



API/EI Research Report 545-A

Verification of lightning protection
requirements for above ground
hydrocarbon storage tanks

First edition, October 2009

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FOREWORD

This publication has been produced at the request of the API RP 545 Task Force and the EI Electrical Committee.

It collates a number of research reports produced by Culham Electromagnetics and Lightning Limited (Culham) who were commissioned to investigate the lightning phenomena and the adequacy of lightning protection measures on above ground hydrocarbon storage tanks.

Currently international, British and United States standards contain requirements relating to lightning protection; however, these have not been verified through practical, scientific testing. As a result of the work commissioned by the API and EI, a new Recommended Practice (RP) is being developed which will incorporate the results of this investigation.

Suggested revisions are invited and should be submitted to the director of standards, API, 1220 L Street, N.W., Washington, D.C. 20005 or The Technical Department, Energy Institute, 61 New Cavendish Street, London, W1G 7AR.

API/EI RESEARCH REPORT

VERIFICATION OF LIGHTNING PROTECTION REQUIREMENTS
FOR ABOVE GROUND HYDROCARBON STORAGE TANKS

PHASE 1

EXECUTIVE SUMMARY

CUL/LT-0234

REVIEW OF LIGHTNING PHENOMENA AND THE INTERACTION WITH ABOVE GROUND STORAGE TANKS

This document describes the phenomena of lightning, and how it is expected to interact with various types of tank designs, in particular with respect to the problems of hydrocarbon fires. It draws on the experience of refinery and tank farm visits by the author, including those reported in EI-Vis1-01 *Visit to oil refinery A* and EI-Vis2-02 *Visit to oil refinery B*, and other sources. The likely strike points on all types of tanks are described, and the current routes over tanks are shown for the fast and slow lightning components. The shunt/rim seal region for an open top FRT is shown to be the most susceptible to ignitions. Aluminium roof geodesic tanks appear to be the most likely type to suffer hot spots and burn through. The electrical properties of steel as a material for tanks is described along with descriptions of thermal and voltage sparking. Protection strategies for open FRTs, for roofed over tanks, and LPG tanks are described. Comments are made on the problems associated with petroleum product within the pontoons or on the surface of a floating roof. An analysis of the operation of the shunt/shell bonding cable suggests that it would play a vital part in suppressing sparking from the continuing current component of lightning, although it would play only a minor role in suppressing sparking from the fast component. The principal USA/UK lightning protection and oil industry documents are reviewed for their content on lightning protection of tanks.

CUL/LT-0235

REVIEW OF TANK BASE EARTHING AND TEST CURRENT RECOMMENDATIONS

The earthing of a storage tank may have important considerations for safety, and protection of instrumentation on the tank, but in practice the tank is likely to be intrinsically well earthed simply by its construction. Even so earthing rods should be (and are) generally used as recommended by international standards. Quality of earthing has little or no significance in storage tank fire protection. The document also discusses the likely currents which shunts may have to carry (up to 11 kA).

EI-EN2-04

LIGHTNING TESTS TO TANK SHELL/SHUNT SAMPLES

Tests at Culham replicated shunt/shell interfaces and subjected them to conducted lightning-type currents. Even clean steel shunt/shell interfaces sparked. Fast current components produce relatively small sparks, whereas long duration currents produce copious spark showers that are believed to be more hazardous. (In practice good protection against the latter currents can be achieved using a roof bonding cable.) Different shunt materials could also present less of a hazard. Currents in immersed shunts tended to cause an eruption of fluid, due to the arc pressure.

EI-VIS1-01

VISIT TO OIL REFINERY A

EI-VIS2-02

VISIT TO OIL REFINERY B

Describe the features seen during two visits to refineries. Some of the practical difficulties of providing and maintaining lightning protection in the field and over many years are observed and discussed, and some photographs are included.

EI-TN1-03

REVIEW OF BURN-THROUGH AND HOT-SPOT EFFECTS ON METALLIC TANK SKINS FROM LIGHTNING STRIKES

Discusses the threat of lightning strikes puncturing steel or aluminium tanks, or of causing internal hot-spots. Aluminium is easily punctured, and so geodesic roofs which use aluminium skins < 2 mm thick would be a hazard if they contained vapours within the flammable range. Steel skins 5 mm thick would not be expected to be punctured by a lightning attachment. Hot-spot hazards for such thick skins have not been investigated, but could be a hazard for severe strikes.

MAIN CONCLUSIONS AND RECOMMENDATIONS

1. Potential ignition hazards exist particularly at shunt/shell interfaces (for open top FRT) and geodesic roofs. The nature of the hydrocarbon, as well as temperature and ventilation, determines whether the vapour could be within a flammable range.
2. Sparking at shunts is inevitable, and is more severe for the long duration currents. Such sparks tend to fall downwards into the seal region, and any gaps between the seal and the shell would increase the likelihood of flammable vapour ignition. Therefore maintenance of the seal is important.
3. The severity of sparking can be significantly reduced, by using earth cables from the floating roof to the shell, or bonding via the ladder.
4. Immersed shunts should present a good solution to hazardous shunt sparking.

CUL/LT-0234**REVIEW OF LIGHTNING PHENOMENA AND THE INTERACTION
WITH ABOVE GROUND STORAGE TANKS****CONTENTS**

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1 INTRODUCTION: THE LIGHTNING PHENOMENON AS RELEVANT TO ABOVE GROUND STORAGE TANKS

1.1 GENERAL

This section provides a summary of the present knowledge on the lightning flash process and attachment mechanism so that the hazard to tanks can be described in terms of natural lightning behaviour.

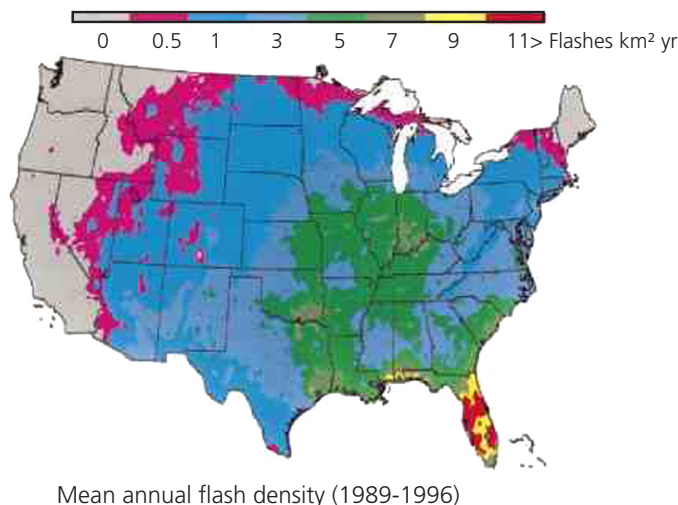
1.2 LIGHTNING STRIKE RATES TO GROUND AND ISOKERAUNIC LEVELS

Taking lightning generally, there is a very large variation in strike rates to ground over the whole globe. This is illustrated in the world isokeraunic map shown in Annex C. Such a map is not ideal for determining the risk to ground structures since it is a measure of the number of thunderstorm days per year, which can only be turned approximately into the desired parameter, that of strike rate/km²/year. A rough formula for this is given in Equation 1:

$$(1) \quad N_g = 0.04 T_d^{1.25} + 300\%/-60\%$$

where N_g is the average strike rate in strikes/km²/year to the ground, and T_d is the ceraunic number, that is, the number of thunderstorm days a year. There are, however, maps of N_g itself available for many parts of the world, mainly those countries that have invested in lightning measuring systems like UK, USA, and some European countries. An example of such a map is shown in Figure 1. Equivalent information for the UK is given in BS 6651:1999 *Code of practice on protection of buildings against lightning*.

Figure 1 Ref 1013 Huffines and Orville American meteorological society lightning ground flash density and thunderstorm duration in the continental United States: July 1999



However, in the absence of such data, Equation 1 can be used to give an approximate value. Knowing N_g , the local strike rate, the risk of a strike to any oil processing or storage tanks can be established, essentially as a simple calculation of the ground surface area of the plant multiplied by N_g . (There are a few refinements to put into this calculation to allow for ground topology, height of structures etc, but this is the basis of the calculation of strike risk.)

Thus the likelihood of lightning damage varies very widely all over the world being highest in humid tropical areas, (≥ 10 strikes/km²/year) and very low in very dry and very cold areas (< 1 strike/km²/year). (The risk of damage also depends on the type of plant: see below.) Lightning also varies according to the season and the time of year. In the UK for example, the highest lightning activity is in the summer. A diurnal variation is also evident. (A statistical correlation between actual tank fires and thunderstorm days has been included in previous LASTFIRE documentation^[5].)

1.3 ELECTRICAL PARAMETERS OF LIGHTNING

The currents in any lightning flash (a flash usually comprises several components or strokes) can range from just a few kiloamperes (kA) up to over 100 kA. This applies to short duration strokes, each of which lasts no longer than 100 microseconds (μ s).

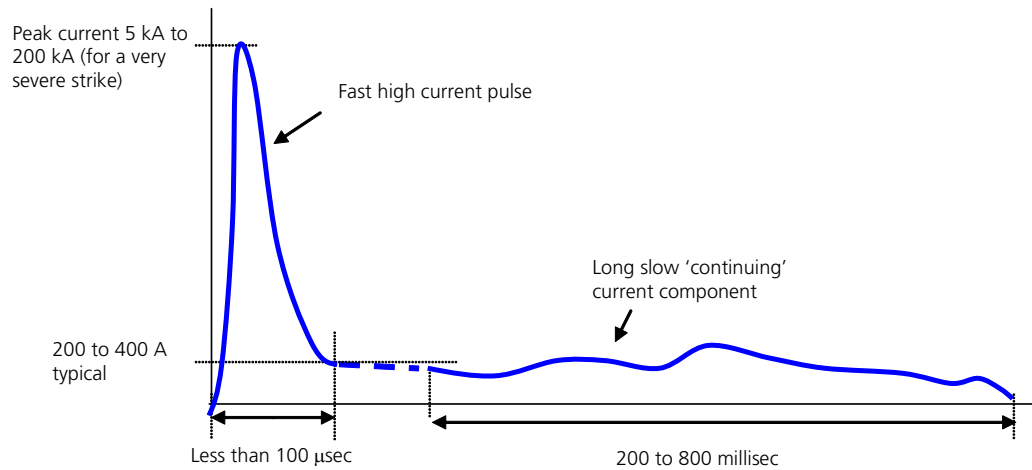
There are also long duration components called 'continuing current' which can be of the order of two or three hundred amperes, lasting up to a few hundred milliseconds (ms). Most of the lightning flashes that strike oil plant will be negative ground flashes, i.e. they come from a predominantly negatively charged region of the thunder cloud. These include high current and sometimes continuing current components and are depicted schematically in Figure 2. This is the main type of lightning to be considered for protection of plant.

Sometimes positive ground strokes occur, though much less frequently, but their characteristics are different. They are usually one long current pulse; often with as high an amplitude as negative flashes, but the duration is so long that the heating and force effects on conductors will be much larger. The positive flashes have a lower rate of change of current than the negative flashes. Thus some aspects of the positive flashes are more severe, and some aspects of negative flashes are more severe, but both types have a wide range of parameters.

Since negative ground flashes are more common, lightning protection is usually based around the characteristics of negative flashes, but with due allowance for where the positive flashes are more severe.

Figure 2 gives an indication of the two most important components, the fast high current pulse and the long slow, low amplitude continuing current. Table 1 gives a summary of the parameter ranges for positive and negative flashes.

Figure 2 Schematic diagrams of the high current and the 'continuing current' components of a lightning strike. Note that the amplitude and time scales of the two waveforms are very different.



Negative flashes can comprise one stroke only, or a quick succession of strokes. Positive flashes normally occur as one continuous flash, with a high peak current and continuing current.

Table 1 Lightning flash parameters

		Percentage exceeding the tabulated parameters		
		95 %	50 %	5 %
Negative flash	1st return stroke kA	7	33	90
	Action integral $10^6 \text{ A}^2\text{s}$	0,006	0,055	0,55
	di/dt kA μs	9	24	65
	charge coulomb	1,3	7,5	40
	Subsequent stroke kA	4,6	12	30
	di/dt kA μs	10	40	160
	No of strokes	1	3	12
Positive flash	Action integral $10^6 \text{ A}^2\text{s}$	0,6	35	250
	di/dt kA μs	0,025	0,65	15
	charge coulomb	20	80	350

Note: some of the parameters quoted here are more severe than are generally used for lightning protection calculations. This is because they are for the much less common positive flashes, so a weighted average is used to obtain the working parameters for protection design. The top limit parameters usually employed are:

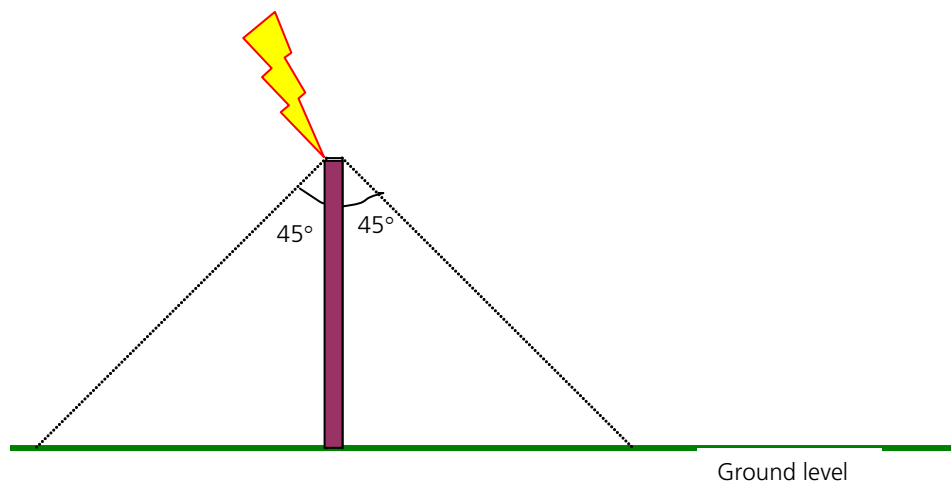
1. $I = 200 \text{ kA}$
2. Action integral = $2.25 \cdot 10^6 \text{ A}^2$
3. Total charge = 200 coulomb
4. $di/dt = 140 \text{ kA}/\mu\text{s}$

1.4 LIGHTNING RISK AND PROTECTION PRINCIPLES

One important fact of the lightning strike to ground phenomenon is that unless ground objects are very high (>150 m) those objects have no influence on the occurrence of lightning in the area. The lightning leader on its way down from the cloud is not affected by ground objects until it is very close to them, say 100 m or less. That is, lightning occurs because of natural processes in the cloud which are virtually unaffected by the ground nature (unless it is mountainous or has very high structures as above). Therefore, in calculating the risk, the presence of the refinery, tank farm etc. makes no difference to the strike rate to that region, so simplifying the risk calculations.

Furthermore, lightning conductors only have a very limited range of 'attractiveness' (normally represented as a 45° right circular cone around the conductor, see Figure 3) and although many attempts have been made to improve the attractiveness of lightning conductors, none has been shown unequivocally to be more effective than the plain lightning conductor, often called a franklin rod. For example, radioactive rods were once promoted as having extra attractive properties, but the claimed 'super-attractiveness' has been discredited (it has been shown by extensive comparative tests and by reference to the physics of radioactive emitters that the devices have no influence on the path of lightning leaders). Radioactive rods have been banned in many countries because the attractiveness is no better than a franklin rod, and because of the potential for causing environmental pollution and health hazards.

Figure 3 'Cone of protection' principle for lightning protection. Objects within the cone shaped volume beneath the dashed lines, all around the vertical pole are within the 'cone of protection', and are at much lower risk from direct strike attachments.



1.5 THE LIGHTNING CLOUD APPROACH, INDUCTION CHARGING, AND SPACE CHARGES

Normally under fine weather conditions there is a steady but weak vertical electric field at the earth's surface. This field is quite weak and very steady. No actual potential differences can be measured between grounded objects, except those which are electrically isolated ('floating' in electrical engineering terminology), because the current flow is zero and all

objects are grounded i.e. joined together. The charge is distributed all over the ground itself and over grounded objects in a way depending on their shape. Horizontal flat surfaces have a very uniform charge distribution (i.e. a similar surface charge density everywhere). The highest surface charge occurs on thin pointed objects like church spires, tops of aerials, tops of lightning rods etc. Where the surface charge is highest the local electric field is the highest (and is the point from which an upward ground streamer could rise to meet the descending leader, described in 1.7).

Thus in fine weather, a static condition prevails with a steady vertical electric field, virtually no ground currents and a small distributed charge on the ground and on grounded objects and structures. This gives way to a different situation on the approach of the storm cloud (assumed negatively charged for this discussion, as is normally the case). The approach of the cloud gives a slow movement of the ground charge and a change in sign. The ground now acquires a much larger distributed positive charge and there is a larger negative vertical electric field. The build up of this positive charge is called induction charging, and is accompanied by a slow movement of ground charge i.e. a small ground current. This small ground current produces the slow replacement of the original small negative charge by the much larger positive charge. By this process a large area underneath a storm cloud has a positive charge, which drifts along the ground surface underneath the cloud as the cloud moves. As before, all earthed objects stay at the same electric potential, but as before, elevated sharp objects will have a very high electric field on the top, but negative not positive. The field may be high enough on some objects to give corona or brush discharges or the well-known maritime phenomenon of St Elmo's fire. Corona, brush discharge and St Elmo's fire are low current effects, not like lightning, and are associated with average currents of microamperes to milliamperes. All sharp pointed upward facing items will tend to give a small current into the air, like leaves on the tops of trees, aerials, and lightning rods. This will often be a silent invisible discharge of only a microamp or two.

All such items are passing current into the air, which is normally a very good insulator, and form a space charge in the air of positive polarity; the size and distribution of the space charge depends on the number of current emitters, their height and especially the wind conditions, because the space charge is attached to air molecules and moves with the air. The presence of the space charge gives a screening effect over the emission points because it reduces the electric field, and often limits the maximum field obtained at the emitters. This process is called space charge screening (or shielding).

Sometimes the surface charge obtained by the induction process on tanks etc. is called a 'bound' charge, but this is a misleading term and is a misnomer because the charge is not 'bound' when it is on the surface of a conductor. It is free to move either slowly, as the clouds drift over the earth, or quickly if a potential difference between the roof and the shell occurs, for example through charge relaxation of the oil, resulting in sparking. The closest any charge becomes to being 'bound' is the charge within the oil itself from frictional charging as it passes through pipes, since its decay is determined by a time constant based on the volumetric resistivity of the product and normally cannot discharge quickly, since the resistivity is very high. Because the resistivity is so high, it plays no part in the conduction of lightning current. The movement of the induction charge on the metallic roof is not 'bound' and depends on the inductance of the roof and the arc at the sparking point, which will be very low. (The term 'bound' charge will not be used subsequently in this document.)

1.6 ROOF SURFACE CHARGING OF TANKS AND BULK PRODUCT CHARGING

This process of induction charging and the surface charge caused by it on the top of tank roofs should not be confused with bulk charging of the product by frictional effects as occur when it is pumped through filters and pipes (see 1.5). This is a quite different effect but it will be responsible for a small current into the shell, floor and roof of a tank as the charge relaxes. However, both the induction charge process and the product charge decay need adequate conductivity between the roof and the shell, which normally will be provided without the need for an earthing cable between the tank shell, by the shunts, the ladder, and the roof drain and so will maintain the roof at the same d.c. potential as the shell. As noted in section 2.1(a), the bonding cable is required for lightning purposes, to short circuit the slow current component. With certain reservations the shunts are usually adequate to carry the fast lightning current pulses, and are the principal current route for the fast component on and off the roof.

It is important to note that in a tank that has an adequately earthed roof, the lightning cloud induction charging process does not cause static charging of the product. The tank roof and shell form a 'Faraday cage' with no electric fields inside, and therefore there is no charging mechanism. Thus lightning has no connection with bulk charging or discharging of the product, as long as the floating roof is effectively earthed to the shell.

1.7 ATTACHMENT PROCESS TO TANKS AND GROUND OBJECTS

Prior to a lightning flash the electric conditions are usually fairly static, with the induction charge on the ground, and on the shell and roof of tanks, with the highest vertical electric field regions being the top of the shell, including the top of any hand rails, lights or other metal objects on the top of the shell, and for a big tank, the tops of items on the roof such as the support leg tubes. This will be particularly so for large tanks when they are above two thirds full or so. This is an important consideration because in the subsequent attachment process any of the items mentioned above could be locations for a lightning strike attachment.

In the usual scenario, the lightning process starts in the clouds, with a stepped leader descending to earth. The stepped leader often exhibits branching on its path to ground as the leader attempts to find the best route to ground. The path of the stepped leader is very irregular because of random variations in the local air conditions and other factors. When the stepped leader is within about 100 m or less from the tank (or ground), the electric field at ground level rises sharply, and the electric field on the highest items becomes high enough to launch an upward streamer towards the down-coming leader. In fact, two or more streamers may rise almost simultaneously from ground objects (tanks, vents, trees etc.) but only one usually is successful in making the connection to the downward leader. When this connection is made the return stroke starts, the high current pulse which gives the bright flash and the thunder, see Figure 4.

The first such stroke is called the 'first return stroke' and is usually the stroke with the highest peak current (average of about 30 kA) and is the longest of the high current pulses, although it is only up to a few tens of microseconds long. Sometimes this is followed by a subsequent stroke (or strokes) of lower amplitude. These are called the fast components. Between subsequent strokes, or immediately following the last stroke, 'continuing current' may flow, referred to as the slow component. Most flashes, including all subsequent strokes and continuing current, take no longer than one second in total, and often much less.

It is standard nomenclature to name the point at which the lightning arc connects with the ground or structure as the 'attachment point'. Names such as the 'entry' point or 'impact' point are not adequate names because it is not useful to distinguish between an

'entry' point, or 'exit' point. The term 'impact' implies that something is thrown down from the sky; all that does happen is that the air is ionised on the route of the current, but no actual downward movement occurs except electrons which pass along the ionised path.

The return stroke current has a high amplitude, (5 kA to 200 kA), and is fast (a few microseconds), and flows as an inductively dominated sheet of current over all objects and the ground. Because of the high rates of change of current in the return stroke and subsequent strokes, the high self-inductance (L) of the roof to shell earth cable (where fitted) would produce a high voltage along it from the relation:

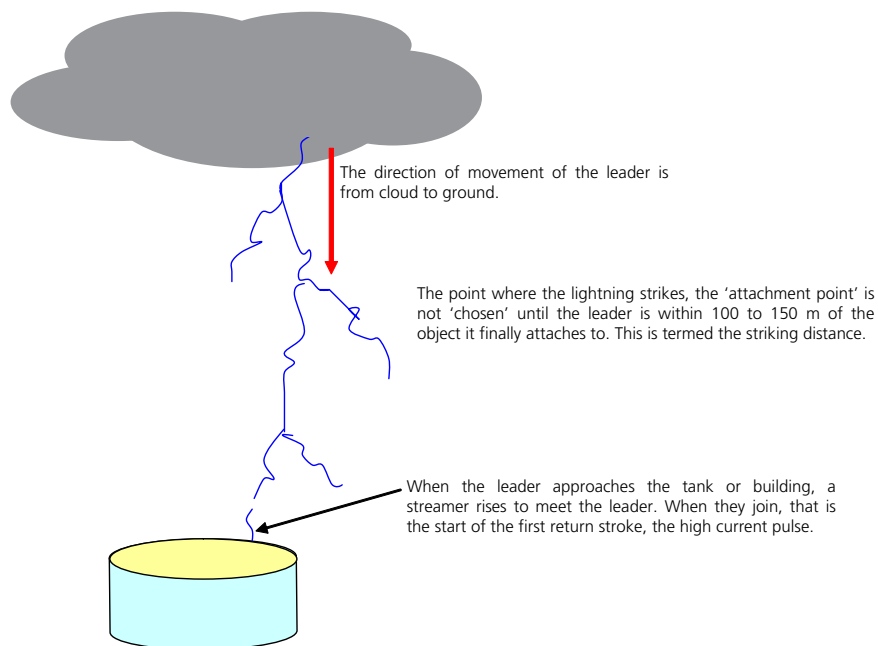
$$(2) \quad V = L \, di/dt$$

For L equal to say 15 μH , and di/dt equal to say 100 kA/ μs , $V = 1.5$ megavolts (momentarily), and this voltage will ensure that the current will flow through the shunts with the potential for sparking. A further point to note is that once a strike has occurred, to the shell, the roof, or nearby, no type of lightning air termination (Franklin rod, radio-active, ESE, or anti-lightning dissipation array) will affect the subsequent route of current.

From wherever the attachment point is, the current will flow as a sheet of current over all conducting objects, up and down the shells over tanks, across the roofs, along the pipes etc. as the current spreads out over a large area, discharging the surface charge.

Thus the role of the air termination system is over once the first return stroke path has been established; the current path is dominated by the shape of objects, their conductivity, and especially the inductance. This applies equally to nearby strikes (i.e. strikes within a few tens of metres) as it does to strikes to the tank itself.

Figure 4 The process of attachment from a lightning cloud to a tank: a stepped leader descends to close to the ground object (tank, building, etc). When it is close an answering streamer rises from the top of the tank shell, or other salient items, to connect to the down coming leader. When they meet the high current lightning flash commences



2 THE INTERACTION OF LIGHTNING WITH STORAGE TANKS

2.1 FLOATING ROOF TANKS (FRT) AND LIGHTNING INDUCED FIRES

Well maintained FRTs are generally a very safe form of storage, but a survey by LASTFIRE has shown that out of the 55 rim seal fires investigated for the survey, 52 of these were caused by lightning^[5]. It is prudent therefore to see if this predominant cause of fires can be eliminated or at least substantially reduced.

The lightning hazards are as follows:

(a) Lightning current attachment to any part of the tank, its shell, instrumentation, on the top (i.e. the dip tube) or to any part of the tank floating roof is a hazard. Strikes to the ground nearby and nearby objects can also be a hazard. Wherever lightning attaches it will cause a large current to flow over the tank shell, across the rim seal shunts and so cause sparking (See Figures 5a, 5b and 5c). The parts of the tank most likely to be struck on a tank are shown in Figure 6.

It is not true that lightning will take only the direct route to earth, (i.e. it will not only follow a lightning conductor straight down to ground). It will instead share between paths according to inductance which means, for a strike to the top of the shell, some will flow over the outer skin of the shell to ground, some on the inner skin down to the level of the floating roof, then across the seal on to the floating roof itself, across the roof, and on to the shell the other side, up and over it down to the ground on the outside.

Note that current does not flow through the metal sheet of the shell, only on the skin surface (See Annex A). This will lead to incendiary sparking as it crosses the seals between the floating roof and the shell. Calculations performed for another similar safety review of a floating roof tank in the UK showed that a voltage, of the order of 60 kV is initially available to drive current through the shunts with the consequent risk of sparking. This mechanism of incendiary sparking has not been described previously in the literature, except in an AEA report^[6] and the LASTFIRE lightning report^[17], but is a very real possibility in open topped floating roof tanks.

A strike to the floating roof itself (or to any projecting item on it) will be worst of all, because all the current has to cross the seals. (The static bonding cable, if fitted, will not prevent this effect as explained above, although it might limit the sparking to only that from the fast return strike, but the slow continuing component might well be shunted by the bonding cable.)

(b) At the moment of a nearby ground stroke the very large electric field existing as the leader approaches will very rapidly reduce to almost zero causing the induced charge on the shell and floating roof to flow away. As with the lightning current effect discussed at a), because the discharge is very fast (approximately 10 Ω s or so), the bonding cable, which will normally be several metres long, will not prevent the sparking between the floating roof and the shell owing to the very large inductance of this cable. However there will be very much less energy in such discharge currents than there would be if the tank was directly struck.

The oil product itself is not charged by this electric field mechanism, charge resides only on the top surface of the metallic roof. Because the product is so resistive, it plays no part in the current transfer process for lightning currents on the tank so for this purpose it can be regarded as an insulator. Resistivity values are given in API 2003 *Protection against ignitions arising out of static, lightning, and stray currents*, where it is shown that even the most conductive black oils are $10^9 \Omega\text{cm}$ compared with $\approx 10^{-5} \Omega\text{cm}$ for steel, a difference of 14 orders of magnitude. Even if crude oil had water in it, bringing the resistivity down by

three orders of magnitude, it would make no difference to the principle that the oil is still so resistive it functions as an insulator for lightning pulses.

(c) Indirect effects – i.e. currents induced or injected into cables and any part of the electrical system by the flow of the main current in the tanks or pipes can cause sparking in level and temperature gauges which might occur in regions of a flammable vapour air mixture in the dip tube for example.

(d) St Elmo's Fire (corona, or 'brush' discharge) might be a problem if the tank is, say, two thirds full or more, due to corona on vapour vents such as the roof support pipes, but is unlikely to cause a problem with the roof below two thirds full height.

Figure 5a Current routes for flash to top of shell. Note that the fast high current pulse flows down the inside of the shell and via the rim seals, and across the top of the floating roof. (Only two routes are shown; in practice, current flows all over the top of the roof and crosses the rim seal all around the perimeter of the roof).

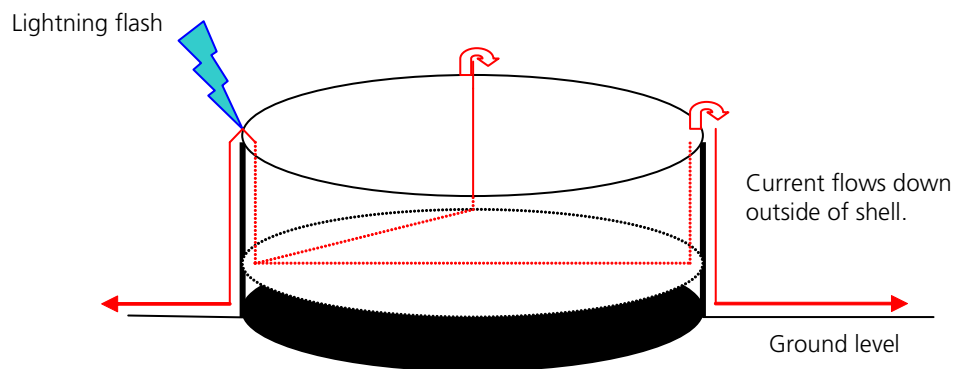


Figure 5b Current routes for flash to floating roof. Note that the fast high current pulse flows across the floating roof in all directions to the rim seals and shunts, and then up and over the shell to ground. (Only if the roof is high is this a likely strike point.)

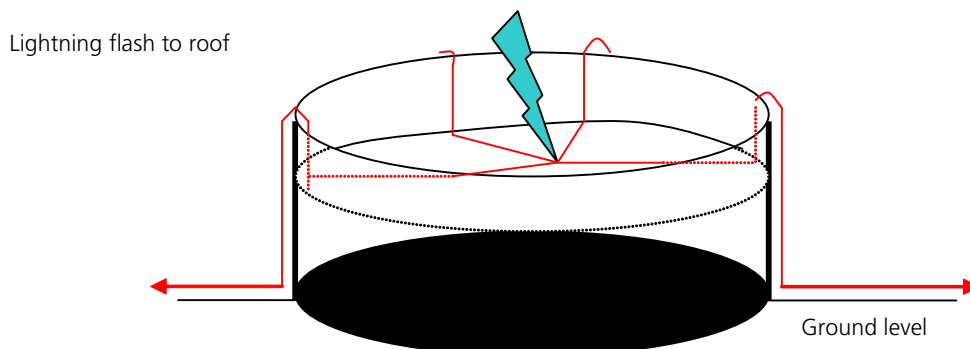
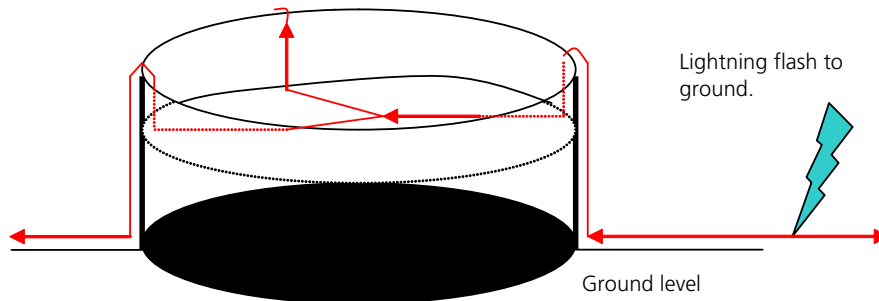
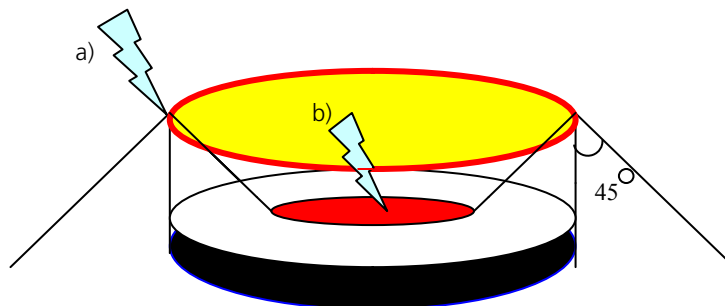


Figure 5c Current routes for flash to ground near a floating roof tank. The current spreads all around from the strike attachment point, including to the tank, up and over the tank and down the far side as shown by the typical current flow lines and arrows. This current flow plan would only apply to the fast high current pulse. The continuing current would flow along the ground and the tank floor only.



(e) All of the effects described in a) to d) can occur, to a lesser or greater extent, with nearby strikes i.e. those within 150 m radius. The effective range over which item c) can be a problem is even larger, since electrical transients can travel a long distance along instrumentation cables and pipes.

Figure 6 Open top floating roof tanks. Possible strike location points for a tank: (a) anywhere around the top edge of the shell and (b) the floating roof (very low probability).



Effect of 'cone of protection':

- Only the top edge of the shell, shown in heavy red, and the region in red on the roof can be attachment points for lightning strikes.
- When the floating roof is high, the red area is larger, and conversely, when the roof is low, the red area is reduced to a small zone in the centre of the roof. No other parts of the tank are liable to take a direct attachment, including the rim seal region.

2.2 DISCUSSION OF LIGHTNING INTERACTION WITH OPEN TOP FRTs

Generally speaking, all of the hazards from lightning tend to be worse when the tank roof is high, although in mitigation there is more chance that wind action will disperse more efficiently any vapour that may be present. On the other hand, even with the roof low, roof to shell sparking is still a potential problem, and a fire started low down in say a crude oil tank may be made worse by exposed wax on the shell inner wall, and the accumulation of vapour, and the enclosing effect of the shell.

A further point that affects the situation very strongly is the type of seal design and its condition of maintenance. Numerous different seal designs are still used, dating back from tanks built about 50 years ago to recent tanks. Some tanks have very good shunts across the top seals, with a strong pressure on the tank shell, while others have far fewer shunts and less pressure. It is not obvious a priori which design is the best. A further variable is the type of petroleum substance in the tank, i.e. whether it is crude oil, which can deposit a waxy layer on the tank shell; or gasoline, where the tank shell is clean but rusty. A further variable is the height of the secondary seal, compared to the height of the foam dam (see Figure 10). The foam dam presumably has a most unwelcome effect, which is to form a 'pool' of vapour between the dam and the tank shell. If the secondary seal/shunt contact point is higher by tens of centimetres than the dam, it is unlikely to be in a region of combustible vapour/air mixture. Seal designs are discussed further in section 4.

2.3 LIGHTNING INTERACTION WITH OTHER TYPES OF ABOVE GROUND STORAGE TANKS

The other types of storage tanks used for petroleum product storage comprise three main types:

- (i) Tanks similar to floating roof tanks but with a light roof of either aluminium or fibre glass, e.g. the geodesic type roof, used for excluding water from the tank and for minimising vapour loss. Also used if the floating roof has to be replaced by an open tank since a much lighter construction floating roof may be employed. These are one of the more vulnerable types of tank to lightning unless certain precautions are taken.
- (ii) Cone roof fixed roof tanks, with trusses and sometimes vertical supports for a shallow cone shape roof. These are usually all steel, and, as with the tanks in 2.3(i) are atmospheric tanks, i.e. they operate at the same pressure as the atmosphere, either through permanently open vents, or sometimes with a pressure – vacuum vent. These tanks are not designed to withstand a pressure difference between inside and out. Sometimes these tanks have some type of floating roof (a 'floater'); the internal floating roof is however usually a much lighter construction than the open topped floating roof. As for (i) above, these tanks can be vulnerable to lightning because of the possibility of a flammable vapour/air mixture inside.
- (iii) Cylindrical or spherical pressurised tanks for LPG. These tanks are designed to store liquefied gasses such as propane and butane under pressure, and are normally fully welded (and gas-tight) steel tanks with no possibility of ingress of air into the tank. The tanks in (i) and (ii) will often enclose a vapour/air mixture above the liquid, which, under certain circumstances, might be flammable, but the LPG tanks being fully sealed and pressurised will, under all normal circumstances, contain only the liquefied gas. They are inherently the safest storage tank with respect to lightning risks, and skin effect keeps the lightning current on the outside of the steel sphere, so the tank contents are totally unaffected by lightning.

2.4 LIGHTNING INTERACTION WITH GEODESIC LIGHTWEIGHT ROOFS

There are two types to consider: (a) aluminium conducting roofs, and (b) fibre-glass or similar non-conducting roofs.

2.4.1 Conducting e.g. aluminium roof tanks

This type of tank has several characteristic aspects that make it potentially vulnerable to lightning. It does not have the problem of open topped FRTs arising from the current flow over the floating roof and across the rim seal gap where the shunts are located. This is because the induction charging and the discharge current paths will be over the top of the conducting roof, and there will be negligible fields and currents inside. However the roof will be liable to a direct attachment to it, with a possibility of burning through thin aluminium skin panels, and so dropping molten aluminium and sparks into the internal volume, which could contain a flammable vapour/air mixture. Furthermore an attachment to the roof or to the top edge of the shell, or even to a pole fixed to the side of the tank as a lightning conductor, could still produce a fire or explosion risk from sparking owing to current flow over the roof structure where there are corroded or poor contact joints between the aluminium skin and support structure.

The hole burning problem will be caused mainly by the long slow component of current, because holes are not burnt in aluminium by the fast high amplitude pulse because its duration is too short. Conversely the fast high amplitude current of the return strike is responsible for the joint sparking because the pulse is so fast that inductive current sharing and skin effect dominate the current flow streamlines (and not resistance) so that current from the strike attachment point will flow all over the entire outside skin of the roof and tank, including through corroded or resistive joints giving sparking. All welded construction is to be preferred, so ensuring good joints, but that is not consistent with having a 'lift-off', or bursting disc characteristic for the roof for pressure relief. Adding simple lightning conductors (i.e. the usual narrow tapes) would make almost no difference to the problem because of the inductive effect mentioned above which will drive current all over the entire outside surface of the tank. The current would not confine itself to relatively thin conductors when there is an adjacent large area of metal.

2.4.2 Non-conducting e.g. fibre glass roof tanks

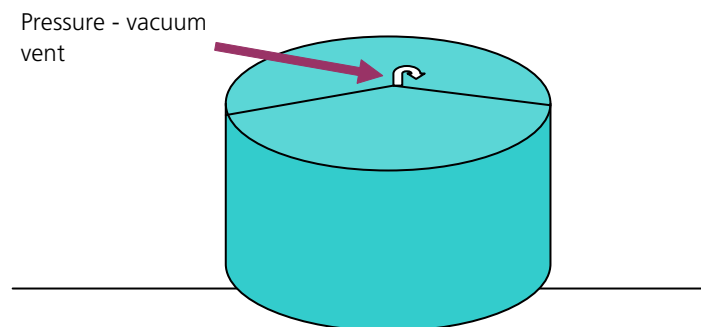
Such a design (although infrequently met with) gives the potential problems of the open top FRT, but with the added danger of the large volume above the internal floating roof. This volume could contain a vapour/air mixture, which could not disperse as easily as for an open top FRT. Strikes directly to the floating roof itself would be very unlikely, since it would require the lightning arc to puncture the fibre glass. If this were to happen though, there would be a severe risk of an explosion if the tank contained an vapour/air mixture. Ventilation or inert blanketing of the volume above the floating roof would be desirable, unless a set of lightning protection conductors were laid over the top of the fibre glass roof. Conductors laid over the roof and bonded into a square mesh of something like 2 m² would go a long way to reducing the current crossing the internal floating roof and hence crossing the seals. The fast return stroke and restrikes would be the main lightning wave-form of concern. The slow components are unlikely to be a problem because of the low resistance to ground from the top of the shell.

2.5 CONE ROOF, OR 'FIXED ROOF' TANKS

The contents of fixed roof tanks are a major factor in safety because of the risk of forming a flammable vapour/air mixture above the liquid. For products where this can happen there is a risk of explosion, unless inert gas blanketing, better seals on internal floating roofs, or ventilation prevent this. Most of the discussion above for aluminium roof tanks applies to fixed roof tanks, although on account of their more substantial construction, the hazards for fixed roof tanks are less. The ideal construction for lightning protection would be an all-welded or very well riveted design so that there are no bad joints between the adjacent steel plates, and so no sparking when the fast pulse of the return stroke passes over the tank. Many fixed roof tanks conform well to this requirement, and so are generally very safe. The main details to be taken care of are the vents, which should be situated where they cannot receive a direct strike, and if the vents are not of the pressure–vacuum type (which are normally closed), flame traps would be needed to avoid ignition of the tank via an attachment to the outlet of the vent. However, flame traps are not without their problems, because they have been known to become blocked, resulting in collapse of the tank. With a steel cone roof, there is no tendency for current to flow inside the tank so the problems with open FRTs do not occur. However, good house-keeping is essential e.g. not having loose bolts on inspection or access covers or on the bolts securing the vents to the tank.

There is little or no advantage to be gained from installing the usual thin lightning conductor tapes on fixed roof tanks, because as explained above, they would carry an insignificant part of the current.

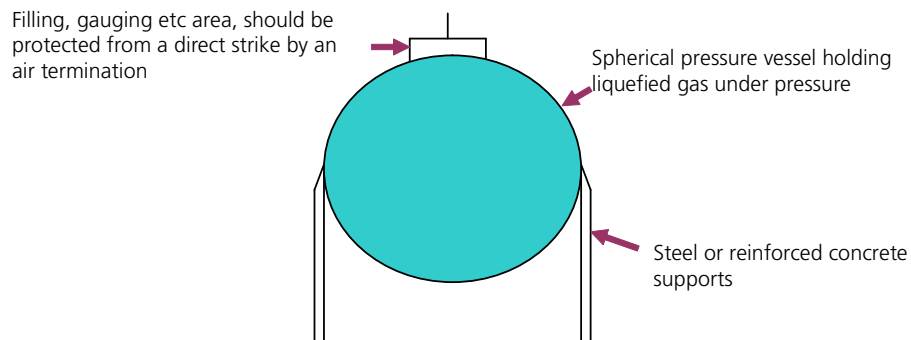
Figure 7 Typical fixed (cone) roof tank with vent at the top. The construction is usually all steel at least 3/16" or 5 mm thick, and welded or riveted. This is generally a lightning proof design. These tanks are usually much smaller in diameter than floating roof tanks.



2.6 PRESSURISED TANKS FOR LPG

This is the safest type of tank because the storage of the liquefied gas under pressure prevents a vapour/air mix from forming in the tank. Also because the tanks are hermetically sealed all welded steel spheres or cylinders, lightning current will stay on the outside as a very thin skin effect current, and will flow to ground without interacting in any way with the tank contents. Thus there is no possibility of incendiary sparking and no mechanism by which sparking could affect the contents. Thus it is to be expected that these tanks would have a very good safety record, which is borne out in practice.

Figure 8 LPG tank, all steel, pressurised, basically a very safe tank for lightning because air cannot get into the tank and there are no sites equivalent to the rim seal of a floating roof tank, where sparking could occur.



3 LIGHTNING EFFECTS ON MATERIALS: ELECTRICAL HEATING AND MECHANICAL DAMAGE; BURN THROUGH AND HOT-SPOTS; THERMAL AND VOLTAGE SPARKING

3.1 EFFECTS DUE TO LIGHTNING CURRENT FLOW THROUGH METALLIC CONDUCTORS

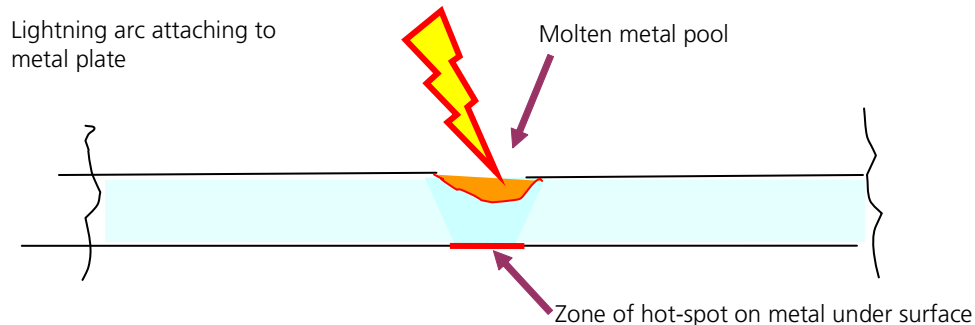
Almost without exception, all of the metal structure and ancillaries of oil storage and processing plant that are in locations where they might carry lightning current are so massive that there is no risk either mechanically or thermally. That is, the mechanical forces caused by the flow of current (electrodynamic forces) and the heating effect ('joule heating'), will normally be negligible compared to the strength and thermal capacity of the steel. This applies even to the usual type of tank rim seal shunts. For even a severe lightning strike, cross sectional areas of only about 10 mm² of copper, 15 mm² of aluminium, or 20 mm² of steel are required to carry the full current of a severe strike. Since the current disperses over many different routes on its way to earth, only within a few centimetres of the attachment point is there a high current density and action integral. Therefore there are exceedingly few places where conducting material will be thin enough to be damaged by lightning current.

3.2 EFFECTS AT THE LIGHTNING ARC ATTACHMENT POINT

Where a lightning arc attaches to any part of the tank, a certain amount of erosion of the metal will occur. For the high current pulse there is usually an insignificant amount of erosion because of the short duration of the pulse. However the long duration, or continuing current, lasts sufficiently long to burn through thin metal sheets or cause hot-spots on the back of thicker metal sheets.

With the usual thickness of steel, (5 mm minimum) there is a negligible risk of lightning being able to melt through steel sheet at the attachment point. The continuing current component is able to melt through just over 1mm if the continuing current charge transfer exceeds about 70 coulombs^[7]. Only a very severe strike exceeds this. (For comparison, aircraft are certificated to the 2 % severity level i.e. only 2 % of strikes exceed the level, which for continuing current is 200 coulombs.) However it is not possible that 5 mm could be melted through although the inside surface will become quite warm. As described in section 2.4.1, burn through has important implications for geodesic dome tank roofs with thin aluminium skins, and might be important for cone roof tanks, but generally not for open floating roof tanks. Also, it is an experimental observation that galvanised steel sheet is very resistant to burn through, even when as thin as 1 mm^[7]. With arc attachment to steel sheets of 5 mm or so thick there is no risk of sparks from the inside surface to other nearby items because the resistive voltages produced by the continuing current are very small.

Figure 9 Effects at the arc attachment point. As well as the molten metal pool (which may go right through the metal, leaving a hole) a hot-spot forms on the underside of the metal plate. It is only the long slow continuing current component that causes this type of damage.



A hazard for very small diameter pipes exists if they are at the top of process or storage vessels or other exposed locations. If the wall of the tube is very thin it could suffer burn through from a lightning attachment; such items should always have a lightning air termination above them, which may be a 'natural' termination like a crane jib, hand rail, light support etc. Only in very few cases will an actual lightning conductor be required. Thus, in summary, very few locations will be at risk from burn through or any other significant attachment point damage.

3.3 DANGER ARISING FROM SPARKING

Apart from aluminium geodesic roofs, sparking is probably the most likely cause of fires from lightning in FRTs owing to the tendency for current from any strike on the tank or closely nearby to drive current across the roof, via the shunts or via any other metal making intentional or unintentional contact between the roof and the shell wall.

There are two types of spark to consider; thermal and voltage sparks:

- (a) A thermal spark is defined as a minute piece of incandescent material which has been ejected from some sparking site, usually a place where tens or hundreds of amps or more are passing through a very poor joint, such as the contact point from a shunt on to the inner shell wall of an open floating roof tank, or from a poorly bolted flange joint etc. The white hot metal sparks falling from welding operation are examples of thermal sparks, which are actually very small particles of metal, burning as they fly through the air. Usually they are less effective as incendiary sources than voltage sparks.
- (b) A voltage spark is quite different. It occurs in a location with a small gap between conducting items where the lightning creates a voltage large enough to cause electrical break-down of the air or vapour/air mixture in the gap. A spark in a car engine spark plug is an example of a voltage spark.

Voltage sparks with an energy above 0,2 mJ could be sufficient to ignite product vapour/air mixtures if they are slightly richer than the stoichiometric mixture. For mixtures away from the optimum, the energy requirement is higher, but even so the energy in lightning induced sparks is likely to be many orders of magnitude higher than this; that is, lightning induced arcs are very powerful ignition sources.

Both types of spark are very incendiary as shown in work at Culham as part of their research into aircraft fuel system lightning hazards; in particular to examine and understand thermal and voltage sparking^[8, 9, 10, 11].

A poorly contacting rim seal shunt on an open FRT is an example of where sparks might occur under lightning conditions. The small contact area and, in practice, the presence of surface treatments or contaminants are conducive to sparking. If there is an oxide layer on the shell or the shunt, the spark will initially be a voltage spark to break down the insulation, followed by current flow in a poorly contacting area giving a flurry of thermal sparks. Normally, non-sparking joints for high current purposes need large areas of contact with clean surfaces and high contact pressure. The problem is potentially worsened by the fact that the electrodynamic force arising from current flow between the shell and the shunt will be in a direction so as to push the shunt away from the tank wall, so making the sparking worse, although in practice the force will be very small unless the roof is very high and the strike occurs to the shell very close to the position of the shunt. It should be noted that because the shunts are normally within the cone of protection of the shell, there is a negligible risk that a strike will ever occur directly to the seal region or to the shunts themselves. Thus the principal sparking problem should be considered as a secondary effect of lightning, i.e. due to current flow from an attachment point which is at least some little distance away. Although previous documents have said that lightning might damage the shunts, the more recent work based on lightning testing shows that while no physical damage is likely to occur, sparking is nonetheless a real hazard^[17].

4 FLOATING ROOF RIM SEALS AND THE LIGHTNING INDUCED FIRE PROBLEM

4.1 INTRODUCTION TO SPARKING AT SEALS

The detailed design of seals including (a) the primary, and (b) secondary seals (where fitted), and (c) the location and design of the shunts (where fitted) and maintenance, play an overriding part in whether incendiary sparking and fires might occur at the seals of open topped FRTs. As described in section 2, a lightning strike anywhere in the vicinity will drive a current across the surface of the roof and will flow on and off the roof via the shunts or other contact points. Where the shell is either corroded or contaminated with non-conducting material e.g. wax etc. or where there are no shunts, there will be sufficient inductive voltage to cause break-down of whatever gap there is in the form of a voltage spark, and the consequent current flow arcing may give thermal sparks also. Thus incendiary sparking is inevitable and the possibility of a fire will then depend on the location of the sparks, and whether vapour leaks create a flammable vapour/air mixture in the region of the sparks. Thermal sparks for this situation are more of a problem than voltage sparks, because the voltage spark (or arc) is localised at the shunt. Thermal sparks on the other hand spray out and fall from the sparking site and so they can spread their effect over a larger volume, especially below the source of the sparks. A discussion on the current required to produce such sparks is given in 4.3.3.

4.2 FLOATING ROOF SEAL TYPES

4.2.1 Primary seals

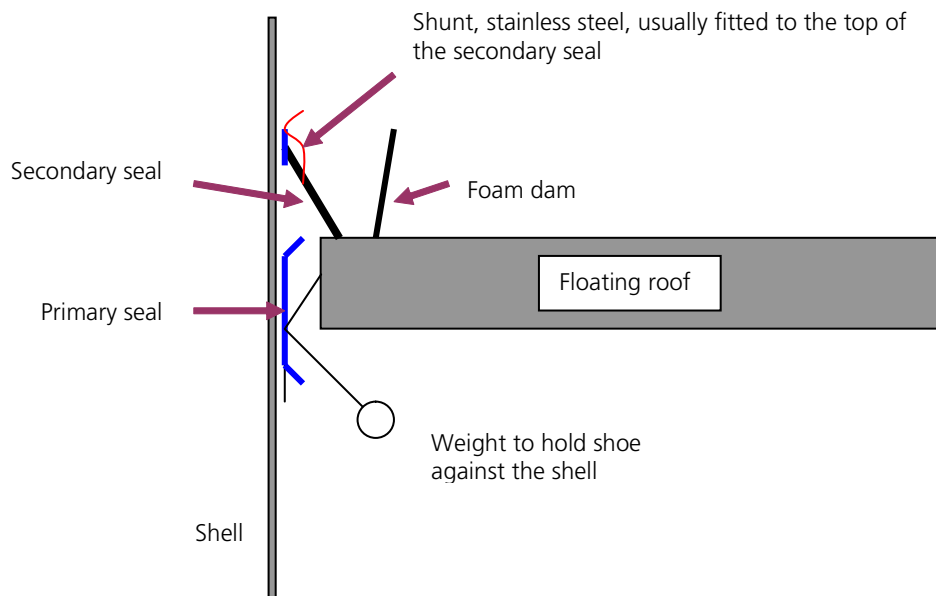
These can be divided up into two main classifications, liquid (or product) mounted (i.e. the seal has the stored product as a liquid in contact with it), or vapour mounted seals (i.e. where the seal is above the liquid surface, having a vapour or vapour/air space between the liquid and the seal). The three main types of primary seal are metallic shoe type mechanical seals, liquid filled seals and foam seals. The metallic shoe type is the oldest, and uses a metal shoe system to slide against the shell, whereas the other types use (normally) a rubberised material to contain the liquid or foam, so that the rubberised material rubs against the shell. Whereas the metallic shoe system provides some sort of electrical contact to the shell from the roof, the other two are in principle insulating or at least very resistive, and might allow static charge to leak away, but would have no effect on lightning. The electrical contact between the shell and the roof given by the metallic shoe seal is probably a big disadvantage, since it could give sparking in a place where there is a possibility of a vapour/air mixture, very close to the liquid, or in the volume between the primary and secondary seals. The use of insulators for the mechanical shoe system will prevent sparking at these locations as long as there are shunts or other conducting paths from roof to shell as alternative safe current routes. Thus such insulators must be used in conjunction with shunts to provide the safe conduction path.

4.2.2 Secondary seals

These seals, as the name implies, are a secondary protection against vapour leaks, and are always mounted above the primary seals, usually in place of the weather shields that have hitherto been used on some floating roof tanks. In some countries there are statutory requirements to fit secondary seals for storage of refined product with a relatively high vapour pressure, to minimise emissions. Secondary seals normally take the form of a flexible wiper mounted on the rim and pressing against the shell, or the 'compression plate' type secondary seals. The compression plates are usually stainless steel at an angle of approximately 35° to the vertical and holding a wiper against the shell, and sealed by a rubber diaphragm all around the entire circumference of the tank. These usually have shunts fixed to the secondary seal so that they contact above the top of the secondary seal where it presses against the shell.

There should never normally be liquid in the space between the primary and secondary seals, but of course, the better the secondary seal works, the more likely it will be that vapour accumulates in the space between them.

Figure 10 Typical floating roof pantograph type primary seal, with secondary seal, shunt and foam dam. The shunt is intended to provide electrical continuity from the roof to the shell.



One of the main problems in seal design is the need to accommodate mechanical imperfections of the tank shell, such as ovality, distortion, effects of settlement of the foundations, and raised items on the shell wall such as rivets or imperfect welds. Thus there are many factors which can make it difficult to ensure 100 % contact of the seals, both primary and secondary, and if mechanical failure is included too, it shows that to minimise losses, and hence to reduce the fire risk, frequent inspection and good maintenance would seem to be essential. One of the main reasons for poor contact between the shell and shunts is out-of-roundness of the shell, often caused by subsidence of the tank shell. Where this opens up gaps between the

secondary seal and the shell, it will often prevent contact of the shunts locally. Gaps between the secondary seals and the shell will allow sparks to fall into the vapour area between the seals from the nearest shunts which are still in contact.

4.2.3 Shunts

These have been fitted for many years to minimise the electrical problems with tanks and often take the form of a spring contact strip, made from stainless steel, fastened to the top of the weather-shield or secondary seal that presses against the shell. They are normally spaced ≈ 3 m (10') apart. As described earlier, these are particularly important for lightning, since although static charging effects should be taken care of by the flexible bonding cable, this lead has a very high impedance for fast lightning pulses, and does not carry much of the current in a strike, apart from the slow component. The shunts, which will have a far lower impedance, will provide the fast pulse lightning current route on and off the roof. However, depending on the absolute current amplitude through each shunt, the physical condition of the contact area and the force with which the shunt presses on the shell wall, it may or may not produce incendiary voltage and/or thermal sparks (see 4.3.3). Also depending on its position relative to the seals and the condition of seal maintenance, sparks produced by the shunt might (or might not) be within, or fall into, a region of flammable mixture.

4.3 DISCUSSION OF SPARKING SOURCES ON SEALS AND SHUNTS

4.3.1 Sparking on metallic shoe type seals

These seals are normally classified as vapour mounted, although in the usual design, the metal shoe is at least partly immersed in the liquid. However, the rim vapour space (i.e. the space between the roof and the shoe) is often vented to air, so allowing direct evaporation from the liquid surface into this volume in which air can freely circulate. Thus with certain stored products or crude, it is possible the rim space contains a flammable mixture which could be ignited by a spark. As referred to in 4.2.1, some mechanical shoe type seals are equipped with insulators to prevent current flow through the mechanism and so prevent sparking. If they are not so equipped this is a severe risk area, and even with insulators there is still a severe risk unless there is a good low impedance alternative path for lightning current to prevent flash-over of the insulators, such as well installed and maintained shunts. Where insulators have not been fitted, there are innumerable possible sparking positions: (a) where the shoe makes poor contact with the shell wall, (b) at joints between the shoe sections, and (c) at any of the linkage joints of the pantograph and weight hangers which are within the rim vapour space. There are a large number of such joints in a big storage tank, see Figure 10. (Note sparking within the liquid is not incendiary because of the absence of air.) The problem of sparking, as explained above, is probably worst when the roof is high and when a strike occurs to the shell top or the roof itself, so giving the highest currents in those shoes or shunts close to the lightning attachment point. As stated previously, it is extremely unlikely that a strike could occur directly to the seals, shunts or the rim vent outlet, even with the roof very high because of the cone of protection principle. Also, since the rim vent will normally be very close to the shell, it is very unlikely that the electric field could be high enough at the exit of the vent to give corona or streamering which otherwise might have caused ignition. Thus in summary, the principal fire problem is sparking at:

- (a) Joints in the pantograph and the shoe if there are no insulators.
- (b) Joints in the pantograph and the shoes if there are insulators but no shunts or any other distributed low impedance connections from the roof to the shell wall.

There is also a problem with sparking at the shunts themselves.

4.3.2 Sparking with liquid and foam filled primary seals

These seals are in effect insulating as far as lightning currents are concerned (although some manufacturers offer static discharging material for the seals which has no effect on lightning). Only if there is a bump device or similar incorporating conducting material or any other aspect of the primary seal which is highly conducting would it be possible to have sparking. Thus, putting other considerations aside, there should not be sparking at the primary seals themselves induced by lightning, but they still require conducting weather shields or secondary seals with shunts to give the necessary electrical contact to the shell. The whole roof cannot be left connected by only the earthing lead to the shell because of the risk of a direct stroke to the roof which would flash-over seals even if there were gaps of several inches. Such a flash-over would produce a very hot and dangerous incendiary arc. Generally, lightning is not a problem with liquid and foam filled seals, as long as the seal region is free from inadvertent metallic conducting paths, but they will need shunts to provide low impedance connections from roof to shell, and for these shunts to be placed above the secondary seals. Experimental data reported in other documents in this programme show that good electrical contact at shunts is in practice difficult to achieve, and that sparking is likely to occur.

4.3.3 Sparking at shunts and weather shields

Shunts are designed to provide electrical contact between the shell and the roof for lightning and static discharge purposes. (The roof bonding cable is not intended for lightning, but it provides a reliable low resistance connection between shell and roof and could well prevent sparking from the slow component, as well as conducting static.) Shunts are spaced about 3 m apart around the seal. As discussed in section 3.3, they do not have the required qualities to be non-sparking contacts, since the contact area is not clean enough or big enough or under sufficient pressure. Determining the threshold level at which sparking occurs can only be effected experimentally, especially when the range of surface conditions is taken into account, including the use of surface treatments to the shell walls and the use of electro-conductive paints^[14]. In work on aircraft fuel systems, sparking occurs in fuel pipe joints, which have poor contact, at currents as low as 1 kA or so, and unless the roof is very low the current will easily exceed this value. With the roof high, a strike to the shell itself of average intensity might be in the order of 30 kA, and the two nearest shunts might be required to carry up to 40 % of the current, about 6 kA each. This is probably well above the sparking threshold for a typical shunt/shell contact. Thus the use of shunts is not a complete cure for the sparking problem, unless methods can be devised to improve the contact conditions so that the threshold for sparking is raised considerably, or the shunt is positioned where sparks do not matter.

(The experimental work on shunts, and discussion on shunts' susceptibility to lightning, which was mostly carried out subsequent to this review, is given in EI-EN2-04 *Lightning tests to tank shell/shunt samples*.)

There are two alternative approaches to the problem, which are concerned with the location of the shunt (and the sparking) with respect to the zone containing flammable vapours. If the shunt contact is located above the top of the secondary seal, given reasonable maintenance of the seals, the sparking will be above the vapour/air zone and as long as there are no other accidental contact points within the zone, any sparking will occur in a region of a very weak mixture, and any thermal sparks occurring should be prevented from falling into the critical zone by the wiper at the top of the secondary seal (see Figure 10 for illustration of this principle). A complication with this scheme is the height of the foam dam. Under normal conditions the dam will tend to accumulate within it any vapour leaking from the seal region. Thus it could be imagined that under fairly still air conditions, and with the roof low, and

with a leaking seal system, that a flammable vapour/air mix could accumulate in the region between the foam dam and the seal. Thus to avoid ignition of this it is desirable to have the shunt contact point as high as, or higher, than the top of the foam dam. This may not be practicable on most tanks because of constraints on the foam dam height with respect to the top of the secondary seal for fire fighting reasons. Also the natural dispersion of the vapour might make this precaution unnecessary, (for example, by the drainage holes at the bottom of the foam dam), so that in practice there may be no need to have the shunt contact point so high. This is a point for discussion and further review.

The alternative method referred to above is to arrange for the roof-to-shell electrical contact to be always immersed in the stored liquid. With this location, any sparks that occur are within the liquid and do not have the necessary air available. This has some disadvantages such as maintenance inspections and repairs and the possible interference with the mechanical shoe system, and wax scraper etc, but there are important advantages in having current flow in a position where there is guaranteed to be no air. This contact system should be compatible with mechanical shoe seals, just as well as with liquid or foam seals, but the voltage available to cause sparking on the insulators of the mechanical shoe system would need to be investigated theoretically and experimentally. (It might be possible to incorporate the contact system into a wax scraper as long as it is always immersed in liquid.)

Owing to the diversity of types of weather shields it is difficult to make general comments, but any type which corresponds electrically to a secondary seal with a contact to the shell above its rubbing edge at the top will have a similar general characteristic. That is, sparks which occur at the contact points will only be prevented from causing ignitions if they are outside the interspace, and are prevented from falling into the interspace.

4.4 LIGHTNING RISKS TO OPEN FRTs FROM SURFACE PRODUCT AND LEAKS INTO PONTOONS

4.4.1 Lightning risk from product on the top surface of open floating roof and roofed over tanks

Where liquid product is on the top surface of the floating roof the lightning hazard depends almost entirely on the exposure of the product and its vapour to direct ignition by the flash itself, or from corona, upward streamers, etc. Thus, the height of the roof will play a large part in determining the actual risk of ignition, since the area for a possible lightning attachment is much smaller when the roof is low than when it is high, and the electric field and corona effects are less when the roof is low. (See Figure 6, where it can be seen that a large annular area of the roof will not normally be struck with the roof low. Note that any type of lightning protection system which aims at inhibiting strikes to the top of the shell runs the risk of diverting the strike to the floating roof itself which makes the problem worse.)

Any type of 'roofing over' will achieve the objective of eliminating direct attachments to any part of the floating roof and so eliminating ignition directly from the lightning arc. Roofing which is non-conducting as defined previously will inhibit direct arc ignition only, but not ignition from corona etc, whereas a conducting roof will protect the tank completely except as discussed in section 5 concerning the build-up of flammable vapours arising from the exposed surface product and the consequent explosion risks from sparking in the roof structure.

Although much less likely, there are mechanisms whereby the surface current flowing over the floating roof surface (from a strike to the shell for example) could cause ignition from sparks at loose metallic items on the roof, debris, chains, the rollers of the steps onto the roof etc, and this is an example of where good maintenance and inspection procedures

will minimise the amount of such metal on the roof. Effective operation of the shunts will, of course, minimise the current flow between the roof and the steps. A possible problem arises from loose contact between the bonding cable and the roof skin which should be minimised by sheathing the cable over its entire length so that apart from the bolted ends, no inadvertent contact can occur.

Generally the current from a lightning strike will not cause an ignition when the current flows along a metal surface covered in product because the current density will be, for the most part, much too low, and the conductivity of the steel too high to cause significant temperature rise, but loose conducting objects in contact with that surface will conduct and might spark, but such sparks are only likely to be incendiary if they are just above the liquid surface. This mechanism could ignite a heavy vapour/air mixture lying on the tank roof even with no actual liquid present.

4.4.2 Product within floating roof pontoons and the lightning risk

As discussed previously, any vapour/air mixture is not at risk when enclosed in a welded gas tight structure. This forms a 'Faraday cage', or more accurately a 'Maxwell shield' around the mixture, so eliminating all sparking from electric or magnetic fields or current flow. However, the pontoons will normally have access hatches, and sometimes vents on them, or in some designs the entire top of the pontoon is detachable, which could completely nullify the inherent protection of a sealed volume. The worst risk is probably a direct strike to an unbolted or poorly bolted pontoon or hatch cover, or to a vent, giving sparking which could ignite an explosion in the pontoon. To minimise this risk, the hatches and vents should be close to the shell wall, (so they are always within the 45 ° cone of protection even with the roof at the top), or be close to alternative air terminations (like roof support legs) which prevent attachments directly to the hatches or vents. Where possible, all joints in hatches, vents etc. should be welded preferably, and not bolted, since welding gives a more satisfactory electrical connection that prevents sparking. As with exposed oil on the top surface of the floating roof, maintenance procedures should be in force which ensure that such an eventuality occurs for only a very small percentage of the life-time of the tank. All metal, removable pontoon covers are very unsafe for conducted or arc attachment effects because sparking is likely. Non-conducting covers would be safer for conducted current because there will be no sparking joints.

5 LIGHTNING IGNITIONS ON ROOFED OVER FLOATING ROOF TANKS

5.1 INTRODUCTION TO ROOFING OF OPEN TOP TANKS

Where open topped tanks are equipped with roofs e.g. geodesic domes, the lightning risk can become very different, and depends on whether the roof is mainly conducting or non-conducting. A conducting roof provides a 'Maxwell shield' over the tank, which minimises current flow within the tank, including the prevention of current flow over the internal floating roof, often referred to as a 'floaters'. Thus the seal problem is very much reduced but sparking in the roof structure or a burn through of thin skin material gives a risk of explosion should it be possible for a flammable mixture to occur in the space above the floaters.

An insulating roof structure is very different, and would still be subject to the problem of sparking at the rim seal and have an explosion problem depending in detail on how the fixed roof was constructed, and as before, whether a flammable mixture could occur in the space above the floaters. These points are discussed in more detail in 5.2.

5.2 LIGHTNING HAZARDS WITH ROOFED OVER TANKS

5.2.1 Conducting roofs

For tanks with a conducting roof (which must have multiple bonds to the shell to qualify as a conducting roof), very little lightning current will flow inside the shell and across the floaters. Thus a major source of ignition, that of sparking at the rim seal area, is removed. This is because the induction charge built up by the storm cloud is confined to the top outer surface of the fixed conducting roof and to the outside of the shell, so the current from a strike discharges this charge and in so doing flows over the outside i.e. the top surface of the roof. This current flow process on the external fixed roof is also assisted by skin effect in the metal and inductive current flow considerations. Thus there is little or no current within the tank. The safety of the tank mainly depends on the detailed design of the fixed roof and whether the leak rate past the seal is low enough, or the ventilation rate is high enough to prevent a flammable mixture building up above the floaters. If a flammable mixture existed in the tank, the fixed roof could be vulnerable to lightning in several ways:

- (a) A direct attachment to a thin roof skin (e.g. 1 mm aluminium) giving burn through and/or molten metal or sparks dropping into the lower part of the space between the fixed roof and the floaters.
- (b) A direct attachment to a vent from the roof which either has no flame trap, or if it does, has a poor joint beneath the flame trap which sparks.
- (c) Corona or streamers from a vent with no flame trap.
- (d) Current flow across poor joints between metal components of the roof, resulting from an attachment or a nearby strike, so producing voltage or thermal sparks.

Thus a direct strike to the tank has the potential for producing a fire or explosion by all the mechanisms (a) to (d), but a nearby strike could only produce an explosion by mechanisms (c) and (d).

Thus to produce the worst event requires a strike directly to the fixed roof itself, and is thus a lower probability event than the corresponding 'worst case' event with an open top floating roof tank, where a strike to nearby the tank or to the tank itself could produce

incendiary sparking. As discussed in section 1.2, the risk depends on the effective area for collection of strikes which could affect the tank, which for an open roof tank will be larger than a roofed over tank. With suitable design and construction techniques, a roofed over floating roof tank (with a metal roof) could be much safer than an open top floating roof, as long as sparking and burn-through of the roof were prevented, or precautions made to ensure that there is always a non-flammable mixture in the vapour/air space above the floating roof.

Prevention of sparking in vent pipes requires that the vent is within the 45 ° cone of protection of a lightning rod, which must not be fixed to the vent in any way except with a non-conducting stay. This precaution prevents current flow in the vent pipe below the flame trap.

5.2.2 Non-conducting roofs

Roofs incorporating large amounts of non-conducting material e.g. fibre glass are difficult to make generalisations about because of the possible use of some structural metal and whether it is interconnected or not. Where small quantities of metal are used and they are not interconnected, the problem with seal sparking will be practically unaltered from that described in section 4, because the metal will not form a 'Faraday cage' or 'Maxwell shield', and will not alter the tendency for current to flow over the floating roof from a strike to the top edge of the shell or nearby, nor will it prevent the induction charge process from occurring on the floating roof. To prevent this, and to prevent the current flow over the floating roof would require an interconnected metallic system in the roof with a mesh size no bigger than approximately 1/20 of the tank diameter, and preferably finer, depending on its height above the floating roof when the tank is full. A geodesic roof with a metal framework and glass fibre panels might meet this criterion. Where the metal is not interconnected, not only does the tank have the potential for rim seal sparking, but also the problems described in 5.2.1 associated with sparking in the fixed roof, depending on where and how metal is used in its construction.

It is important as referred to previously that adequate precautions are taken to ensure that a flammable mixture cannot occur in the tank. A further risk for structures with small quantities of metal might be structural failure of fibre glass (resulting in the possibility of roof collapse) if lightning currents cause explosive arcing within it, e.g. between non-interconnected metal components or in fine wires used for X-raying the lay of the fibres.

Where the roof is entirely insulating or has insufficient metal to form a conductor for lightning over the top, it might be necessary to provide metallic lightning conductors over the top of the tank, and bonded to the top of the shell, to prevent lightning damage to the roof. The design of lightning conductor systems is described in BS6651:1999^[4], NFPA 780^[12], DIN and IEC standards, where design data for fixed and catenary systems are given.

6 LIGHTNING HAZARDS TO CONE ROOF (FIXED ROOF) TANKS

Along with open floating roof tanks, these are the other most common type of tank encountered in bulk storage petroleum tank farms. They are normally all steel, having a steel shell generally similar to a floating roof tank, and an almost flat conical shaped roof of steel, supported by internal trusses, and occasionally with upright support stanchions too (see Figure 7). These tank roofs are usually a much heavier and more substantial construction, usually welded or riveted, than the type of tank discussed in section 5.2. The top is usually very smooth and free from hardware, the most usual items being vents of various types and access hatches and instrumentation items. Thus there are very few items to act as lightning air terminations for a lightning attachment to the tank; the vents, hatches, and instrument heads being the only ones.

Thus it would be more possible for this type of tank for a strike to the actual roof skin, as distinct from the very low possibility of a strike to the skin of an open floating roof tank. So for this type of tank in particular, knowledge of the burn through and hot-spot characteristics and skin thicknesses usually encountered are necessary. These are usually steel, which has good burn through resistance and its thickness is usually sufficient (5 mm or 3/16"), but the hazard arises from the fact that the large volume above the liquid and below the conical roof may contain a flammable vapour air mixture. This potentially is a lightning risk, although with the usual thicknesses of steel, neither complete burn through nor a hot-spot hot enough and lasting long enough to cause an ignition is likely, but these factors will be tested as part of the experimental programme. Tank roof thinning due to corrosion is a possible cause of problems, and it is possible that the corrosion could bring down the skin thickness from a minimum of 5 mm to much less, so making hot-spots or burn through more possible. However, against that possibility, it is unlikely that a strike will occur exactly to a very thinned area, and in any case the attachment is more likely to occur to slight projections like raised rivet heads or the edges of overlapped steel sheets. For a smooth top tank of welded construction this might not be the case, and attention should be paid to roof corrosion (no part of the tank skin other than the roof is ever likely to take a direct attachment).

A further possible cause of ignition is from sparking associated with the fast high current return stroke of lightning. This is a similar problem to that described for geodesic roofs in section 5.2.1, and is associated with sparking at poor joints between adjacent metal parts forming the conducting path. With the fast high current lightning impulse, current tries to flow as a sheet of current all over the outside skin of the tank and inductive voltages are large and drive current through any bad joints. However in practice, this is likely to be a much lower probability of an ignition source than with geodesic roofs, because the typical cone roof tank is much more substantially built, with solid welded or riveted joints in the cone skin (the shell, of course must be welded or riveted to be liquid tight, and so is unlikely to be a sparking hazard), although the detail of the cone roof fastening to the shell might not be so spark free depending on the method of construction.

That leaves the vents, breathers, hatches and instrumentation as the only other sources of ignition. Continuously open vents which are potential attachment points for lightning and where the lightning could attach very close to the open vent (from which a vapour/air mixture is venting) should be equipped with a flame trap. The flame trap should preferably have welded joints between it and the tank to avoid the risk of sparking in the pipe between the tank and the flame trap. If bolted joints are used, they must be solidly bolted to make a very sound current path to the cone roof without sparking. Standard pressure – vacuum breather vents are more satisfactory in that they are likely to be closed for most of the time and so less likely to allow a vapour/air ignition to propagate into the tank. This type is generally approved by the industry for use without flame-traps (see review of NFPA 30

Flammable and combustible liquids code in Annex B). Loose hatches could also be a hazard with sparking at the loose bolts. Generally, non-conducting hatches pose less of a problem for this, because there is no tendency for current to pass through a poor joint.

Sparking at instrumentation is a general problem with all types of floating roof and atmospheric tanks. The major factor for safety of both cone roof and geodesic roof tanks is the type of petroleum product stored in the tank, whether it has been 'spiked', and whether any system is used in the tank to reduce the possibility of a flammable vapour/air mixture. Thus tanks where the liquid volatility is in the range of producing a flammable vapour/air mixture, and which don't have an internal floating roof, or any inerting method, are most at risk.

7 LIGHTNING HAZARDS TO LPG TANKS

Owing to the all welded gas tight construction of these tanks, and the absence of air or oxygen inside the tank, these tanks are the most safe against lightning effects. Lightning current flow in the tank will be as a thin skin effect dominated layer on the outside skin only, thus no current will interact with internal parts of the tank or its contents and there is no significant risk. However, it is possible for damage to occur to instrumentation if it is exposed to a direct strike at the top of the tank. If lamp support poles on the tank do not fulfil the function of an air termination over all the exposed pipes and instrumentation at the top of the tank, a pole should be installed to give 45 ° cone of protection over the instrumentation. Hand rails and all other metal support structure should be assessed for their ability to provide cone of protection coverage.

Overall, LPG tanks, both the spherical or cylindrical types, are the safest type of tank against the hazards of lightning.

To the authors' knowledge, this type of tank has never been involved in a lightning induced fire or explosion incident, and the reasons for this are very clear owing to its construction which keeps lightning current out of the petroleum liquid/gas volume, and equally important, maintains an oxygen free atmosphere in the tank.

8 SUMMARY OF LIGHTNING EFFECTS ON ABOVE GROUND STORAGE TANKS

8.1 THE LIGHTNING PROCESS

- 8.1.1** The lightning strike rate to ground has a strong geographical dependence, being highest in the tropics and lowest in cold or dry regions.
- 8.1.2** Lightning intensity, i.e. the magnitude of strikes is very variable (5 kA to over 100 kA) and does not have a correlation with the strike rate to ground, but there is a correlation with the type of strike, whether positive or negative. Positive strikes are generally more severe, but are uncommon except in particular areas of the world such as Sweden and Japan.
- 8.1.3** Unless very tall, such as sky-scrapers, masts and towers etc. or mountains, the presence of ground objects has no effect on the strike rate to ground. Strikes are initiated in the cloud and progress to ground by a leader. The path is essentially random.
- 8.1.4** Metallic structures, which usually include all above ground storage tanks and refinery/processing equipment, usually function as their own air terminations, but sometimes special lightning conductors are installed. These are often called Franklin rods, or finials. The metallic structures also act as their own down conductors, so that lightning protection requires only the addition of adequate earthing by means of earth rods or connections to the site earth system.
- 8.1.5** As a part of the whole lightning phenomenon, induction charging of the ground underneath the lightning cloud occurs; this is a slow process. At the moment of a lightning flash this charge is fully or partially discharged in a high amplitude fast current pulse, giving a surface current over all grounded objects, including over open topped floating roofs.
- 8.1.6** The lightning current from its attachment point on the tank or structure does not travel straight down to ground. The route it follows is usually the one of least inductance, resulting in the current flowing over the whole surface of structures as it spreads out radially from the attachment point and finds a route to earth discharging the induction charge. During this fast discharge process, the high impedance of the earthing cable causes the current to discharge via the rim seals, through the shunts or the mechanical shoe seal or through the secondary seal. The product is too resistive by many orders of magnitude to play a part in the lightning current conduction process.
- 8.1.7** The zone of protection concept suggests that with the tank roof low there is a low probability of a strike to the roof. The most likely attachment points would be around the top of the shell. With the roof high, a strike could occur to the roof but would normally attach to the tops of the support legs or other stress raisers. Thus it is extremely unlikely that a strike would occur to the rim seal area or the shunts directly, or to the inside or outside wall of the shell below the top, or to the flat decking of the roof.

8.2 EFFECTS ON MATERIALS

- 8.2.1** Because storage tanks are steel structures, and good conductors, the thermal effects of current flow through the steel are normally insignificant. Most metals are able to carry lightning currents very safely, since only very small cross section areas of steel, aluminium and copper are required to carry the entire lightning flash currents. These are 20 mm², 15 mm² and 10 mm² respectively. Thus shunts etc. will not be damaged by lightning to the tank, either directly by the current or from force effects. The sparking at the contact point will result in negligible erosion of the shunt material.
- 8.2.2** The lightning attachment point is the only place where any obvious damage to steel might be seen, but it is believed that steel as thin as 2 mm may be sufficient to prevent burn through with a severe strike. 5 mm is certainly satisfactory, although experimental confirmation is being obtained of this and of the temperature reached on the back surface (the hot-spot) of the steel sheet.
- 8.2.3** It is possible that thin small bore pipes (for example on the tops of storage and process vessels) might be damaged by a direct attachment to them. Such pipes and instrumentation on the tops of tanks should not be exposed to direct strike attachment. Some simple form of air termination above them is needed to prevent a direct strike. A similar principle should apply to equipment on the tank gauger's platform; it should be within the 45 ° cone of protection of a lightning conductor, which could be a metal lamp post, hand rails or a simple steel pole.
- 8.2.4** Lightning is a high voltage and a high current phenomenon, so high voltages are available to cause flash-over or high voltage breakdown of insulators. Thus any scheme to protect against lightning using insulators must allow for the very high voltages, and provide sufficiently large insulators, or an alternative safe path for the current which limits the voltage stressing the insulators. The high currents can cause incendiary sparking at poor joints in metallic components.
- 8.2.5** Thermal and voltage sparking is probably the principal cause of rim seal fires. This arises from the current crossing the rim seal; and because of, in practice, the poor joint which occurs between the shunt and the shell, which is not a satisfactory design for passing current with no sparks. The poor joint is due to the presence of rust, wax, surface coatings etc. on the shell and insufficient contact area and pressure.
- 8.2.6** By contrast, fully welded gas tight steel tanks, as used for LPG, which have no equivalent of the rim seal are, in fact, self protecting, and require earthing only.

8.3 PROTECTION METHODS TO PREVENT LIGHTNING INDUCED RIM SEAL FIRES

- 8.3.1** Low leakage seals maintained in good condition are a primary protection principle.
- 8.3.2** Since lightning currents are difficult to prevent (except by roofing over the tank with metal, or having a mesh type catenary system over the entire tank, which is not very practicable) it is

necessary to provide a method of permitting the surface discharge currents to flow between roof and shell without giving incendiary sparks. This could be achieved by two approaches:-

- (i) Shunts which do not spark under any conditions (very difficult).
- (ii) Shunts located where any sparks do not occur in, or fall into, a region of flammable mixture (more easily attainable).

8.3.3 To achieve the objective of 8.3.2(ii) there are two main approaches; either have the shunt contact points above the secondary seal, where any sparks produced are outside (and cannot fall into) a region of possible flammable mixture, or have the contact points below the liquid level, so the possible sparking sites are entirely submerged in liquid which excludes air from the spark source. Submerged contacts will require some theoretical and experimental assessment to determine their feasibility.

8.3.4 The mechanical shoe type seals are the more difficult to prevent sparking but fitting insulators to the hangar system (as provided by some tank builders) and by providing good shunts, above the secondary seal or immersed within the liquid, could cure the problem as long as care was taken in the design of the immersed contacts to minimise inductance, and so minimise the voltage stressing the insulators. Likewise, liquid and foam filled seals should be fitted with shunts, either above the secondary seal or as immersed contacts, as discussed above.

8.3.5 In general a bonding cable and the shunts spaced 3 m apart are required on all open roof tanks.

8.4 PROTECTION OF ROOFED OVER TANKS

8.4.1 With conducting roofs the rim seal problem is largely eliminated, but depending on the detail of the roof construction, and whether a flammable mixture might be present above the floating roof, there might be a risk of explosion from sparking etc. in the fixed roof.

8.4.2 With non-conducting roofs, the rim seal problem is almost as severe as with fully open tanks; also, sparking in the roof structure could be a problem, again, depending on detailed construction and the presence or otherwise of a flammable mixture in the tank. It is possible that lightning could induce roof structural failure through arcing in confined spaces which damages structural members. In some cases the installation of a lightning protection system might be beneficial in the form of tapes attached across the top of the roof, or a catenary system above it.

8.5 LIGHTNING EFFECTS ON ROOF SURFACE PRODUCT, AND PRODUCT IN PONTOONS

8.5.1 Product on the surface of the roof could, in principle, be ignited by lightning, particularly with the roof very high, but it is fairly unlikely to be from direct strike ignition since the strikes would normally attach to roof support legs and other elevated objects. The ignition is likely to come from sparking at roof level caused by the presence of loose metal objects, chains, the earth bonding lead if unsheathed etc.

8.5.2 Product in pontoons. This could be an explosion hazard if the design allows sparking at vents or on the hatch covers to ignite any enclosed flammable mixture resulting from it.

8.6 LIGHTNING EFFECTS ON CONE ROOF TANKS

- 8.6.1** Cone roof tanks can be compared to conducting geodesic roof tanks, except that the usual construction method is much more substantial, so giving less risk of sparking in the roof structure.

Also, because the roof is usually 4 mm thick steel, the burn through and hot-spot risk is very much reduced. This will be subject to experimental confirmation. A conducting roof prevents the rim seal sparking problem of open top floating roof tanks, so that if the cone roof tank has an internal floater, sparking at its rim seal is very unlikely. This, however, does not remove the need for a bonding cable from the floater to the shell for electrostatic discharge purposes, and shunts might be necessary in certain instances.

- 8.6.2** Vents, hatches, gauge heads etc, are possible attachment points for lightning and hence the possible sites for incendiary sparking. Vents other than the pressure-vacuum breather type should have a flame trap if the vent is situated somewhere on the tank where it can take a direct strike. Good maintenance should include ensuring that all hatches etc. with metal covers are firmly bolted, and no other loose connections exist to vents or instrument heads.

8.7 LIGHTNING EFFECTS ON PRESSURISED LPG TANKS

All steel welded and pressurised tanks containing LPG are very safe from lightning and the risk to the tank itself is negligible. However, they do need earthing, as for all petroleum plant, and no equipment on the top of the tank should be exposed to the risk of a direct strike attachment. A lamp support pole or a simple steel pole is sufficient to provide cone of protection coverage over the top of the tank.

9 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations made in this desktop review have in some cases now been modified by the output from the complementary testing programme. Where this is the case the appropriate testing documents are referenced in section 10 and additional comments made.

- 9.1 There are some very useful documents which have laid the ground work for a more thorough investigation of the seal sparking problem. However, most of the standards on lightning protection available to the oil industry, or prepared by oil industry organisations, are out of date and/or insufficiently detailed and so do not give adequate advice for the protection against lightning of open top floating roof tanks and other types of above ground storage tanks.
- 9.2 Protection of open floating roof tanks is feasible, by due consideration of the mechanisms of sparking, and by applying protection methods which prevent sparks in regions of flammable mixtures. This is possible for the main types of primary and secondary seals, although there may be a considerable cost penalty in equipping some types of tank, especially pantograph types where there are many joints and hinges in metal components.
- 9.3 It is useful to know the thickness of metal skins needed to provide protection against direct lightning attachments. EI-TN1-03 *Review of burn-through and hot-spot effects on metallic tank skins from lightning strikes* discusses this further by reviewing available data. Steel skins of 4 mm thickness or more appear to have adequate protection against puncture, but hot-spots in 4 mm skins could be hazardous. Aluminium skins of 3 mm are easily punctured by lightning attachments, and generally geodesic skins are thinner even than this (e.g. 1,5 mm).
- 9.4 The threshold level for sparking at the contact of shunts to the shell wall has been addressed in EI-EN2-04 *Lightning tests to tank shell/shunt samples*. This report notes the low levels of current required to initiate sparking, as well as the severity of sparking. It is especially severe from the long duration currents. It also shows how protection from the latter can be substantially improved by relatively simple bonding of the tank roof.
- 9.5 Where fixed roofs are installed over floating roof tanks, the lightning problem might be alleviated considerably, but only if the roof is electrically conducting, sufficiently thick to eliminate burn through and incendiary hot-spots, and the space above the floating roof is maintained free of a flammable mixture. A non-conducting roof, depending on details of the roof and the presence of a flammable mixture, could be safer.
- 9.6 It would appear that the liquid immersed shunt concept is worth pursuing since the advantages of it sound very promising as a way to prevent incendiary sparks from occurring in a region that could have a vapour/air mixture. This approach has been supported by testing in EI-EN2-04 *Lightning tests to tank shell/shunt samples*.

10 REFERENCES

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¹ See Annex B.1.

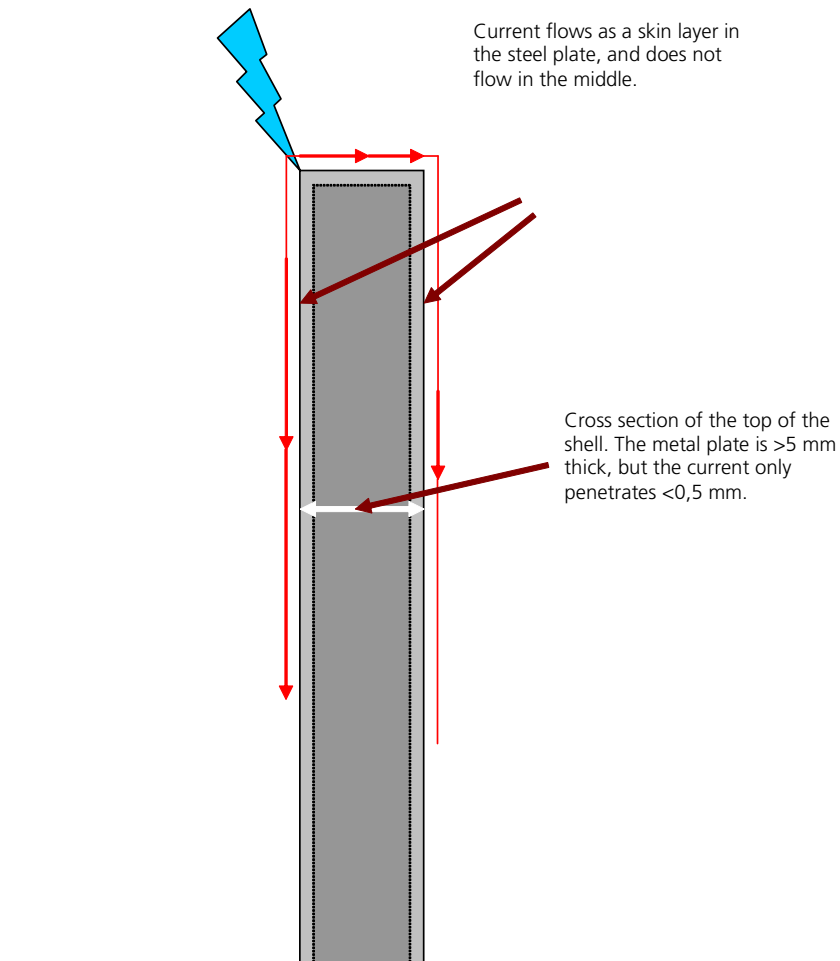
² See Annex B.3.

ANNEX A

SKIN EFFECT IN STEEL SHEETS

For fast pulses of current, the skin effect principle requires current to flow as a thin skin layer on each side of the conductor, but not through it from one side to the other (see Figure A.1). This accounts for the current flow lines in Figures 5a, 5b and 5c.

Figure A.1 Cross section of the top of the steel shell, showing how current flows as a thin skin layer on each side of the metal in a layer less than 0,5 mm thick. The fast pulse current cannot flow through the steel from one side to the other; it has to flow over the surface. Only very long duration pulses can flow through the steel from one side to the other i.e. pulses lasting at least many tens of milliseconds.



ANNEX B

REVIEW OF DOCUMENTS

Note: This review was undertaken at the time of the investigation, not at the time of publication.

B.1 BS 6651:1999 CODE OF PRACTICE ON PROTECTION OF BUILDINGS AGAINST LIGHTNING³

This document is unchanged from the previous 1992 edition in respect of items affecting storage tanks, although there are many other detailed alterations. As in the 1992 edition, no specific mention is made of protecting FRTs or any other type, although it is still a very useful general purpose protection document.

B.2 API RP 545 RECOMMENDED PRACTICE FOR LIGHTNING PROTECTION OF ABOVE GROUND HYDROCARBON STORAGE TANKS

This is under preparation, and will encapsulate findings from this investigation.

B.3 NFPA 780 STANDARD FOR THE INSTALLATION OF LIGHTNING PROTECTION SYSTEMS 2000 EDITION⁴

This document contains rather more than BS 6651 on tank protection, and although it goes some way towards useful protection advice, it needs to be updated to take into account the recent findings on tank sparking mechanisms and protection techniques.

In 6.4.1.1 item 3 says '...all vapour or gas openings shall be closed or provided with flame protection...'. It would have been useful to mention pressure-vacuum vent valves specifically as suitable vents, without the need for flame traps.

In 6.4.1.2 on floating roof tanks, there is some very confusing advice especially in section (b) on protection, where it is stated '... Tanks without a vapour space at the seal shall not require shunts at the seal'. This is not in accordance with good practice, and the present study confirms that it is good practice always to have rim seal shunts.

On the question of nomenclature, the first paragraph of 6.4.2.1(a) refers to the rims of tanks, apparently meaning the top of the shell, rather than the usual usage where the rim is the region of the floating roof nearest to the shell.

In summary, this document could be improved by editing to bring it in line with current practice.

³ Since publication of this report, this standard has been superseded by BS EN 62305: 2006 *Protection against lightning*.

⁴ Since publication of this report, this standard has been superseded by NFPA 780 *Standard for the installation of lightning protection systems* 2008 edition.