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Preventing Direct Lightning Strikes

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Background

The Beginnings

Protection against direct lightning strikes has been a subject of controversy since the days of Benjamin Franklin. In 1752, Benjamin Franklin introduced a lightning strike collection system. Subsequently, it became known as the "Franklin System," and the more contemporary name is the "lightning conductor", air terminal or lightning rod.

Shortly after its introduction, a controversy developed between those who believed in sharp pointed rods and blunt rods. Since both of these views lacked a physical foundation or statistical data at that time, the debate continued until very recently.

The effectiveness of the Franklin System of stroke collection has been questioned for over 100 years. Again, because there was no foundational physics, minimal test data or organized statistics presented to justify the manufacturer claims, they continued in use because of the lack of alternatives, other acceptable standards or political reasons.

In 1963, Dr. R. H. Golde(1) concluded a study of strike collection system data and reaffirmed the conclusion of Oliver Lodge and Richard Anderson from their work that "acceptance of a fixed value for the area protected by a lightning conductor is unjustified." Then, expressing in a more positive manner: "The attractive range of a lightning conductor should be regarded as a statistical quantity depending primarily on the severity of the lightning strike." They further added that "a lightning strike of average intensity would be attracted over a distance of about twice the height of the conductor." Then a subsequent "however" described several mitigating factors that would compromise those estimates. All of these statements were made without any reference to any form of foundational physics. Random unorganized statistics formed the basis for all conclusions and recommendations resulting in a "we always did it that way" attitude.

Recent Events

From the completion of Benjamin Franklin's work up to early 1960, no significant concept changes or improvements were made. However, some changes were made in the appearance, application or deployment methods for the lightning collector/conductor. No major changes were made in the collector concept, beyond the addition of up to four points being oriented in several directions, usually 90 degrees from the vertical. These changes were a potential improvement from the logic point of view, but were not justified by statistics or physics.

The next step was to change the logic behind what was assumed to be the protected volume. The industry standards groups agreed that the "cone of protection" theory was optimistic at best and various groups seemed to agree independently that the logic should switch to the "rolling sphere" concept as shown in figure 1. This change was based on the idea that R_1 represents the strike distance of a lightning strike and that a down-coming lightning leader should collect to the object at H_1 or to the ground before collecting anywhere inside the orange area. When determining the protected area using the rolling sphere method, the R_1 value is a single number. For example, NFPA 780 uses an R_1 value of 150 feet (46m). The rolling sphere method does not account for shorter strike distances than R_1, which would allow a strike to slip into the protected area, or competitive factors, which make some locations more likely to collect a strike than others.

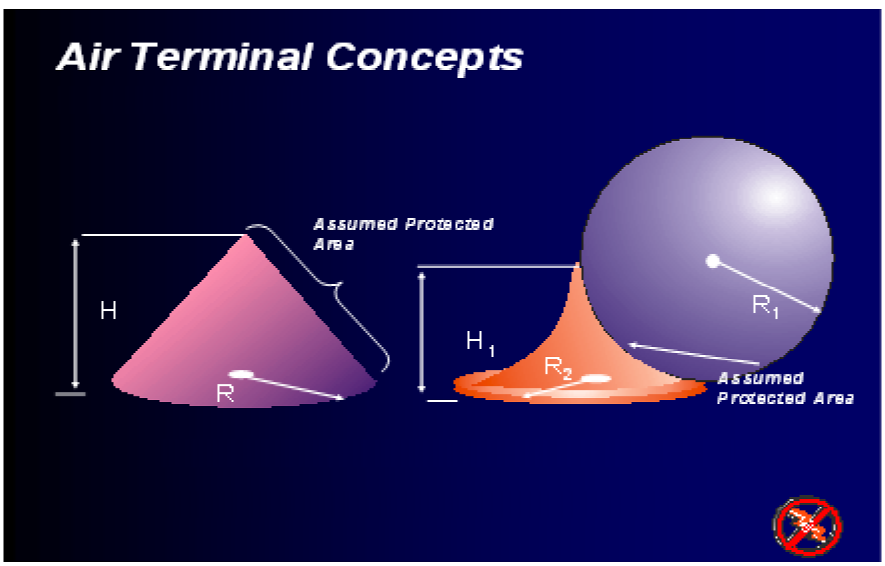

Figure 1: Air terminal concepts showing cone of protection (left) and rolling sphere (right)

As time marched on, the industry and related standards groups realized that the "rolling sphere" theory was also of limited success. There were no statistics or valid tests that substantiated the basic premise or confirmed the theory. This started a shift to the more sophisticated air terminals most to be known as "early streamer emitters" (ESEs). These devices were developed based on the premise that some form of sophisticated collector could be developed that would launch a collective streamer much earlier or extend it further than the conventional Franklin rod. Various techniques were implemented. Most have proven to be no better than the Franklin rod. Of the four or five concepts offered, only one appears to offer some slight improvement in launching the streamer, but the resulting benefit was not significant enough to justify the expense. As with all the ESEs, the few tests that were made proved to be inadequate in that the competition was not considered. Attempts to authorize a standard based on the ESEs have failed within the USA because at least two independent studies funded by the U.S. National Fire Protection Association (NFPA) failed to find any evidence of their value over conventional rods.[2 & 3] The NFPA publishes the NFPA 780 Standard for Lightning Protection in the USA.

Tests conducted by Professor Charles Moore and associates of the New Mexico Institute of Mining and Technology at the mountain top lightning laboratory in Socorro, New Mexico, indicated that blunt rods are more effective than sharp rods or ESEs[4].

One significant study funded by the NFPA [3] was conducted to determine the validity of the ESE concept. The study was conducted by three independent consultants [3]. As part of the study, the consultants, out of necessity, also compared the ESE to the Franklin rod, which proliferated into an in-depth study of both system concepts. The study results were "earth-shaking" for the lightning protection industry. The study states the following conclusions:

1. ESEs and Franklin rods are of generally equal capability.
2. The current NFPA 780 document that supports the use of Franklin rods is based on "historical precedent" rather than by experimental and scientific validation.
3. Neither ESEs nor Franklin rods appear to be scientifically or technically sound when evaluated in field tests under natural lightning conditions.
4. The existing NFPA Standard 780 should be reformulated to a "recommended practice" at best.
5. The recommendation that the existing 780 standard does not satisfy the NFPA criteria for a standard.
6. Formation of a new protection systems standards committee was recommended.

In summary, the present situation is as follows:

1. The Franklin System of lightning collectors remains in use for mostly political reasons.
2. ESEs are not recognized in the U.S. because of a lack of technical foundation and field test failures.
3. Testing has indicated that blunt lightning rods perform better than sharp-pointed rods and an ESE concept in a valid comparative test.

The Scientific Alternative - Strike Prevention with the Dissipation Array System (DAS)

DAS Composition and Functional Characteristics

The Dissipation Array® System (DAS®), generically known as a charge transfer system (CTS), is the only lightning strike prevention system. That is, the system actually prevents the termination of lightning strikes within any area defined as "protected". This includes the premise that there will be no terminations to the ionizer/array. A violation of this premise is considered a failure. Although this collection mode is considered a failure for the DAS, it is the primary and only mode of protection provided by a standard lightning protection system.

A typical functional DAS is illustrated by figure 2 when under the influence of a storm cell. Referring to that figure, the three basic subsystems are illustrated. These are:

1. **The ground charge collector (GCC)** is deployed such that it will collect the charge induced on the area or facility to be protected. This is analogous to the conventional grounding system except the GCC is a collector and not an earthling system for strikes. As such, the deployment objectives are totally different. The GCC could be the existing system if the ground grid is common and obtains less than 5 ohm earth contact.

2. **The charge conductor (CC)** is analogous to the conventional down conductor; but should be thought of as an "up conductor" because its function is to conduct the collected charge to the ionizer, providing a low surge impedance path in the process. Building steel and towers which are designed to provide an uninterrupted continuous path to ground are often acceptable charge transfer conductors.

3. **The charge transfer mechanism (the ionizer)** is the charge transfer component, and the most design sensitive. Its function is to transfer the collected charge to the adjacent air molecules via a principle known as "point discharge." The resulting ions make up what is known as "space charge", a mixture of charged and uncharged particles. This space charge forms a buffer between the protected site and the storm cell. The result of this buffering effect is a reduction of the electrostatic field at and below the DAS.

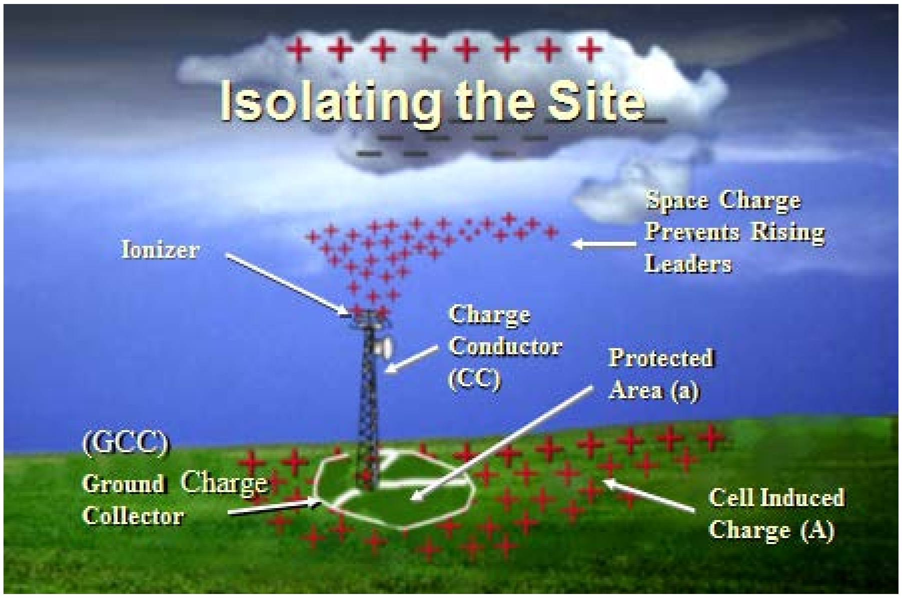

Figure 2: Typical DAS installation showing three subsystems

Since the objective of DAS designers is to prevent lightning strikes to a protected area, the system design must accomplish three sub-objectives. These are (1) preventing any protected site or structure from generating an upward moving leader, (2) delay progress of the descending lightning leaders into the protected area, and (3) suppressing any upward rising streamers from the protected site or structure.

1. Preventing any Protected Site or Structure from Generating an Upward Moving Leader

These upward leaders, which could develop a conductive channel and initiate a strike to the site, are usually initiated by tall structures in excess of 100 meters in height or mountain top facilities of any height, where the combined elevation will permit a voltage on the uppermost structure in excess of 10^6 volts during the discharge process.

Studies conducted by Dr. Bazelyan [(6)] and his associates developed the proof required to assess and eliminate this risk. It was found that the use of an optimized ionizer could build up and maintain a space charge in the potential strike zone that would prevent the launch of a collective leader through that space charge. Practical applications of the principles developed by Dr. Bazelyan have been published by Dr. Drabkin and associates [(7)].

A rare condition was experienced in areas where positive discharges were common and the launch of a rising lightning leader is common. In these cases, the space charge density must be much higher than for the descending negative discharge. Peak lightning currents and related charges for positive discharges are initiated from earth to reach peak currents of up to 200,000 amperes. The negative discharges descending from the storm cell rise to peaks of only 100,000 amperes. It therefore requires nearly twice as much space charge in areas where the positive discharge is experienced; the electrostatic field is usually much higher in those situations, thereby producing more ionization.

2. Delay Progress of Descending Lightning Leaders

Preventing the termination of a randomly delivered descending lightning leader is a significantly greater problem. To understand the details of the termination phase of a lightning leader approaching a DAS, it is necessary to understand the leader situation just before "touchdown". This is illustrated by figure 3, a very unusual photograph that is paramount to understanding the DAS performance. It depicts the situation at a few microseconds before termination. Please note that there are many branches, with at least six in the foreground. All are about the same distance above earth; one must terminate. The objective is to prevent that one from termination on or in the DAS protected area.

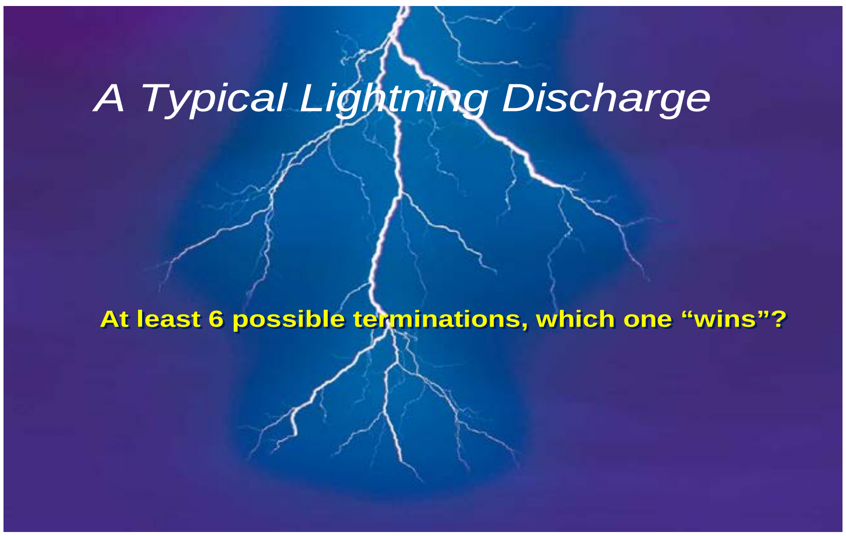

Figure 3: Leader situation before termination

The lightning leader is approaching termination at an average rate of up to 0.4 meters per microsecond for the last 100 meters or so. To deal with that closure rate, a significant volume of space charge must already be in place before leader propagation and the remainder will have to be generated as a reactive charge within 50 to 100 microseconds as the leader approaches.

The pre-strike space charge is fixed by the ionizer size, electrostatic field and the time between discharges and space charge migration rate. A combination of the electrostatic field, updrafts created by the storm and forces defined by Coulombs Law cause a constant flow of ion current and a constant migration of charge between the ionizer and the storm cell as described by atmospheric physicist, Dr. Alton Chalmers(8). This space charge, being of opposite polarity of the descending leader, will partially neutralize and impede the progress of the downward leader, if the space charge density is high.

3. Suppressing the Upward Rising Streamer

In order to prevent lightning from striking within a specified zone, a DAS collects the induced charge from thunderstorm clouds within this area and transfers it through the ionizer into the surrounding air, thus reducing the electric field strength in the protected zone. The resulting reduced electrical potential difference between the site and the cloud suppresses the formation of an upward streamer. With no leader/streamer connection, the strike is prevented.

Figure 4 shows the electric field measured at two locations, one under a DAS within the protection zone and the other remote from the DAS by approximately 300 meters, outside the protection zone. The blue line is the e-field away from the DAS and the orange line shows the field strength under the DAS. Peak e-field magnitudes within the protected zone are approximately 50% of the peak e-field magnitudes outside the protected zone during storm activity.

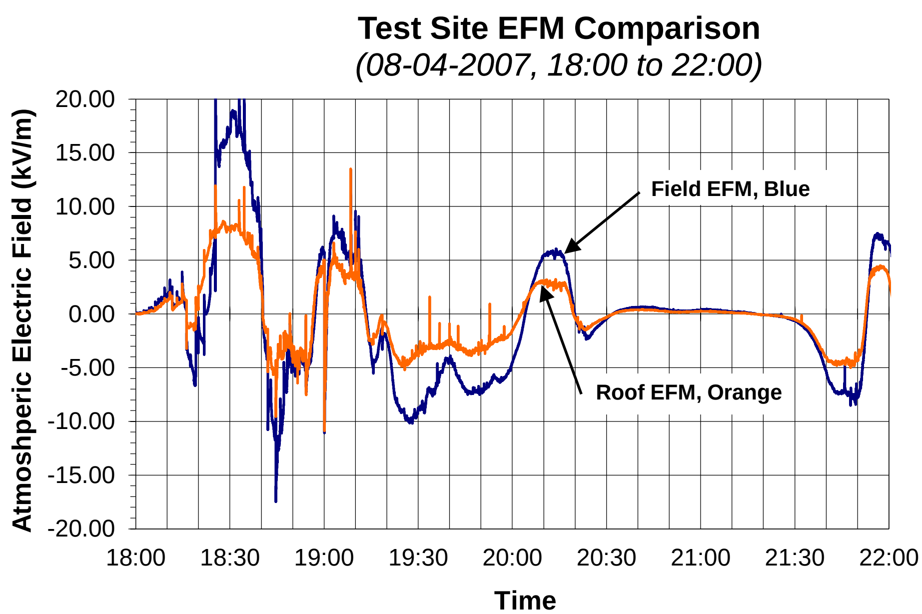

Figure 4: Electric field measurement during thunderstorm

As stated, DAS technology is based on the hypothesis that production of positive space charge in the region around the DAS reduces near-surface electric field strength to levels below which streamer formation is likely. With no streamers emanating from the structure of concern, the leader is more likely to connect to streamers originating from either unprotected adjacent structures (both manmade and natural) or from any air terminals installed on these unprotected structures.

By delaying the termination of one branch, the alternate termination point could be as close as 100 meters from the DAS or as far away as several kilometers. This is a random variable; therefore, there is no way to predict the next closest termination point. For example, if the leader is traveling at 1,500 km/sec and is 1 km away from the nearest streamer generator, called point A, to the DAS, the DAS must delay the formation of an upward streamer by only 0.006 seconds for the leader to attach to the streamer at point A.

The streamer is initiated when the local electric field is on the order of 350 to 600 kV/m. The object in a higher electric field is going to initiate an upward streamer earlier than one in a lower electric field.

How the Prevention Concepts Work Together

Figure 5 superimposes this situation onto a DAS protected tower site wherein one branch is approaching the DAS. The DAS responds by increasing the space charge density. Figure 6 illustrates the reactive space charge created by the approaching lightning leader branch. The resulting dense space charge suppresses the launch of a counter leader and the situation progresses to that illustrated first by figure 7 and then by figure 8. One branch has now terminated on a tree, all of the other streamers are withdrawn; and finally, the DAS created space charge is also withdrawn through the DAS ionizer creating a reverse discharge current flow, lasting only a few microseconds. All of those charges that are in the branches and around the ionizer take part in the neutralization function as illustrated by figure 8. The earth returns to the state when the storm cells are discharged or not present.

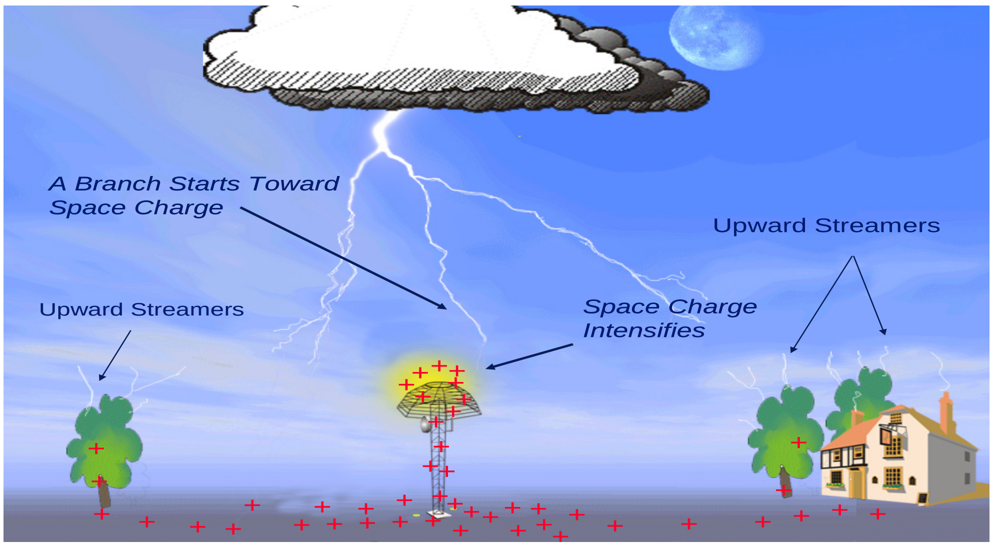

Figure 5: Lightning branch approaching tower with DAS

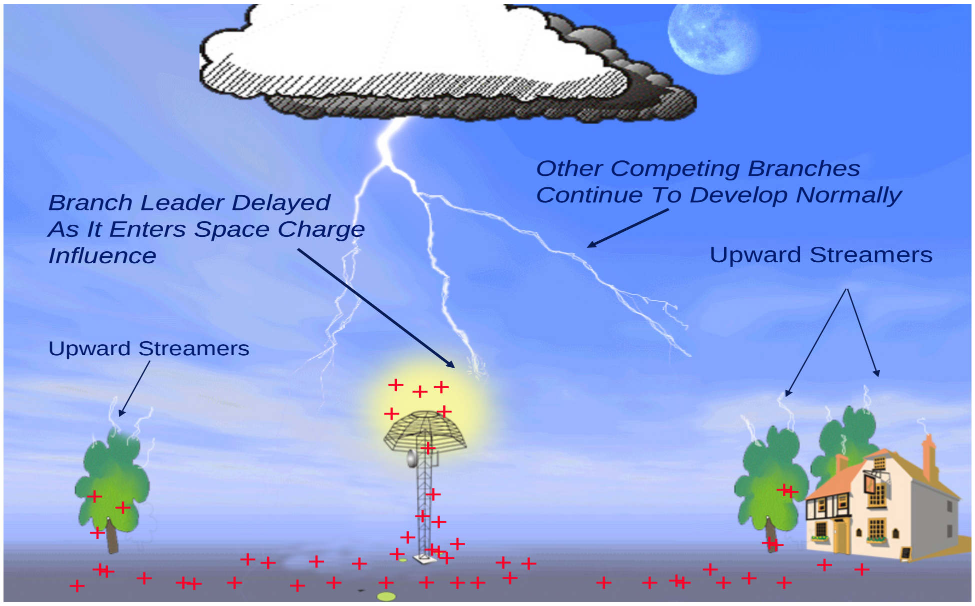

Figure 6: Reactive space charge created by the approaching lightning leader branch

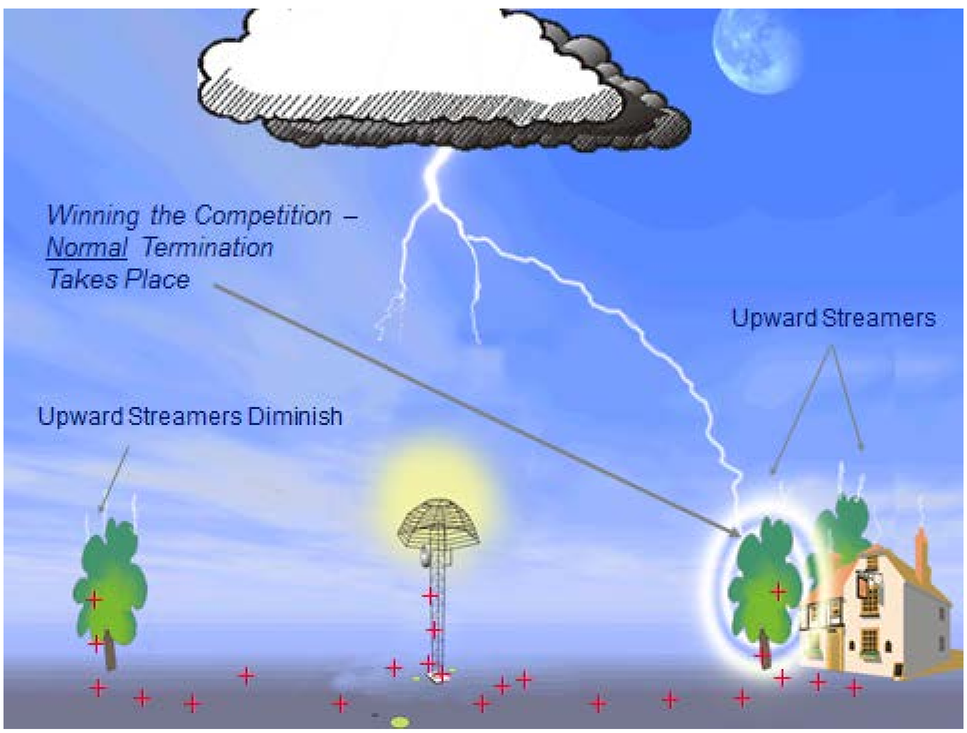

Figure 7: Lightning branch connecting with tree, other streamers withdrawing

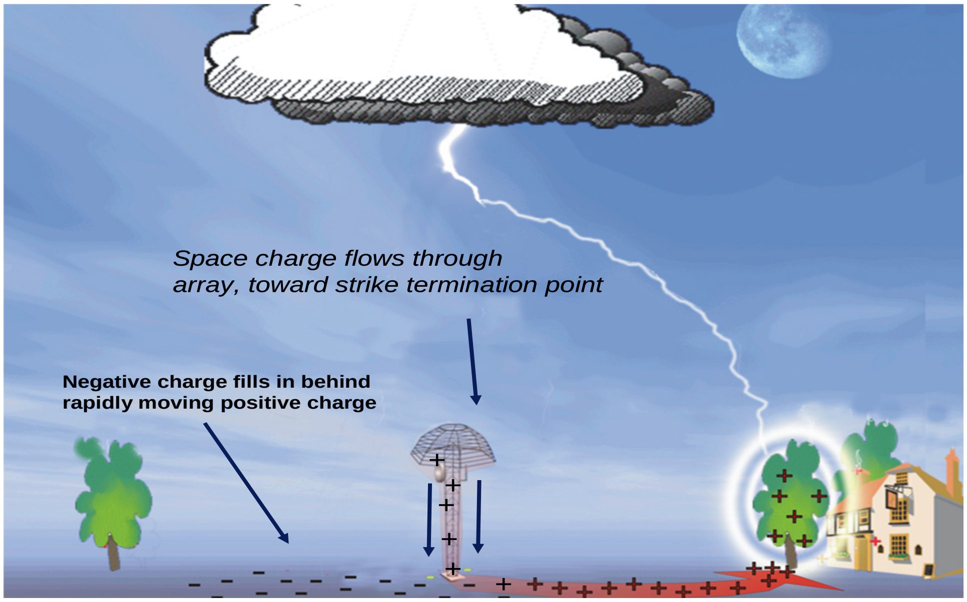

Figure 8: Charge flowing to strike terminus, others returning to neutral state

Figure 9 illustrates the current flow through the DAS during this process. Two full charge-discharge cycles are illustrated. Please note that the current flow rises exponentially at first, and then at a discrete point, the rate in current flow becomes progressively less. That is, the change in flow (di/dt) is constantly decreasing, as a result of the space charge buildup. The increased space charge density limits the penetration of the increasing electrostatic field. The Russian studies show that the **rate of change** in current flow would reach zero in a few milliseconds. However, as illustrated, the current flow drops rapidly to zero when a branch terminates.

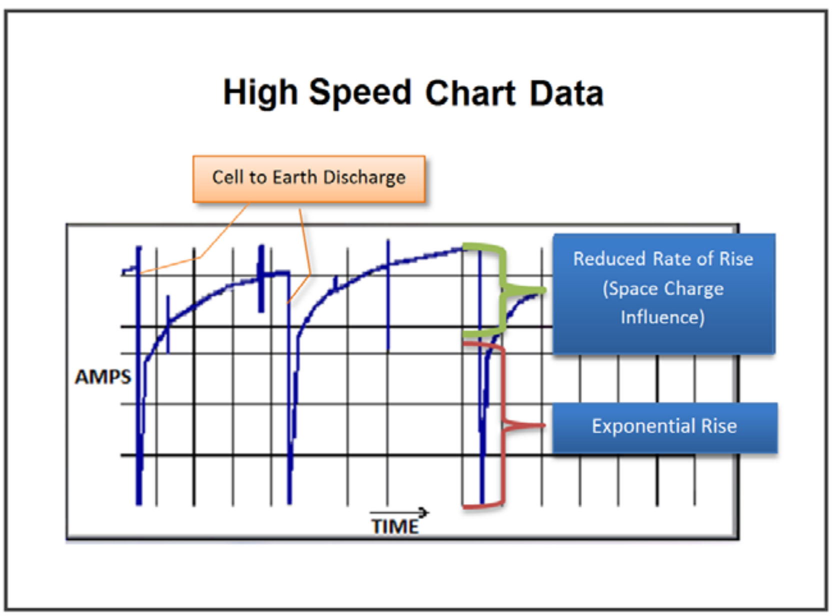

Figure 9: Current flow through DAS during thunderstorm

DAS Application Criteria

The selection of a DAS ionizer is a semi-arbitrary decision. That is, there is no hard and fast rule, but rather, it involves a review of the influencing factors and a selection based on a tradeoff between those parameters. The factors that influence this decision are:

1. The geographical location of the site and its related isokeraunic number and/or flash density
2. The height of the facility structures
3. The distribution of peak return current
4. The geography of the site
5. Loss potential

1. The isokeraunic number (K) is related to the geographical location and the number of potential strikes (N) for a given square kilometer per year, where:

$$N = 0.04K^{1.25}$$

So, if the isokeraunic number is 100, the average number of direct lightning strikes to each square kilometer in that area is expected to equal 12.7 strikes per year. (This equation is taken from IEC 1024-1-1.)

2. The height of the structure will determine the strike collection risk. Heights (H) of up to about 80 meters on flat land may collect the strikes within a diameter of about 2H. Therefore, if the facility has an area of 0.1 square kilometers, and the expected number of strikes per square kilometer is 20, then the facility will collect about 2 strikes per year. However, structures of over 100 meters will **initiate** more strikes than the simple collection rate estimate. Further, the higher the structure, the larger is the number of strikes initiated.

3. The distribution of peak currents in a return stroke is presented in figure 10 which is based on worldwide data. So as an example, if a given location received 100 strikes per year, 50 would peak at 30 kA or less and one may peak at 100 kA.

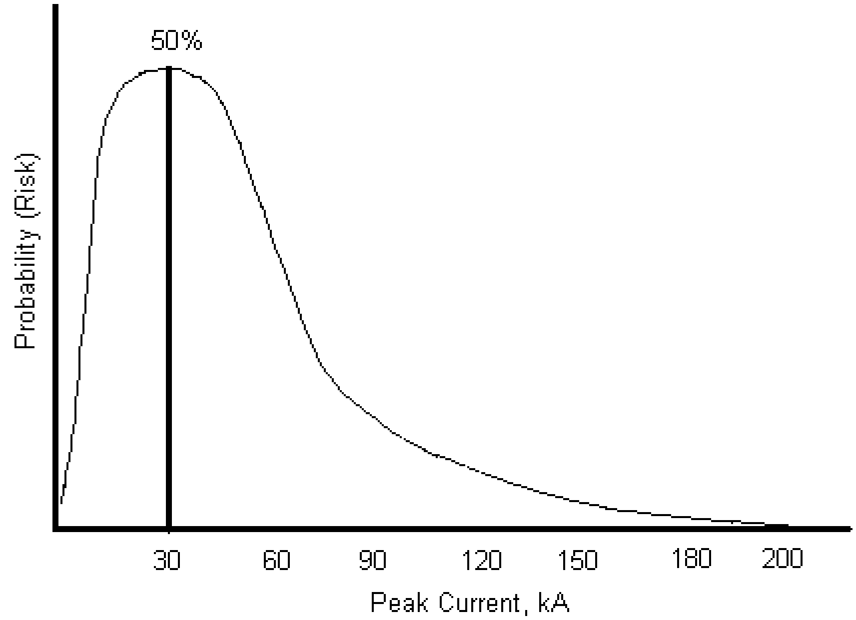

Figure 10: Distribution of peak lightning currents

4. The geography of the site and its location will influence the risk of a strike termination. Only general rules can be used to deal with this parameter. These include:

1. Mountain tops tend to have more frequent strikes.
2. Flat land and valleys tend to have less frequent strikes than mountains, however, the peak currents tend to be greater.
3. Waterfront areas are highly vulnerable to storms approaching from the sea. The number of strikes is higher than that expected for flat land and the peak currents also tend to be higher.

5. Potential losses due to a lightning strike to the site can have significant negative consequences. It is not uncommon to have a strike create catastrophic physical damage to buildings, structures and product that could cost in the millions of dollars. Further, the risk to personal safety must also be considered. Even though these are valid concerns, in most applications, it is the secondary effects of a lightning termination that create financial losses for that site. These secondary effects include damaged electrical systems, instruments, communications equipment and command and control circuits. This can and will lead to a high-dollar replacement cost of the damaged electrical/electronic systems as well as the associated downtime for that plant. In many cases, the loss of production can far exceed the replacement cost of the affected equipment. Depending on the type of facility and its purpose other costs and considerations may include regulatory fines, law suits and degradation in public perception.

General DAS Selection Rules

Again, most of the foregoing criteria are to be used as guidelines. However, there are some rules that must be considered mandatory. Where 100% strike prevention is required:

1. The DAS ionizer must be correctly sized to protect the desired area and/or structure.
2. That ionizer must present a smooth surface without any discontinuities.
3. Any ionizer of lesser size is based on accepting some level of risk acceptable to the customer.

Conclusion

The data presented within the foregoing paper presents the results of over 40 plus years of research, development and the application of the Dissipation Array System technology. The demand for proof of performance is reasonable; however, the definition of "proof" is more difficult. The Bryan Report [(3)] defined proof as including three constituents:

1. Basic physics – the relationship between the protection and the related environment
2. Test data – instrumented assessment of performance
3. Statistics – the accumulation of significant sample size of operational systems

1. Basic Physics
Doctors Bazelyan, Raizer and Aleksandrov, of the Russian Academy of Science, completed over two years of study centered on charge transfer system (CTS) technology resulting in proof of the scientific foundation for the CTS concept, as recorded in ten technical papers presented to several scientific societies[(6)]. These studies represent an update of the theory of operation from those early explanations used by LEC in prior publications. The key concepts are:

1. The DAS suppresses the launch of an upward leader when installed on tall structures greater than 100 meters in elevation.
2. The DAS delays the progress of an approaching leader/branch to permit termination elsewhere.
3. A reduction in near surface potentials is realized due to the reduction in the E-field within the protected zone, thus delaying the formation of upward streamers from structures within the protected zone.

2. Test Programs
The test programs were and are the most difficult to execute. Lab tests are useful for optimizing DAS design parameters. In-situ tests are the only acceptable form of test for a DAS. Two such tests were conducted in Singapore for government agencies. Three such tests were conducted in Japan on operational sites by Hitachi.

3. Statistics
The statistics on the operation of the DAS shows that 40 year plus history on over 3,140 systems and 54,000 system-years of operation has vindicated the DAS as scientifically sound. The DAS is now referred to generically as the "charge transfer system" or "CTS".

In summary, the technology is sound, the basic physics has been established, the performance statistics are voluminous and the test data collected by LEC and others provides a firm foundation. The theory of operation has been expanded to provide a more detailed explanation of the final phases of the DAS protective actions, as the lightning leader completes termination elsewhere. The DAS design concepts remain virtually unchanged; some parameters have been refined and clarified over time. The charge transfer system (CTS) or Dissipation Array System has achieved worldwide acceptance within most of the major industries in its over 40 plus years of history.

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