MITIGATION OF THE LIGHTNING HAZARD FOR ABOVE GROUND HYDROCARBON FLOATING ROOF STORAGE TANKS

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INTRODUCTION

Since 2005 the Energy Institute (EI) and the American Petroleum Institute (API) have been jointly sponsoring a programme of work "*Verification of Lightning Protection Requirements for Above Ground Hydrocarbon Storage Tanks*". EI Consultancy Project S402 [API/EI 2009a]. The work has been a collaborative venture between the Energy Institute, Brian Burrows Lightning Consultancies, and Cobham Technical Services, Lightning Testing & Consultancy (formerly Culham Lightning).

The test results and recommended mitigation measures have been disseminated within API/EI and will be used as part of a new document being drawn up by the RP 545 task group, which will specify Lighting Protection measures for above ground storage tanks [API/EI 2009b].

In the initial phase of the programme a review was made of present installation practices, in which visits were made to two UK refineries and their associated tank farms. Typical lightning protection methodologies could then be seen in practice, as well as the practical aspects of maintaining lightning protection in a difficult operating environment. Whilst absolute protection against fires from lightning strikes might be uneconomic to implement, there is benefit in adopting simple approaches which will significantly reduce the risk.

In subsequent phases lightning simulation tests were carried out to tank components in various configurations to help understand the mechanisms which can lead to ignitions and explosions, and how to avoid or mitigate them.

IMPORTANT ASPECTS OF LIGHTNING BEHAVIOUR

In order to design efficient lightning protection it is important to appreciate how lightning attaches, and the way in which the injected lightning currents then flow and behave. What makes absolute lightning protection difficult to achieve is the fact that much of lightning's behaviour is random or statistical. We illustrate this by briefly looking at some aspects of lightning behaviour.

THE LIGHTNING ATTACHMENT MECHANISM

Most lightning strikes develop as weak "leader" discharges propagating from the cloud downwards. This "leader" creates a breakdown path through the air in a series of jumps 25 m to 100 m in length. Only when it is within a similar distance from the ground, or grounded structure, is the strike point determined, when it makes its final jump to the nearest point. This then completes the electrical connection between cloud and ground and the main lightning current can then begin to flow. It follows that even if there are tall structures nearby, they do not necessarily get struck, because the downward propagating leader does not see such a structure unless it comes to within perhaps 25 m to 100 m of it.

One method that is often used to predict where lightning could strike is that of the "rolling sphere". To apply this, imagine rolling a 25 m radius sphere around an installation such as a tank farm. Those points which can be touched by the sphere are considered as possible strike locations. Figure 1 shows the possible lightning attachment points to a floating roof tank devised in this way, and also shows the protected regions where attachments would not be anticipated.

The rim of the tank shell has a higher probability of attachment, because those attachments which would have otherwise gone into the protected regions are attracted to the rim. However, even if such high points are more likely to be struck, we mustn't forget that most strikes simply hit random locations on the open ground. So on tank farms small ground level tanks or pipework may also be struck. Moreover for large floating roof tanks the floating roof itself can be struck, particularly when it is high.

THE LIGHTNING CURRENTS

Once the lightning attachment has been made, current can then flow between the cloud and ground, and will flow outwards from the strike point to neutralise the charges which the cloud had induced on the surface of the ground. The shape of the current waveform tends to follow set characteristics, but the magnitudes of the currents vary widely from strike to strike.

A lightning strike is considered to be made up of different current components; these are considered separately for convenience because they are of very different magnitudes and duration. Figure 2 shows typical current peaks and durations for different current components of a severe strike. Note that the waveform shown in the plot is distorted for clarity. The fast current (200 kA, 100 μs duration) is actually 1000 times higher amplitude than the long duration currents, but the long duration currents last 10,000 times longer. So this schematic plot hides the vast differences in scale of the two currents. Because of this difference in scale the different current components

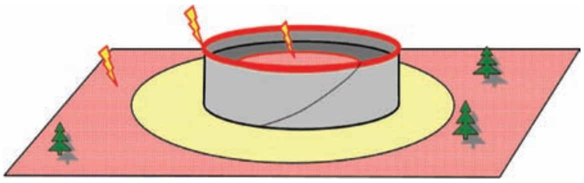

Figure 1. Possible locations for lightning attachments in the vicinity of a floating roof tank (shaded red/pink). These locations can easily be imagined in terms of the points which can be touched by a 25 m rolling sphere

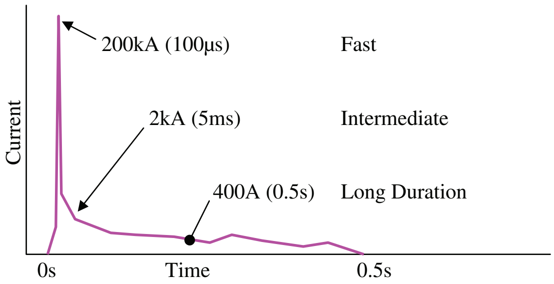

Figure 2. Typical components of a severe lightning attachment. The fast component contains the very high peak current and most of the energy, but the long duration currents present the risk of hot-spots and melt-through on tank skins

behave differently, both in the way they flow and in the risk they pose, and this is discussed further in section 4.

There are also wide statistical variations in these parameters. So for example, although about 2% of strikes can exceed 200 kA peak current, median strikes peak at only 30 kA or so.

REVIEWS OF TANK FARMS AND GENERAL OBSERVATIONS ON LIGHTNING PROTECTION

The main aim of this study has been to understand the causes of fires and explosions from lightning, and help prevent them. Ignitions generally can be caused by **sparking**, especially at loose contacts, or touching surfaces which are not well bonded together; it can occur at current levels of a few amps, and such currents can be found a large distance from a strike point.

For tank skins, **puncture** or the formation of **hot spots** can also ignite flammable vapour mixtures within.

Ignitions can only occur if there is a flammable vapour mixed with air. So protection can also be achieved by, for example, inerting vapour spaces above volatile liquids to minimise oxygen concentration. In other cases ventilation may be appropriate, so that if there is a location where sparking can occur there is not a sufficient concentration of hydrocarbon vapour to ignite.

We now look at some of the specific types of installation which were reviewed in the initial part of the programme.

1) **Solid vented tanks** of welded construction will not be prone to sparking if lightning currents flow through them, as they present a continuous skin. Such tanks were considered relatively well protected from the lightning hazards of puncture or hot-spot during an attachment to the roof. The review concluded from existing lightning test data [Zischank 1996, Kern 1988–91, Mariani 2000], that for >4 mm steel skins puncture from lightning attachments was unlikely, and although hot-spots might occur, for skins >5 mm they would not be hazardous. So 5 mm steel skins appear to be safe.

Vents or other outlets can present a risk of lightning ignition propagating back into the tank, and this may be the case even if suppressors or pressure/vacuum valves are used (because the overpressure from lightning may defeat these by forcing ignitions past these barriers). A good approach is a vent such as an inverted U where the outlet rim will not itself be an attachment point, and which incorporates flame arrestors or pressure/vacuum valves. However any bolted flanges where components fit to the tank could generate sparking if lightning currents flow through the flange, and if the bolts penetrate the tank.

Solid vessels such as those used for pressurised LPG storage are inherently safer because they contain a mixture which is above flammable range; their design for withstanding pressure necessitates thick steel walls, which means that they are well protected against lightning induced puncture.

2) **Geodesic tanks** were not studied in detail, but possible ignition hazards were noted; for example a geodesic roof which is of aluminium panels less than 2 mm thick would readily be punctured by a direct lightning attachment. There may also be the possibility of sparking at joints and connections in such roofs.

3) **Floating roof tanks** are recognised by the industry as being susceptible to rim fires following lightning strikes. It is clear when looking at these installations, that the shunts installed around floating roof tanks for electrical bonding rarely make good metal to metal contact with the tank wall. One reason for this is the hard rust layer on the shell surface, but the difficulty is especially severe on crude oil tanks, where a waxy deposit tends to build up between the shunt and the wall. Because of these effects we would expect sparking to readily occur at these shunt interfaces. This unavoidable effect is compounded by the fact that the shunts usually lie just above the secondary seals. It can be difficult to maintain a good vapour barrier at this seal, and there is often a discernible gap, which would allow sparks to fall down behind the seal and into the vapour space below. The nearer the shunt is to the secondary seal, the greater the risk.

So although good maintenance practice is going to help reduce the possibility of ignition by isolating any arcing from flammable vapours, there are also improvements that can be made to bonding configurations. This work on floating roof tank bonding interfaces represented a major part of the experimental programme and is the main content of this paper.

OVERVIEW OF CURRENT FLOW AND SITES OF ARCING IN FLOATING ROOF TANKS

A typical installation of a large floating roof tank might have shunts disposed all around the rim (typically 3 m apart), and one or two roof bonding cables. The question is whether these can safely carry the lightning currents which would flow across them in the event of a strike to the floating roof, or to the tank rim. To answer this we have to revisit the waveform given in Figure 2. This depicted the typical severe lightning waveform as a **fast current** component (of <1 ms duration) followed by a **long duration current** which remains fairly constant over 0.5 seconds or so.

The **fast** lightning current reaches its peak in 10μs or so, and behaving as high frequency currents do, will try to spread out to follow the least inductive path – it certainly does not simply take the "path of least resistance". So if there is a roof bonding cable, the fast current barely flows through it, since the cable's high frequency impedance (its inductance) is simply too high.

Voltage drop along such a cable is given by

$$V = L \cdot \frac{di}{dt} \tag{1}$$

Where the inductance L/m is $\sim$0.5 μH/m, or say 25 μH for a 50 m long roof bonding cable, and the rate of change of lightning current $(\frac{di}{dt})$ can be 10^{11}A/s. So the voltage drop down such a cable would be 2.5 MV if it carried all of the lightning current, and this voltage would stress the gap between the roof and the shell. Of course this doesn't happen; because of the available voltage, breakdowns will occur at many shunt locations around the roof rim, and the lightning current then shares across these paths. If there is a possible current path through shoes or pusher plates then these too will share the current [Figure 4].

If there are installations with multiple short bonding cables from roof to shell (eg spooled cables) we can follow the same calculation. For example 10 cables each of 10 m length would have a combined inductance of $\sim$0.5 μH, and would generate a voltage of around 50 kV between roof and shell. This voltage would still be sufficient to break down gaps of over 10 mm to establish parallel paths from roof to shell.

A strike to the rim will result in similar behaviour, with current spreading out across the roof via the shunts.

The **long duration** currents are essentially DC currents, and are not deterred by the inductance of the roof bonding cable. Therefore a high proportion of the long duration current could flow through the roof bonding cable if its resistance were low enough.

Figure 4 illustrates a generic floating roof design, and the possible paths which might exist for current to flow off the roof. Any glancing contacts around the rim, especially the shunts, will carry the current. But there are also other potential paths in some installations, especially the route through the pusher plate, and these are potential sites of sparking. In the next section we describe experiments to study how such contacts behave when conducting the anticipated levels of lightning current.

EFFECTS OF CURRENT FLOW BETWEEN FLOATING ROOF AND SHELL

Tests were conducted under this programme to help understand the behaviour of the interfaces between the shell and

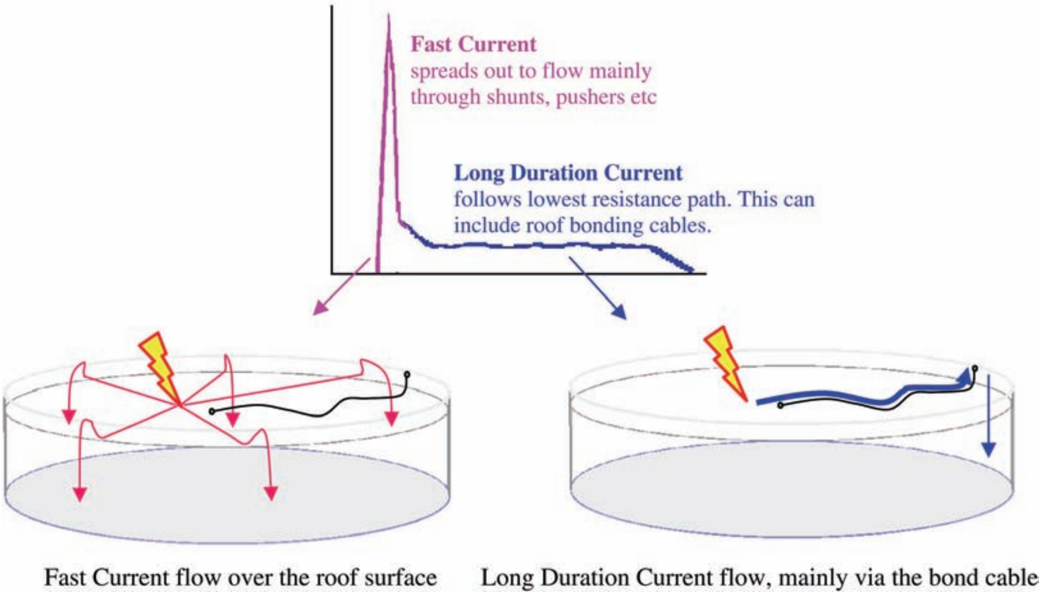

Figure 3. Typical distribution characteristics of the different components of the lightning current waveform. The waveform is split schematically into a fast and long duration component, and the lower figures show the predominant distribution patterns for these currents

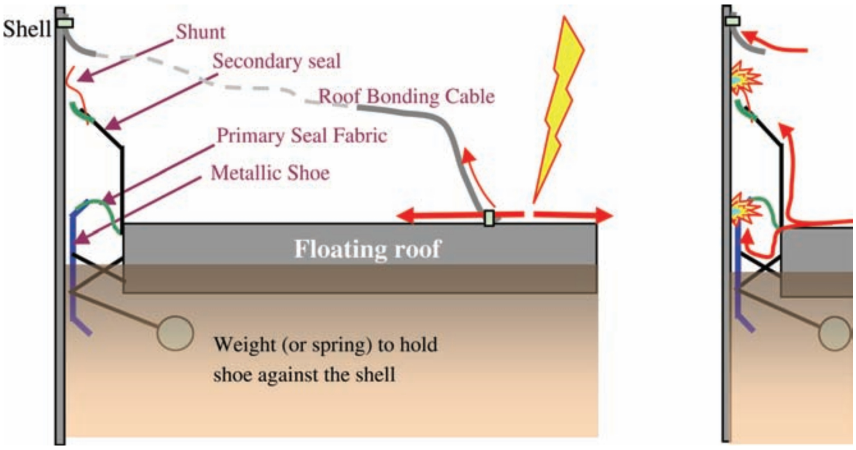

Figure 4. Typical floating roof installation showing primary seal, secondary seal, and shunt. The shunt is intended to provide electrical continuity from the roof to the shell, but in practice any other fortuitously touching or nearly-touching contacts will also carry current

the floating roof whilst carrying the levels of lightning currents which might be expected in practice.

Initially the main focus of tests was the shunts, but later tests looked at the mitigating effects of roof bonding cables, and/or the consequences of using submerged shunts.

Test Current Levels

As there are very many shunts in an actual tank installation, the fast component will divide between many shunts. The long duration currents will tend to take the lowest resistance path. In the worst case all of the long duration current could flow through one shunt.

Because of this we expected a shunt to have to carry up to:

1. A fraction of one twentieth of the expected severe strike high energy fast components i.e. 10 kA–20 kA out of the full threat 200 kA
2. A relatively large proportion of the long duration currents. i.e. 400 A average for 0.5 s, 200C charge transfer

The initial tests were carried out by injecting separately these fast currents, and the long duration currents, across shunt-shell interfaces. Figure 5 shows a photograph typical of those taken during such tests. In this example a shell sample coated with crude oil wax deposit was used. This test included only the Fast current components at 12 kA (15 µs to peak, 50 µs duration). The arc at the shunt-shell interface is obscured by the shunt, but it has caused a plume of burning vapour (flash flame) to be emitted from the waxy coating. Trails of fast moving spark particles are also visible; these are in fact particles of steel, burning at a high temperature as they travel through the air [Haigh, 1989].

An equivalent result for testing with only Long Duration currents is shown in Figure 6. This result is for a current of 800 A for 5 ms, which is a little different from the actual threat (400 A for 0.5 s) but still produces copious sparks. These types of sparks are larger and moving more slowly than those shown in Figure 5. We know from testing experience and from earlier reported studies that larger, slower, particles are more likely to ignite flammable vapours [Haigh, 1989]. This is presumably because it is necessary to heat a critical sphere volume of the gas to sufficient temperature for ignition to propagate [Magison 1998], and this is more easily achieved for slower larger particles.

These showers of burning particles ejected from between the shunt and the shell tend to travel parallel to the shell, which makes them liable to travel through any small gaps between the secondary seal and the shell.

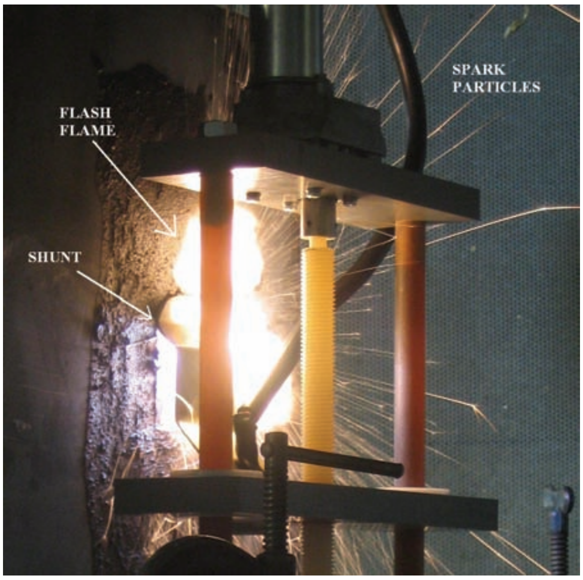

Figure 5. Conduction of Fast Current component only (12 kA) between a stainless steel shunt and a steel shell with waxy deposit applied

Figure 6. Test result for conduction of Long Duration Currents only, at 800 A for 5 ms

Other points which were noted in these initial tests:

1. In all tests a short arc occurs at the contact point between shunt and shell, and this would undoubtedly ignite any flammable vapour at that location. However the shunt is normally in a relatively ventilated region outside the secondary seal.
2. These intense showers of burning particles which are ejected from the interface by the long duration currents can fall and ignite vapours sitting at a lower level.
3. Such sparking was slightly less intense if the shell was new clean steel, but could not be eliminated.
4. Contact load was varied for rusty shell samples, but did not appear to be a factor in reducing the intensity of sparking.

So it appeared that little could be done at the shunts themselves to prevent sparking occurring, as the nature of the sliding contacts, and the inevitable rusting/contamination of the shell, exclude the possibility of good electrical contact.

The same is unfortunately true of any conductive paths through the metallic shoe which spaces the floating roof away from the shell. If the shoe provides a conductive path from shell to roof, arcs would be expected to form at discrete locations around it. These would be in an unventilated region between primary and secondary seals, a location susceptible to relatively high concentrations of hydrocarbon vapour.

It is worth noting that a lightning attachment to the rim of the tank shell will also result in copious sparking at the direct attachment point, with sparks again falling down from the rim towards the secondary seal. Whilst a well fitting secondary seal is the best protection against this being an ignition hazard, there are other possibilities to reduce the hazard from this (such as attracting the lightning to locations other than the rim, such as air terminals, or the walkway).

EFFECTS OF ROOF BONDING CABLES

The major threat from sparking at shunts occurs when they carry the long duration currents. Because these currents are slow changing, we expect that low resistance roof bonding cables would be effective in diverting much of this current off the roof, thereby bypassing the shunts.

Some experiments were performed to study the effectiveness of different roof bonding configurations in diverting current around the shunt-shell interface.

There is a great statistical variation in the sparking produced from test to test, and so to help understand what was happening at the contact point, the emitted light was monitored with a fibre optic/photomultiplier system. This helped determine the time at which the arc extinguished, and current followed the parallel path through the shunt.

In other tests the current distribution between the shunt path and the bonding cable path could be monitored, and an example of this is given in Figure 7. For this test a roof bonding cable of 100 μH inductance and 110 mΩ resistance was used as the parallel path. Even with this relatively slow test waveform the current intially takes the less inductive path aross the shunt interface, but at longer time the preferable path is through the bonding cable and the arc at the shunt goes out at 1.4 ms. In some tests a weld formed at the shunt, and current then continued to take this path through the shunt, but as no arc is then involved this is not a hazardous condition.

Figure 8 shows two tests at a higher level, and with longer duration currents, in which the arcing at the

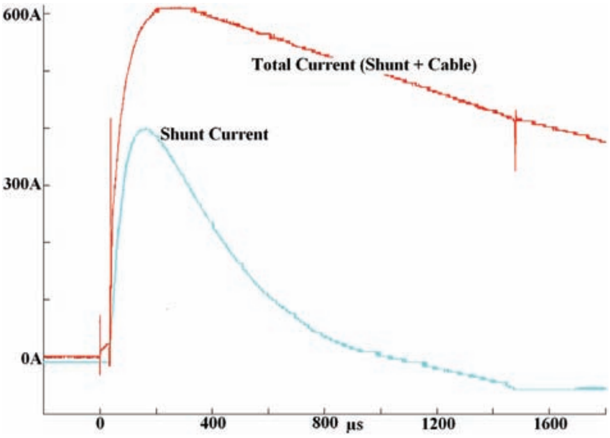

Figure 7. Distribution of current crossing shunt-shell interface and parallel roof bonding cable. The total current is shown, plus that part of it flowing through the shunt. The difference flows through the roof bonding cable.

shunt-shell interface was monitored and recorded as a light signal. In each case a bonding cable of 100 μH inductance was connected to bypass the shunt, and the resistance of the cable was 210 mΩ (left) and 40 mΩ (right).

The figures show the current (upper red trace) plotted against time, with the light plotted below on the same time scale. For the higher resistance 210 mΩ cable a stable arc continues at the shunt interface for most of the test waveform, and the light signal is maintained. For the 40 mΩ cable the arc rapidly extinguishes. The crucial factor is that the resistance of the cable has to be low enough to carry 400 A whilst developing a voltage less than 14 V. Arcs cannot be sustained if the voltage driving them drops below 14 V, and once the voltage falls below this value at the shunts then any arcs will extinguish.

To satisfy this, the roof bonding cable and its terminations must therefore have a total resistance of <35 mΩ. At this value the voltage drop down the cable would be 14 V at the expected current average of 400V.

As there will still be some arcing because of the fast currents, arcing is not eliminated. But by this relatively simple approach of ensuring a low resistance roof bonding cable, refining what is in any case a widespread practice, the magnitude and therefore the risk from sparking will be reduced.

SUBMERGED SHUNTS

In some circumstances shunts can be installed below the liquid line. This has obvious advantages, as sparking here is not an ignition hazard, since there is no vapour/air mixture to ignite. The major concern was that any arcs formed beneath the fluid line could throw up a plume of liquid and sparks. So tests were initially carried out with arcs formed at shunt interfaces beneath water. Subsequently, and once the mechanisms were understood, some more definitive tests were carried out under motor oil, with shunts submerged so that the arcing interface was from 20 mm to 450 mm below the oil surface. The results of these tests are summarised briefly here:

- With shallow submersion under oil (20 mm), an eruption of fluid and bubbling occurred, and sometimes sparks and a jet of sooty flame.
- With submersion under oil of 300 mm or greater no ignition hazards were observed even without bonding cables. (up to a high level of 44 kA [Fast] plus 200C [Slow])
- If interfaces straddle the fluid line then arcing is much more likely to occur at or above the fluid line, as the fluid is a good insulator.

So if all current paths (other than a roof bonding cable) can be constrained to >300 mm below the fluid line then the main hazard is effectively eliminated.

CONCLUSIONS AND RECOMMENDATIONS

For floating roof tanks it is difficult to provide good lightning current paths between the floating roof and the shell. Even if a roof bonding cable is provided, the fast current will take other available paths such as the shunts, forming arcs across small gaps if necessary. If metal to metal contact exists where the shunts meet the shell, arcing is still likely as the high current flows across the small area of contact. Where the arc occurs in an environ-

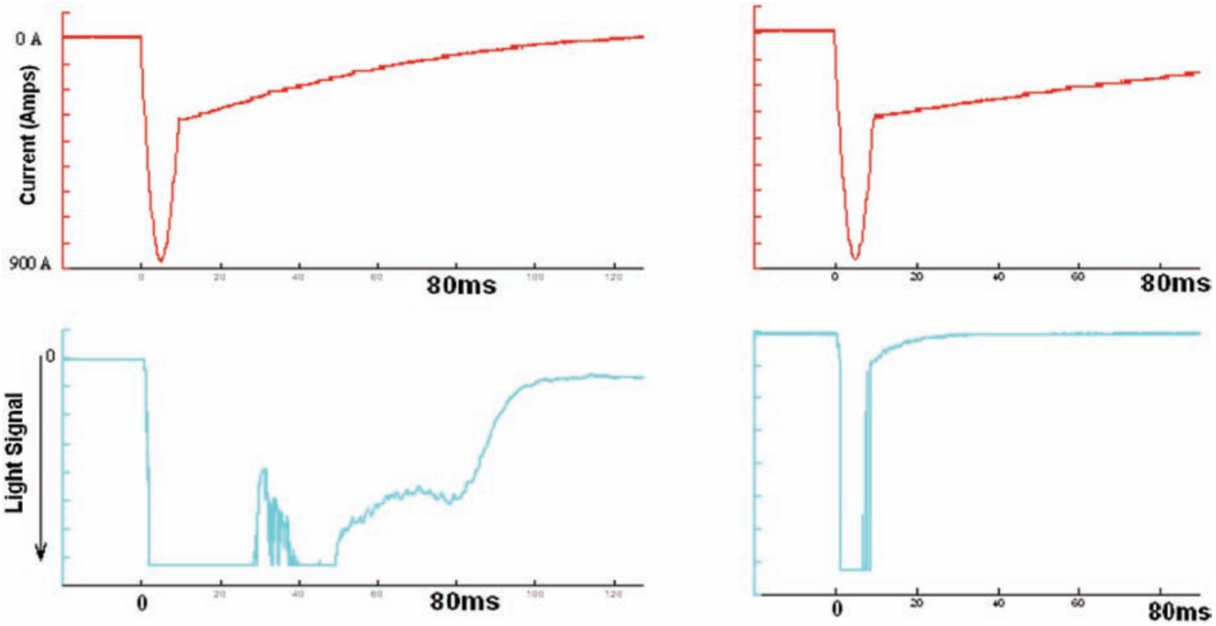

Figure 8. Current (upper trace) plotted against light at shunt interface for two different bonding cables. Both signals −ve going. The arc is rapidly extinguished in the case where a low resistance (40 mΩ) bonding cable is used

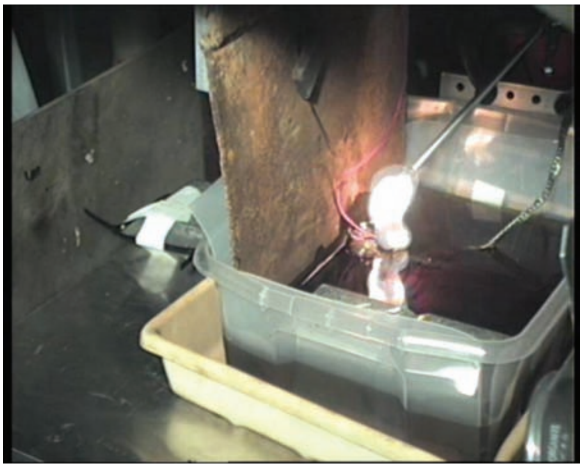

Figure 9. Ball of burning vapour emitted from oil surface, after test to shallowly submerged shunt [frame from video sequence].

ment which is within flammable range then ignition is inevitable.

Arcing at external shunts is at least in fairly well ventilated space, although it can produce burning spark particles which can fall downwards towards the seal. If the seal is not tight against the shell they can fall behind and into the region above the primary seal.

This hazard can be mitigated against by the use of a low resistance roof bonding cable, which reduces the intensity of the showers of sparks. An overall bonding resistance of <20 mΩ should be sought, which includes a safety margin over the figure of 35 mΩ given above. The common industry practice of using more than one bonding cable (for redundancy) will also help in this regard.

If shunts can be submerged, then this is a good solution, and if the contact point is submerged below 300 mm, a ignition source at this interface is unlikely, even without roof bonding cables. Shallower submersion depths can result in burning particles and flame being ejected by slow current arcs, but the use of roof bonding cables reduces this threat. So in summary for submerged shunts:

Fast Currents – submersion at >100 mm gives excellent protection
Slow Currents – submersion at >300 mm gives excellent protection
submersion at 100 mm to 300 mm would require bonding cables

The shoe or pusher plates inside the primary seal can often also provide a fortuitous current path, and if so, arcing is likely to occur during a roof strike. As these locations are within a vapour-rich region they are potentially more hazardous. The only solution here is to ensure that they are not current paths by incorporating isolation. Roof bonding cables will not help.

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