LIGHTNING--ITS EFFECTS AND SOME SIMPLE SAFEGUARDS IN REGARDS TO OILFIELD OPERATIONS

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Abstract

This paper discusses the occurrence and characteristics of lightning-related phenomenon, and the damage which it may cause to commonly used oilfield equipment such as tank batteries, power lines and transformers, ESP systems, drilling rigs and pulling units. The paper provides some considerations when deciding if a lightning protection system is warranted for a given facility and it presents some guidelines in the design of practical "Brute-force" protection methods, using a blend of published research from non-petroleum industries and operational experience in the oilfield. Case histories, illustrating both effective and ineffective designs are given.

Introduction

The annual destruction of property by lightning in the United States is estimated to be in excess of $800 million[1]. This includes forest and building fires, disruption of electrical service, aircraft damage and livestock injuries. In addition, about 600 people are killed annually and another 1500 injured. There is no central clearinghouse to compile oilfield lightning-related damage statistics and many events are considered routine and go unreported, however this writer estimates lightning-related oilfield damage in the Permian Basin alone to be between $51 and $85 million annually[2], excluding associated downtime.

There is some degree of randomness regarding lightning strikes and there are seldom first-hand witnesses to a hit or the resulting damage sequence. Consequently, the subject of lightning damage in the oilfield is surrounded by mystery and myth, opinions vary widely and the subject of what, if anything, can be done about it still leaves room for speculation. Lightning protection in the oilfield, other than selected store-bought surge protection devices, is found to be the exception rather than the rule. Brute-force protection systems are usually installed only after a catastrophic event. This approach to problem solving suggests an attitude of helplessness and/or tolerance toward lightning damage in the oilfield.

This paper will discuss the sequence of a normal lightning strike, how one can assess the probability of a given facility being hit, the likelihood that the facility will suffer damage if hit, and what you can do about it.

The Sequence of a Lightning Strike

The earth is constantly discharging electrons to the atmosphere via pointed and protruding objects such as trees, leaves, towers and other structures. This gradual loss of electrons creates a voltage potential between clouds and the earth. When the voltage potential gets high enough, the air insulator between clouds and the earth suddenly ruptures and a literal avalanche of electrons flow back to earth[3]. This phenomenon is known as lightning and it is simply nature's way of maintaining the earth's electrical balance. At any given time, about 2000 thunderstorms are active worldwide, and where there is thunder there is also lightning. Lightning hits the earth somewhere about 100 times every second[3].

Results of experiments using high-speed photography and radar imaging show that lightning behaves as an electrical charge in the sky, which ***desperately*** wants to reach out and distribute itself back into the earth. The sequence of a normal "cloud-to-ground" lightning strike is shown in Figure No. 1. The strike begins with a faintly luminous "stepped leader" of ionized air extending downward from the base of a cloud. The leader travels downward in increments of perhaps 50-200 yards, pausing along the way for about 50 microseconds each to determine the least resistive path through the air. While the leader from a cloud is heading downward, an upward ionization of air, created by pointed and protruding earth objects, is occurring simultaneously. This upward channel of ionized air is called a "streamer". As the leader gets closer to the earth it causes the streamers to extend upward more rapidly, as if they were trying to intercept the leader. By the time the leader has reached within 100 yards of the earth, the die has been cast and nature has made a final decision as to exactly where the lightning will strike.

Once the leader has intersected a streamer from earth, the "return stroke" begins. The return stroke provides us with the brilliant visible flash of light which we call lightning. Since the leader has paved the way by providing a complete path of ionized air between the cloud and earth, the return stroke travels upward much faster and more decisively than the leader's path downward. The return stroke carries a high current and heats the air to about 50,000 degrees F. The rapid heating of air causes the air to expand fast enough to break the sound barrier. The result of this expansion is a sonic boom we know as thunder. The entire lightning sequence from stepped leader through dissipation of energy by the return stroke, is usually over in 0.2 to 2.0 seconds. This sequence is so rapid that our eyes cannot identify the various steps involved.

General Electric and Westinghouse conducted extensive lightning research during the period 1920-1950. Table No. 1 presents some typical aspects of lightning as taken from their research and that of others. It is important to note from Table No. 1 that the current in a lightning hit is extreme (10-345 KA), the potential voltage involved is extreme (10-100 million volts), and the duration of the strike is extreme (peak currents are only maintained for perhaps 5-20 microseconds). Lightning is so powerful that it cannot be duplicated full-scale in the laboratory.

Probability of a Given Structure Being Hit by Lightning

There is a vast difference between the likelihood of a given structure actually being hit by lightning and the likelihood that the structure will sustain damage if it is hit. This section addresses only the probability of a structure being hit. The dominant factors which increase a given object's susceptibility to being hit are:

- Location of the structure on the earth
- Relative height of the structure, as compared to the surroundings
- Degree of isolation from surrounding structures

Location of the structure on the earth is important. Figure No. 2 is an isoceraunic map showing the average annual number of thunderstorm-days experienced at various locations across the United States. Being located in an area which has a greater number of thunderstorm-days increases the likelihood of being hit by lightning, all else being equal. One can see from the map that the Permian Basin can expect 35-40 thunderstorm-days per year. There is also some evidence which suggests proximity to surface or near-surface anomalous conditions (such as buried ore deposits, and possibly caliche beds) may also increase the probability of being hit.

Height relative to the surroundings is important. Cloud-to-earth lightning will seek out the least resistive overall path to earth and often, but not always, that will involve the shortest path. Relative height above the surroundings serves to minimize the distance lightning must travel between the cloud and the earth. Figure No. 3 shows the probability of a relatively short and isolated structure being hit in an area which is subject to about 35 thunderstorm-days per year, all else being equal. For relatively short structures a large projected structure area appears to increase the probability of being hit. The probabilities shown in Figure No. 3 correlates well with Santa Fe Energy's operating experience in the Permian Basin.

Figure No. 4 shows the probability of a relatively tall and isolated structure being hit by lightning. The projected area of a tall structure is not an important factor, however note that the likelihood of a tall structure being hit increases rapidly above a height of about 800 feet. When structures get this tall, "earth-to-cloud" strikes are predominate and the streamer seems to play a stronger role in determining where lightning strikes. In many cases involving extremely tall structures, the lightning strike is actually initiated by the structure rather than the cloud.

Areal **Isolation** from surrounding features appears to be another major factor in regard to hit probability. All else equal, a structure which is areally isolated from other structures of similar height is more likely to be hit. It is unknown why this is the case. It may be a matter of "safety in numbers", or perhaps the individual streamers emitted from several structures of similar height may serve to decrease the effective streamer height of any single structure.

Contrary to popular oilfield opinion, the materials of construction have little to no bearing upon the probability of an object being struck by lightning[6], however as will be shown later, the materials of construction has a major impact upon the ability of a structure to escape damage from a lightning strike.

Lightning-Related Damage in the Oilfield

Lightning-related damage can be caused by one or more of the following actions/reactions:

1. Heat and possibly vaporization of materials from the extreme current flow
2. Side-flashing or arcing to adjacent structures as a result of the extreme voltages
3. Damage to equipment from induced current/voltage/frequency fluctuations

The above actions/reactions are common to many industries. In the oilfield we have the following additional damage possibilities:

4. Ignition of flammable/explosive vapors by the strike or side-flashing
5. Ignition of flammable/explosive vapors by corona discharges
6. Possible hydrolysis and subsequent ignition of water in storage vessels

In the absence of electronic and electrical equipment, flammable ignition or side-flashing issues, once an object has been struck by lightning the ability of that object to avoid damage is directly related to the ease with which the current can pass through that object and dissipate safely to earth. If the object being struck and the path into the earth is conductive enough, damage should be minimal to non-existent. A good example of this favorable characteristic is the well-grounded and steel-framed Empire State Building which gets hit by lightning an average of 23 times per year, yet suffers no damage. Conversely, non-metallic equipment has a high electrical resistance and therefore it is subject to intense heating if it takes a direct hit or if it is in the grounding path of a hit. The essentially instantaneous current rise inside of a highly resistive material causes rapid heating and vaporization of the material[7]. A good example of this unfavorable characteristic is when fiberglass tanks are either hit directly or are caught in a grounding path and essentially vaporized.

Lightning-related experiences and opinions in the oilfield vary widely, however Table No. 2 provides one ranking of selected operational equipment by its apparent susceptibility to being hit, and by the apparent frequency of actual damages reported. The lists are almost mirror images. An explanation for this apparent discrepancy lies in the degree to which these pieces of equipment are likely grounded. A discussion of the apparent hit and damage frequency is given below:

Drilling rigs do get hit by lightning[9] although the reported frequency is surprisingly low. Correlation with Figure No. 3 indicates a 147 foot isolated drilling rig in the Permian Basin can expect to be struck about once every five years. Drilling rigs are usually so well-grounded that damage is minimal to non-existent, so perhaps they get hit much more frequently than is reported. Of four first-hand witnessed drilling rig hits reported, one involved a strike to the derrick while drilling and sustained no damage. One was out of the hole at the time the derrick was struck, and damage included a melting of derrick lights. One suffered catastrophic damage when lightning by-passed the derrick entirely and hit the SCR control room of the diesel-electric rig. Another reported hit by-passed the derrick and hit near top of the substructure, blowing off all rust and paint in the proximity of the hit, injuring two men working on the BOP accumulator and igniting fires at every connection on the butane line serving the rig. This latter case illustrates that lightning currents can take multiple parallel paths in getting to ground.

Pulling units also get hit by lightning[9], although the reported frequency is low. One eye-witness reported seeing lightning hit a derrick crown and flashes which arced among the derrick beams on the way to ground. No damage was reported, however one floor hand was shocked. There was one stand of tubing in the hole, indicating some degree of grounding to the wellbore. In another instance, a pulling unit had just started to rig down when lightning struck the crown block. All tires of the pulling unit were blown out and holes were blown in the earth at each deadman. In that instance, the derrick was still erected but not physically connected to the well. Grounding conditions in the latter case were undoubtedly poor, and the deadmen were probably set in resistive soil, as is typical for the Permian Basin. This latter case also illustrates that lightning can take multiple parallel paths in getting to ground.

One would expect treater stacks and dehydration towers to be hit frequently, however only one person interviewed reported actually having seen a treater get hit by lightning. That incident resulted in a rupture of the vessel[9]. Treaters and dehy towers, although they are usually set on a non-conductive concrete pad, are typically well-grounded by virtue of being connected via metallic flowlines to wells in the area. The one reported incident occurred on a battery which had recently undergone upgrading one year earlier and a few months before the treater was hit, a tank was hit and exploded. Possibly the recent battery modifications involved well tie-ins using non-metallic piping, which would not have afforded a grounding of the treater.

Electric power lines are normally protected via horizontal shields or neutral wires, running above or below the main power lines and which are connected to ground wires at periodic intervals along the route. Electric line protection is also provided by lightning arrestors and reclosers, which route power surges to ground or interrupt, respectively. The most frequently reported damage to electric lines per se, was damage to the non-conductive poles when subject to a direct hit.

Pumping units can be relatively tall and isolated structures, yet only one witness reported actually seeing a pumping unit get hit. The lightning hit near the tail bearing assembly of a 1280 Air-balanced unit, powered by a natural gas prime mover. The well was an isolated 3 mile stepout to an existing field, and was located on the extreme top of a hill. Damage included partial melting of the tail bearing assembly and required replacement of the walking beam. Pumping units, like drilling rigs and pulling units may be hit much more frequently than is known and sustain little, if any damage. They typically will be well-grounded through the bridle and steel sucker rods.

Tanks made the top of the hit list in regards to damage frequency and extent of damage. Tanks are subject to damage from direct hits, being in a parallel or series grounding path, and side-flashing with ignition of flammable vapors. It is estimated that operators in a four county area east of Midland lose upwards of 40-60 tanks per year due to lightning-related damage[10]. Although the API states that metallic tanks in contact with the ground have proved to be sufficiently well-grounded[8], they may not be well-grounded if sitting on oil-soaked earth, insulated from the ground using gravel and/or felt paper, sitting on otherwise resistive soil or if connected using non-metallic piping. When non-metallic (i.e. fiberglass) tanks are directly struck or are in the grounding path, the results of a lightning hit is usually spectacular for everyone except the operator. Numerous tank explosions were reported and included full tanks, empty tanks, partially full tanks, stock tanks, water tanks, metal and fiberglass tanks.

Electronic devices containing printed circuit boards or microprocessors do not like power surges. Variable Speed Drives for ESP's appear to be particularly susceptible to failure during lightning storms. Other ESP related component failures thought to be associated with lightning include motors, cables &

splices, standard control panels, three-phase transformers and auto-transformers, in that approximate order. Transformers serving ESP's, while occasionally damaged, were not reported to be frequently damaged.

Motors and control panels for pumping units are usually grounded to the wells they serve, however they are a frequently reported source of damage. This was somewhat surprising in view of the apparent rarity with which transformers were damaged. If motors are burning up because of power line surges, then either the line fuses and lightning arrestors are not doing their job, or they cannot react quickly enough. Another explanation for the apparent discrepancy may be because motors could be caught in the middle of a parallel grounding path lightning could seek if it strikes the pumping unit. Contrary to popular opinion, current does not go to path of least resistance. It goes inversely proportional to the resistance, and if only 1% of a 100 KA strike to the horsehead went through the motor (and 99% went down the bridle), the motor would still receive about 1000 amps, or 4761% of the normal full-load current of a 15 HP motor.

Other Sources of Lightning-related Damage

Benjamin Franklin was one of the first to observe that sharp pointed objects lose ions faster to the atmosphere than flat or smooth surfaces. This type of electron flow around pointed objects is normally quiet and invisible, but if a great enough voltage difference exists the ion collisions can yield enough energy to make air luminous when a thunderstorm passes overhead. This visible ionization is called a "corona discharge" (a.k.a. St. Elmo's Fire) and it can sometimes be seen as a blue aurora of a few inches depth on protruding objects. During the instant before a lightning hit the corona may extend upward for 10-15 feet[3]. A corona discharge has been seen on church steeples, lightning rods, power lines, blades of grass and even the tips of fingers. This normally slow dissipation of energy has a current of perhaps 1-4 microamps and sometimes can be heard as a hissing sound, or as static on an AM radio. Metallic ventilation pipes or similar protrusions can produce a corona discharge which could ignite explosive vapors, even without a lightning flash[6]. Visible corona discharges appear to be more prevalent at higher altitudes, in humid air and in temperature ranges of 15-50 degrees F. Bluish-white corona discharges have been observed on oilfield tank stairways, walkways and vent lines[9], and they may be responsible for some tank explosions which are otherwise attributable to a direct hit.

Obviously, ignition of flammable vapors from tanks can occur in a direct hit or a near-hit which arcs or flashes to any vapors. Not so obvious is the static electricity which can be created by friction of dust or liquids against a non-conducting object. While this action is not lightning-related, it may be the cause of some events which are blamed on lightning. In experiments with pumping into insulated fiberglass tanks, potentials up to 11,000 volts were generated and the tank sparked when a grounded conductor was brought near the tank[8]. API recommends grounding all metallic fittings on non-conductive tanks, and limiting the fill velocity. One witness[9] reported being shocked by a stairway serving a fiberglass water tank which was filling.

It is also possible for a non-conductive tank to explode in the total absence of a gas or liquid hydrocarbon blanket. One mechanism of explosion could be lightning hitting a metallic vent line, seeking ground via the non-conductive tank, then vaporizing the tank due to intense and rapid heating. Another possibility[9], not discussed in the literature reviewed, is hydrolysis of the tank contents. If lightning has struck a vent line serving a non-conductive tank, the current may choose a path through the water in the tank on its way to ground. Such a high current passing through water could ionize the water into hydrogen and oxygen, ignite same and either launch the tank as a rocket or blow up the tank. One witness[9] reported seeing a fiberglass tank at a new SWD battery hit by lightning and launched about 30 feet vertically into the air. The bottom of the tank stayed on the pad, and a pale yellow flame was seen exiting the tank along its trajectory. No flame was spread when the tank landed some 100 feet away. The launching of a second fiberglass tank from the same battery was observed by the same witness perhaps 45 minutes later, again with a pale yellow flame exiting the tank bottom. There was essentially no natural gas vapor at the facility at the time of the first hit, and certainly no vapors by the time of the second hit. Burning of hydrogen gas is suggested, because if hydrogen is burned in the presence of glass it will often have a yellowish color as the result of sodium impurities typically found in glass.

Does Your Oilfield Equipment Need Lightning Protection?

For most operators, lightning protection on basic oilfield facilities is the exception rather than the rule[9]. Lightning protection may not be cost effective for all installations. To determine if a given facility should have protection an operator should consider the following questions:

How likely is the installation to be hit?

- Location?
- Relative height?
- Relative isolation?
- History of previous hits to the facility or the proximity of the facility

What is likely to be the consequence of a hit?

- Loss of life and/or personal injury?
- Explosion or fire?
- Spills of oil, water or release of gas?
- How costly is the facility and would downtime be extensive?

What can be done to reduce the hazard potential, how likely is it that the protection system will actually work if needed, and what is the cost of that protection?

Lightning Protection--Some Design Considerations

Protection from the effects of lightning is a matter of degree, rather than an absolute. There are two general methods by which an operator may provide lightning protection for a given facility. One is to take precautions to avoid being struck in the first place. The other is to take steps to minimize damage as the result of a hit, side-flash or corona discharge. Only the operator is equipped to decide which, if either, method is appropriate for his circumstances.

Avoidance of a Lightning Hit

Lightning tends to seek out tall objects on the earth because hitting tall objects will ease its route to ground and even non-conductive objects are more conductive than air. Since we cannot change the thunderstorm-day frequency of the area we are working in, the only ways to avoid being struck by lightning are to avoid isolation of the facility to the extent practical, and to maintain a low profile relative to the surroundings.

One may be able to avoid isolation by locating your facility in the proximity of existing and hopefully taller structures, such as power lines, radio towers or even trees. Maintaining a low profile can be pursued by selecting topographically low areas where possible, avoiding any tall protruding objects mounted directly on the facilities, and possibly installing lower profile facilities (i.e. low tanks, horizontal treaters and separators, etc.).

On tank batteries, avoid pointed protrusions of pipe such as vertical vent lines, which can serve as lightning rods. Installation of vertical vent lines, especially those on individual tanks, is an like raising your hand to volunteer for something. If you raise your hand in this case, nature may call on you in a bad way. The use of horizontal vent lines and an in-line PV valve serves to reduce battery height, helps exclude oxygen from the tanks and provides a flame arrestor of sorts in the event the vent line vapors are ignited. If vented vapors can be considered to be an ionized streamer, the installation of horizontal vent lines with in-line PV valves may serve to reduce the effective battery streamer height by 10 to 25 feet, even though the physical reduction is only perhaps 2-6 feet. In other words, there may be beneficial multiplier effects in changing the orientation of the vent assembly on tanks and reducing emissions.

If one cannot locate the facility low relative to the surroundings, it may be possible to raise the surroundings. This is the purpose of a lightning rod system...to raise the surroundings relative to an object needing protection from a direct hit. A lightning rod does not "repel" lightning. Quite the opposite, it serves as a tall object relative to the facility being protected, and if lightning hits in the area it is hoped the lightning rod will act as a sacrificial lamb for your facility. Although a lightning rod system ***increases*** the probability that a strike will occur in the proximity of your facility, a properly designed system can offer substantial damage avoidance protection for many structures. Conversely, an improperly designed system can aggravate lightning-related problems.

A lightning rod system creates an upward traveling, invisible spark during the instant before a hit. The height of this traveling spark is on the order of 10-100 yards long when it meets the leader from a cloud[7]. While other pointed and protruding objects on the facility also create this traveling spark, we want the lightning rod effect to dominate other effects around a facility, such that it takes the hit.
There are three equally important portions to a lightning rod system, as shown in Figure No. 5 and explained below:

- The lightning rod proper
- The down conductors
- The earth connection

The lightning **rod proper** is a vertical conducting rod which is positioned such that it is located above the object to be protected. In this manner the upward streamer leaving the rod can intercept the downward leader from a cloud, thus preventing the leader from directly hitting the facility. The rod can tend to "lure" the strike away from other nearby objects. Lightning rods are commonly constructed of 5/8" copper (Cu) or brass. Although the rod end shape is controversial, this writer sides with Benjamin Franklin in recommending a sharply pointed rod to enhance streamer height just prior to a hit.

"Reasonably complete protection" occurs in a downward 45 degree "cone of protection", using the tip of the rod as the cone apex. API[8] recommends using a 45 degree cone for rod heights not exceeding 50 feet. The United States Lightning Code specifies a 45 degree cone design for protection of dangerous structures (i.e. buildings containing explosives), and a 60 degree cone is allowable for non-dangerous structures. Lightning codes in Canada and Great Britain are more restrictive. If a horizontal wire is strung above an object as a lightning rod, a "tent of protection" is provided parallel to the axis of the wire. A wire can cover more area than a rod, but one loses the perceived pointed-end streamer benefit of a vertical rod.

The **down conductors** connect the rod proper with the earth ground rods. They need to be large enough to carry the current from the rod to the earth without melting. The U.S. Code suggests 1/4" Cu or 3/8" Aluminum for the down conductors. For most hits, a #6 Cu wire is sufficient, but #4 Cu gives a much larger thermal and mechanical factor of safety. Avoid sharp bends of the down conductor. It has been calculated[11] that a 200 KA current passing through a right-angle bend will tend to straighten that bend with a torque of 5,500 ft-lbs.

Due to high potentials (perhaps 500,000 volts) between the down conductor and ground, it is possible to arc several feet to adjacent metal and cause induced damage. Therefore, all nearby metal objects should be grounded, including buried pipes and cables, and the down conductors should be separated from adjacent objects by at least 10 feet. The down conductor length should not exceed 100-150 feet.

The **connection to the earth** is usually made with ground rods. Ground rods are typically 5/8" Cu of 6-10 foot lengths. The National Electric Code recommends that rods be buried at least 8 feet deep, however this does not necessarily insure good grounding in the dry, resistive soils of the Permian Basin. The ability of ground rods to dissipate energy rapidly to earth is very important, and the practical goal is to have less than 10 ohms of resistance from the ground rod into the earth. Yet this goal may be difficult or impossible to achieve in the Permian Basin due to the nature of our soils. If the current cannot dissipate easily to earth it will seek another conductor, and in doing so the current can dig a trench in the earth. In highly resistive soils, damaging currents can spread outward from an area hit for several hundreds of feet[3].

Soil resistivity is important and highly variable, yet soil resistivity measurements are seldom made in the Permian Basin, even by utility companies[9]. The resistivity of any soil is affected by the soil type, the concentration of dissolved salts, the moisture content, the temperature, the grain size and the degree of compaction. Table No. 3 shows some relative resistance rankings of various soil types and rock formations, and it can be used as a guide in the absence of measurements for a given site.

Moisture content of the soil is an important variable, because water usually conducts electricity well itself and it dissolves various salts in the soils, thus expanding the ground electrical network. It is interesting to note that a tree with 30% moisture content conducts electricity about 1 million times better than kiln-dried lumber[3]. Do not hesitate to utilize naturally-occurring low lying areas for earth grounding purposes, as they may have more moisture content than higher areas. If the ground is resistive, you may also want to consider salting the earth around the ground rods by adding 4 lbs of salt per 100 lbs of soil fill to a 5' radius around each rod. Salting can reduce a protection system's electrical resistance by a factor of 50 or more[11]. Unfortunately, salting also increases corrosion of the ground rods and it may require annual inspection or replenishment of the salt due to leaching. Any oilfield operation that requires annual maintenance should be avoided if possible. If environmentally acceptable for your location, consider salting the ground rods with produced water occasionally.

It is seldom that a single ground rod will suffice for any code requirements (other than Code of the West) in Permian Basin soils. If your facility is particularly critical then soil resistivity measurements, multiple ground rods and/or the drilling of metal-cased and uncemented wells into acquifers may be necessary to achieve a good ground. Reference No. 6 is a good source for measuring soil resistivity and the effects of multiple ground rods, driven at various depths and set in various orientations.

Minimization of Damage

Once appropriate safeguards have been taken to minimize the chances of being hit, there are several simple steps which, based on a preponderance of the evidence, could be taken to minimize the potential damage from lightning strikes.

Drilling rigs should endeavor to keep the bit in the hole when thunderstorms are nearby. The drillpipe serves as an excellent ground rod when water-based muds are used. Depending on auxiliary grounding systems may not be reliable if the soil resistivity is high. Those brief periods of time when the derrick is raised and not grounded by the drillpipe pose the greatest risk of damage during a thunderstorm.

Pulling units should keep the tubing in fluid and the elevators connected to the tubing during a thunderstorm. Avoid rig-up and rig-downs during thunderstorms. Those brief periods of time when the derrick is raised and not grounded pose the greatest risk of damage during a thunderstorm.

Avoid connecting treaters or gunbarrels with non-metallic, non-grounded piping. The connecting plumbing may be the only ground mechanism in service.

To minimize damage to tanks, do not connect an isolated, pointed and protruding object which could serve as a lightning rod, in series with a resistive material such as fiberglass. On fiberglass tanks, do not use vertical individual vent lines. If lightning strikes that particular vent, the tank will almost assuredly explode. Figure No. 6A shows an example of a battery which is considered to be more prone to hits and more prone to damage than it has to be. The tanks of Figure 6A have excessive protrusion, excessive structure and streamer height and a non-conductive tank has been put in series with a likely grounding path. The alternative layout shown in Figure 6B is considered to be less prone to hits or damage. It has reduced protrusions, reduced structure and streamer height and a metallic route to ground from the fiberglass vent line terminal. There is also reason to believe that having the vent line terminal on the fiberglass tank side of the battery is better for minimizing damage potential than having it on the steel tank side, because this orientation allows the momentum of a lightning hit at the vent terminal to exit the vent line assembly at a steel tank rather than a fiberglass tank.

One can also minimize damage to non-conducting tanks/gunbarrels by making them more conductive. One way of doing this is grounding the fluid in the tank. Another approach is to paint or impregnate the tank with a conducting material. Another technique is to provide a conductive protective "shield" above and around the tank. Still another method, untried in the oilfield to our knowledge, is to follow the lead of aircraft manufacturers [13]. When Douglas Aircraft Corporation had trouble with lightning blowing 14" diameter holes in the non-conductive Radomes of their DC-8's, they taped 3/8" wide x 0.003" thick aluminum foil to the Radome and grounded the foil to the airframe. Thereafter, when lightning hit the Radome the foil strips were vaporized but the Radome itself was undamaged. The foil could be easily inspected on the ground, used as a "tattletail" that the Radome area had been hit, and then replaced as necessary. Perhaps such a foil tape could be applied to existing fiberglass tanks and gunbarrels in critical installations.

If you are experiencing frequent vent line fires or corona discharges, consider a simple grounding of the vent line to earth, installing a PV valve and using non-metallic piping downstream of the PV valve. Consider grounding the stairway and walkway also. The "trickle charge" effect of a corona discharge can be easily dissipated, even into a relatively resistive soil.

If you are experiencing excessive motor and panel failures on pumping units, consider that lightning may be striking the pumping unit rather than just creating a transient in the power lines. Is the motor in a parallel grounding path that a strike might take in getting from the horsehead to ground? If so, consider grounding your walking beam and/or samson post directly to the tubinghead, or installing a lightning rod system adjacent to the pumping unit.

If you are experiencing excessive failures of variable speed controllers on an ESP, consider replacing the drive with a standard panel. If you must have variable rate control, consider a few extra stages in the pump and a surface adjustable choke in-lieu-of a VSD.

If you are experiencing excessive ESP cable failures at the round-to-flat splice after a thunderstorm, consider making a similar but less hardy 90 degree bent connection at the surface, such that it may fail before the subsurface connection.

If you are experiencing repetitive transformer failures or very shallow ESP cable burnouts at a location where the power line abruptly ends or takes a sharp change in direction, consider installing a dummy pole and extending the power line one more length along the normal axis of the power line. This gives the current a chance to follow a straight line momentum path, rather than directing it into strictly into your facility

Case Histories

These case histories were selected to illustrate some of the points raised in this paper.

Case A: Vent Line Modification--Martin County, Texas

Prior to 1993 this operator had experienced the loss of about 3-5 tanks per year as a result of lightning. Batteries hit involved only steel stock tanks, with individual vertical vent line risers and no PV valves. In 1993 the operator modified 140 batteries in this area by laying the vent lines horizontal and installing PV valves inward from the vent line terminal. The operator has not lost a single tank in this area in the 4 years subsequent to this simple modification.

Case B: Excessive Motor Burnouts--Martin County, Texas

During 1997 an operator lost 4 motors, 2 POC's and several control panels on three problem wells over a two month period. The failures followed lightning activity in the area. The overhead power line did not have a ground system, however it served about 20 other wells that were not experiencing problems. It was noticed that the three problem wells were served by underground take-offs and were about 500 feet further from the power line than the non-problem wells. Because of this isolation, it was suspected that lightning may be hitting the pumping units and attempting partial grounding through the motors. The operator has installed a lightning rod to one problem well, grounded the samson post on another problem well, and left the third well alone as a control. The results are not yet established.

Case C: Battery Blown Up--Gaines County, Texas

This isolated battery protruded noticeably above the surrounding flat terrain and had been operational for only 3 months when lightning (per eye-witness) hit the installation in 1988. The battery, consisting of a H-750 fiberglass gunbarrel, a H-500 fiberglass water tanks and four H-500 steel stock tanks was completely destroyed by the explosion. Damage was estimated at $104,000. The operator believes the water tank had an individual riser at the time of the strike.

In an effort to avoid a recurrence, the rebuilt battery was equipped with a 4 pole lightning rod system and a protective wire shield surrounding the new fiberglass gunbarrel. Test holes dug on location revealed a bed of caliche underlying the entire location at a depth of 3 feet. With such a resistive soil, the earth connection was made using a network of 26 ground rods which radiated outward from the battery. Horizontal metallic vent lines connected all tanks and the vent lines were grounded on either side of the fiberglass gunbarrel gas boot.

Subsequent to the rebuild, lightning has struck and damaged a drilling rig operating one location north of the battery, and lightning has struck and damaged the power line running just west of the battery. On two occasions, the foreman has parked his vehicle just north of the battery and has been unable to re-enter the vehicle without receiving a shock which arced 1" from the door handle to his hand. Upon recent inspection, three out of eight wire shields guarding the gunbarrel show evidence of extreme heat and/or melting, and twelve of the sixteen down-conductors used show evidence of carrying a high current surge. Other than some melted shield wires on the gunbarrel, the battery has not received any damage subsequent to rebuilding in 1988.

Case D: Frequent Lightning Hits in Area--Eddy County, New Mexico

This operator's battery is located in the bottom of a 200 foot deep rock canyon. While the battery was being built in 1994, a drilling rig on a nearby location in the canyon bottom was struck by lightning. Recognizing the potential for lightning damage to this $500,000 facility, a lightning protection system was installed prior to start-up. It consisted of two vertical poles with rods and a horizontal wire which spans the length of the battery, and graphite impregnated fiberglass downcomers into the water section of all fiberglass tanks. Since the ground is solid dry rock, the soil resistivity is high. The down conductors, the water tanks downcomers, the stairway and walkway and the lightning rods are connected to a buried carbon-bed. Thoughts of "salting" the carbon-bed continuously with produced water were dismissed as being environmentally unacceptable, so a 275' hole was drilled to moist soil, and 2 7/8" uncemented steel casing was stacked out on bottom to serve as a main ground rod.

The battery proper has sustained no damage since completion, despite numerous thunderstorms in this area. In 1997 lightning was observed hitting the chain-link fence which surrounds the battery and then arcing about 10 feet outside the battery to some electronic controls which were melted. The operator continues to experience lightning-related problems with electronics in the proximity of the battery.

This operator also experiences a high failure frequency of round cable to flat cable splices on ESP's in this area. They are experimenting with locating a similar 90 degree splice at the surface, to see if it might fail preferentially to the subsurface splice. Results are not yet established.

Case E: Multiple Hits at Same Battery--Midland County, Texas

This operator's battery has been hit by lightning at least three times over the course of a few years, which dispels the rumor that lightning won't hit in the same place twice. The first hit destroyed only a fiberglass water tank. The second hit also involved a fiberglass tank, but the subsequent fire destroyed most of the battery site, causing over $200,000 in damages. The third hit was to a steel tank. The operator has removed all fiberglass tanks from this installation, however vertical vent line risers have been retained.

Case F: System Modification--Yoakum County, Texas

This 1963 vintage waterflood was being expanded in 1988. The expansion included installation of H-750 bbl fiberglass tanks at three satellites which had been served by H-500 steel tanks. Because of the additional 8' of tank height the operator made an assessment of the need for lightning protection. It was decided to install lightning rods on two of the satellites which were served by underground power lines, since they appeared more isolated than the third satellite which was adjacent to a large overhead power line.

An assessment was also made of protecting the central tank battery, which is an extensive and expensive facility. After considering the difficulty in protecting the battery and the minimal lightning damage history in the field, a conscious decision was made to avoid lightning rods for the central battery on the basis that it could do more harm than good.

Conclusions

When assessing lightning protective measures which can be made for your operation, it may help to stop thinking of lightning as being merely a "transient current". Think of it as being a release of 5000 million horsepower in the blink of an eye. It will tend to go where it wants to go and do what it wants to do. It wants ***desperately*** to get back into the earth. We must try to guide rather than direct this amazing amount of power.

Within any given area of the Permian Basin, lightning will tend to hit objects that are **isolated** and **taller** than the surroundings. The figures included in this paper provide a means of assessing the probability that your installation or facility will get hit by lightning. Contrary to the "old wives tale" which states that lightning won't strike twice, there is reason to believe that lightning may be more apt to strike the same area multiple times. Some batteries have been reported to have been struck four times before aggressive corrective action was taken[9]. If your facility has ever been struck and damaged by lightning, prudency demands that you change something as the facility is rebuilt.

A summary of guidelines to avoid being hit, and to avoid damage if hit is shown below:

Guidelines to avoid being hit include:

- Maintain a low profile relative to the surroundings
- If you cannot lower the structure, consider raising the surroundings with a lightning rod system.
- Avoid protruding or pointed structures coming off the facility
- Avoid isolation of the facility if possible

Guidelines to minimize damage include:

- Do not put non-conductors in a likely grounding path (especially avoid vertical individual vent lines on fiberglass tanks)
- Do not connect treaters, tanks or gunbarrels with non-metallic, non-grounded piping
- Do not rig-down or rig-up pulling units during a thunderstorm
- Avoid tripping of drillpipe during thunderstorms
- Use in-line PV valves on horizontal tank vent lines
- Maintain at least 10 feet distance between objects likely to be hit and other structures
- Ground vent lines if you experience vent line fires or see corona discharges
- Ground the samson post of pumping units if you experience excessive motor failures
- On pulling units, keep the tubing in fluid and elevators connected to the tubing during a thunderstorm

Since there is some degree of randomness regarding lightning strikes, you will never win the Medal of Honor for installing a lightning protection system because you will seldom know with certainty that your system is working. If you are completely successful in avoiding future damage to an installation, then the protected facility will simply sit quietly through future thunderstorms. While you may observe some tattletail signs of a non-damaging hit, you will not be able to prove beyond a shadow of a doubt that the protection system has done anything, and human nature will have your associates saying, "it wouldn't have gotten hit anyway". On the other hand, since there is no such thing as absolute protection, if you install a well-designed protection system and the facility gets blown to bits the next day you can always chalk it up to the Third Law of Thermodynamics.

References:

1. Extrapolated from U.S. Department of Commerce Statistics, Environmental Science Services Administration Data, Washington, D.C., December 1966 base information.
2. Extrapolated and prorated upward to all operators in the Permian Basin using in-house annual damage estimates to ESP cables, tanks battery explosions, electrical/electronic control failures and motor replacements.
3. Peter E. Vicmeister, The Lightning Book, Doubleday and Company, 1961
4. Adapted from M.A. Uman, Lightning, McGraw-Hill, New York, 1969, J.L. Marshall, Lightning Protection, John Wiley and Sons, 1973, Peter Vicmeister, The Lightning Book, Doubleday and Company, 1961, et. al.
5. Adapted from Westinghouse Editorial Service, Proc., IRE, February 1943
6. J.L. Marshall, Lightning Protection, John Wiley and Sons, 1973
7. Martin A. Uman, Understanding Lightning, BEK Technical Publications, 1971
8. API Recommended Practice 2003, Protection Against Ignitions Arising out of Static, Lightning and Stray Currents, Fifth Edition, American Petroleum Instituted, Washington, D.C., December 1991
9. Personal interviews with selected industry personnel

10. Personal interviews with selected industry personnel and extrapolation of in-house records on Martin County batteries.
11. R.F. Ficchi, Electrical Interference, Hayden, New York, 1964
12. E. Hanle, The Complex Impedance of the Earth's Surface at Radio Frequencies and Its Measurement, NTZ-Commun. Journal, No. 3, 1966
13. M.P. Amason, Space Aeronautics, 1959

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Table 1

Some Physical Aspects of Lightning[4]

Stepped Leader	Range (average to extreme)
Length of steps	50 to 200 yards
Velocity of propagation	85 to 1477 miles/second
Time to reach earth	20 milliseconds average
Return Stroke	
Velocity	28,400 to 79,500 miles/second
Time for flash to reach cloud	100 microseconds average
Time to reach peak current	2-30 microseconds
Peak Current	10-345 KA
Duration of Peak Current	5-20 microseconds
Length of Bolt	3 to 9 miles
Horizontal distance	5 to 100 miles
Vertical distance	3 to 4 miles
Voltage potential	10 to 100 million volts
Diameter of bolt	2 to 7 inches
Temperature of bolt	40-50,000 degrees F
Charge transferred	25-200 Coulombs
Duration of event (leader thru dissipation)	0.2 to 2.0 seconds
Peak KW of average stroke	3750 million KW
Peak HP of avg stroke	5025 million HP
KWH of average stroke	250 KWH
Economic value of energy released @ $0.06 per KWH	$15.00

Table 2

Oilfield Facility Apparent Susceptibility to Lightning Strikes and Lightning Damage

Facilities Most Susceptible to a Lightning Hit[A]	Facilities Sustaining the most Lightning-related Damage[B]
Drilling Rigs	Tanks
Pulling Units	Electronics
Electric Lines/transformers	Motors/Controls
Pumping Units	Transformers
Dehydration Towers	Electric Lines
Battery Equipment Treaters Tanks Motors/Controls	Pulling Units Drilling Rigs
	Pumping Units

A: From consideration of relative height and degree of isolation
B: From interviews with industry personnel regarding damage frequency and extent of damage

Table 3

Some Rankings of Electrical Resistance for Various Soils, Materials and Rock Types

(Adapted from reference No. 12)

Material	Relative Electrical Resistance
Mineral Oil	Extremely resistive
Ice	Extremely resistive
Rock Salt & anhydrite	Extremely resistive
Distilled Water	Highly resistive
Crystalline Rocks	Highly resistive
Sand & Gravel	Moderately resistive
Sandstones & Gypsum	Moderately resistive
Limestone	Moderately resistive
Clayey sand and shales	Moderately conductive
Mountain Water	Moderately conductive
Loam and sandy clay	Moderately conductive
Ground Water	Moderately conductive
Salt Water	Conductive
Metallic Ores	Conductive

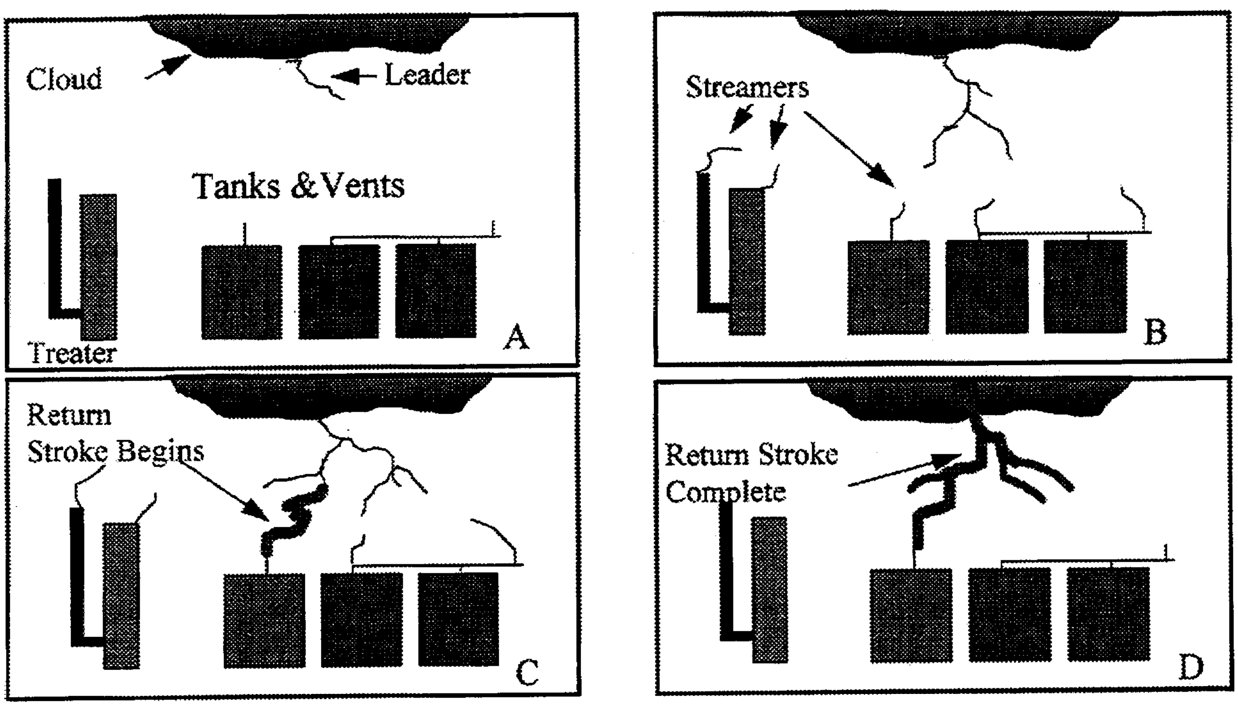

Figure 1 - Cloud-to-Ground Lighting Sequence A: Stepped leader exits cloud and seeks earth. B: Leader extends downward and streamers extend upward. C: Leader intersects with streamer to complete circuit. D: Return stroke is complete and electrons flow rapidly to earth.

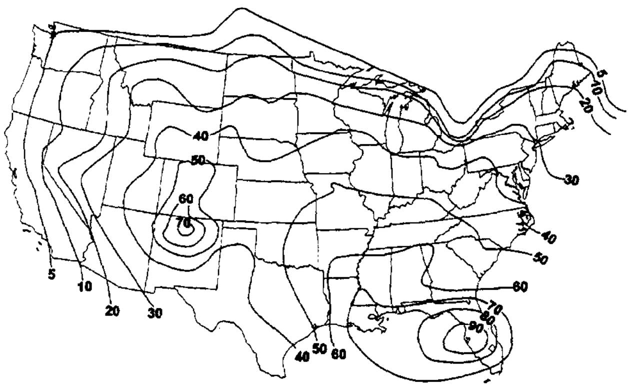

Figure 2 - Isoceraunic map showing the average number of thunderstorm days per year in the United States, from Weather Bureau statistics.

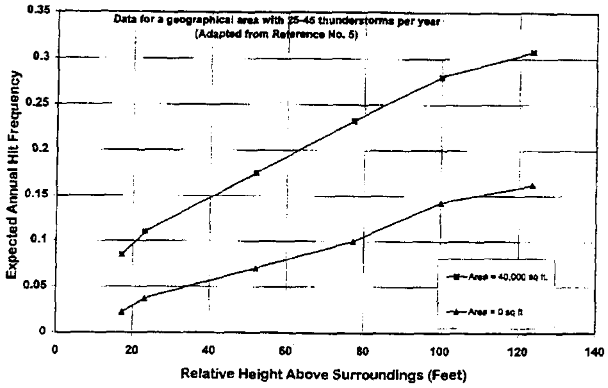

Figure 3 - Lightning Hit Frequency for Short Structures

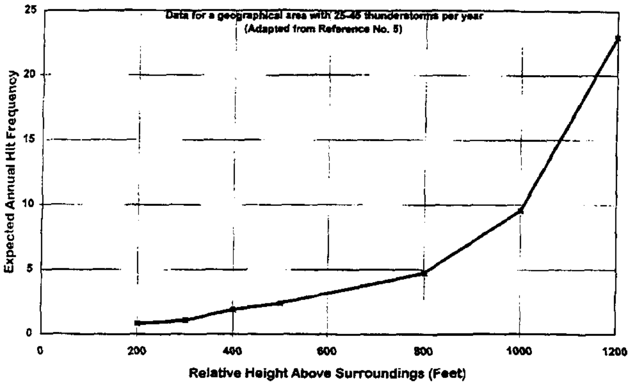

Figure 4 - Lighting Hit Frequency for Tall Structures

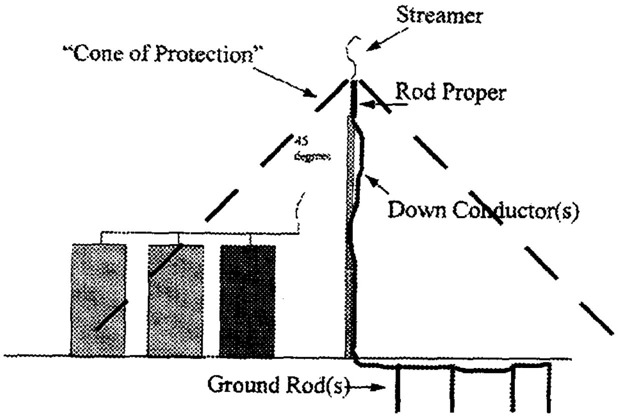

Figure 5 - Schematic of Lightning Rod System

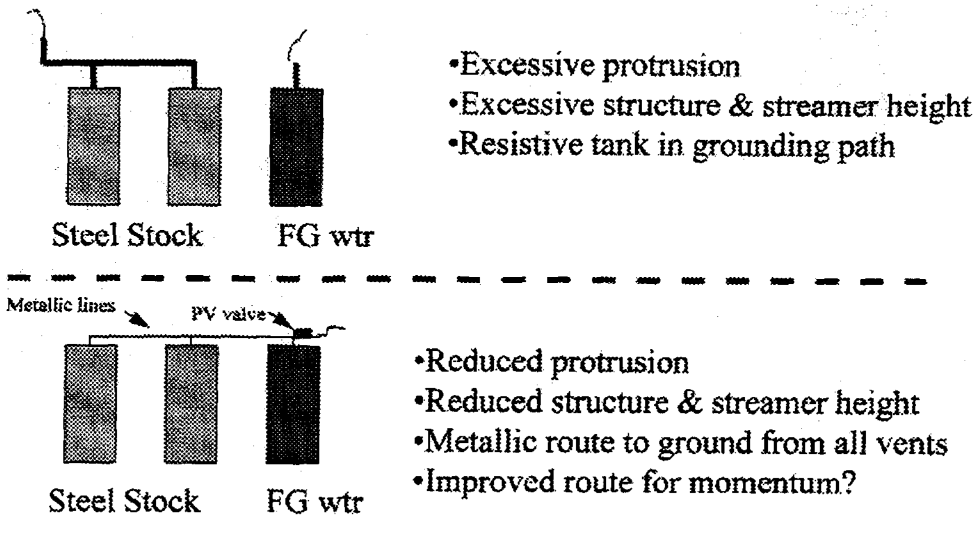

Figure 6a & 6b - (6a) Higher Hit and Damage Probability. (6b) Lower Hit and Damage Probability