LIGHTNING PROTECTION AT PETROCHEMICAL FACILITIES – PART 2 LIGHTNING PROTECTION STANDARDS

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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 2 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, NFPA 780, IEC 62305

I. INTRODUCTION

Fundamentally, lightning strikes higher points with a somewhat conductive path to ground. Those properties are extremely important to the petroleum handling industry since oil and gas structures tend to be higher than the surroundings, the structures are somewhat to very conductive, and have the added risk of highly flammable products and vapors.

The basics of lightning control have been known since Dr. Benjamin Franklin's breakthroughs and related work by others in the 1750's. Nevertheless, over the past 20 years, there have been significant advancements in the understanding of lightning development and the intricacies of control.

Most electrical engineers succumb to the myths and mysteries of lightning and protection. Our objective is to address the science of lightning through history up to the development of industry standards. Keep in mind that lightning is just another electrical circuit [12], [19].

Protection of petrochemical facilities from lightning damage is governed by a series of standards published by various national and international Standards Development Organizations (SDOs). The contents of those standards, in particular the significant changes that have occurred in the last 20 years, will be dealt with in the following sections. A list of the applicable standards is shown below:

- NFPA 780:2017 – *Standard for the Installation of Lightning Protection Systems [14]*
- IEC 62305:2010 – Protection against Lightning (Parts 1 – 4)[31] - [34]
- API 2003:2015 – *Protection Against Ignitions Arising Out of Static, Lightning and Stray Currents.*
- NFPA 77:2014 – *Recommended Practice on Static Electricity[35]*
- API 545:2009 – *Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids [36]*
- ANSI/CAN/UL 96:2016 – *Lightning Protection Components*[37]

NFPA 780 states as its purpose "to provide for the safeguarding of persons and property from hazards arising from exposure to lightning".[14] This is similar to the language used in IEC 62305 which states "Lightning flashes to, or nearby, structures are hazardous to people, to the structures themselves, their contents and the installations as well as [electric] lines…the application of lightning protection measures is essential."

The approach taken in this treatise is to address the various sections of a Lightning Protection System (LPS) design and installation with references to the appropriate articles of various standards. This is, by necessity, a very brief synopsis of the various design requirements and sections of the standards that apply, with emphasis on those areas which have been significantly updated.

In addition, an analysis of the detrimental results that occur from not following standards design requirements will be offered.

NFPA 780 governs design and installation in North America, while IEC 62305 controls design and installations elsewhere. National differences in IEC 62305 will not be addressed here. The other standards addressed above provide background information and specific requirements, but generally refer to NFPA 780 or IEC 62305 for final implementation. The general process for design of an LPS can be seen in flowchart form in Figure E.1 of IEC 62305-3.[33]

II. SITE LAYOUT

As with any good design, the work put into the beginning of the project sets the stage for a good, finished project. If possible, lightning protection design should be performed prior to construction of the facility. There are a considerable number of underground lines and connections that are required for a proper design and installation of an LPS, and it is much easier and more efficient to get these components in place before tanks, lines, vessels and other equipment are set. This is especially true of the grounding system.

Article 7.3.7.1 of NFPA 780 requires a “ground ring” to be provided for any structures that can contain flammable vapors. This ring should conform to the requirements of Article 4.13.2 or 4.13.7 of 780. This is a notable change in the requirements and clarifies the necessity for additional grounding for petrochemical facilities. Oftentimes this will require soil studies, including water and alkalinity content, to be described in more detail below. If no other installation work can be done prior to construction of the facility, design and installation of the ground ring only requires the overall size of the facility, tank or vessel to be protected. If necessary, other connections can be made as the design is finalized.

Realize that the design criteria and decisions to be made are iterative in nature. As one design decision is made, the impact of that decision on the risk analysis, and other areas of required design *must* be evaluated.

A. Risk Analysis – Striking Distance Selection

The first step in deciding on the design parameters of the system is the performance of a risk analysis that takes into consideration the type of the structure being protected and the product(s) it contains. NFPA 780 Annex L contains an updated risk analysis methodology. This analysis is largely based on the requirements contained in IEC 62305-1. The purpose of the risk analysis is not to determine whether or not lightning protection should be provided (structures handling flammable liquids or vapors should always be protected), it is to determine the level of protection that is required in order to reduce the risk of damage to an acceptable level. As such, the detailed analysis methodology contained in 780 L.6 or IEC 62305 is recommended.

One of the more significant outputs of the risk analysis is the determination of the striking distance for the design. The striking distance is defined in NFPA 780 as “The distance over which the final breakdown of the initial lightning stroke…occurs” (Art. 3.3.40). It corresponds to the radius of the rolling sphere used for placement of air terminals, as discussed below. A smaller striking distance requires more tightly spaced air terminals and resulting increased protection.

NFPA 780 7.3.2 requires a striking distance of 30m (100ft) or less. IEC 62305-1 gives detailed lightning data and risk factors for Lightning Protective Levels (LPL) with striking distances between 20m (65 ft) and 60m (200ft). For petrochemical facilities, a striking distance of 20m or 30m is required by IEC 62305-1.

B. Soil Study

The next step is evaluation of the soil conditions. The type of soil dictates the extent of grounding that is required. The resistivity of the soil, both surface and subsurface, dictate the type, arrangement and number of grounding electrodes necessary (in addition to the ground ring). NFPA 780 4.13.8 dictates various steps which should be followed in dealing with sandy, gravelly, shallow or rocky soil conditions. IEC 62305-3 Article 5.4 details steps for various soil resistivity conditions. In worst cases, concrete encased electrodes become necessary to enhance contact with earth. Concrete encased electrodes are suitable for any location.

C. Hazardous Area Classification

To ensure proper design, it is necessary to perform a hazardous area classification for the facility receiving protection. NFPA 780 Art. 7.2.1, 7.3.4, and 7.3.6 require various components of the LPS to be either outside the hazardous areas or for calculations to be made to ensure that the temperature rise of the components cannot cause ignition of the hazardous atmosphere. IEC 62305-3 Annex D (normative) contains additional requirements for operating in a combustible atmosphere, including the requirements that all parts of an external LPS must be at least 1m away from a hazardous area. In order to comply with either set of requirements a classification must be completed either in compliance with NFPA 70 Chapter 5 (API 500 or API 497) or IEC 60079-10-1. Fig. 1 shows one example of a hazardous area classification around a tank vent.

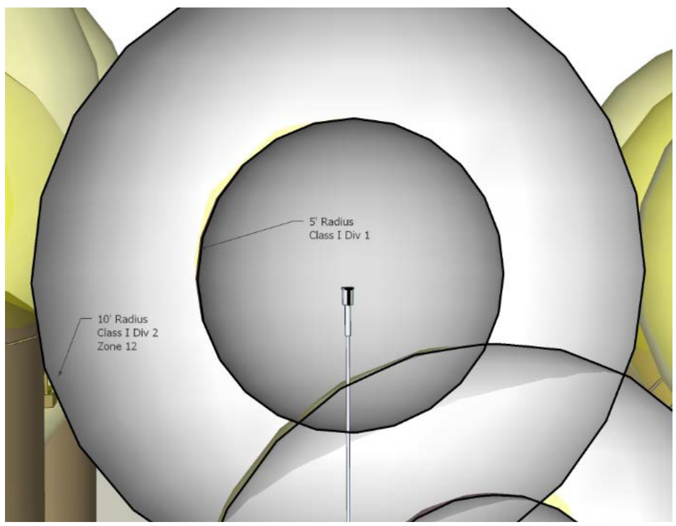

Fig. 1 - Hazardous Area around Tank Vent

D. External Lightning Protection System Selection

Early in the design process, a decision must be made whether the LPS will be an external LPS, with designed air terminals, or will rely on the natural components of the facility to be protected. Vessels that are electrically continuous, tightly sealed to prevent flammable gasses from escaping, and have a thickness in excess of 5 mm (3/16”) steel or 7mm aluminum (IEC only) can be considered to be “self-protecting” in that it is unlikely that a lighting stroke attachment will penetrate the vessel (assuming proper grounding) (780 Art 7.2.2, 7.4.2; IEC 62305-3 D.5.5.2). In practice, very few atmospheric tanks or vessels, with the exceptions of those containing sealed venting systems, can be considered to be inherently self-protecting.

Even for these natural component systems, proper grounding is required, and an external LPS may be desired based on the particular risk to the facility. Practically all other petrochemical systems require an external LPS.

The next decision is whether the external LP system will be isolated from the protected vessels or connected to them. The key requirements for this decision are the positioning of the various components relative to the hazardous area classifications and the ability of the heat from the conductors to cause ignition of escaping gases or combustible materials on the structure (780 Art 7.2, 7.3; IEC 62305-3 Art 5.3).

For single structure systems, such as a large tank, stand-alone vessel, or remote monitoring facility, design of a connected external LPS may be reasonable. The external LPS still must meet all of the requirements of positioning of air terminals and avoidance of hazardous atmospheres. The simple connected LPS would be a "traditional" Franklin rod and downcomer system, with rods spaced based on the striking distance selected. For locations such as production tank batteries, gas processing facilities, or refinery units with multiple interconnected vessels, an isolated external LPS system is recommended. Isolated LPS systems are usually mast designs and/or catenary wire systems.

E. Sideflash and Bonding Distance Calculations

The sideflash distance has a significant impact on the location of downcomers for an isolated LPS. These calculations are in NFPA 780 Art 4.6.5 and in IEC 6203-3 5 Art 6.3. The longer the connection between the point of attachment and the grounding location, the more separation that must be maintained between the downcomers and the protected structure. This greatly affects the position of masts or overhead wire supporting towers. It also can affect the number of overhead attachment wires required and the location of those wires.

Similar to the sideflash distance, the bonding distance also can be calculated very early in the design process and will dictate the number of downcomers in the system. Grounded metal bodies within the bonding distance of the LPS downcomer must be bonded to the LPS. NFPA 780 Art 4.16.2.5 and 4.16.2.6 contain the formulas for these calculations.

III. GROUNDING SYSTEM DESIGN

The grounding system design is one of the more crucial and commonly overlooked elements of the LPS design. Historically, grounding of LPS has, largely, been limited to the de-minimis provisions contained in Chapter 4 of NFPA 780 and Article 5.4.2.1 of IEC 62305-3. This was understood, erroneously in most cases, to require only a single ground rod. A second ground rod was sometimes added for large locations, or where "supplemental" grounding was needed.

However, with the publication of the 2017 version of 780, grounding requirements for petrochemical facilities have undergone a significant improvement. Article 7.3.7.1 now requires a ground ring electrode (or ground loop conductor supplemented by grounding electrodes) for any structure "containing flammable vapors, flammable gases, or liquids that can give off flammable vapors." This requirement is for essentially all petrochemical related structures, with the possible exception of office buildings.

Fig. 2 shows an example of a ground ring surrounding a vessel containing flammable liquids, along with some related connections.

The ground ring electrode requirements are contained in Article 4.13.4 of NFPA 780 and include the following:

- Ground ring fully encircles the structure
- Ground ring in direct contact with earth (or encased in a concrete footing)
- At least 0.5m (18") deep
- Main size lightning conductor *or* grounding conductor the same size or larger
- Can include additional grounding electrodes (plates, rods, etc.)
- Materials for ground rings are limited to copper (tin plated) due to deterioration of aluminum in soil.

In IEC 62305-3, a ground ring is classified as a Type B arrangement and is described in Article 5.4.2.2. Article D.3.3 states that type B arrangement is preferred for all lightning structures that can contain a combustible atmosphere. Art. 5.4.3 states structures with "high risk of fire" use Type B earthing arrangement.

IEC Type B earthing systems require the following:

- Ring conductor external to structure (or foundation electrode) forming a closed loop
- In contact with the soil for at least 80% of length
- At least 0.5m deep
- Mean radius determined by protection class and soil resistivity (Figure 3 of IEC 62305-3)
- Additional electrodes (as necessary) at points where downcomers connect
- Materials allowed include copper and various forms of steel. However, as discussed in previous works, steel materials (with the possible exception of copper clad steel) are discouraged for use in grounding systems. [38]
- Earth resistance (low frequency) 10Ω or less

In addition to the basic requirements of ground rings described above, several other factors impact the design of the grounding system including:

- Topsoil < 18" (780 Art 4.13.8.1)
- Sandy soil conditions (780 Art 4.13.8.2)
- Zero property line conditions (780 Art 4.13.8.3)
- Soil resistivity (62305-3 Figure 3)

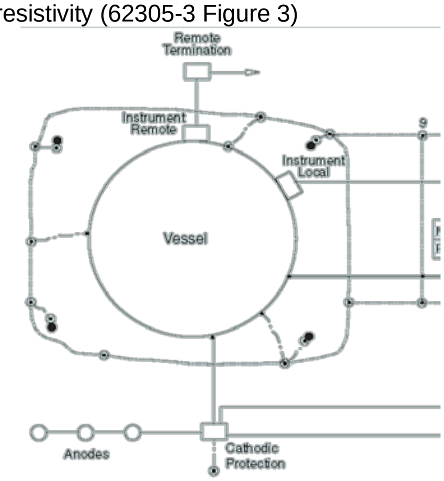

Fig. 2 – Ground Ring

Each of the above conditions require additional length of grounding conductor through the use of a larger ring, rods, plates or radials.

The addition of an additional electrode (rod, plate or radial) at each location a downcomer connects to the ground ring is highly recommended. This allows for further localized dissipation of any lightning energy conducted to these points.

During construction, and prior to final bonding, the earth contact resistance (low frequency) should be measured and recorded. Ten Ohms or less is required by IEC 62305 and recommended for NFPA 780 compliant systems. The expected earth contact resistance should be calculated and compared to the measured value. Resistance values higher than expected should be remedied by the installation of additional ground electrodes.

In some configurations, a single ground ring encircling all structures on a location is impractical. In such configurations, multiple ground rings can be used to encircle different structures. Underground, main size conductors should then be used to provide bonding interconnections between the ground rings.

Grounding of metal tanks is always an item for discussion when designing and installing an effective LPS. Part of the consternation is that different standards have vastly different views on the necessity of grounding metal tanks.

API 545 Annex A (informative) makes the statement that flat bottom [steel] tanks resting on the “ground” need not have additional grounding for the purpose of lightning protection. This applies whether or not a protective membrane exists beneath the tank. It should be pointed out that this discussion is only informative and is not part of the standard. It is also important to note that this discussion only applies to API 650 welded steel tanks.

API 2003 makes a similar statement in Art 5.4.1. According to this document, metallic tanks and equipment that are in direct contact with the ground are sufficiently well grounded. An exception is made in this document for tanks that are above non-conducting membranes (such as those used for release prevention). Metallic tanks that are insulated from ground require additional grounding connections. Significantly, direct reference is made to NFPA 780 in the text of Art 5.4.1 for “more information on grounding practice for lightning protection”.

IEC requirements are somewhat more stringent. Tanks in tank farms require earthing (earthing = grounding) at one point and bonding of the tanks with each other. Isolated tanks must be earthed as discussed above and require one earthing connection for tanks up to 20m (65 ft) in diameter (or length), and two earthing connections for tanks larger than 20m. Note that a ground ring is still the preferred arrangement of ground conductors for tanks that may contain flammable fluids(62305-3 D.5.5.2).

NFPA 780 has the most comprehensive requirements for grounding of metal tanks. In addition to the ground ring requirements discussed above, a metal tank must be grounded as follows: (780 Art 7.3.7)

- By connection to a grounded metallic piping system with no insulated joints.
- By a minimum of two connections to the ground ring at a maximum of 100ft separation around the perimeter of the tank.
- A tank resting directly on earth 6m (20ft) in diameter is self-grounding.
- A tank resting directly on bituminous pavement 15m (50ft) in diameter is self-grounding.
- If an insulating membrane (environmental) exists, then there is no self-grounding.

IV. AIR TERMINALS PLACEMENT

A. Air Terminal Selection

Air terminals are often referred to as strike termination devices (STDs). The function of STDs, according to NFPA 780 and IEC 62305, is to safely attach, intercept and conduct safety the current in the design lightning strike. IEC 62305-1 provides the parameters for the Class of LPS designed to, including the minimum and maximum strike size (current). Part III of this primer will address the efficacy and scientific reliability of non-conventional protection systems. The discussion below applies to those systems covered by NFPA 780 and IEC 62305, which are those air terminals specifically intended to intercept, attach to and dissipate the strike energy.

B. Air Terminal Placement

The selection of the type of air terminal approach is the most visible part of the lightning protection system. Once the approach has been determined, the location of the air terminals must be mathematically or geometrically calculated.

Regardless of the design approach taken, placement of the air terminals for petrochemical facilities requires the Electro Geometric Model (EGM) or Rolling Sphere Method for those installations governed by NFPA 780. This requirement is contained in 780 Art 7.3.2 (discussing striking distance of 30m). In a notable change to NFPA 780, the discussion of mast and catenary systems and the rolling sphere method, has been moved to Chapter 4 (Art. 4.8.3), making it clear that these methods of protection are applicable to all structures, not just those containing flammable vapors. Historical methods, such as the angle method, are restricted to multiple level roof structures and are not applicable to petrochemical equipment.

For structures conforming to IEC 62305, the protection angle method is “suitable for simple shaped buildings”, the mesh method is suitable where “plane surfaces [roofs] are to be protected” and the rolling sphere method (EGM) is suitable in all cases. For all petrochemical facilities, the rolling sphere method is preferred by IEC 62305. EGM is the safest known method for determining air terminal placement.

The rolling sphere method of air terminal placement is described in IEC 62305-3 Art A.2 and NFPA 780 Art 4.8.3. In simplest form, the rolling sphere zone of protection includes the space “not intruded by a rolling sphere” (780 Art 4.8.3.1) with a striking distance determined as set out above. NFPA 780 Art 4.8.3.3 provides a calculation for the horizontal protected distance for an air terminal as described in (1).

$$d = \sqrt{\mathrm{h_a}(2R - h_a)} - \sqrt{\mathrm{h_s}(2R - h_b)} \quad (1)$$

where

d = horizontal protected distance

h_a = height of the air terminal

R = rolling sphere striking distance radius

h_b = height of the lower roof (top of the object)

$$P = h_1 + \left\{ \left(\cos \left[90^0 - sin^{-1} \left(\sqrt{R^2 - \left(\sqrt{D^2 + (h_2 - h_1)^2} / 2 \right)^2} \Big/ R \right) - tan^{-1} \left((h_2 - h_1) / D \right) \right] \right) * R \right\} - R \qquad (2)$$

Where

- P = Lowest point of rolling sphere (above ground)
- h_1 = Height of air terminal 1
- h_2 = Height of air terminal 2
- D = Horizontal distance between air terminals
- R = striking distance (radius of rolling sphere)

Equation (1) is useful for the "outside" edges of air terminals, where the rolling sphere would be touching an air terminal and the ground. For spaces between air terminals, the lowest point that the rolling sphere would intrude below the top of the air terminals is necessary for determining the separation

This can be used for the area between masts, catenary wires, or traditional air terminals. Note that the low point of the rolling sphere should be above both the structure to be protected, and also above and outside any hazardous areas identified.

The calculation is extremely useful since the equation can be programmed in a calculator for quick checks, where the rolling sphere requires a computer model.

Fig. 3 displays graphically the locations and distances used in (1) and (2).

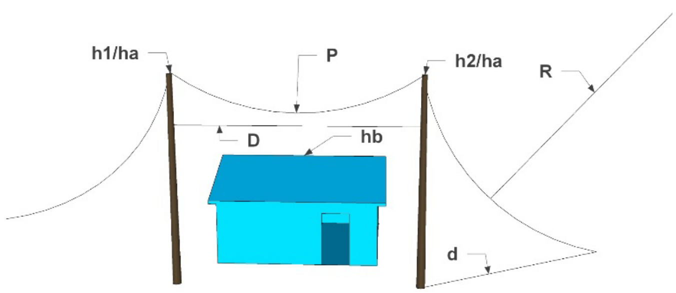

Fig. 3 - Rolling Sphere Protected Distances

In addition to those identified above, Franklin rods should be attached at the top of masts, and the top of poles supporting overhead shield wires. This ensures that any lightning attachment occurs at a piece of the LPS, rather than some other unprotected component.

V. CONDUCTORS

A. General Requirements

Lightning rated conductors are required to interconnect the various components of the lightning protection system because of the extreme currents and heat encountered. In effect, lightning conductors are used to connect all air terminals to each other and to the grounding system. The primary requirement is that each air terminal be connected to the earthing system via at least two paths (780 Art. 4.9, 62305-3 5.3.1). The length of the conductors should be kept to a minimum to minimize interconnection impedance.

of air terminals of a specific height, or for determining the height of air terminals necessary for protection of structures.

The calculation required is not contained in the standards, nor has it been identified in any previous publications. The low point of the rolling sphere between two air terminals can be calculated using (2).

Down conductors are defined as those conductors connecting from the LPS components to the earthing system.

Sizes of main lightning conductors are determined by the materials used and the anticipated strike size (LPL class). Table 4.1.1.1.1 of NFPA 780 shows the minimum size of 29 mm^2 (#2 AWG) for Cu conductors and 50mm^2 (1/0 AWG) for Al conductors. IEC requirements are 50mm^2 (1/0 AWG) for both Cu and Al stranded conductors (62305-3 Table 6). Various other sizes specified in both documents consider solid conductors or solid tape (strap).

The routing of lightning conductors is to be downward. A rise of no more than ¼ slope is allowed when conductors need to go up and over an object. (780 Art. 4.9). "U" or "V" pockets, as shown in Fig. 4, must be avoided. If such pockets are unavoidable, a main size down conductor must be provided at the base of the pocket (L3) (780 Art. 4.9.4). Bends of conductors must have a radius of bend 8 inches or greater and must be no tighter than 90º (780 Art. 4.9.5).

The intent of avoiding U or V pockets is two-fold. The first is that any compound bends create a location where magnetic fields can interact and the effective impedance of the connection increases as a result. The second is that U pockets create a potential for flashover between the two sides of the pocket.

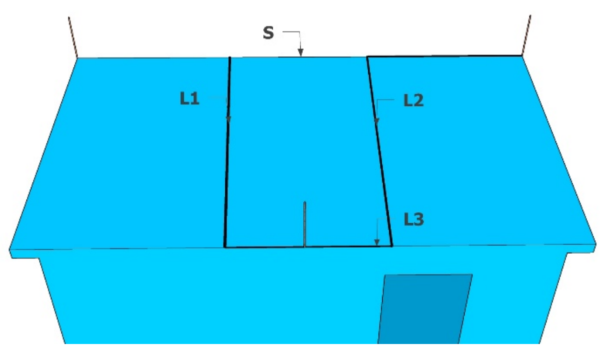

Fig. 4 - U Pocket

IEC 62305-3 Art. 5.3.4 specifies that when U or V pockets (loops) cannot be avoided, the distance between the two sides of the loop (S) exceed the flashover distance described in Art. 6.3, where the length of the conductor is L_1+L_2+L_3. This directly addresses the flashover risk from U pockets and limits the impedance risk by separating the conductors, so the increased impedance is relatively minimal.

For non-isolated systems, cross-run conductors are required to interconnect main lightning conductors at 15m (50ft) intervals, or closer depending on the Class of LPS.(780 Art. 4.9.7.2, 62305-3 Art 5.3.3)

B. Down-conductors

Down-conductors are those portions of the lightning protection system which connect the air terminals to the earthing system. These are main size lightning conductors. At a bare minimum, even for the simplest structures (such as a small vessel), a minimum of two down-conductors are required (780 Art. 4.9.10, 62305-3 Art. 5.3.1 (a)). The purpose of this is to reduce, to the extent possible, the impedance between the strike termination devices (STDs) and the ground system.

The total number of down-conductors, however, depends on the size and configuration of the structure. Larger structures (in excess of 76m (250ft) in perimeter) require a down-conductor for each 100 ft. of perimeter (780 Art. 4.9.10.1). Take note that for multiple interconnected “vessels”, such as at a tank battery or plant, the perimeter of the structure is the outside dimensions of the whole interconnected battery or unit. These facilities would be irregularly shaped structures which require additional down-conductors necessary to provide a two-way path from each STD (780 Art. 4.9.10.3).

For IEC systems, the distance between down-conductors, for a non-isolated LPS, is dependent on the class of LPS being designed. These classes are defined in IEC 62305 and are determined by the size of the lightning strike protected against. Distances range from 10m (33ft) for Class I and II to 20m (65 ft) for Class IV systems.

Overall, the length of the down-conductors, from the STD all the way to the grounding connection, should be kept to a minimum (62305-3 Art. 5.3.1.b). IEC 62305-30 states, in a note to Art. 5.3.1, that use of additional down-conductors, interconnected with loop systems, reduces the chance of sparking and ignition. Down-conductors all terminate at the ground ring (preferably at a point where additional grounding electrodes are located) and are connected to the ground ring by permanent means, such as welding (780 Art. 4.13.1.1).

Particular cases arise when masts are used as strike termination devices. Each mast requires at least one down-conductor. A metallic mast itself can be used as the down-conductor, if it is electrically continuous and has a wall thickness of at least 1.63mm (0.064”) (780 Art. 4.6.3.4). IEC 62305-30 requires the resistance measured from any part of the mast to the earthing system be less than 0.2Ω. (Art. D6.5). For overhead wire (catenary) type air terminals, there needs to be at least one down-conductor for each supporting structure (62305-3 Art. 5.3.2).

When down-conductors are coursed along structural steel or reinforced concrete columns, a portion of the lightning current will flow through the structural components. To control the potential for spark (and ignition) from a difference in potential, the down-conductor must be bonded to the column at both the upper and lower extremities. (780 Art 4.9.13). For tall columns, additional connections must be made every 60m (200ft).

For locations with hazardous environments, downcomers should be outside the calculated hazardous location (780 Art 7.3.4.3, 6230-3 Art. D.5.1). If down-conductors must pass through the hazardous area, the conductor must be continuous and steps must be taken to ensure that the autoignition temperature of the hazardous environment is not exceeded (780 Art. 7.3.4.2, 62305-3 D5.1). This calculation involves the current of the anticipated strike, the duration of the event, the impedance of the conductor and the path to ground.

IEC 62305-3 addresses the protection of personnel from hazards at or near the down-conductors. Not only do the down-conductors create a touch hazard, but the energy being dissipated into the soil can create a step potential hazard. The protections employed generally include: (1) keeping personnel more than 3m (10ft) away from the down-conductors through the use of barriers or warning notices, (2) the use of a meshed (grid) earth termination system, or (3) with a system that has 10 or more down-conductors (62305-3 Art 8.2).

VI. BONDING

Bonding is the electrical connection of conductive components of the structure to each other and the ground systems. Bonding is not connecting parts of the LPS together, but rather for those conductive portions that are not part of the LPS. The size of the bonding conductors is determined by the type of material used. For NFPA 780 compliant systems. Copper bonding conductors must be 13.3mm^2 (#6 AWG) or larger, while aluminum conductors must be 20.8 mm^2 (#4 AWG) or larger. Bonding straps must be at least 12.7mm (0.5”) wide with thickness of 1.30mm (0.051”) for copper or 1.63mm (0.064”) for aluminum (780 Art 4.1.1.1.1).

IEC compliant systems require Copper conductors have a cross section of 16mm^2 (#4 AWG) while aluminum conductors need a cross section of 25mm^2 (#2 AWG). While allowed in IEC 62305, steel conductors are not recommended (62305-3 Art. 6.2.2).

Bonding must be provided between all grounded metal objects and earth. These components can, and will, carry portions of the lightning current. A list of the grounded metallic objects includes at least the following: (780 Art. 4.14, 62305-3 art. 6.2)

- Electric service grounding electrode
- Communication grounding electrode
- Antenna system grounding electrode
- Water piping
- Gas piping
- Underground conduits
- Lightning protection grounding
- Tank rings
- Concrete reinforcing bars
- Metal framework of a structure

The basic bonding requirements stated above must be exceeded to ensure that there are no discharges, melting or spraying effects in any location (780 Art 7.3.5, 62305-3 Art. D.5.1.2). In practice, this means that all metal components that could possibly be in a hazardous environment are bonded together and to the earthing system. As an example, see Fig. 5.

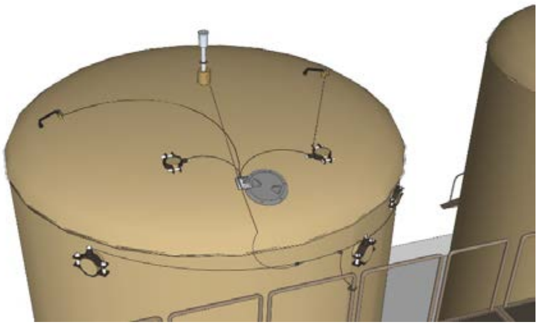

Fig. 5 - Tank Vessel Bonding Design

Fig. 6 - Tank Vessel Bonding Install

Above ground piping systems shall be connected every 30m to the earthing system (62305-3 D.5.5.3). For tank farms or batteries with multiple storage tanks, the tanks shall be connected to each other. This bonding should be at grade level, but in no cases more than 12' above grade (62305-3 Art D.5.5.2, 780 Art 4.14.1). This is represented in Fig. 7.

The requirements for bonding of floating roof tanks is contained in Art 7.4.3 of NFPA 780 and D.5.5.2 or IEC 62305-3. Additional information can be obtained from Art 4.2 of API 545 and Art. 5.4.2.2 of API 2003.

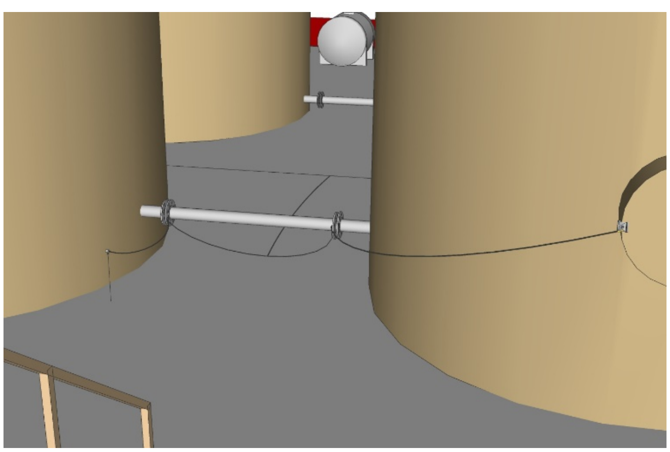

Fig. 7 - Tanks Bonded Together Design

Fig. 8 - Tanks Bonded Together Design

VII. SURGE PROTECTIVE DEVICES

The use of surge protective devices (SPDs) on incoming power and telecommunications lines is a vital part of a stable, effective lightning protection system. For 780 compliant systems, SPDs are required for all incoming power and communications systems. Additionally, SPDs at any point that an electrical or electronic conductor leaves a structure and travels to another structure more than 30m (100ft) away must be used (780 Art 4.20.2.1,4.20.2.2, 4.20.2.3). NFPA 780 does allow elimination of SPDs under engineering supervision if the surge calculation reveals negligible energy on the protected equipment, or if the addition of SPDs would compromise safety (780 Art 4.20.2.5). Such a decision should be recorded in writing after a full and complete analysis is completed.

Characteristics of the SPDs required are delineated in NFPA 780. Power SPDs must protect against a 1.2/50μS and 8/20μS waveforms, with a nominal discharge current of at least 20kA (8/20μS) per phase. Communication line SPDs require listing for comm. systems and require a 10kA (8/20μS) per line dissipation. The maximum allowable voltage rating of the SPDs (per mode) is delineated in NFPA 780 Table 4.20.4 and ranges from 700 Volts for 120V Single Wire systems to 1800 Volts for 480V Delta 3 Wire systems (780 Art. 4.20.3). The minimum continuous operating voltage of the SPD must exceed the upper tolerance of the utility power system (780 Art 4.20.5.2).

IEC compliant systems have simpler requirements. SPDs must be installed on each line coming into the structure. SPDs must comply with IEC 61643-1 and IEC 61643-21. They must be sized so the current dissipation exceeds the calculated lightning current that can flow on the conductor. Additionally, the maximum voltage protection level must not exceed the withstand level of insulation between the parts. (62350-3 Art 6.2.5) All SPDs should be positioned outside any hazardous areas, if not approved for use in a hazardous environment (62305-3 Art D5.1.1).

Connection of the SPDs is delineated in NFPA 780. Art 4.20.5. TABLE 1 summarizes the power connections.

For communication lines, (1) all SPDs shall be grounded (not using a lightning down-conductor), (2) must provide common mode protection, and (3) shall take into account performance of the communication system. Additionally, a supplemental ground reference point must be installed if the system ground is more than 6m (20ft) away. (780 Art 4.20.6)

TABLE 1
SPD Connections

Location	Connection
Grounded Power Service entrance	L-G or L-N *
Power service entrance with no neutral	L-G *

*(additional L-L and N-G connections are allowed)

All SPDs must be installed per NFPA 70 (NEC) and must be accessible for inspection and should be regularly inspected.

Surge protection of systems internal to the structure requires a coordinated SPD system using a protection zone concept with multiple internal lightning protection zones (LPZ). The factors for such design are in IEC 62305-4. This process is complex and is part of, yet separate from, the structural lightning protection described in other parts of this paper.

VIII. INSTALLATION REQUIREMENTS

Once the design is completed, the installation begins. The installer must communicate with the designer during the installation process to ensure that the design parameters are met, and that any questions regarding details of the design can be addressed. NFPA 780 requires that the installation of LPS be completed in a neat and workmanlike manner and that the individual(s) responsible for the installation be certified for fitness on the requirements of NFPA 780. Additionally, third party certification may be required (780 Art. 1.5).

IEC 62305-3 recommends the following for design and installation (E.4.1):

- Installation should be performed by LPS installers.
- Installer should receive training in proper installation in compliance with the standard.
- Installer should be capable of assessing the effects of the lightning discharge and be familiar with protection techniques.

In addition to these requirements, it is recommended that the LPS designer have an active role in evaluating the quality of the installation per the design. Comparison between design documents, such as those seen in Fig. 5 and Fig. 7 and installation photographs or inspection, such as those shown in Fig. 6 and Fig. 8 can help the LPS designer ensure that the installation was completed consistently with the design documents. Further, it helps the LPS designer ensure that the installation documents

IX. MAINTENANCE AND INSPECTION

Both NFPA 780 and IEC 62305 contain informative annexes regarding recommended maintenance, testing and inspection of lightning protection system components (780 Annex D, 62305-3 Annex E). In addition, NFPA 780 Art 1.6 requires that maintenance recommendations shall be provided to the owner at the completion of installation, and that periodic inspection be completed by the owner. In daily operation, portions of the LPS are often disconnected, moved, repositioned or removed. A robust inspection and maintenance system must be in place to prevent this from occurring, or to identify these improper events at the earliest possible time.

Without maintenance and inspection of the lightning protection system, the long-term effectiveness of the system is only a guess. A good maintenance and inspection protocol includes, at a minimum, the following. (Additional means and methods are addressed in the standards.)

- Inspect at least annually, staggered to perform inspections in all seasons.
- Inspect for good mechanical condition of the LPS components, including tightening of connectors.
- Test continuity of conductors.
- Inspect and test SPDs.
- Inspect and measure of the ground system
- Refasten loosened connectors or bonding.
- Evaluate the system to determine whether changes have occurred which require additional LPS additions or modifications.

Each owner of a protected structure should work with the LPS designer to create a comprehensive, site specific, inspection and maintenance program based on the actual conditions at the site. Good record keeping of inspection intervals, measurements, testing results and maintenance actions taken is important for long-term evaluation of the system, as well as when a strike occurs.

X. CONSEQUENCES OF NOT FOLLOWING STANDARDS

As discussed in the introduction, the purpose of the standards is to prevent lightning damage to people and structures. It follows, then, that the consequences of not following the standards is damage to personnel or to facilities. After evaluating hundreds of incidents where appropriate standards were not followed in the design, installation, maintenance or inspection of lightning protection facilities, a list of the most common errors made, as well as the consequences of those errors has been compiled. The following paragraphs summarize these findings

A. Improper Grounding

By far ,the most common error made in the design and installation of LP systems is improper grounding. In the design phase, the soil conditions are often ignored, or limiting assumptions made. In the installation phase, rods are not driven to full depth (often because of rock formations), and adjustments, such as laying rods horizontally, are not made. Further, during install, design characteristics such as a ground ring, which is required per NFPA 780, are ignored because of the difficulty of installation, particularly in a brownfield installation with underground piping.

The consequence of improper grounding is that lightning energy, which has been intercepted by the air terminals, cannot be effectively dissipated in earth. This results in the energy from the lightning stroke elevating the voltage of the LP system, often causing ignition or melting of components.

B. Tight Turns on Downcomers

The second common error identified is the bending of downcomers in sharp, 90° bends of much less than 8” radius, and the installation of U-pockets or V-pockets in the downcomer. This is often the result of non-lightning certified electricians wanting to make the installation look "neat" and orderly, as you would power cable installations.

The consequence of such an installation is a significant increase in the impedance of the downcomers at lightning frequencies. Recall that the rise time of lightning is in μS, and the fundamental frequency of lightning is in the order of MHz. Thus, a slight increase in inductance due to sharp bends can create a significantly large increase in impedance. As a result, lightning energy causes portions of the LPS system to have an elevated voltage relative to the protected structure, and to other parts of the LPS on the other side of the tight bend. Elevated voltage can lead to arc-over, resulting in ignition or other damage to equipment.

C. Improper Air Terminal Placement

Oftentimes, LPS designers or installers make the mistake of relying on old, outdated air terminal placement guidelines such as the "angle method" rather than the EGM required by all standards for petrochemical installations. This leaves portions of the protected structure exposed to lightning attachment, and the resulting damage to facilities and personnel.

D. Use of "alternative" LPS designs

The standards all adhere to the concept of intercept lightning energy (air terminal), conduct the energy (downcomers) and dissipate the energy (ground system). Other alternative methods attempt to take a different approach, such as dissipation of lightning energy, delaying the stroke or creating "early" streamers. These alternative systems invariably rely on a proprietary air terminal design, and often purport benefits which reduce the number of air terminals installed.

None of these alternative approaches are approved methods of lightning protection according to the standards. The result of using these type systems is exposing portions, if not all, of the facility to lightning attachment. Part 3 of this primer will address alternative protection schemes.

XI. FUTURE WORK – OTHER PARTS OF PRIMER

This Part II of the LPS Primer, addresses conventional lightning protection standard requirements and recommendations. In Part III we will explore non-conventional lightning protection systems claims, science and challenges.

As a reference, Annex A contains a 3-dimensional representation of a properly designed catenary wire based lightning protection system for a petrochemical storage and processing facility.

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XIII. VITAE

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Tommy W. Gillaspie, J.D. After playing football at Harvard and graduating *cum laude*, Tommy started his law career 36 years ago defending health care providers with Vinson & Elkins in Houston, TX. He then formed the Gillasplie Law Firm which specialized in all forms of personal injury and construction defect litigation.

The decades of honed skills are now brought to bear on behalf of the numerous subrogation claims handled by Donato Brown Pool and Molemonn, P.C. A skilled litigator, Tommy heads up trial teams bringing cases in New Mexico, Colorado and across Texas involving all matter of complex technical litigation. Over the past several years, Tommy has worked on numerous lightning protection cases across the nation, developing a first-hand knowledge of the interplay between science, law, and the ever-evolving standards that rule the world of lightning protection systems.

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ANNEX B

EXAMPLE LIGHTNING PROTECTION SYSTEM FOR TANK BATTERY