Technical Note on

Chemical Storage Tank Arc Discharge Mitigation

Albin J. Gasiewski Ph.D., CTO, Enventa, LLC

and

Lee B. Howard, Electrical Engineering Manager, Lightning Eliminators & Consultants, Inc.

November 2, 2013

This technical note discusses a means for mitigating electrical discharge inside volatile chemical storage tanks, as assigned for study by Lightning Eliminators & Consultants, Inc. (LEC), in July, 2013.

Background: The problem of electrical discharge and subsequent explosive detonation of the ullage inside chemical storage tanks containing methane-infused fluids is becoming more widespread as the use of new non-metallic storage tanks proliferates. Such tanks are typically made of non-corrosive but otherwise insulating materials (either fiberglass resin, PVC, or similar insulating plastics), have no continuous metallic grounding conductors within or outside of the tanks, and are exposed to the electrical environment in the vicinity of lightning-producing thunderstorms. They are often used to store fluids used in hydraulic fracturing. The gas inside the tank above the fluid level (the tank's ullage) can contain a stoichiometrically explosive mixture of oxygen and methane or other similarly volatile hydrocarbon gas. Such a mixture is amenable to explosive detonation upon either arc or strong corona discharge within the tank.

Conventional metallic tanks form a Faraday cage of conducting material around both the fluid and potentially explosive ullage, thus ensuring that electric fields never approach appreciable values within the tank. However, the lack of a continuous conducting boundary resulting from the use of non-metallic tank walls permits electric fields to approach breakdown strength in response to a nearby lightning discharge. Furthermore, depending on the specific conductor geometry, enhanced local electric fields that exceed breakdown strength can occur near either small metallic objects or even dielectric objects within the ullage region of the tank. Such conductors include small boltheads or other metallic fasteners, as well as other electrically good conducting materials within the tank (e.g., including droplets of the fluid itself and the fluid surface corners). Enhanced fields at sharp conductors can occur during either the incipient or active phase of a nearby lightning strike, but gaseous dielectric breakdown and subsequent ullage ignition will likely only occur during a nearby strike event.

Since the fluid inside the tank is often laden with salts, it can be expected to be of moderate to high ionic content. As such, its conductivity can range from a low value of ~0.001 S/m to values for heavily brackish water that can easily exceed a few S/m. Such fluids have relaxation time constants of less than ~1 nsec, but for low saline contents (i.e., spring water) this time constant can be as long as ~1 μsec. In either case, these fluid masses behave as good electrical conductors on the time scale of an atmospheric electrical transient, and thus redistribute surface charge throughout their volume rapidly during the nearby strike event. The transient produced by this event is thus effectively shielded by charges on the fluid surface and does not manifest itself within the volume of fluid itself.

However, the transient can produce a strong field within the ullage. It is well known that high electric fields occur where conductive materials form sharp corners or points. For example, the electric field around a simple spherical metallic object immersed in an otherwise uniform electric field will be up to a factor of three times as large due to the electric polarizability of the object. If the object is needle-like (for example, a rivet or long bolt) this field amplification factor can be significantly higher, readily approaching a factor of ~10x for many common fasteners. The field amplification effect occurs not only around good conductors but also at the ends of long dielectric objects, albeit to a slightly lesser extent that depends on the dielectric constant of the object. For example, for a sphere of fiberglass with a relative dielectric constant of 4.2 the amplification would be a factor of approximately two times that of the external field.

Origin of Tank Explosions: *It is hypothesized that the cause of recent explosions of ullage in fracture fluid storage tanks is the result of the above field amplification near sharp ungrounded metallic objects or sharp dielectric protrusions.* Rapid increases in the external field of order 2MV/m per millisecond will cause field amplification on many small dielectric and conducting objects within a non-metallic tank. The rapidity of this field change does not permit time for charge to bleed off through the insulating tank walls, and thus to null out the applied external field from the lightning transient. A rapidly increasing field that exceeds the local dielectric breakdown strength at a location in the vicinity of a lightning strike can readily produce additional localized corona or even arc discharge by exceeding the breakdown strength of the gas mixture. Note that the breakdown strength of ullage gases may also differ from that of air, as well. For example, carbon dioxide, hydrogen, and helium all serve to lower the breakdown strength of air, and can contribute to a somewhat lower overall breakdown strength if present in the ullage. The presence of such sharp conductors is thus to be avoided in order to minimize field enhancement anywhere within the ullage. Alternately, the use of proper shielding can reduce the likelihood of the transient producing high fields within the ullage.

Retrofitting Non-metallic Tanks for Safety: The recommended solution to the above problem is to create a Faraday cage, even if incomplete, around the non-metallic tank. This can be done using copper grounding wire, mesh fencing, or other metallic tubing or structural material around the tank to enclose it in a metallic "birdcage" structure, along with connecting this structure to a low-impedance earth ground at the base of the tank. An incomplete Faraday cage might be formed by, e.g., two looping arches of wire or other conductor over the tank, each offset at 90 degrees to each other. Such an incomplete Faraday cage will provide a large fraction of the ultimate field rejection inside the tank obtainable using a complete metallic skin, but is far less expensive. Using four such arches at 45^o azimuthal offsets will provide a significant degree of transient field rejection inside the tank.

Additional protection from charges that may be built up on the surfaces of the fluid mass can be obtained by use of a non-corrosive grounding electrode inserted into the fluid and electrically connected to the external Faraday cage conducting members. The electrode should be connected to the Faraday cage near the top of the tank at a convenient access port. This electrode, along with the moderate conductivity of the fluid itself provides a means of rapidly discharging the fluid surface – which will become charged at its surfaces when exposed to a strong transient electric field. Such charge will preferentially accumulate near the fluid mass' "corners" (e.g., the periphery of the top surface of the fluid, particularly for a concave meniscus), at which locations field amplification due to sharp dielectric corners can occur. The electrode, if grounded, will also be partially effective as the Faraday cage since it will also serve to null the vertical component of the field within the ullage. In fact, since this electrode needs to be grounded, there will always be at least one conductor of the Faraday "birdcage" going to ground outside of the tank. A partial Faraday cage will thus necessarily be built when this conductor is installed.

Such an electrode needs to be highly corrosion resistant (e.g., stainless steel) to maintain and provide high conductivity to the fluid mass. A large contact area is desired to keep the overall time constant of the system shorter than the time scale of the transient strike event. This time constant is governed by the geometry of the fluid surfaces and the effective resistance of the fluid surface to the conducting electrode.

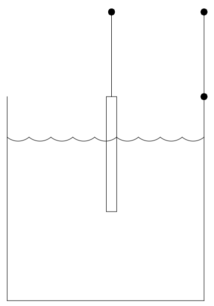
In general, it is not recommended that any additional sharp metallic objects be placed inside the tank, and especially within the region of the ullage. Such additional metallic objects – whether if grounded by connection to the electrode conductor or ungrounded – can serve to enhance field strengths and initiate discharge within the ullage. Therefore, the geometry of this conducting electrode should be that of a smooth cylinder, lacking any sharp corners or points, for the express purpose of minimizing the potential of corona discharge within the exposed ullage. Any sharp features on the electrode, and specifically, splines meant to either increase the conductivity of the electrode to the fluid or to induce corona within the ullage, may serve to produce some shielding space charge within the ullage but at the greater risk of producing an arc discharge within the ullage. *Depending on the volume and duration of this discharge the presence of splines within the ullage will serve to increase risk of an explosion above and beyond that of a purely cylindrical conductor.* For this purpose, a smooth walled stainless steel pipe serves as an ideal electrode.

While it is argued that sharp splines radiating from an electrode increase risk of igniting the ullage it is also the case that they serve to reduce the resistance of the electrode to the fluid surfaces in which they are immersed, but only insignificantly. While a “wire brush” electrode has far more geometric area by which to contact the fluid than a cylindrical electrode of comparable diameter, the electrical potential within the vicinity of the wire radials is effectively a constant as a result of the screening of any field in the fluid by the wires themselves. Accordingly, the wires improve the overall conductivity of the electrode to the bulk fluid mass by no more than ~2-3 times relative to the conductivity provided by a smooth surface cylindrical electrode, of roughly the same diameter.

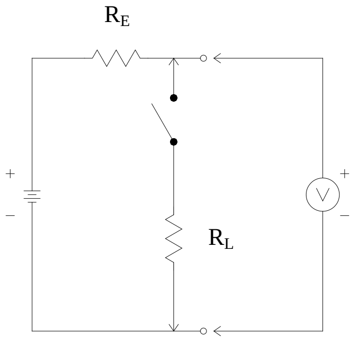
The tank and electrode (whether wire brush or pipe) form a coaxial resistive-capacitive circuit. Tests to determine the electrode resistance were conducted at LEC using both distilled and salt water solutions. Care was taken to derive the Thevenin resistance in order to compensate for any cell potentials that may have been formed by the tank and electrode circuit. In order to determine the effective resistance of the electrode to the tank, the relation $R_E = R_L [(V_1/V_2)-1]$ is used

where,
R_E = Electrode resistance
R_L = Resistance of load resistor
V_1 = Open circuit voltage
V_2 = Closed circuit voltage

For more information on this subject matter please contact Lee Howard at LeeH@lecglobal.com



Tank with coaxial electrode



Thevenin equivalent circuit

The results for distilled and salt water resistance testing are provided in Tables 1 and 2, respectively. In the case of the cylindrical electrode, a hollow stainless steel pipe with plugged bottom was used. This arrangement precluded additional conductivity to the fluid due to currents from the inner walls of the pipe.

Pipe: 1" Diameter, Plugged Hole							
-	R_L =	9868	Ohm				
V_1		V_2		R_l			
0.789		0.530		4822.287			
0.778		0.525		4755.436	Avg =	4805.491	Ohm
0.772		0.518		4838.749			
	R_L =	4956	Ohm		Overall Avg.	4834.130	Ohm
V_1		V_2		R_l			
0.774		0.394		4779.898			
0.762		0.384		4878.563	Avg =	4862.769	Ohm
0.756		0.379		4929.847			
						Ratio of pipe to wire-brush:	1.9
Wire Brush: 0.5" Diameter cable with 2.5" wire bristles							
-	R_L =	9868	Ohm				
V_1		V_2		R_l			
0.853		0.663		2827.934			
0.837		0.662		2608.610	Avg =	2707.892	Ohms
0.827		0.650		2687.132			
	R_L =	4956	Ohm		Overall Avg.	2610.976	Ohms
V_1		V_2		R_l			
0.834		0.551		2545.459			
0.830		0.549		2536.678	Avg =	2514.060	Ohms
0.826		0.552		2460.043			

Table 1: Comparison of internal resistances for distilled water using wire-brush and smooth cylinder conductors in a coaxial tank.

For more information on this subject matter please contact Lee Howard at LeeH@lecglobal.com

Pipe: 1" Diameter, Plugged Hole

-	R_L =	701	Ohm				
V_1		V_2		R_I			
0.922		0.594		387.569			
0.902		0.575		399.213	Avg =	403.841	Ohm
0.914		0.569		424.740			
	R_L =	351	Ohm		Overall Avg.	374.813	Ohm
V_1		V_2		R_I			
0.901		0.452		350.001			
0.896		0.450		348.046	Avg =	345.785	Ohm
0.897		0.456		339.307			

Ratio of pipe to wire-brush: 3.3

Wire Brush: 0.5" Diameter cable with 2.5" wire bristles

-	R_L =	701	Ohm				
V_1		V_2		R_I			
1.000		0.861		113.684			
1.002		0.855		120.537	Avg =	115.625	Ohm
1.107		0.953		112.654			
	R_L =	351	Ohm		Overall Avg.	112.541	Ohm
V_1		V_2		R_I			
1.091		0.835		107.510			
1.074		0.809		115.003	Avg =	109.457	Ohm
1.060		0.815		105.858			

Table 2: Comparison of internal resistances for saltwater using wire-brush and smooth cylinder conductors in a coaxial tank

The tests show a near equivalence of the wire-brush and cylindrical electrode resistances, in spite of the larger diameter/surface area of the wire brush electrode. The near-equality of these resistances is the result a near-equipotential region established by the brush wires within the interstices of the wire brush electrode.

Additional laboratory tests of the discharge time constant of a high voltage charge on a tank/electrode system further reveal that the resistive-capacitive (RC) decay time constant is not significantly different for the wire brush electrode that for the smooth cylinder electrode (Figures 1 and 2). It is seen that the discharge of the capacitive system is not governed primarily by the resistance presented by the electrode, but rather by the bulk properties of the fluid and the geometry of the tank. As a result, there is no significant advantage to using a wire brush electrode in discharging the tank system.

For more information on this subject matter please contact Lee Howard at LeeH@lecglobal.com

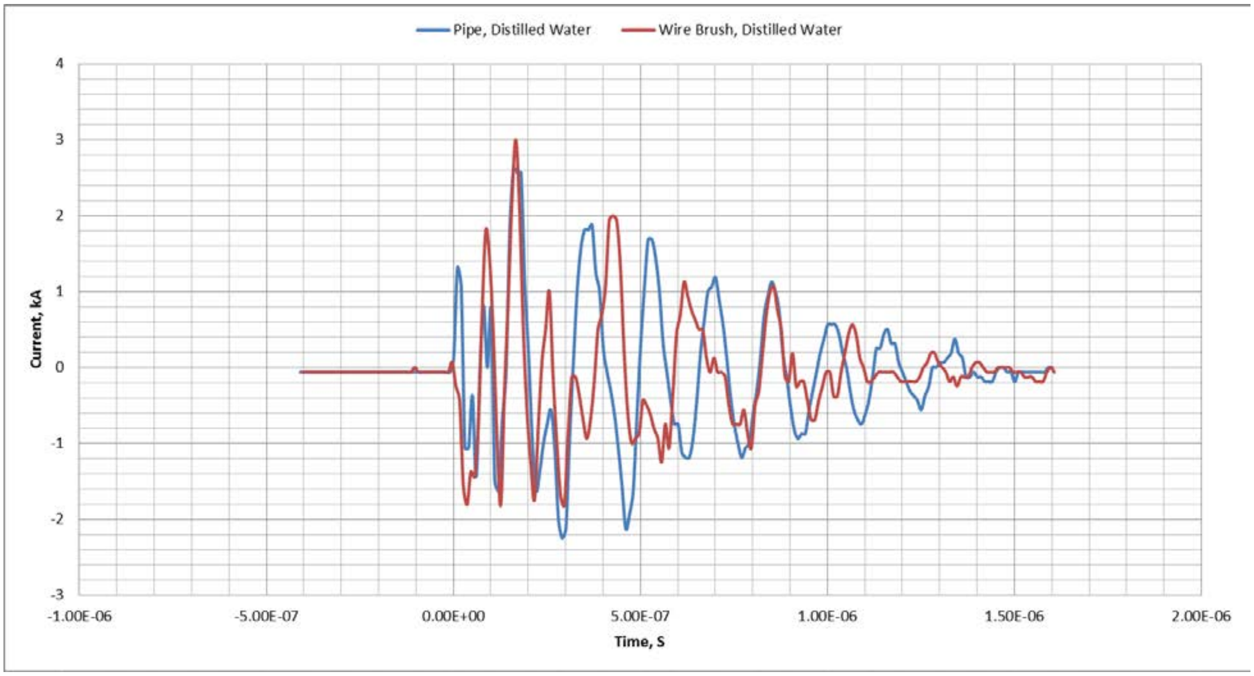


Figure 1: Comparison of transient discharge of a high voltage source into distilled water for a coaxial system using wire brush and smooth cylinder electrodes.

Figure 1 compares the results of transient discharge testing on a simulated storage tank using two types of test electrodes. The test electrodes were comprised of a roughly 5 inch diameter stainless steel wire brush and a 1 inch diameter hollow plugged stainless steel pipe for the cylindrical electrode. Both electrodes were submerged coaxially in a tank filled with distilled water. The electrodes were submerged to the same depth and tested separately.

From the distilled water testing for the smooth cylinder and wire brush, the data clearly show that for both of the two electrode geometries the transient response exhibits an envelope that decays at approximately the same rate. It can be gathered from these decay rates that the discharge of this capacitive system is not governed by the resistance presented by the specific type of electrode, but by other either bulk properties of the fluid or the geometry of the tank. These measurements provide further evidence that there is no advantage of the wire brush in discharging the tank system.

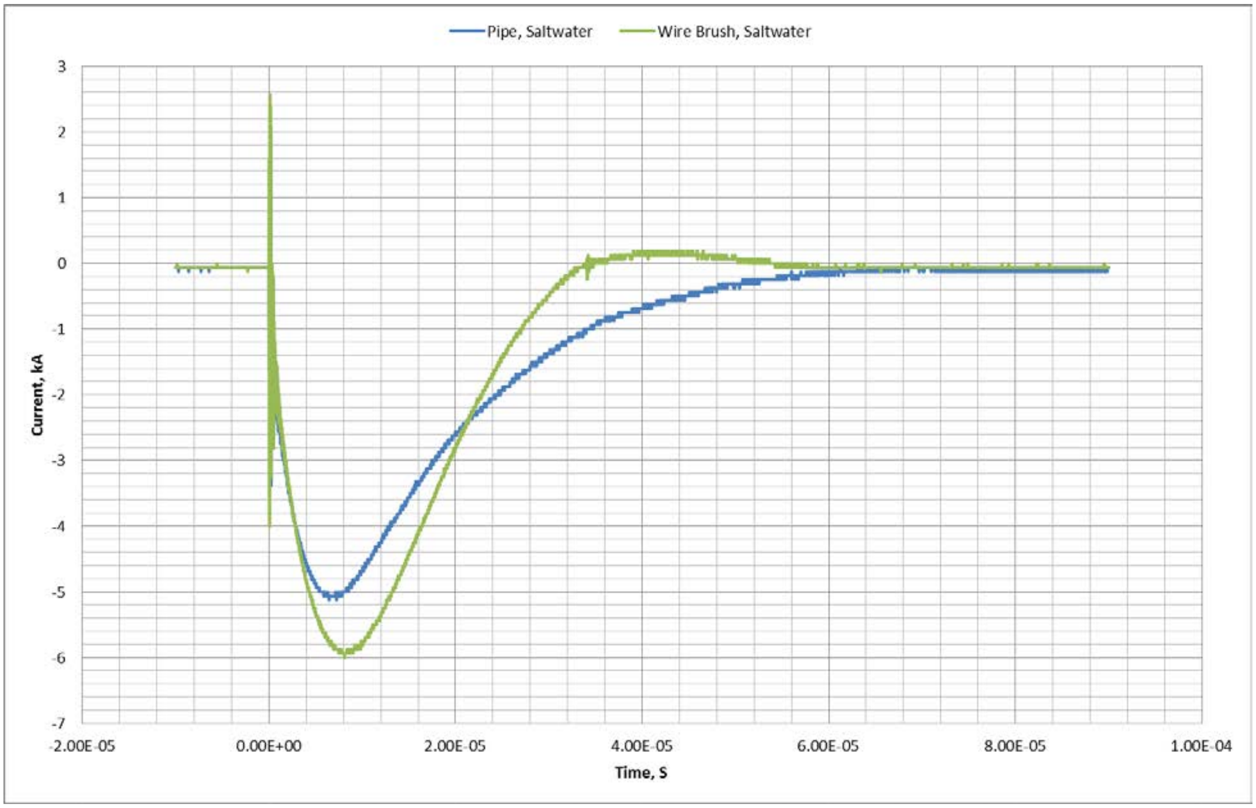


Figure 2: Comparison of transient discharge of a high voltage source into saltwater with conductivity ~4 S/m for a coaxial system using wire brush and smooth cylinder electrodes.

Figure 2 compares the same discharge test results for a solution of NaCl and water comparable in salinity to that of seawater (~4 S/m). The devices were submerged to the same depth and tested separately. The brush data in the discharge curve exhibits a near-critically damped oscillatory behavior - as can be seen in the overshoot and decay present at ~35 usec. The wire brush shows an underdamped response that is the result of an increase of series inductance, with the capacitance of the system between the brush and cylindrical electrodes and tank wall assumed to remain the same. In contrast, the cylindrical electrode shows critical damping representative of less inductance – as would be expected from a hollow tube. The increased inductance of the wire brush is due to the many tiny wires along the length of the brush along with the comparatively small diameter cable that is used to hold these tiny wires in place. While the cylindrical electrode appears to display a longer discharge time, the oscillation of the brush discharge waveform tends to obscure the similarity of the electrode resistances.

The LEC test data corroborate the hypothesis that the wire brush does not appreciably reduce the resistance to the tank walls, and thus does not aid to any appreciable extent in discharge of the tank. These observations are consistent with the theory that the wire brush forms a single equipotential surface of approximate diameter of the bristles themselves, and thus the extra surface area provided by the wires does not reduce the resistance of the electrode to the bulk fluid.

Conclusion: The tank resistance and discharge analyses show that the discharge rate for a wire brush electrode is not appreciably different than for a smooth surface cylindrical electrode of similar diameter. Two conclusions can be drawn:

1. With regard to the resistances of the electrodes to the bulk fluid and their ability to discharge a surface charge, they are nearly equivalent, although since the cylindrical electrode exhibits less series inductance it is preferred.

2. The supposed benefit that the splines would provide inside the tank does not outweigh the risks associated with the possible generation of corona discharge or arcing.

Due to the potential for igniting the ullage above the fluid and the insignificant improvement in fluid conductance, such wire brush electrodes are thus not recommended. In contrast, the ability to neutralize surface charge on the surfaces of the fluid and thus to mitigate field enhancement near electrically exposed edges of the fluid mass (i.e., at the periphery of the top surface of the fluid mass) is better served using a *non-corrosive cylindrical electrode running* from the top of the tank down to the bottom of the fluid. This electrode, along with a primary means of electric field reduction in the ullage using even an incomplete external Faraday "birdcage" can be expected to provide the highest reliability means of retrofitting non-metallic chemical storage tanks for lightning safety.

For more information on this subject matter please contact Lee Howard at LeeH@lecglobal.com