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Total Lightning Protection for Floating Roof Petroleum Storage Tanks

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Introduction

Lightning protection systems for floating roof petroleum storage tanks (FRTs) should do more than just intercept incoming lightning strikes, because an intercepted lightning strike is still likely to cause ignition of the tanks' contents. A completely effective lightning protection system (LPS) should be designed to protect against BOTH direct lightning strikes and the effects of nearby lightning strikes. A *total* LPS should isolate the FRTs from both types of threats, to eliminate all lightning-related risks.

Background

Lightning-related petroleum storage tanks fires are not uncommon. According to a review of petroleum storage tank fires between 1951 and 2003, the number of tank fires reported in the worldwide media is in the range of 15 to 20 fires per year. Of the 480 tank fire incidents reported in the media, about one-third have been attributed to lightning. [Ref. 1] Another study, sponsored by 16 oil industry companies, found that 52 of 55 rim seal fires were caused by lightning, and concluded that "lightning is the most common source of ignition." [Ref. 2]

How Lightning Causes Tank Fires

Lightning strikes are characterized by very high stroke currents arriving in a very brief amount of time. An average lightning strike delivers about 30,000 amps of electricity to ground within a few milliseconds. This current will flow across the surface of the earth until the cell between the thundercloud and earth is neutralized. The current will flow in all directions, although the amount will vary in proportion to the paths of lowest impedance. Some key lightning parameters are listed in Appendix One.

The mostly likely strike location on an FRT is the top of the rim or the gauge pole. However, lightning may endanger an FRT if a stroke terminates on (1) the roof, (2) the shell, (3) anything attached to the roof or shell, such as the gauge pole, or (4) a structure or the earth near the FRT. If lightning terminates on any of these locations, a portion of the total lightning current will flow across the roof-shell interface. If lightning should terminate on the tank shell, as illustrated in Figure 1, sizable currents will flow across the roof-shell interface.

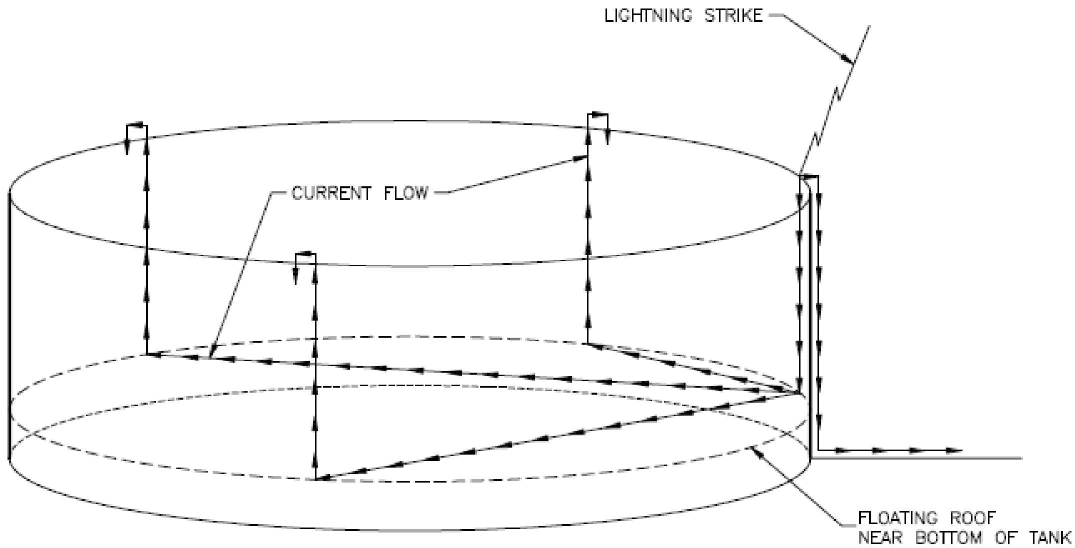

Figure 1: Illustration of Current Flows Resulting from Lightning Strike to Tank Shell
(Note that current flows across the roof-shell interface in numerous locations.)

If lightning terminates in the vicinity of an FRT, either to the earth or to a structure as illustrated in Figure 2, smaller currents will flow across the roof-shell interface. In either case, lightning-related currents will flow across the roof-shell interface. If the impedance between the roof and shell is high, arcing will occur across the seal interface.

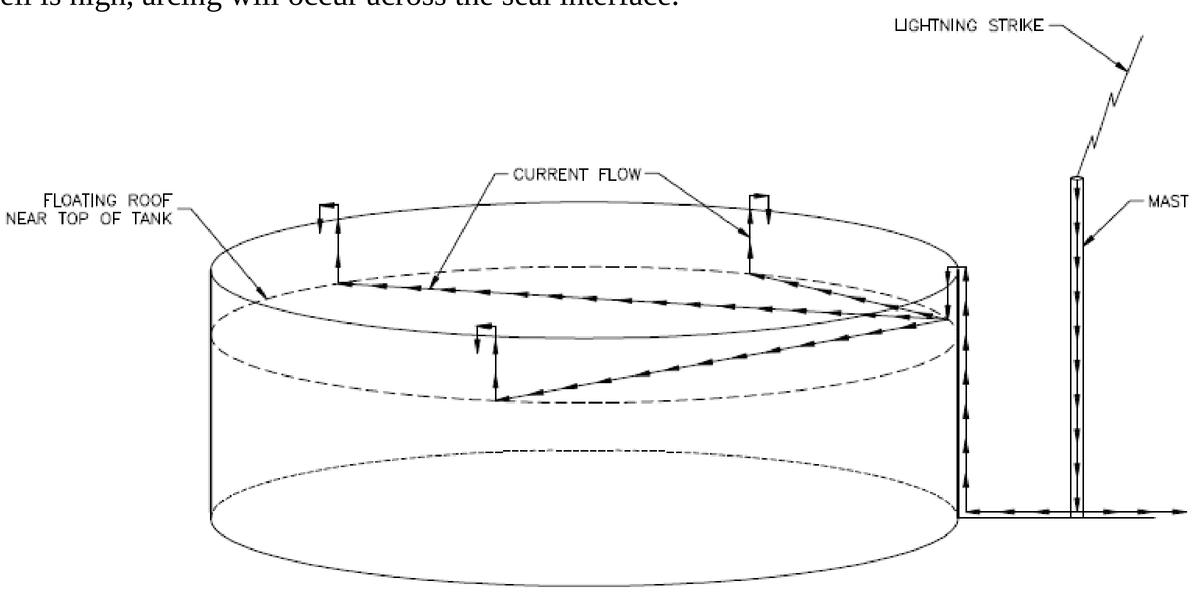

Figure 2: Illustration of Current Flows Resulting from Nearby Lightning Strike
(Note that current flows across the roof-shell interface in multiple locations.)

A typical lightning stroke contains numerous components, as shown in Figure 3 and delineated in Table 1. The fast component, or first return stroke (Component A in the figure) is extremely brief yet contains the peak current. The long, slow component (Component C) contains less current than Component A, but is defined as the continuing current component. Component C lasts much longer than the other components and thus contains the most energy. *The slow Component C lasts 500 to 2,000 times longer than the fast Component A.*

Between Components A and C is a transitional, intermediate phase (Component B), where the current transitions from fast to slow. Following Component C, additional subsequent return strokes (Component D) typically occur, followed by additional Components B and C, etc., which typically continue to flow until the entire lightning flash is exhausted.

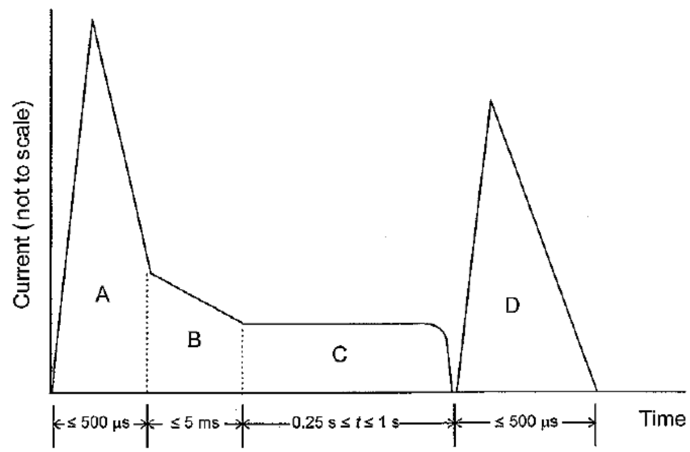

Figure 3: Lightning Flash Components (not to scale) [Ref. 3]

Component	Amplitude, kiloamperes	Charge Transfer, coulombs	Duration, milliseconds
A (first return stroke)	200 (+10%) peak	not available	≤ 0.5
B (intermediate current)	2 (± 20%) average	10 (± 20%) max	≤ 5
C (continuing current)	0.2 to 0.8	200 (± 20%)	250 to 1000
D (subsequent return stroke)	100 (± 10%) peak	not available	≤ 0.5

Table 1: Parameters of Lightning Flash Components [Ref. 3]

API Response

Because of the high incidence of lightning related tank fires, the American Petroleum Institute (API) formed technical committee 545 to investigate the cause of these fires, evaluate tank designs and write a standard to force changes in petroleum storage practices. API sponsored testing proved that *shunts will arc under all conditions*, whether they are clean, dirty, rusty, well-maintained, etc. Other key findings of the 545 test program included the following:

1. The fast component of the lightning stroke did not cause ignition of flammable vapors, whereas the long duration component did cause ignition. [Ref. 4] The fast component of the lightning stroke is too brief and has too little energy to ignite flammable vapors.

2. Bypass conductors will carry the intermediate and long duration components of the lightning stroke. [Ref. 5] If these components were allowed to continue to flow through the shunts,

sustained, hazardous arcing would occur at the shunts, which would ignite any flammable vapors present.

API Recommendations

After years of testing and deliberation, in October 2009 the API published API RP 545, *Recommended Practice for Lightning Protection of Above Ground Storage Tanks for Flammable or Combustible Liquids*. This document makes three key recommendations to improve the lightning safety of petroleum storage tanks with external floating roofs, as follows:

1. Install *submerged* shunts between the roof and shell every 10 feet (3 meters) around the roof perimeter. The shunts should be submerged by one foot (0.3 meters) or more, and if existing above-seal shunts are present, they should be removed.

2. Electrically insulate all seal assembly components (including springs, scissor assemblies, seal membranes, etc.), and all gauge and guide poles, from the tank roof. The insulation level should be *one kilovolt* or more.

3. Install bypass conductors between the roof and shell no more than every 30 meters (100 feet) around tank circumference. These bypass conductors should be as short as possible and evenly spaced around the roof perimeter. They should have a maximum end-to-end resistance of 0.03 ohms and be of the minimum length necessary to permit full movement of the floating roof.

Evaluation of API RP 545 Recommendations

1. Submerged Shunts: Shunts are used for the conduction of the fast and intermediate duration components of the lightning stroke current. The API acknowledges that arcing occurs between the shunt and shell during all lightning events. If the shunt is submerged, then theoretically the arcing will occur where no air/oxygen is present, and ignition will be avoided. Providing submerged shunts on new tanks will require substantial design changes. On existing tanks, the changeover from above-seal to submerged shunts will be very costly and will require major overhauls. In addition, because they are submerged, these shunts will be extremely difficult to inspect and maintain.

2. Insulation of Seal Components and Poles: Insulating these components will encourage lightning currents to travel through preferential paths (shunts and bypass conductors) rather than arcing between the roof and shell. However, it is debatable if the recommended insulation level of *one kilovolt* will be sufficient to cause the desired outcome. As with No. 1 above, substantial design changes and costly field modifications will be required to implement this recommendation, with attendant inspection and maintenance issues.

3. Bypass Conductors: Bypass conductors are used for the conduction of the intermediate and long duration components of the lightning stroke current. One of the observations from testing was that the fast component of the lightning stroke did *not* ignite flammable vapors, and that it was the long component of the lightning stroke that caused ignition. With conventional, above-seal shunts, the sustained arc at the shunts lasted long enough to ignite

flammable vapors. Because bypass conductors will provide a positive bond between the roof and shell, the bypass conductors will present a lower impedance connection between the roof and shell, as compared to the shunts. Therefore, the long component of the lightning current will be diverted away from the shunts and through the bypass conductors. The installation of bypass conductors is relatively easy and inexpensive, on both existing and new tanks. And because they are external, bypass conductors are easy to inspect and maintain.

Types of Bypass Conductors

In response to these requirements, the marketplace has provided tank owners with a choice between two different types of bypass conductors: (1) a conventional fixed length, stranded conductor or (2) a retractable conductor wound on a spring-tensioned reel. The ideal bond between the FRT roof and shell would have a low impedance across a wide range of frequencies. The ideal bond would also be easy to install on new tanks and to retrofit onto existing tanks. The ideal bond would also be easy to inspect and test, and to replace if necessary.

LEC has developed a roof-shell bonding mechanism that fulfills all of these requirements. The LEC Retractable Grounding Assembly (RGA) provides the lowest possible impedance bond between the floating roof and tank shell. It is easy to install on both new and existing tanks. It is also easy to inspect, test and maintain. The RGA has been patented for use on FRT's by Lightning Eliminators & Consultants, Inc., of Boulder, Colorado USA. See Figure 4.

Figure 4: LEC Retractable Grounding Assembly (RGA) on Floating Roof Tank

The conductor on the RGA is spring-tensioned, meaning that it automatically retracts on the reel when it is not under tension. Therefore, the conductor is always as short as possible, regardless of the position of the roof. In other words, the RGA is always "*of the minimum length*." API RP 545 requires that the bypass conductors be "…of the minimum length necessary.…" [Ref. 6]

In addition, the conductor on LEC's RGA is constructed of braided copper strands. Copper is 40 times more conductive than stainless steel, which is used by some other types of bypass conductors. Stainless steel bypass conductors will not meet the 0.03 ohm requirement of API RP 545.

Comparing Conventional and Retractable Bypass Conductors

An FRT is most at risk, and all of the hazards from lightning tend to be worse, when the roof is high. During these conditions (when the tank is full or nearly full), the lightning current flows will be concentrated in the shunts directly below the lightning strike location, as illustrated in Figure 5. In comparison, when the tank's roof is low and a lightning strike terminates on the tank, the lightning current disperses and is more evenly distributed among the available roof-shell bonds, as illustrated in Figure 6.

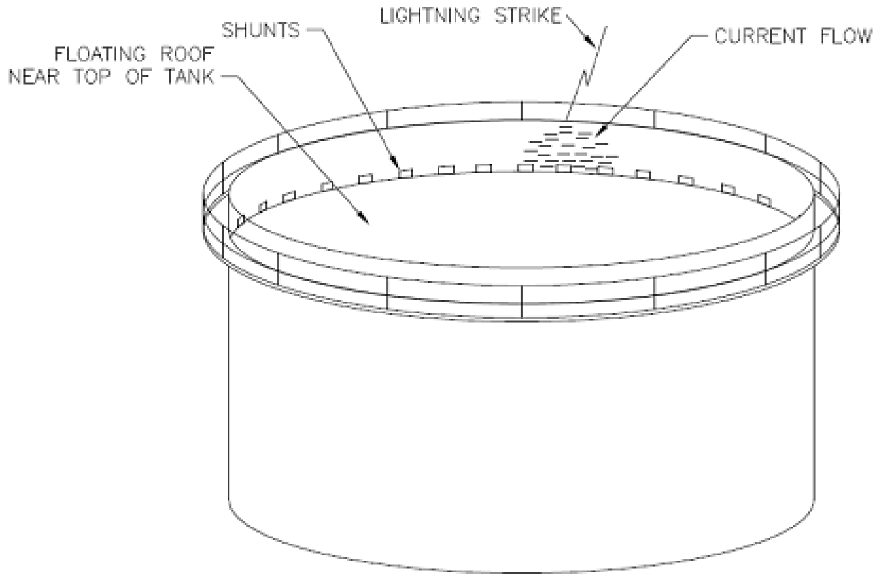

Figure 5: Concentration of Lightning Current Flow when Roof is High

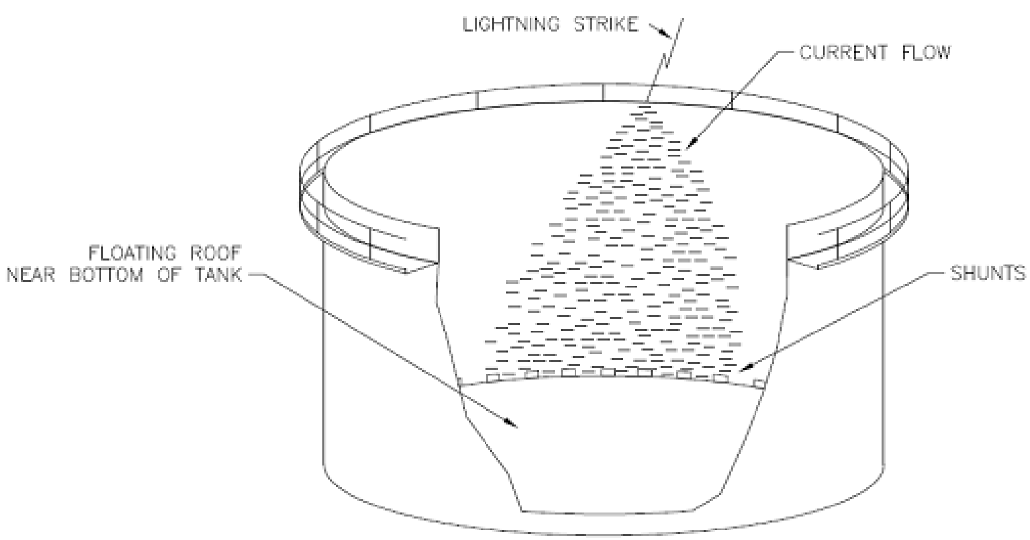

Figure 6: Dispersion of Lightning Current Flow when Roof is Low

Now compare the impedance of the two types of bypass conductors (conventional and retractable) during high-roof and low-roof conditions. During high-roof conditions, *when the tank is most at risk*, the conventional bypass conductor will be randomly splayed and coiled on the tank roof, as illustrated in Figure 7. In comparison, when the roof is high the RGA conductor will be as short as possible, as shown in Figure 8, and provide about *one-sixth of the impedance* of conventional bonding cables. [Ref. 7]

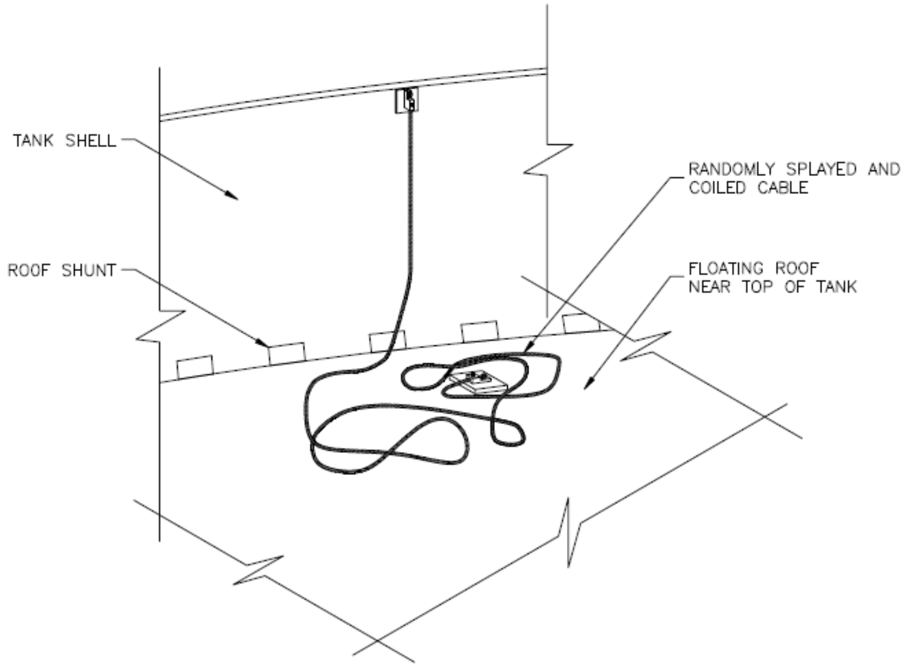

Figure 7: Conventional Cable as Bypass Conductor

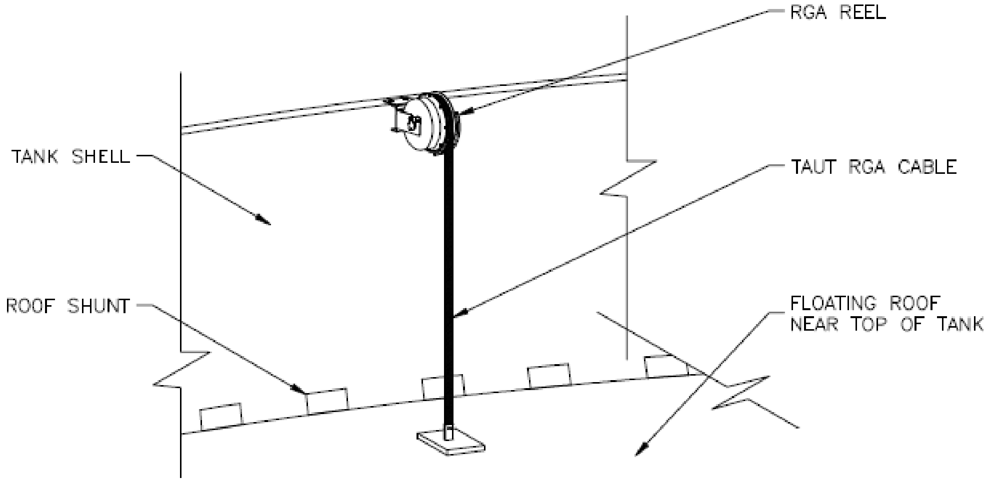

Figure 8: RGA as Bypass Conductor

Direct Lightning Strike Protection

As can be derived from the parameters shown in Appendix One, a direct lightning strike will cause an abrupt voltage rise of tens of thousands or millions of volts at the point of termination. If a lightning strike were to terminate directly on an FRT, it is likely that the voltage between the seal assembly components and the roof, and/or the gauge and guide poles and the roof, would exceed the API recommended insulation level of one kilovolt. This could easily lead to the formation of an arc in a dangerous vapor space.

Obviously, the safest possible environment for an FRT, even with RGAs, would be one where lightning does not terminate directly on the tank. This can be accomplished by the installation of a Dissipation Array System (DAS) on the FRT. A DAS is a lightning strike *avoidance* system that will prevent the termination of lightning strikes on itself or on the protected structure. The DAS produces a combination of effects on the protected structure, which include:

1. The reduction of the electric field on the protected structure.
2. The reduction of charge accumulation on the protected structure.
3. The retardation of upward streamers being launched from the protected structure.

Hundreds of FRTs have been protected using DAS with no known failures. Numerous field tests of the DAS have been conducted in real world applications. The results from one such test at a customer site is shown in Figure 9, where the electric field strength was measured both inside and outside the protected area. As you can see, the electric field strength within the protected area is substantially lower than that outside of the protected area. When the thunderstorm is most severe, the separation between these two lines is greatest. The average field reduction during these severe periods is 55%. The reduced electric field will suppress the development of upward streamers from structures within the protected area.

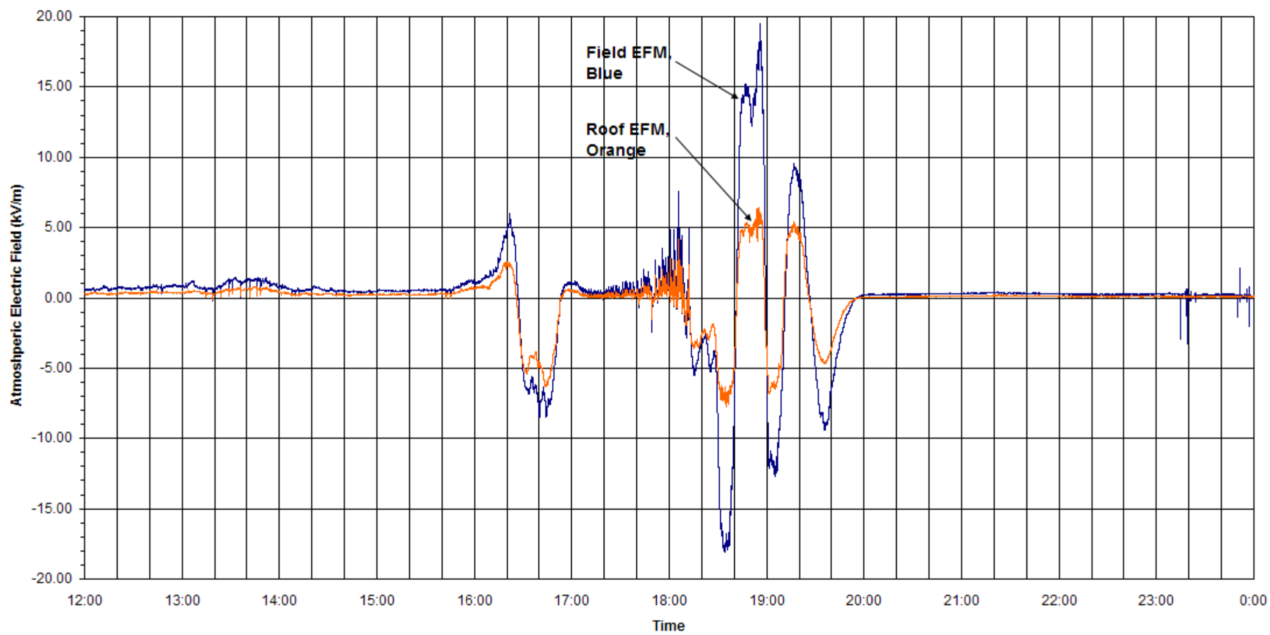

Figure 9: Electric Field Measurements Inside and Outside of a DAS Protected Area [Ref. 8]
(The measurement inside the protected area is labeled “Roof EFM, Orange”.)

In another DAS field test at a customer site, the customer recorded lightning activity 3 years before and 3 years after DAS installation. After the DAS installation, the customer realized an 80% reduction of lightning strikes within a 500 meter radius of the DAS, as shown in Figure 10, plus recorded zero direct strikes to the protected structure.

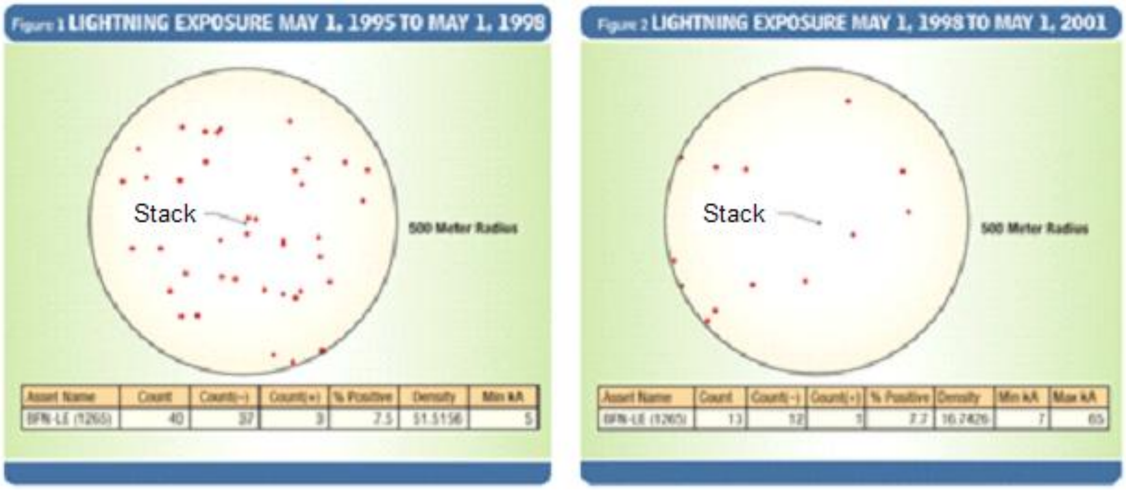

Figure 10: Lightning Strikes in Vicinity of DAS Protected Structure [Ref. 9]
(Diagram on left is before DAS installation; diagram on right is after DAS installation.)

Similar results have been found by several independent, third party tests, including those conducted by References 10, 11 and 12.

Lightning Risk Management for FRTs

It is important to understand that the two solutions presented herein (RGA and DAS) function independently of each other. Therefore, the implementation of one solution and not the other will have different effects on overall safety assessment of an FRT. Evaluation of each solution with respect to risk management is an effective way to understand each solution's unique benefits and quantify the return on investment.

The average frequency of lightning activity in an area is shown in Figure 11. Obviously, an FRT located in a high lightning area, such as in the southeast United States, central Africa or Southeast Asia, will have a greater lightning risk assessment than an FRT located in a low lightning area. However, just because a tank may be in a low lightning area does not mean that the lightning risk is zero, which is why API 545 is written to include all tanks without regard to their location. Although lightning activity may be infrequent, there is always some risk and it can be roughly quantified.

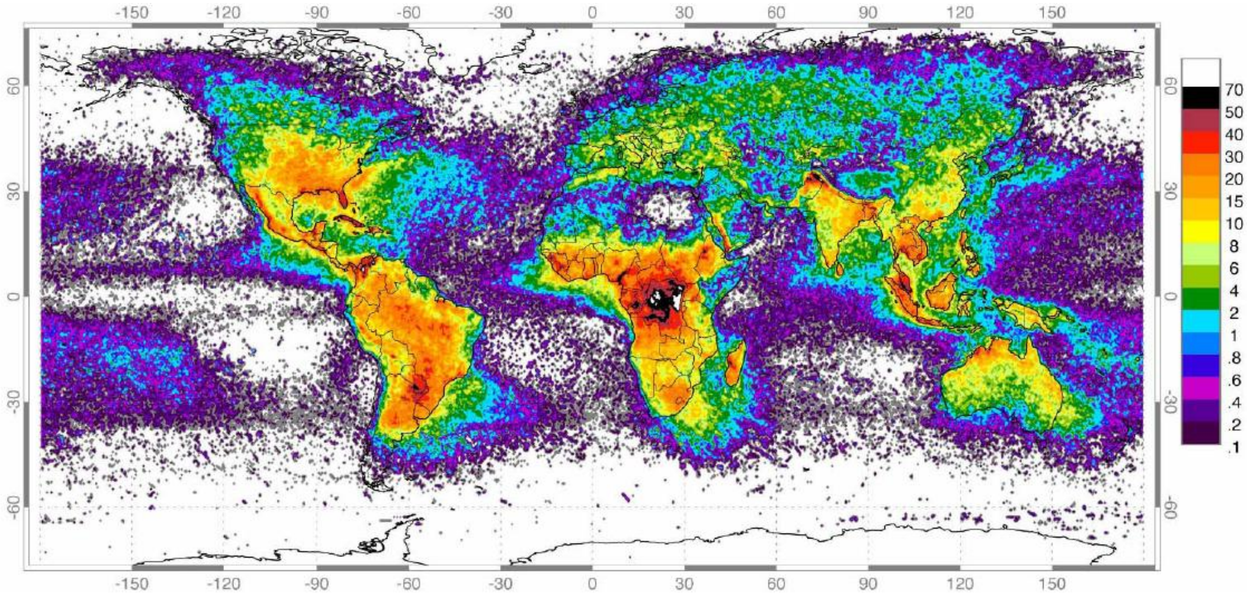

Figure 11: Lightning flashes per square kilometer per year [Ref. 13]

Just because there is a low probability of lightning directly striking an FRT does not mean that the event is impossible, because there is still some inherent risk. Therefore, the DAS is recommended for prevention of direct lightning strikes and is necessary to completely eliminate the possibility of all direct lightning strikes. By implementing DAS, an operator is truly eliminating all risk associated with direct lightning strike activity.

Summary

Lightning protection of FRTs requires an exercise in risk management analysis. The level of protection required is dependent upon the tank owner's comfort with risk tolerance. An owner who is not willing to accept any risk of lightning related damages to their FRT should implement both DAS and RGA systems to completely isolate the tank from all lightning activity.

However, an FRT owner may choose to accept some level of exposure to lightning danger. In this case only one mode of protection might be considered. The likelihood of a lightning strike terminating *in the vicinity* of an FRT is greater than the likelihood of a lightning strike terminating directly on an FRT. Because a strike in the vicinity may cause lightning-related currents to impact the FRT, LEC recommends that the RGA solution be implemented first. This will provide a high level of risk reduction for the FRT. Because the RGA and DAS function independently of each other, DAS can be added at later date if an owner's risk tolerance should decrease. If the FRT owner desires to eliminate the *total* lightning-related risk, then both DAS and RGA systems should be installed.

APPENDIX ONE:

Key Lightning Parameters

[References 14 and 15]

Peak Current, negative first strokes (50^{th} percentile)	30,000 Amps
Peak Current, negative first strokes (95^{th} percentile)	80,000 Amps
Flash Duration, negative flashes (50^{th} percentile)	13 milliseconds
Flash Duration, negative flashes (95^{th} percentile)	1100 milliseconds
Range of Strokes per Flash	1 to 30
Average Number of Strokes per Flash	3 to 4
Peak Temperature	> 50,000° F

The upper limit parameters usually employed for lightning strokes are as follows, although these values may be exceeded during severe thunderstorm conditions:

- Current (I) = 200,000 amperes
- Total charge = 200 coulombs
- Rate of change of current (di/dt) = 140kA/µs
- Action integral = $2.25x10^6$ A^2s

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