERENCES

[1] R. A. Durham, M. O. Durham and T. W. Gillaspie, "Lightning Protection at Petrochemical Facilities - Part 2 Requirements of Standards," *2021 IEEE Petroleum and Chemical Industry Committee Conference (PCIC)*, 2021.

[2] R. A. Durham, M. O. Durham and T. W. Gillaspie, "Petrochemical Facility Lightning Protection Primer: Part 1: History and Basic Science," in *IEEE Industry Applications Magazine*, vol. 27, no. 2, pp. 47-56, March-April 2021, doi: 10.1109/MIAS.2020.3024492.

[3] Turns, B.F., 2006. Benjamin Franklin and lightning rods. Physics Today, 59(1), p.42.

[4] Labaree, L.W., The Papers of Benjamin Franklin (New Haven, 1959-). X, 299, p.194.

[5] Preece, W. H. (1880) XLVIII. On the space protected by a lightning-conductor, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 10:64, 427-430

[6] Le Conte, J. "On the space protected by a lightning conductor", Nature, 23,286 Feb 24, 1881, Nature Publishing Group.

[7] Cage, John M., LIGHTNING PROTECTION, U.S. Patent 1,743,526, filed December 27, 1926, Issued January 14, 1930.

[8] WILCOX, E. H. "Lightning Prevention." Scientific American 137, no. 6 (1927): 489–92. http://www.jstor.org/stable/26122166.

[9] Carpenter, Roy B. Jr.., SYSTEM AND EQUIPMENT FOR ATMOSPHERICS CONDITIONING, U.S. Patent 7,180,698, filed August 5, 1977, Issued Dec. 25, 1979.

[10] R. B. Carpenter and R. L. Auer, "Lightning and Surge Protection of Substations," in *IEEE Transactions on Industry Applications*, vol. 31, no. 1, pp. 162-170, January-February 1995, doi: 10.1109/28.363035.

[11] "Review of Lightning Protection Technology for Tall Structures", ONR, NASA, FAA, USAF, Houston, TX, 1975

[12] Moore, C. B., William Rison, James Mathis, and Graydon Aulich. "Lightning rod improvement studies." Journal of Applied Meteorology 39, no. 5 (2000): 593-609.

[13] W. Rison, C. B. Moore and G. D. Aulich, "Lightning air terminals - is shape important?," *2004 International Symposium on Electromagnetic Compatibility (IEEE Cat. No.04CH37559)*, 2004, pp. 300-305 vol.1. doi: 10.1109/ISEMC.2004.1350045

[14] Rizk, Farouk AM. "Modeling of lightning exposure of sharp and blunt rods." IEEE transactions on Power Delivery 25, no. 4 (2010): 3122-3132.

[15] "Lightning Protection Multipoint Discharge Systems Array Tests Orlando, Sarasota & Tampa Florida 1989", FAATC T16 power Systems Program, ACN-210, FAA, Washington, D.C., Feb 1990.

[16] D. W. Zipse, "Lightning protection systems: advantages and disadvantages," in *IEEE Transactions on Industry Applications*, vol. 30, no. 5, pp. 1351-1361, Sept.-Oct. 1994, doi: 10.1109/28.315250.

[17] D. W. Zipse, "Lightning protection systems: an update and a discredited method vindicated," Industry Applications Society 46th Annual Petroleum and Chemical Technical Conference (Cat. No. 99CH37000), 1999, pp. 37-51, doi: 10.1109/PCICON.1999.806422.

[18] Hossam-Eldin, Ahmed A., and Mahmoud I. Houssin. "Study of the effect of dissipation points on the lightning protection." International Journal of Scientific & Technology Research 1, no. 2 (2012): 46-51.

[19] Bazelyan, E. M., and M. M. Drabkin. "Scientific and technical basis for preventing lightning strikes to earthbound objects." In Power Engineering Society General Meeting, 2003, IEEE, vol. 4, pp. 2201-2208. IEEE, 2003.

[20] Bazelyan, E. M., Yu P. Raizer, and N. L. Aleksandrov. "Corona initiated from grounded objects under thunderstorm conditions and its influence on lightning attachment." Plasma Sources Science and Technology 17, no. 2 (2008): 024015.

[21] Rison, William. "There Is No Magic To Lightning Protection; Charge Transfer Systems Do Not Prevent Lightning Strikes." New Mexico Institute of Mining and Technology, Langmuir Laboratory for Atmospheric Research. Artículo para NLSI, www. lightningsafety. com (2002).

[22] R. H. Golde, Lightning. New York: Academic, 1977, vol. 1 and 2.
[23] M. A. Uman, The Lightning Discharge. San Diego, CA: Academic, 1987.
[24] S. Chauzy, S. Soula, 1987: General interpretation of surface electric field variation between lightning flashes. J. Geophys. Res., 92, 5676–5684.
[25] Chalmers. J. A., Atmospheric Electricity, Pergamom Press, London 1967.
[26] R.B. Bent, S. Llewellyn, “An investigation of the Lightning Elimination and Strike Reduction Properties of Dissipation Arrays, ONR, Nov. 1975.
[27] Moore, C. B., Aulich, G. D., Rison, W., “Measurements of lightning rod responses to nearby strikes”, Geophys. Res. Lett, VL - 27, IS - 10, SN - 1944-8007, doi:10.1029/1999GL011053
[28] Standard for the Installation of Lightning Protection Systems, NFPA 780, National Fire Protection Association, Quincy, MA, 1992, 2004, 2011, 2014, 2017, 2020.
[29] Protection Against Lightning, IEC 62305, International Electrotechnical Commission, Geneva, Switzerland, 2010.
[30] Van Brunt, R.J.; Nelson, T.L; Firebaugh, S.L.; Early Streamer Emission Lightning Protection Systems – Literature Survey and Technical Evaluation NISTIR 5621, National Institute of Standards and Technology, Gaithersburg, MD, 1995.
[31] Capart G.P. LIGHTNING ARRESTOR WITH IONIZATION CHAMBER, US Patent 1,996,321 filed March 5, 1931, granted April 2, 1935.
[32] Capart A. Radioactive Lighting Arrester, US Patent 2,854,499 filed August 31, 1953, granted Sept 30, 1958.
[33] Van Brunt, Richard J., Thomas L. Nelson, and Ken L. Stricklett. "Early streamer emission lightning protection systems: An overview." IEEE Electrical Insulation Magazine 16, no. 1 (2000): 5-24.
[34] ROBERTS, J. Ionizing Radiation and Lightning Hazards. Nature 210, 514 (1966). https://doi.org/10.1038/210514a0
[35] Cassie, A.M, “The effect of a radioactive source on the path of a lightning stroke”, tech. rep., Electrical Research Association, Surrey, UK, 1969.
[36] A.A. Moghissi, P. Paras, M.W. Carter, and R.F. Barker, "Radioactivity in consumer products," tech. rep., Nuclear Regulatory Commission, 1978.
[37] Lefort, L.; Boilozz, Pascal; Lefort, M; Lamin, Bernard; Method and Apparatus for Protection against Lightning, US Patent 4,752,854 filed Nov 25, 1986, granted June 21, 1988.
[38] Wang, K.; Li, X.; Method and Device of Compound Active and Passive Plasma for Lightning Protection; US Patent 7,760,483 B2 filed Jan 27, 2005, granted July 20, 2010.
[39] Hyde, R.A; Ishikawa M.Y.; Kare, J.T; Weaver T.A; Wood L.L.; Wood, V.Y.H; Polarized Lightning Arrestors, US Patent Publication 2011/0013333 A1; Published January 20, 2011.
[40] K. P. Heary, A. Z. Chaberski, S. J. Gumley, J. R. Gumley, F. Richens and J. H. Moran, "An experimental study of ionizing air terminal performance," in *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1175-1184, April 1989, doi: 10.1109/61.25601.
[41] Allen, N L, Cornick, K J, Fariclosh, D C, Kouzis C M; “Tests of the Early Streamer Emission Principle for Protection Against Lightning”, IEEE Proc. Sci. Meas. & Tech, Vol 145, pp 200-206, 1998.W. Rison, "A study of lightning strikes in the vicinity of a radioactive preventor," tech. rep., New Mexico Tech, Langmuir Laboratory, Socorro, New Mexico 87801, 1991.
[42] C.B. Moore, J.A. Mathis, and W. Rison, "Report on the exposure of eighteen air terminals along the crest of the Magdalena mountains in New Mexico during the 1994 thunderstorm season," tech. rep., New Mexico Tech, Langmuir Laboratory, Socorro, NM 87801,1994.
[43] W. Rison, "A study of lightning strikes in the vicinity of a radioactive preventor," tech. rep., New Mexico Tech, Langmuir Laboratory, Socorro, New Mexico 87801, 1991.
[44] NFPA Standards Council Minutes, April 6-7, 1989, topic 88-39.
[45] NFPA Standards Council Minutes, Oct 3-4, 1991, topic 90-29.
[46] NFPA Standards Council Minutes, January 12-3, 1994, topic 93-100.
[47] NFPA Standards Council Decision 94-11, January 12, 1994.
[48] NFPA Standards Council Decision 95-26, August 3, 1995.
[49] US District Court D. Arizona, 287F Supp. 2d 1038 (Arizona 2003), CV962796PHXROS, Order granting MSJ, Oct 23, 2003.
[50] US District Court D. Arizona, 287F Supp. 2d 1038 (Arizona 2003), CV962796PHXROS, Order and, Oct 7, 2005. Injunction
[51] Proposed NFPA 780 TIA 1209, National Fire Protection Association, January 15, 2016.
[52] NFPA Standards Council decision #05-11, January 13, 2005.
[53] *Lightning Protection Components, ANSI/CAN/UL 96 Sixth Edition,* Underwriters Laboratories, Jun 2016.

XI. VITAE

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