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Lightning Related Ignition Mechanism and Associated Protection Techniques for Storage Applications

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Abstract

Lightning can pose a myriad of threats to operations involving flammable vapors and liquids that give off flammable vapors. This paper focuses primarily on storage facilities and associated operations but the principles can be applied to any operation or installation where a flammable environment may exist. General principles of protection from a lightning threat are provided, along with a discussion of specific threats presented by operations in which flammable vapors may be present. The evolution of protection considerations is also discussed. Techniques for protection from direct attachment are provided to address those situations where an external flammable vapor could exist in the vicinity of a storage vessel. Threats produced by nearby lightning and strikes to associated piping and electrical conduits are also addressed. The elimination of both external and internal potential differences that could lead to dangerous arcing is discussed. This paper also provides a discussion of the difference in grounding system impedance versus static grounding techniques as they relate to the dissipation of lightning currents and explains their significance in minimizing the probability of arcing between structural components and systems. The principles discussed are summarized in the context of the development of a lightning protection plan.

1. Introduction

The hazard presented by lightning activity to operations associated with the presence of flammable vapors and liquids that give off flammable vapors is well recognized, but the specific threats associated with lightning activity and associated failure mechanisms may not be as well understood. At the request of the American Petroleum Institute (API), the National Fire Protection Association Committee on Lightning Protection (NFPA 780) has established a Task Group to review the requirements of their chapter on the protection of flammable vapors, flammable gases, or liquids that can give off flammable vapors [1]. It is important to note that these standards and other recommended practices are developed as “minimum acceptable” requirements. Ignition sensitivity of the contents and configuration of the containment structure may require additional considerations in protecting the contents from a lightning threat.

It is also noted that many incident investigations involving flammable materials which cite lightning as a cause go into little detail in explaining the specific failure mechanism. Those papers that do discuss failure mechanisms generally only speculate as to the cause of the event; which leaves little for those developing standards to determine how the event could have been prevented. This paper provides information that may be of use to investigators of lightning-related incidents in identifying possible ignition mechanisms that may be related to a specific incident. It also provides information that may be helpful in determining specific failure modes when lightning is suspected to be a contributor.

Finally, this paper identifies the basic elements of a lightning protection system for structures used to protect structures containing flammable vapors along with a description of their function in providing protection from lightning. It is intended that this may be useful to those specifying lightning protection and/or assessing the need for additional protection measures.

2. Lightning Threat Mechanisms

2.1 General

Lightning activity can create a variety of threats to operations involving flammable vapors or liquids that may give off flammable vapors. These threats can be manifested in the form of physical (mechanical) damage to structures and their appurtenances, thermal damage including the ignition of contents, and electrical damages due to overvoltages/overcurrents or electrical arcing. The net result of such threats can be loss of productivity, loss of production equipment, release of material and, in the worst-case, explosive rupture of containment vessels due to ignition of flammable vapors.

2.2 Physical (mechanical) threat

A direct strike to a storage vessel can lead to the threat of mechanical forces related to the shock wave created by the rapid expansion of air in the channel associated with the return stroke. Significant mechanical forces are also produced when a lightning impulse current is routed through sharp bends in conductors. These forces can be sufficient to separate conductors from fasteners as the electromagnetic forces straighten the bends and in some extreme cases, damage the conductor itself.

2.3 Thermal threat

The threat of thermal ignition of flammable vapors that may exist in the vicinity of a direct strike attachment point is difficult to mitigate. This is a consideration for both non-metallic and metallic roofs. The temperature in the plasma channel of a return stroke can reach 50,000° F. Ignition of a flammable atmosphere can result should the attachment point be in the vicinity of a faulty seal or gasket.

There can also be erosion of metal at the arc attachment point. Burn-through of the metal skin of a storage vessel is possible if the thickness of the shell is too thin. Such a penetration can allow leakage of material into and out of the tank if the hot spot does not ignite the internal contents. It is also important to consider that energies sufficient to burn through the metal may not be required to cause thermal ignition of the contents.

Kern [2] reported that laboratory testing has shown that temperatures at un-punctured interior surfaces opposite to the point of strike exceeded 100° C for 2 mm thick aluminum and stainless steel metal sheets when subjected to impulse currents. A temperature of 94° C was recorded for 2 mm thick soft steel from the same threat. Of greater importance is the thermal threat presented by strikes with long duration currents which Kern reported can lead to internal temperatures of more than 1000° C without burn-through for some sheets of unspecified metal thickness. Long duration current testing was also conducted on metal sheets of thicknesses specified to meet strike termination requirements. Temperatures recorded for 4 mm thick soft steel and stainless steel reached 950° C with values for 5 mm thick soft steel reaching 750° C and 570° C for stainless steel. The thermal time constant for the steels create concern because these high temperatures can remain on the interior surface for a long time.

2.4 Electrical threat

Direct or nearby lightning strikes can produce electrical overvoltages and overcurrents resulting in possible damages to electrical power distribution, instrumentation, and control circuits and associated hardware. The damages could result in electrical data upset, generate erroneous control and instrumentation signals, damage communication hardware, or cause permanent loss to electrical and electronic hardware.

Arcing due to voltage differences between metallic components has been suggested to be the most likely cause of tank fires due to lightning; especially in floating roof tanks. API/EI Research Report 545-A [3] reports that 52 of the 55 rim seal fires investigated as part of the 1997 LASTFIRE survey were caused by lightning. There are a number of scenarios which can produce a threat of electrical arcing. Some of the most common scenarios are discussed below.

A direct strike to an open-top metal floating roof tank can lead to electrical arcing across the floating roof seals regardless of whether the attachment point is to the tank shell or the floating roof itself. Static bonding cables can possibly limit the sparking but cannot prevent the arcing from such a threat [3].

When impulse currents resulting from direct or nearby lightning strikes are injected onto a grounding electrode, a substantial voltage could be developed. The magnitude of this voltage is a function of the value of peak current and the impedance to remote earth of the grounding system. As the voltage of the grounding system increases from 0 volts to hundreds of thousands or millions of volts, there is a probability of arcing between items connected to the grounding system and any ungrounded conductive items or independently grounded conductive items. This arcing can not only occur between the metal shell of a tank and isolated or insulated conductive items in or on the structure but also occur across flanges with isolating gaskets or piping which is not electrically continuous.

A charged cloud produces a vertical electric field onto the earth's surface. A resulting charge is distributed over the ground and objects on the ground. Horizontal flat surfaces will exhibit a uniform charge distribution. Structures in the vicinity of a charged cloud will concentrate the local electric field depending upon the geometry of the structure, with maximum charges appearing at the areas of maximum electric field concentration. Typical examples of locations on a storage vessel where maximum charge is likely to concentrate are the rim at the top of the vessel, handrails, lights, or other objects (such as conservation vents, etc.) on the top of the vessel. The slow movement of ground charge provides induction charging of a storage vessel. This charge generally is not significant for fixed roof metallic tanks and should not affect the charging of internal material due to the Faraday-type shield provided by the construction of the vessel. However, it can present a significant threat to a floating roof tank.

The charge that will be induced on the tank is neutralized almost instantaneously by a lightning strike that collapses the field. At that time, a heavy ground current flows to neutralize the ground charge. The voltage on the vessel shell is relaxed by the dissipation of the lightning current into the earth much faster than what is sometimes described in the petroleum industry as "bound" charge in the vapor space and along the oil surface for low conductivity liquids; creating a potential for internal arcing in the storage volume between the liquid surface or charge pockets in the vapor space and the tank shell.

3. Strike Termination

3.1 General

The component of a lightning protection system designed to intercept a downward leader and provide a path to earth of the resulting return stroke(s) is the strike termination system. Types of strike termination systems recommended for use for the protection of vessels containing liquids that may produce flammable vapors are Faraday-type and isolated strike termination systems.

3.2 Faraday-type strike termination

It is generally accepted that an electrically continuous metallic shell of a tank containing flammable vapors having a thickness equivalent to 3/16-inch (4.8 mm) steel or greater can serve as a lightning strike attachment point [4][5]. The international lightning protection standard indicates that a thickness of 5 mm steel or 7 mm aluminum requires no additional strike termination components provided that the temperature rise of the inner surface at the point of strike does not constitute a danger [6] (even though it allows for a 4 mm thickness where there is no danger of explosion).

The majority of flammables storage vessels often have protrusions that extend above the tank frame. These items would be required to be provided with strike termination devices if they fail to meet the metal thickness requirement. Typical examples are light fixtures, conservation vents, thin pipes (such as dip pipes), and thin electrical conduit. The following paragraphs offer methods for providing this supplemental protection.

3.3 Isolated strike termination

A number of technical papers that address direct strikes to structures containing flammable vapors discuss threats associated with high resistivity materials such as petroleum products, toluene, and xylene [7]-[13]. Buccella and Orlandi [12] indicates that a direct lightning strike to a grounded metal vessel filled with an insulating charged liquid (such as some hydrocarbons) can create a strong electric field in the air space above the oil and a high potential at the oil surface.

Britton has described through numerous publications [14][15][16] the process of charging of internal liquids having conductivities of 1pS/m or less and the resulting liquid surface potentials produced by the movement of such liquids. Extensive literature is available concerning the threat of electrostatic discharges associated with the charges that may exist along a liquid's surface and in charged vapors but little literature other than Buccella [13] is available to suggest the presence of internally charged vapors in metallic containers as a result of lightning activity.

Buccella [13] proposes a numerical method to compute the reduction of the voltage at the interior of a metallic tank provided by an external lightning protection system (LPS). The lightning protection system, its associated grounding system, and the shell of the metallic tank are modeled according to their equivalent circuit parameters and a SPICE analysis is conducted on the lumped circuit network to determine the electric voltage on the vessel boundary. A Finite Difference Time Domain method then uses the boundary conditions valid at the interior of the vessel defined by the computed voltage distribution from the SPICE analysis, to determine the probability of an internal voltage sufficient to initiate an internal spark of sufficient energy to ignite charged vapors that may appear in the vessel.

Buccella uses this method to provide an example of the magnitude by which the isolation of the lightning current from a tank can decrease the voltage on the internal shell of a metal tank. A 5 millimeter thick, 10 meters tall, 6.4 meter diameter steel tank filled to a height of 5 meters with a petroleum product having a conductivity of 1pS/m is considered with a 100 kA lightning impulse current having a rise time of 0.8 microseconds and time to half value of 80 microseconds (similar to those values given in IEC 62305-1 [17] as characteristic of a subsequent stroke). It is shown that a reduction of potential at the inner boundary of the container of about 90% is achieved by a LPS with 5 interconnecting conductive elements isolated from the container as little as 20 centimeters. It was also shown that increasing the spacing to 40 centimeters and/or increasing the number of parallel conductors to 10 provided little additional reduction of voltage potential on the interior of a tank.

Isolated lightning protection systems allowed by NFPA 780 [4] for the protection of structures containing flammable vapors utilize masts and/or overhead (or catenary) wires. IEC 62305-3 [6] requires that all parts of the strike termination devices and down conductors for structures containing hazardous areas shall be located a minimum of 1 m from a hazardous area, where possible.

3.4 Non-isolated or hybrid strike termination

Neither United States standards nor the international lightning protection standard specifically allow a lightning protection system with air terminals and down conductors installed directly on a structure containing flammable vapors. However, it is identified in 3.2 above that the metallic shell of a tank could serve as both the strike termination device and down conductor. Buccella [12][13] explains the significant benefit from even a minor isolation of the lightning current from the shell of a tank containing a flammable atmosphere. While the authors concur with Buccella's assessment that there is benefit to the isolation of lightning current from the shell of a flammables storage vessel that may contain charged liquids or vapors, it is unclear why a Faraday-type strike termination system is allowed and yet it may not be allowed to add an air terminal integral to the structure (properly bonded to the metal shell) to protect protrusions from the metal shell that may not meet the thickness requirements (such as lights, conservation vents, etc.). The limited use of air terminals as a supplement to a Faraday-type system to provide protection for such protrusions could be considered in future revisions of standards.

4. Grounding

The international lightning protection standard for structures with risk of explosion [6] requires that all tanks used for the storage of liquids that can produce flammable vapors or used to store flammable gases shall be grounded at a minimum of one point. It is recommended that this grounding component be a ground ring electrode external to the structure or a foundation earth electrode but allows that a steel tank bottom serve as the ring electrode as long as it maintains contact with the earth. For tanks in tank farms, the tanks shall be interconnected. This interconnection may be provided by electrically continuous piping. Isolated tanks (which are not interconnected with other tanks) require an additional grounding connection only when the diameter or maximum dimension exceeds 20 meters.

NFPA 780 [4] identifies that any of the following methods can provide a minimum acceptable grounding method for aboveground tanks:

(1) a grounded metallic piping system without insulated joints,
(2) vertical cylindrical metallic tank of at least 6 meters (20 feet) in diameter resting on earth or concrete, or at least 15 meters (50 feet) in diameter if resting on bituminous pavement,
(3) a minimum of two grounding electrodes at maximum 30 meter (100 feet) intervals along the perimeter of the tank.

For tanks installed where an insulating membrane isolates the tank from remote earth, NFPA 780 requires grounding using method (3) above. Numerous other standards and recommended practices, including API 2003 [5] and API 545 [18], accept the minimum grounding methods identified above although neither API recommended practice identifies a minimum contact dimension (diameter or contact surface area) as in NFPA 780. Unlike NFPA 780 and API 2003, API 545 does not suggest that supplemental grounding be required when there is an elastomeric liner in or under the tank bottom; even though it would be expected to have the effect of reducing the conductivity between the tank floor and the ground. The logic is that additional paths to earth will be provided by piping and cables attached to the tank.

API recommended practices suggest that tank grounding is not an important contributing factor in the prevention of arcing, rim-seal fires, or ignition of the contents in tanks. It is agreed that the grounding method used for storage tanks has little influence on the prevention of rim-seal fires or ignition of vapors in the vicinity of a direct strike but a low impedance grounding system could have a beneficial influence on the maximum level of ground potential rise and the peak voltage that will appear on the shell of the tank. Lowering the peak voltage on the shell of a tank will reduce the probability of arcing to ungrounded or remotely grounded objects as well as between the interior of the tank shell and any charged vapor-air mixtures or liquid surface potential that may exist in the interior of the storage vessel.

It is a common assumption that the low frequency value of grounding system resistance measurements is sufficient to characterize the response of the grounding system from a direct lightning strike threat. However, Figure 1 forwards a plot of resistance and impedance versus frequency derived from measurements made on a 6 meter diameter tank sitting on a concrete base which is immersed in a mixture of sand and water [19]. The blue (top) curve represents the overall impedance of the grounding system, the green (middle) curve represents the resistive component and the dotted red line represents the negative of the reactive component of the impedance (-X is used for clarity because it mirrors the impedance trace). The grounding system frequency response of this metal tank is similar in characteristics to the limited number of measurements of petroleum or chemical tanks made at locations worldwide (although the specific values change from site to site). As can be observed from the data provided in the figure, a very good grounding system value of approximately 1 ohm begins to increase in impedance at frequencies above 20 kHz due to inductive reactance and exceeds 40 ohms at the highest frequency of 1 MHz. The actual value of voltage that would appear during the onset of a lightning current pulse would be significantly greater than one would assume based on a calculation using only the low frequency value of grounding system resistance.

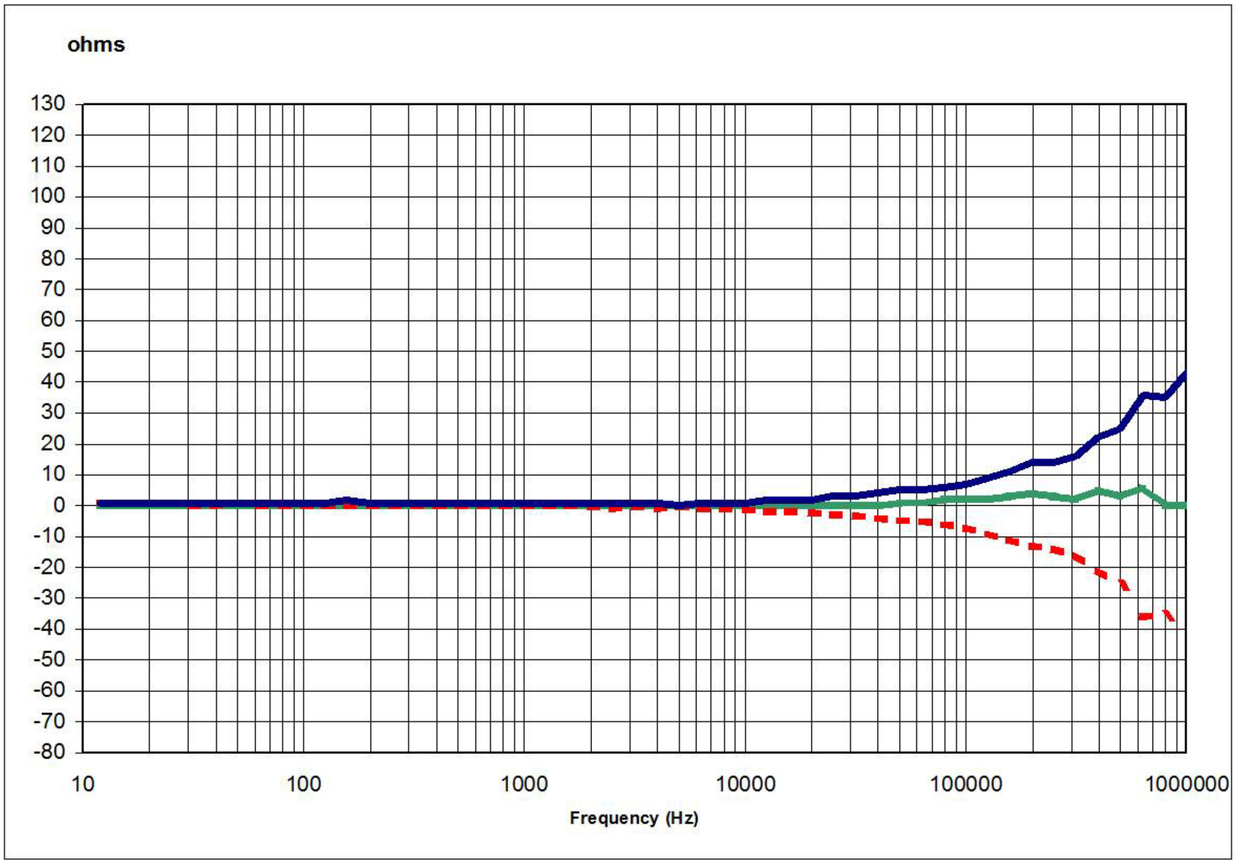

Figure 1. Impedance versus Frequency for 6 meter diameter metal tank

Grounding system impedance analysis has been reported for several applications [20][21]. However, there is not enough grounding impedance data on metallic tanks sitting on concrete pads to draw clear conclusions as to efficacy of this grounding technique. The data available does not appear to suggest that the capacitive effect noted from the impedance measurements reflects that which would be expected from analytical calculations. Additional study is recommended to determine whether this discrepancy is due to the limited amount of data currently analyzed or whether there are other factors such as interconnection of reinforcing steel in the pad, age of the concrete pad, moisture in the concrete, location of insulating membranes, or depth of concrete between the metal tank bottom and reinforcing steel in the concrete pad.

Much literature is available discussing the reduction of the overall resistance of a grounding system due to the ionization of the local earth in the proximity of grounding electrodes conducting significant impulse currents into the earth. The absolute value of the effect of such ionization varies so much by the specifics of each installation that the authors suggest the phenomena be acknowledged but not considered in the design or analysis of the response of the lightning protection grounding system.

5. Potential Equalization

5.1 General

It is generally agreed that the most common cause of ignition of flammable atmospheres in and around structures housing materials that may produce flammable vapors is electrical arcing due to voltage differences between conductive objects. The primary method to reduce such electrical arcing is to equalize the potential between the grounding system for such structures and any ungrounded or independently (remotely) grounded metal objects that may be installed in or on the structure.

5.2 General bonding

The general bonding requirements for lightning protection systems are applicable as the minimum acceptable potential equalization requirements for structures housing materials which may produce flammable vapors. The installation of a ground loop conductor is recommended for these applications as the primary method for interconnection of incoming conductors. In the case of metallic storage vessels, national and international standards allow metallic shell to serve as the ground loop conductor.

All incoming conductors, including piping and electrical conduit, must be interconnected with this common ground bus regardless of whether it enters the structure above or below earth. Electrically-continuous structural components such as structural steel or significant metallic ladders may be used as bonding points to transition to the equipotential ground bus where allowed by code. Permanent internal metallic components should be welded to the metal frame of a steel storage vessel where applicable to decrease the probability of insulation due to contamination from by-products such as wax or corrosive material.

Finally, attention should be paid to the length of conductor used to provide potential equalization. The inductive reactance associated with the length and routing of a conductor could result in a potential difference sufficient to cause arcing at the time of maximum current rate of rise even though it provides an effective bond at lower frequencies associated with significant current flow.

5.3 Floating roof tanks

Floating roof tanks provide significant potential equalization challenges. The construction techniques required to create open top floating roof tanks present potential ignition hazards due to arcing across the non-continuous metallic surfaces. In the case of floating-roof tanks, the floating-roof must be effectively bonded to the main tank shell. This bonding is provided through the installation of shunts bonding the floating roof to the tank shell or through a metallic ladder bonded to the shell.

The design of seals and shunts and their relative locations needs to be carefully considered but is outside the scope of this paper. Additional information on the design and testing of shunts for floating roof petroleum applications can be found in API/EI Research Report 545-A [22].

Culham Laboratory conducted lightning current testing on shunt/shell interfaces and identified that flexible bonding conductors of 35 mm width and minimum thickness of 3 mm should be applied between the tank shell and the floating roof at about 1.5 m intervals around the roof periphery [22]. The bonding conductors must be arranged so that they cannot form a re-entrant loop. They also found that some sparking at the shunts cannot be avoided. Culham results indicated that even clean steel shunt/shell interfaces sparked. When these sparks occur in the vicinity of damaged or leaky seals, ignition of flammable vapors will likely occur. For such installations, maintenance of the seals is critical to reducing the susceptibility to direct and nearby lightning strikes. Immersion of the shunts in the liquid is also an option. The immersion will reduce the oxygen to levels below that which would support ignition. However, Culham reported their testing revealed that currents in immersed shunts tended to cause an eruption of fluid, due to the arc pressure. It is unclear as to whether this eruption of fluid would provide sufficient oxygen to support ignition.

6. Lightning Protection Plan

6.1 General

It is recommended that a lightning protection plan be developed for structures containing flammable vapors to identify the need for lightning protection, identify maintenance and inspection procedures, and establish procedures for termination of any necessary operations at the approach of a thunderstorm. Lightning risk assessments are available in both the IEC and NFPA lightning protection standards to support in determining the need for protection of structures by specific application and can also be used to determine any requirements for the termination of operations. Maintenance and Inspection recommendations are discussed below.

6.2 Maintenance and inspection

IEC 62305-3 requires that lightning protection and grounding systems installed to protect structures with the risk of explosion (including flammables storage tanks) be inspected at regular periodic intervals. This inspection shall include electrical testing every 12 to 14 months as determined by the authority having jurisdiction. NFPA 780 also provides recommendations for the maintenance and inspection of lightning protection systems but is not specific to flammables applications.

Maintenance and inspection plans for flammables storage areas should be tailored to the specific application and physical limitations of the site. For example, in older plants there may not be available real estate to perform earth resistance testing of grounding systems; even when individual electrodes can be isolated. In those cases, it may be more effective to conduct point-to-point bonding testing. The use of visual inspections to verify the efficacy of bonding connections and critical installations can be very effective in many applications.

Periodic inspections for flammables storage areas should also address the inspection and maintenance of seals for floating roof tanks to minimize the probability of a flammable vapor in the vicinity where sparking may appear between the tank shell and floating roof. This is also critical for all tanks in those locations where direct attachment is most probable.

6.3 Termination of operations

There are some operations that may be susceptible to lightning activity or that may result in the generation of charged vapors. The termination of such operations may be beneficial in reducing the risk of ignition of a flammable atmosphere. For example, the loading operations of materials with conductivities of 1 pS/m or less could create an internal charge cloud that is susceptible to internal arcing. A direct or nearby lightning strike could create a collapsing electric field that could lead to an internal arc between the charged vapor and the internal wall of the metal tank, causing ignition of the contents. The use of lightning warning systems in the lightning protection plan can provide advance warning to allow the termination of any necessary operations.

7 Conclusion

Some incident investigations citing lightning as a cause of ignition of flammable vapors are unable to identify the specific ignition mechanism because of the damage to the storage vessel.

Some, such as Oland [10], cite the possibility that a flanged connection for a level alarm, manway, or PV valve which provided enough of a gap to produce a spark. It is critical in the analysis to not only consider the possibility of the creation of an arc but also consider whether the energy in the arc is sufficient to ignite the atmosphere.

Others cite the possibility of arcing between the tank shell and "bound space charge" inside the tank even though there is no identified charging mechanism to create such a "bound charge." While the generation of charged liquid surfaces and vapor clouds is acknowledged, the application will produce a relaxation time for such charges. For materials with conductivities of 50 pS/m or more, the relaxation time is less than one second.

It is acknowledged that there are applications where a "minimum acceptable" lightning protection system for a structure containing flammable vapors could consist of nothing more than a 5 mm or more thick steel continuous metallic container sitting on earth, with or without a release prevention barrier membrane. The 5 mm thick shell should be sufficient to prevent burn through and a tank diameter of 6 m or more should provide enough surface area contact with earth to dissipate currents into the earth regardless of whether surface arcing is produced. The majority of these vessels will also contain numerous connections to piping and grounded electrical conduit that will provide additional paths to earth that will act as supplemental grounding electrode. However, it must also be noted that additional considerations may be required depending upon the conductivity and ignition sensitivity of the contents.

The most common failure mode resulting in ignition of flammable atmospheres is generally agreed to be arcing in the vicinity of a flammable vapor. This is most often caused by a difference in potential between ungrounded or independently grounded conductors located close enough that the potential difference exceeds the breakdown voltage of the atmosphere. This can be resolved by either increased bonding or separation of the independently grounded conductors. For floating roof tanks, the design and location of the bonds are critical.

An additional threat that must also be assessed is the thermal threat that can result from a direct strike. The thermal effect of lightning current flow is not thought to be an issue but the actual lightning attachment point may be. If the material thickness is not sufficient, burn through can occur or a hot spot sufficient to ignite the contained vapors can appear on the inner surface of the metal. This is best addressed by sufficient thickness of the shell of a tank if a Faraday-type protection system is used or to provide strike termination devices that would terminate the strike prior to attachment to the structure.

It can be shown that isolation of lightning currents from the shell of a metallic tank can reduce the voltage that can appear on the inner shell of a metallic tank. The use of isolated lightning protection systems such as masts or groups of masts interconnected by overhead wires can be particularly useful when the acceptable risk of an event is very low and the contents of the structure contains a liquid of conductivity of 1 pS/m or less. The limited use of air terminals as a supplement to a Faraday-type system to provide protection for such protrusions could be considered in future revisions of standards.

Finally, future study is suggested to determine the efficacy of the grounding electrode represented by a metallic tank sitting on a concrete pad. It is also suggested that standards committees consider the possibility of the use of a hybrid lightning protection system to allow air terminals to be installed on metal tanks to protect protrusions that may not meet the thickness requirements of a Faraday-type system.

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