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Lightning Burnthrough to Containment Breach of 55-Gallon TRU Waste Drums

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ABSTRACT

We investigated by arc-plasma heating the feasibility of attributing inherent lightning protection to 55-gallon DOT 7A, Type A, open head carbon steel drums made of 1.5 millimeter painted carbon steel, designed to protect Department of Energy transuranic nuclear waste. The Sandia Lightning Simulator transferred continuing current in 300 ampere (A), 400 A, and 500 A tests to achieve a 350 coulomb charge transfer and simulate cloud-to-ground lightning attachment to test coupons and 9 drums. A tungsten electrode was placed 0.75 inch from the drums. High-speed photography was recorded to observe the exterior containment breach, or "first light," seen on camera when burnthrough opened a hole in the containment. Sheet metal burnthrough occurred between 18 and 71 coulombs in lid and rolling hoop tests, but 12-gauge closure ring tests did not result in burnthrough, which suggests this feature may provide an inherent air terminal protective feature.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
A	Ampere
BL	Barrel lid
C	Coulomb
CCG	Constant/Continuing Current Generator
CG	Cloud-to-Ground
DC	Direct current
DUT	Device under test
EPDM	Ethylene Propylene Diene Monomer
kA	Kiloamperes
kV	Kilovolt
kW	Kilowatt
LANL	Los Alamos National Laboratory
ms	Millisecond
NNSA	National Nuclear Security Administration
ns	Nanosecond
Sandia	Sandia National Laboratories
SLS	Sandia Lightning Simulator
SRNL	Savannah River National Laboratory
TRU	Transuranic
V	Volt
WIPP	Waste Isolation Pilot Project

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1. INTRODUCTION

The threat to be evaluated from lightning to rubber gasket-sealed 55-gallon drums containing low-level radioactive waste is that of lightning burnthrough, which creates one potential avenue to breach the single-walled containment barrier (afforded by the drum's thin steel walls) and Ethylene Propylene Diene Monomer (EPDM) flat gasket. Transuranic (TRU) waste is radioactive waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years. Transuranic elements are those greater than uranium on the Periodic Table of Elements. Figure 1-1 shows a DOT 7A Type A carbon steel waste drum (far left), the closure ring assembly drawing Detail B depicts the EPDM gasket (callout 3), which is visible in the next photo (black ring against red paint) of the TRU drum lid interior, followed by a photo of the closure ring bolt (far right).

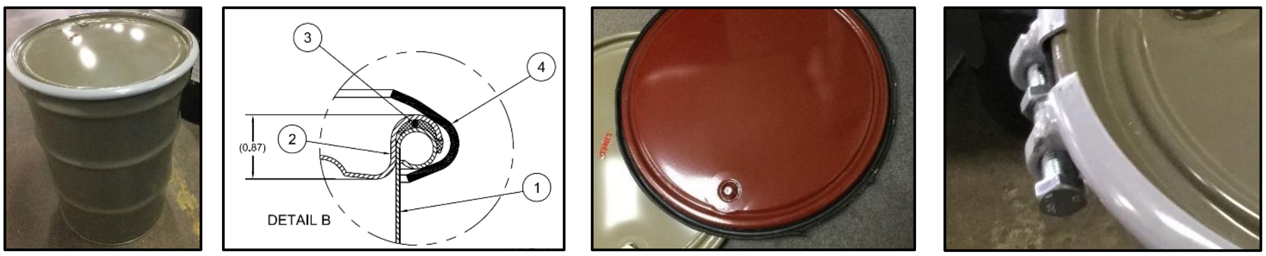

Figure 1-1. DOT 7A Type A carbon steel waste drum.

Lightning burnthrough is the phenomenon by which lightning arc root attachment to a metallic barrier heats, melts, and—depending on the barrier's thickness and composition—eventually breaches the barrier, producing a hole through which contaminants may escape, potentially including sub-visible radionuclide particulates. The lightning phenomenon that drives burnthrough is the relatively low-current amplitude, hundreds of amperes long duration (hundreds of milliseconds), slowly-varying continuing current generated in lightning flash events that often follow the initial fast rise (hundreds of nanoseconds), high peak current (tens of kiloamperes) return strokes. The graphic in Figure 1-2extracted from Military Standard (MIL-STD)-464C (December 2010) [1] depicts a two return stroke, Time versus Current lightning flash.

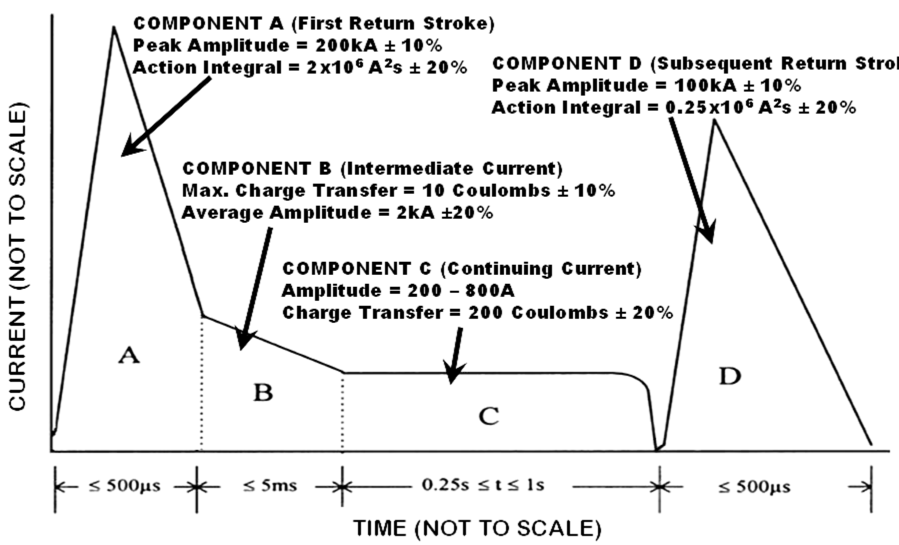

Figure 1-2. Time vs Current graphic from MIL-STD-464C [1].

The Sandia Lightning Simulator (SLS) Constant/Continuing Current Generator (CCG), depicted in red in Figure 1-3, was used to conduct tests on 55-gallon carbon steel drums and small steel coupons that represented the drum lid, clamp ring, and sidewall thicknesses. The CCG is a commercially available, 500-kilowatt direct current (DC) power supply capable of producing 500 amperes DC at 500 volts DC, which is used to simulate the continuing current (Component C from MIL-STD-464C) associated with lightning return strokes in natural lightning. A photo of the CCG is shown in Figure 1-4. The SLS also features two oil-filled high voltage tanks equipped with megavolt-class Marx generator capacitor banks that can provide Components A and D return strokes as depicted in Figure 1-2.

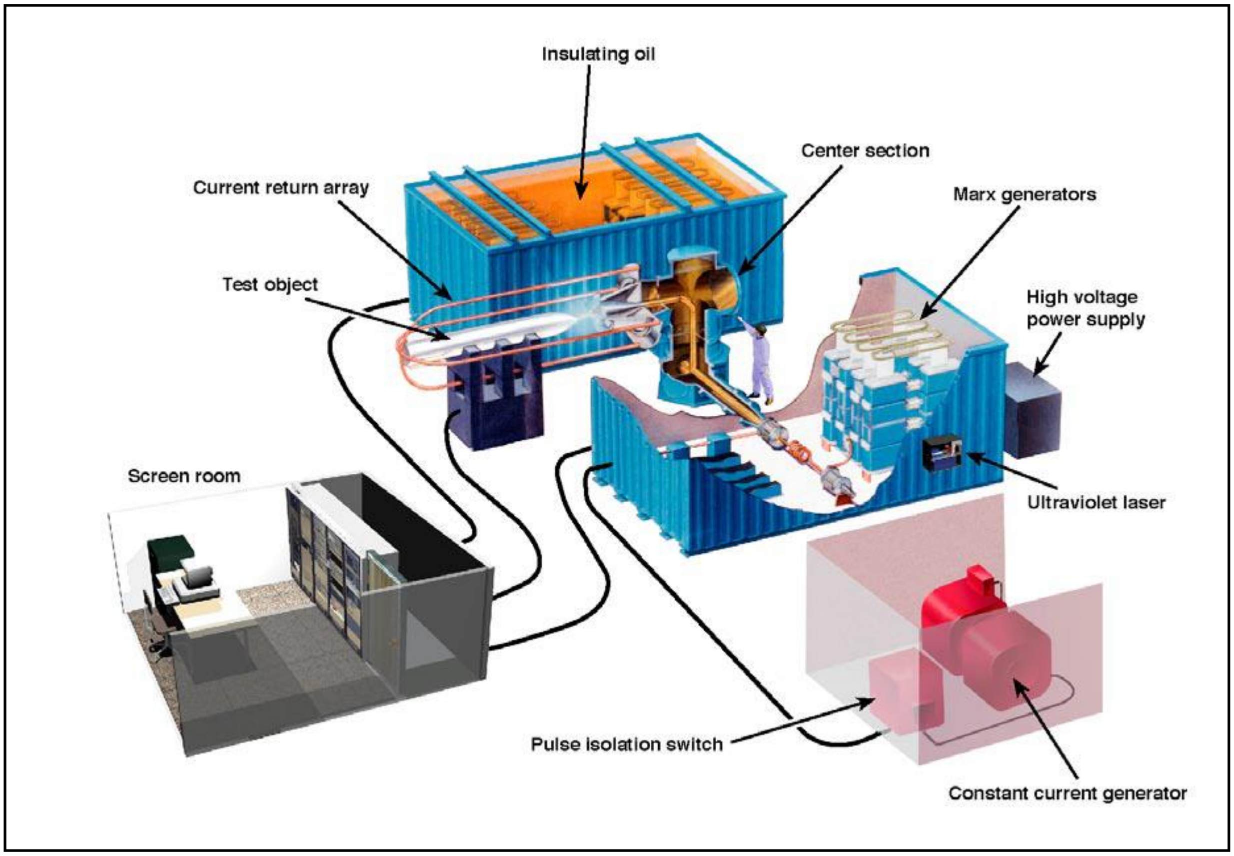

Figure 1-3. Sandia Lightning Simulator.

Figure 1-4. Continuing Current Generator.

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2. EXPERIMENTAL SETUP

Two test series were used to evaluate lightning burnthrough characteristics of 55-gallon commercial and transuranic (TRU) waste drums. The first test series focused on a set of 5 inch-diameter aluminum and steel coupons. Aluminum (T6061 alloy) coupons have been tested at the Sandia Lightning Laboratory (SLS) in previous studies and served as a baseline checkout of the recently installed Continuing Current Generator (CCG) prior to the steel coupon tests. Alloy 1008 steel coupons were used to replicate the steel alloy used in commercial Skolnik Industries (Chicago) CQ5508 and CQ5508L TRU waste drums later tested in these experiments. The 55-gallon TRU waste drums—the main subject of the proposal—are made of painted carbon steel (1008 alloy) and have representative thicknesses of 16-gauge (1.5 millimeter (mm)) for the main body, bottom, and lid. The closure bolt ring that clamps the barrel lid to the barrel main body is 12-gauge steel (2.7 mm). A conformal EPDM rubber gasket underneath the lid creates a seal to the barrel body when the bolt ring is secured to keep drum contents effectively leak tight against particulate escape, which is crucial for TRU drum low-level nuclear waste containment prior to shipment and long-term storage below ground at the Waste Isolation Pilot Project (WIPP), New Mexico. See Appendix A through Appendix E for details about the generic CQ5508 and CQ5508L 55-gallon TRU waste drums and Material Safety Data Sheets for paints and coatings used on these drums.

The focus of the tests covered in this report is on the potential for lightning burnthrough to breach drum containment during the continuing current phase in a lightning flash. In a natural lightning flash, the continuing current is preceded by a lightning return stroke at step leader attachment and - in some cases - is followed by additional return strokes and more continuing current. Four return strokes and three inter-stroke continuing current intervals of 60 milliseconds (ms) each is considered a median (50%) value in lightning flash events accepted as the "direct-strike lightning environment" for nuclear weapons by the U.S. Department of Energy (DOE) [2]. The SLS, as notionally pictured in Figure 1-3, is designed to deliver two back-to-back return strokes, plus continuing current between the two return strokes. Prior experience indicates the initial return stroke will not burn through 16-gauge steel alloy; however, it provides a path for the continuing current, including the process of arcing through painted surfaces. It is that continuing current that is primarily responsible for the burnthrough process. Figure 2-1 shows an example of a 100-kiloampere (kA) return stroke charge transfer of approximately 14 coulombs (C), or ampere-seconds. By contrast, the continuing current tests in this report were nominally 500 C. The 100-kA return stroke was produced with the Marx generators seen in Figure 2-2 (output view) and Figure 2-3 (side view). The capacitors in the Marx generators store the energy necessary to produce the desired current for an individual return stroke. The output view shows two Marxes electrically connected in parallel with the output current delivered at the bottom-center of the photo, and each of the Marx grounds at the bottom left and right. The side view shows some of the basic components: charge buses, capacitors, resistors, the trombone (top ground), and trigger bar. **Brief description on Marx operation**: The oil-submerged Marx capacitors are charged in parallel via the plus and minus charge buses. Once the capacitors are fully charged, a command high voltage trigger is applied to the trigger bar, which nearly simultaneously triggers all the spark gap switches and which then discharge to the capacitors in a series electrical configuration into the device under test (DUT).

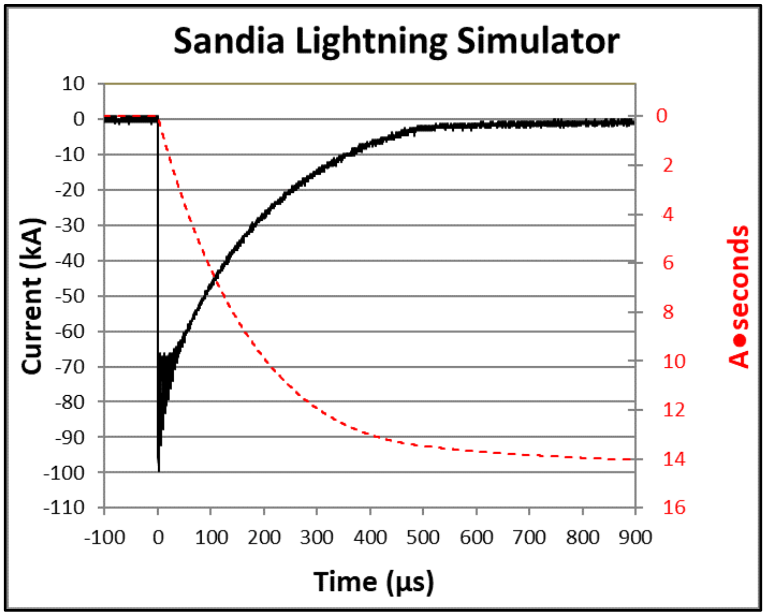

Figure 2-1. SLS return stroke.

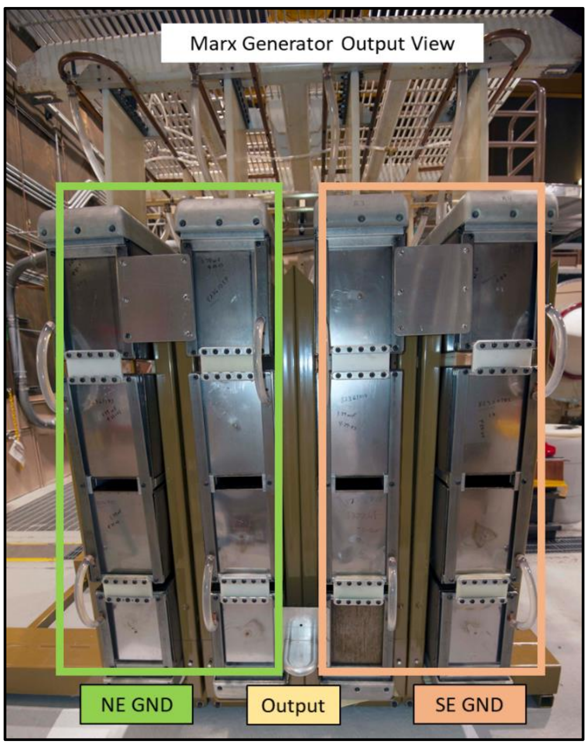

Figure 2-2. SLS Marx generator output view (removed from oil bath).

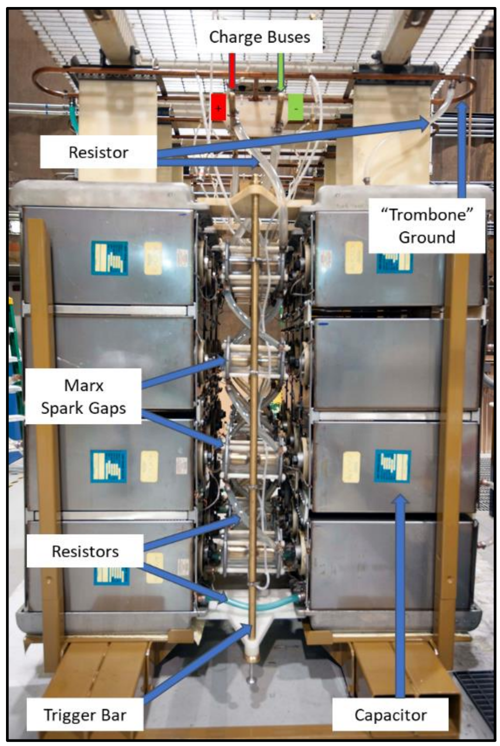

Figure 2-3. SLS Marx generator side view.

For demonstration purposes, individual return strokes with charge transfers of 16 C and 4.7 C were first applied approximately 1 hour apart to the painted carbon steel lid of a 55-gallon drum (CQ5508). A sharpened tungsten electrode was used for the CCG tests on coupons and barrels. The tip of the sharped electrode was placed 0.75 inch from the barrel lid, and the return current back to the SLS CCG was via 0.5 inch-diameter copper tubing. The basic setup configuration is shown in Figure 2-4. Post-test results are provided in Figure 2-5. The individual return strokes easily penetrated the painted surface of the lid as seen by the melted slag on the lid surface. Delivering microsecond waveforms similar in shape to that seen in Figure 2-1, the approximate return stroke peak currents for the 16 C and 4.7 C tests were -113 kA and -33 kA, respectively. The median lightning return stroke peak current amplitude given in Uman (2010) [2] is 30 kA, and we demonstrated in this test one return stroke will easily deface the painted barrel down to the base metal of the barrel lid at 33 kA, but no burnthrough was noted. Since the continuing current begins after the first return stroke, the SLS has for many years used a starter wire to simulate lightning attachment, which establishes a low resistance cloud-to-ground (CG) current path during the first return stroke to form a lightning channel. The starter wire establishes a viable single connection point to a DUT to minimize arc wander, which may otherwise occur, producing nearby slag deposits created by the first return stroke. The starter wire is attached to a sanded base metal surface on the DUT with either copper tape or conductive epoxy in an attempt to provide the arc root with a single point to attach to the base metal, which then concentrates the arc plasma in one area to further maximize the potential for burnthrough.

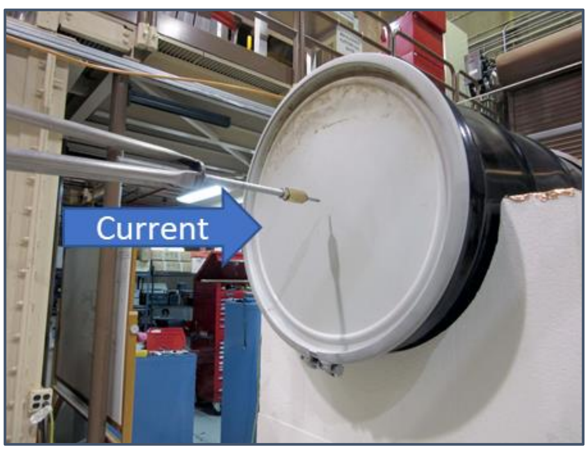

Figure 2-4. SLS return stroke setup.

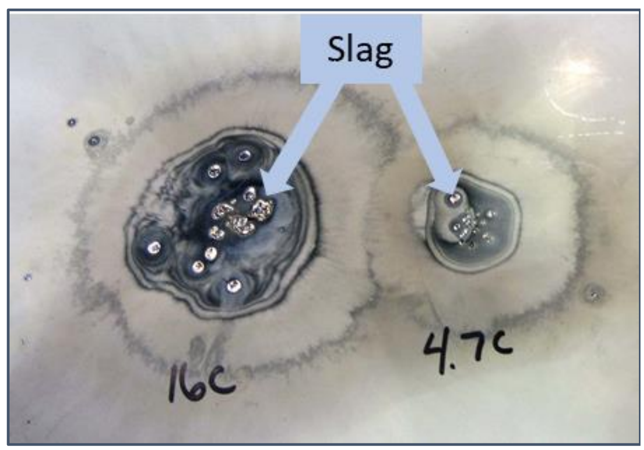

Figure 2-5. SLS return stroke post-test attachment surface damage (no burnthrough).

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3. BURNTHROUGH

Sheet metal burnthrough at high current is a multi-physics phenomenon involving electromagnetics, thermodynamics, fluid dynamics, and plasma physics, making it both difficult to understand and interesting to study. In some ways, lightning burnthrough is analogous to arc welding, so it is often possible to consult welding physics literature to guide an understanding of the burnthrough process. Figure 3-1 [3] illustrates the relevant mass and energy transfer physics associated with an arc plasma interaction with a metallic surface that characterizes the arc welding process—the same processes thought to occur during lightning burnthrough. The interaction can be divided into two main regions: (1) the area above the metal, and (2) the "melt pool," which is the region consisting of molten base metal at the site of burnthrough, resting atop a presumedly ever-decreasing solid phase lamination of base metal. Important physics for describing the burnthrough process takes place in both regions. A still frame image from high-speed video captured during one barrel lid test is shown in Figure 3-2. The tungsten cathode is outlined by the dotted gray line. The arc plasma (bluish-gray) and plasma jet (reddish) can easily be seen in the photo. The melt pool seen in the photo was very dynamic throughout the burnthrough process as witnessed by high-speed photography (Hyperlink provided below) , sloshing about as the hole was being formed, often times bubbling above the base metal. https://digitalops.sandia.gov/Mediasite/Play/e7e4ed944d11485887efdc24dacd299b1d

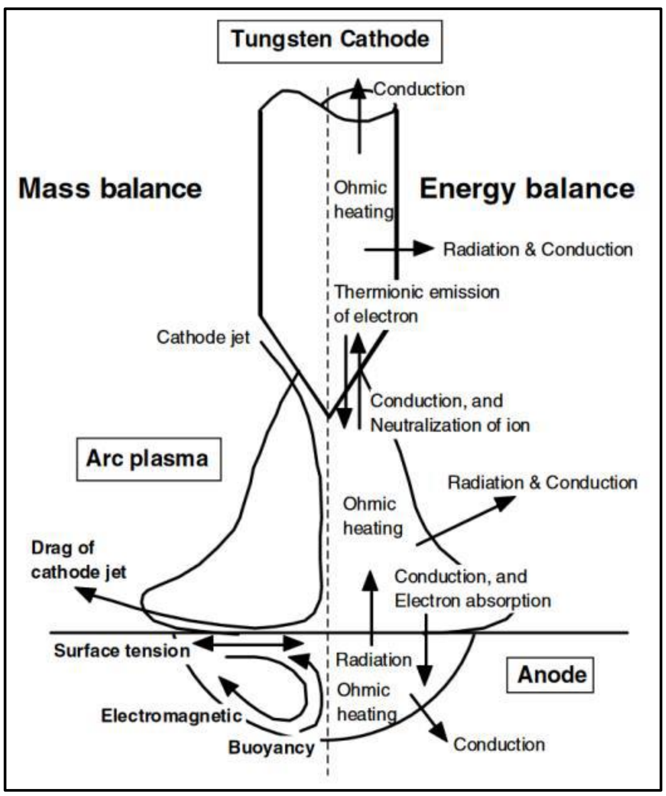

Figure 3-1. Schematic illustration of energy and mass balance of the arc welding process [3].

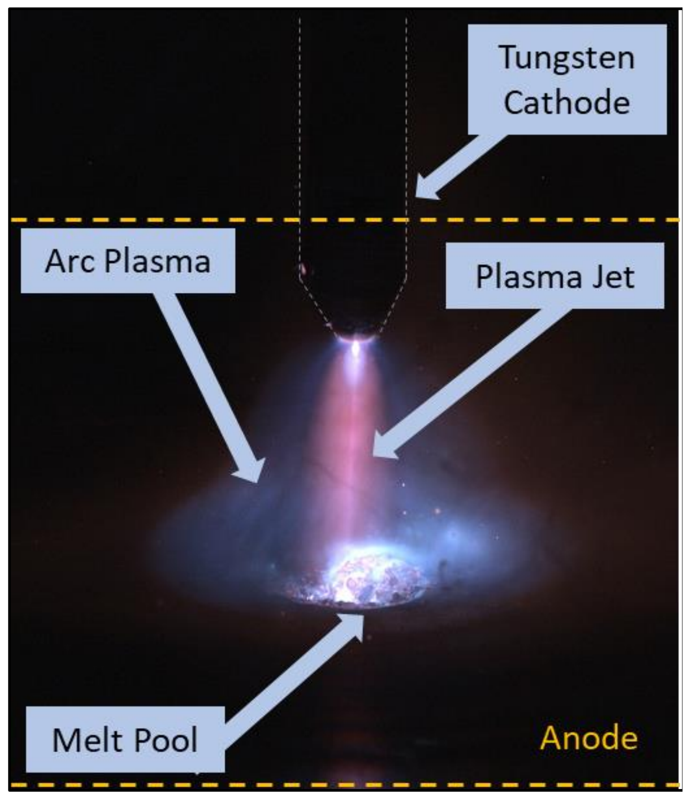

Figure 3-2. Melt pool from drum lid coupon test.

3.1. Coupon test setup and configurations

Burnthrough tests were performed in the Sandia Lightning Simulator (SLS) at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. The SLS is a unique lightning test facility within the Department of Energy (DOE) complex that is capable of simulating lightning high peak current return strokes up to 200 kiloamperes (kA), continuing currents, and a combination of two return strokes and continuing current. For a more detail description of the SLS, the reader is referred to Caldwell and Martinez (2005) [4].

The continuing current generator (CCG) used to simulate continuing current is a model MTD500-500/480+HS+LXI (Magna-Power, Flemington, New Jersey) and is capable of a 500 ampere (A), 500 volt (V) direct current (DC) output. The CCG is programmable in current amplitude and duration from 20 milliseconds (ms) to continuous DC and has an inherent rise and fall time of approximately 20 ms. The use of a programmed sequence provides for a high degree of repeatability test-to-test.

Data was first collected on unpainted steel alloy 1008 coupons. Coupon thicknesses of 16-gauge (used to represent the barrel body, bottom, and lid) and 12-gauge (used to represent a 55-gallon drum closure ring) were tested. Coupons of 10-gauge and 7-gauge were also tested to investigate steel thicknesses that may be resistant to burnthrough, which may prove useful for future lightning designs for 55-gallon drums or other applications where lightning burnthrough is a concern. The choice of 7-gauge (0.179 inch thick) was used as an upper bound on coupon thickness, since it is the approximate combined thickness of 16-gauge (barrel thickness) plus 12-gauge (closure ring thickness), which overlap at the flat gasket seal. Some tests were also performed on 16-gauge coated coupons that were cut from transuranic (TRU) drum lids. Two different electrode configurations were used, direct and indirect, which are discussed in section 3.1.2.

3.1.1. Photometric Setup to Determine Burnthrough Elapsed Time

Figure 3-3 shows the photometric setup used for the vertical coupon burnthrough tests (front view). Two cameras were used to view the burnthrough event. Camera 1 was used to directly view the back side of the coupon under test. Camera 2 was directed at a mirror to capture the front side of the coupon under test. Time to burnthrough was assessed as "time to first light" seen by Camera 1 in our experiments (reported in Table 3-2 and following tables) and was determined visually in manual picks from recorded high-speed videos. "Time to first light" is defined as the time from camera triggering by a signal from the CCG and continuing until Camera 1 recorded a visible white spot of light (first light) on the back of the coupon or drum under test. This time to burnthrough was then correlated to charge transfer as Coulombs (C), or ampere-seconds. Figure 3-4 shows the view of the SLS output and coupon holding fixture, as well as the camera and mirror positions. The SLS CCG drive current arced to the coupon at the SLS output tungsten electrode and returned to earth ground at the CCG located in an adjoining room via the 0.5 inch-diameter copper buss bars (current return conductors) seen attached to the coupon holder test rig platen. Figure 3-5 shows the current path from the SLS output electrode through a vertically oriented coupon and back to SLS ground through the four current return conductors.

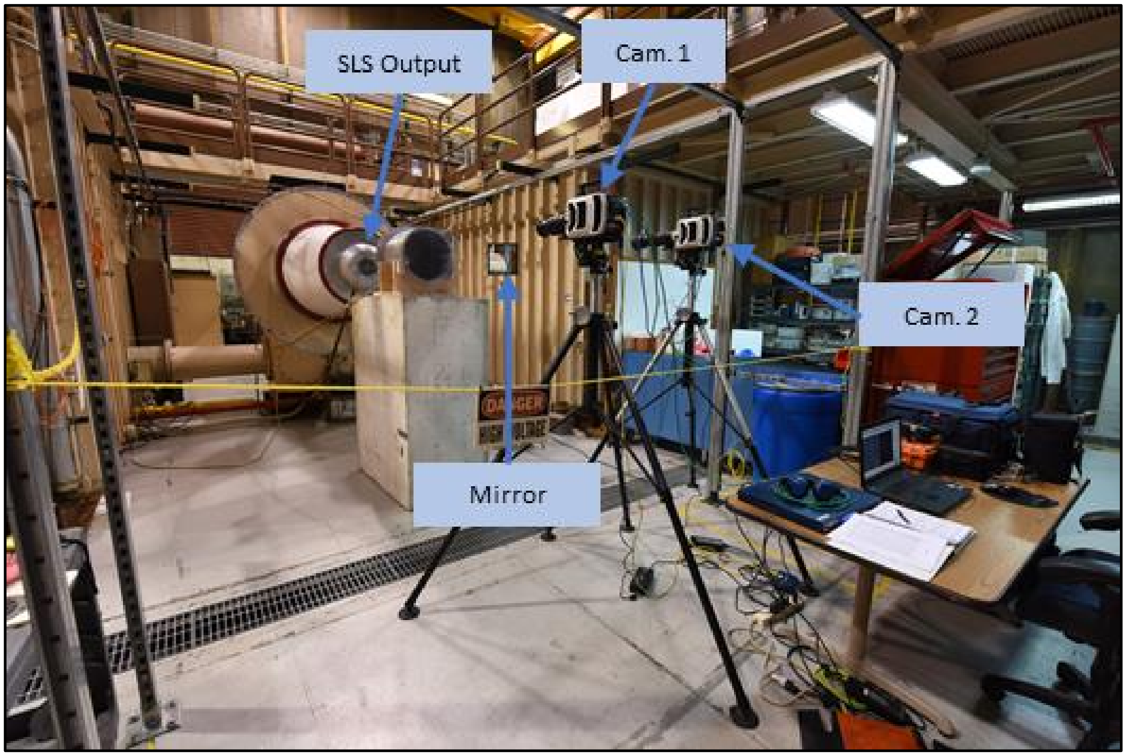

Figure 3-3. Photometric setup front view.

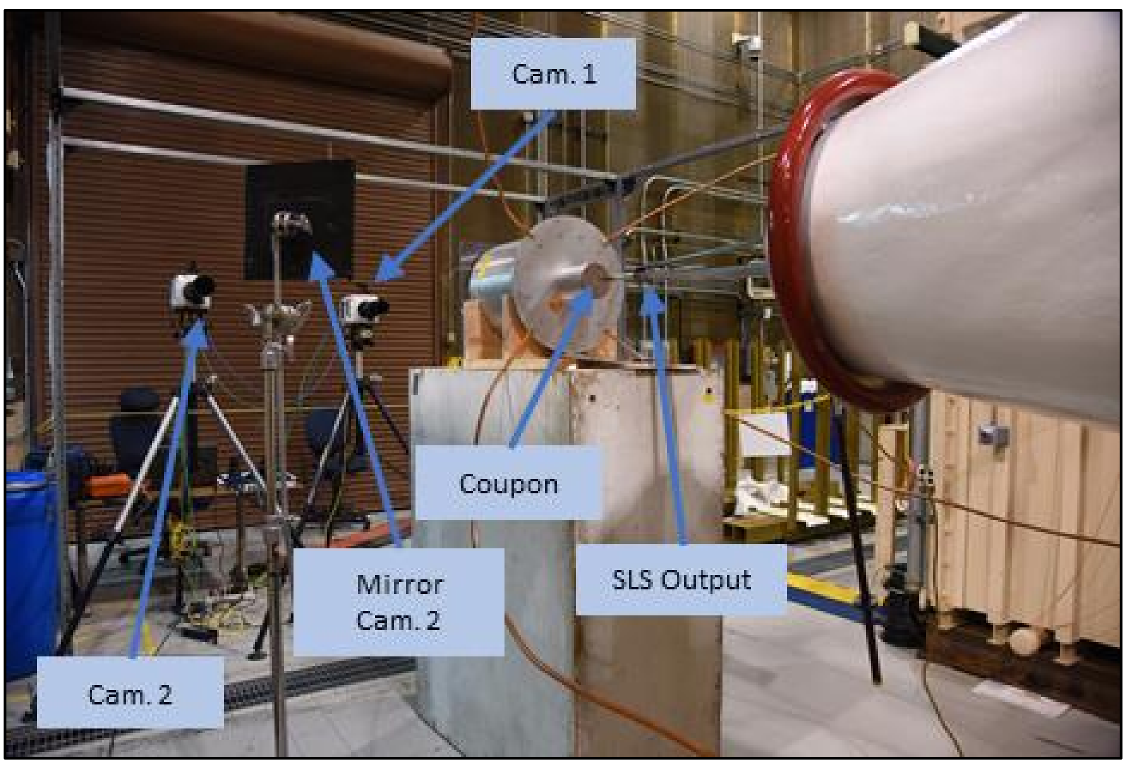

Figure 3-4. Photometric setup coupon view.

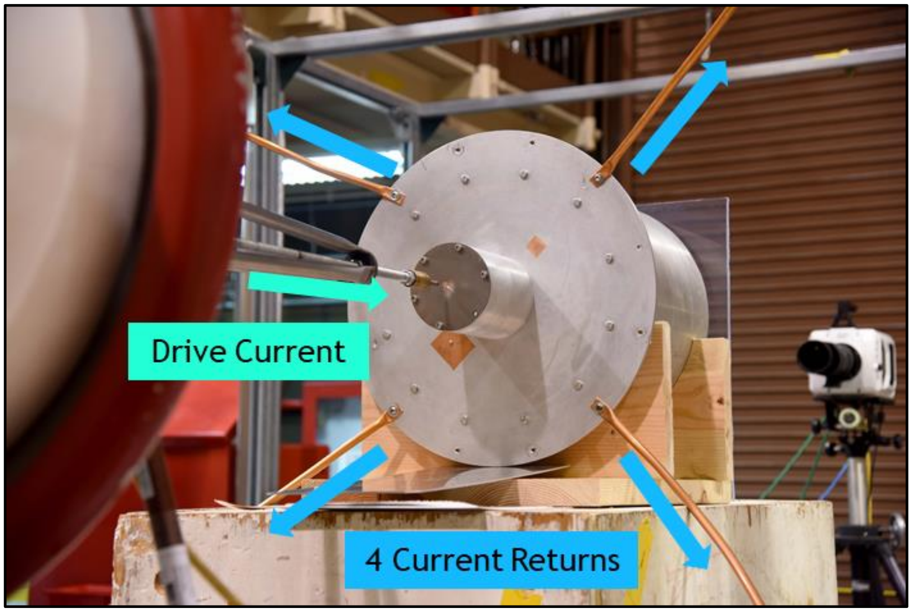

Figure 3-5. The 5 inch-diameter coupon on test rig with copper returns.

Figure 3-6 shows the setup used for the horizontal coupon burnthrough tests, which also used two cameras to view the burnthrough event, in like manner to the vertical tests. One camera (not shown) was used to directly view the top of the coupon, while a second camera was directed at a mirror seen visible underneath the coupon to capture the burnthrough moment of first light. In the horizontal coupon tests the current was applied vertically onto the coupon, and two current return conductors were used to direct the current back to ground (as shown in Figure 3-6).

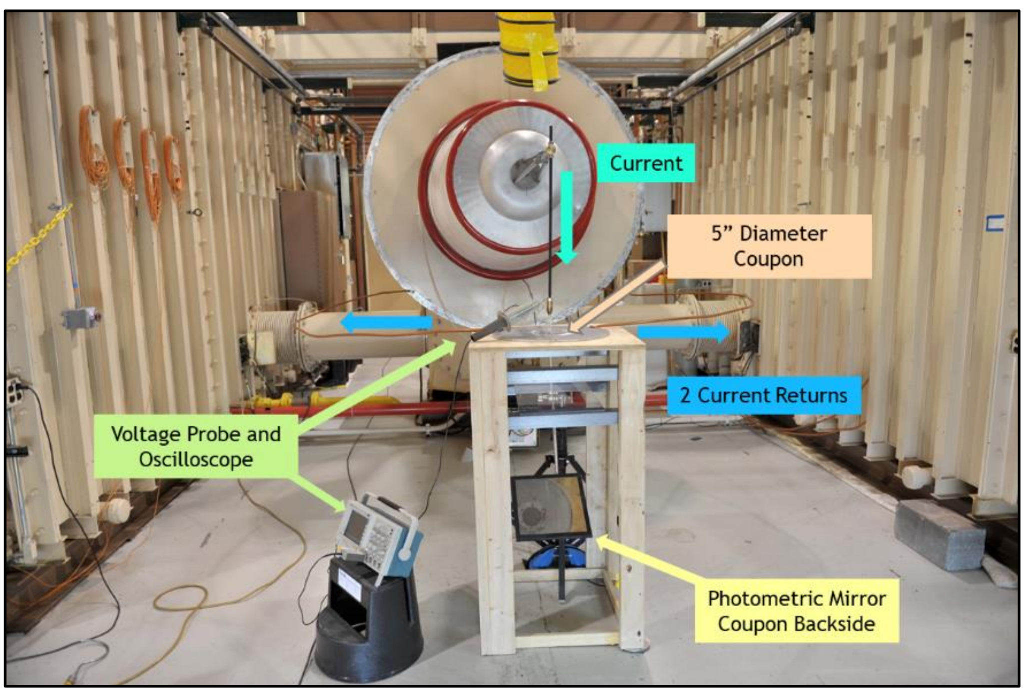

Figure 3-6. Horizontal coupon setup.

3.1.2. *Direct and Indirect Electrode Configurations*

The methods used to generate a simulated lightning arc and induce attachment for these burnthrough tests are shown below. Figure 3-7 shows a direct (non-diverter tip) electrode configuration involving a sharpened 0.25 inch-diameter tungsten electrode and a copper starter wire used for vertical and horizontal coupon tests. Figure 3-8 shows an indirect (plasma diverter) electrode configuration that incorporates a 0.5 inch-diameter polytetrafluoroethylene cap with slots milled out on its sides, which is placed over a flat-tipped 0.25 inch-diameter tungsten electrode and copper starter wire that was similarly used for both vertical and horizontal coupon tests. Figure 3-9 and Figure 3-10 show the corresponding direct and indirect electrode configurations, respectively. The differences and purposes of using these two configurations is explained in section 3.1.3. In both vertical and horizontal cases, a 0.25 inch-diameter tungsten electrode was used, and the tip of the electrode was positioned 0.75 inch from the coupon. Initial electrical contact was made between the electrode output of the SLS and the coupon using a sacrificial 0.015 inch-diameter copper starter wire. After the application of current, the starter wire burns away and an arc path between the electrode and coupon is established to simulate the conducting lightning channel present after lightning attachment. The time it takes for the copper starter wire to burn and establish a steady arc between the electrode and coupon is highly variable and can range from approximately 5 milliseconds (ms) to approximately 25 ms.

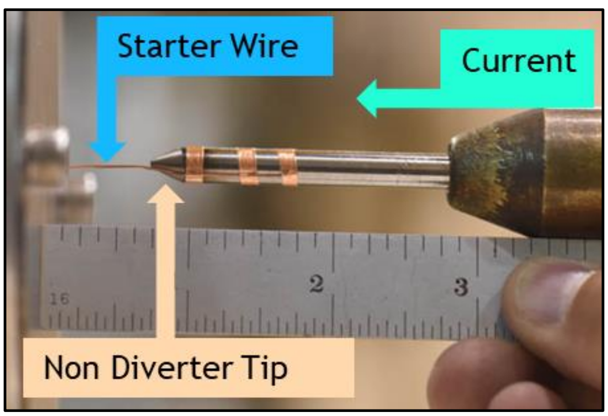

Figure 3-7. Vertical coupon direct electrode.

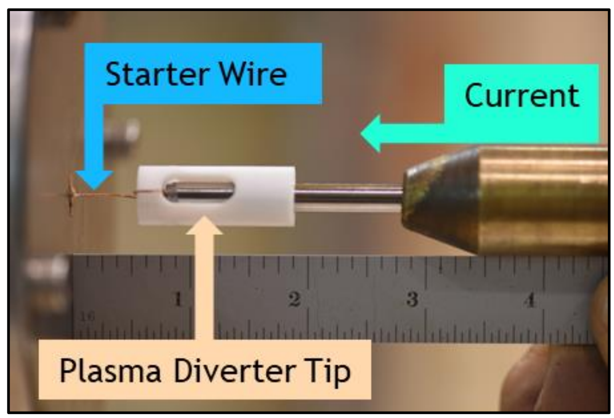

Figure 3-8. Vertical coupon indirect electrode.

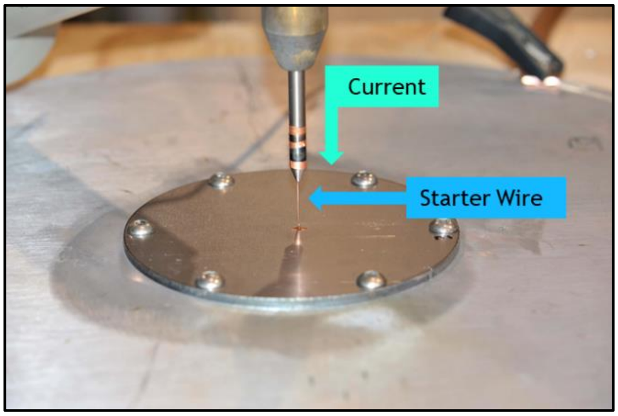

Figure 3-9. Horizontal coupon direct electrode.

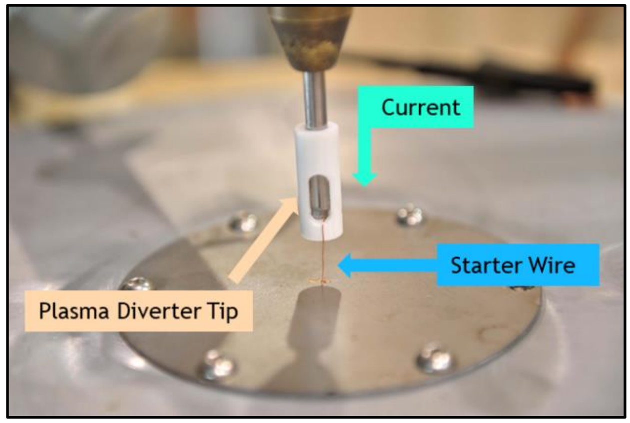

Figure 3-10. Horizontal coupon indirect electrode.

3.1.3. *Differences in Direct and Indirect Electrode Configurations*

The differences in the arcs produced by direct and indirect electrode configurations seen in high-speed photography are shown in Figure 3-11 stills. Both images were captured with the same shutter speed and exposure settings. Figure 3-11(a) shows a 500 A arc produced by the direct electrode, and Figure 3-11(b) shows a 500 A arc produced by the indirect electrode. The visible differences between the two methods include apparent self-illuminated lines of electromagnetic flux normal to each other for the indirect electrode and connecting in a cross shape versus a more anticipated curved arc. The purpose of the indirect electrode configuration was to decouple the arc and electrode plasma jet. The electrode plasma jet consists of spalling tungsten particles that are ejected normal to the electrode surface at a high velocity. The indirect electrode configuration minimizes the interaction of the electrode plasma jet with the burnthrough process on the coupon surface by re-directing tungsten particulates away from the attachment point. In general, the direct electrode configuration is a more severe burnthrough insult that should cause burnthrough to occur more quickly and produce greater overall damage. Both types of phenomena could occur in lightning interactions in nature. The indirect electrode represents direct lightning arc root attachment in air, and the direct electrode represents the scenario of lightning-induced arcing between two metal objects bridging the lightning channel.

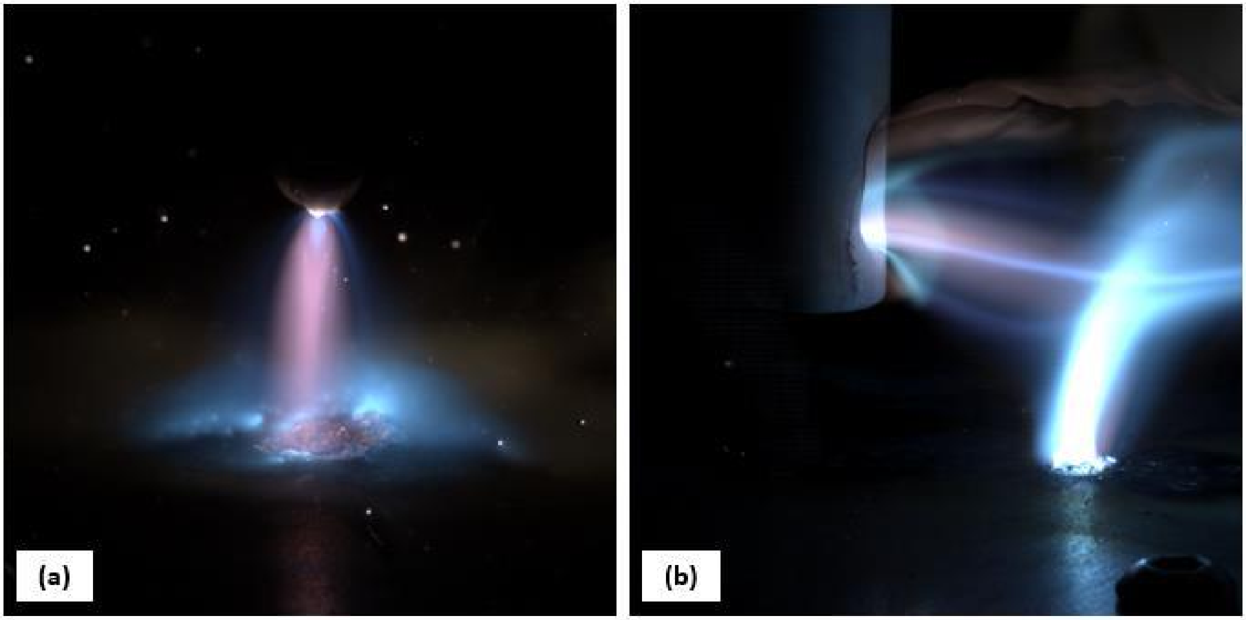

Figure 3-11. 500 A arc on 7-gauge 1008 steel alloy: (a) direct electrode and (b) indirect electrode.

Figure 3-12 shows the results of experiments in which the burnthrough occurred on two different gauge 1008 steel alloy coupons. Both experiments used the indirect electrode configuration with the coupon in the horizontal orientation and CCG settings producing a 500 A arc for 700 ms. Figure 3-12(a) shows the damage to a 16-gauge coupon, and Figure 3-12 10(b) shows the damage to a 12-gauge coupon (which is nearly double the thickness of the 16-gauge coupon). For scale, recall that the diameter of the polytetrafluoroethylene cap is 0.5 inch. Given the same amplitude, duration, and charge transfer, the damage done to the 12-gauge coupon is noticeably less than that done to the 16-gauge coupon, as expected.

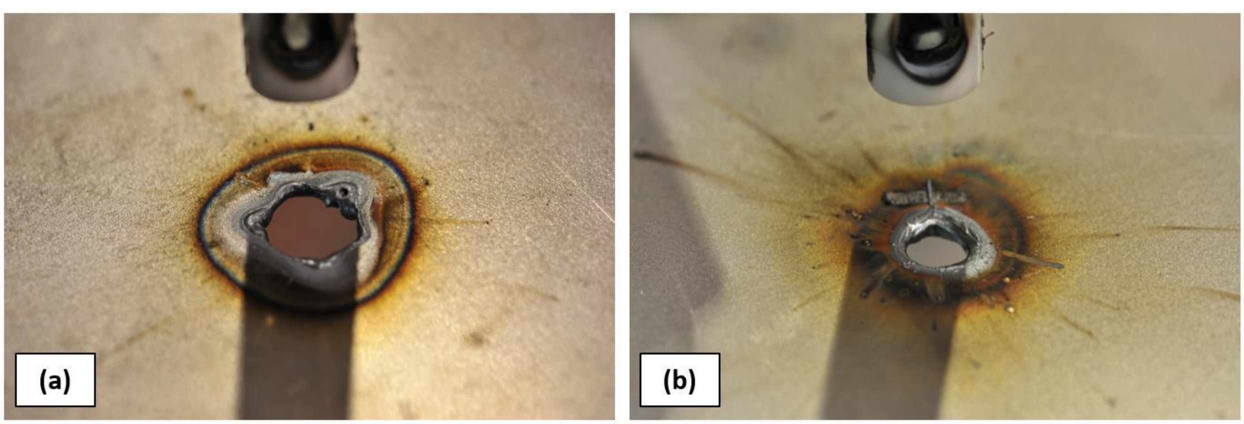

Figure 3-12. 500 A 700-ms indirect electrode: (a) 16-gauge 1008 steel alloy and (b) 12-gauge 1008 steel alloy.

3.1.4. Tests on Uncoated 1008 Steel Alloy Coupons

Data was collected on uncoated 1008 steel alloy coupons. The coupon thicknesses tested included 16-gauge (representing most surfaces of a 55-gallon drum) and 12-gauge (representing the drum's closure ring), with 10-gauge and 7-gauge coupons also tested to investigate steel thicknesses that may be resistant to burnthrough. Coupons were tested with both direct and indirect electrode configurations using horizontal and vertical coupon orientations. For comparison, all tests were conducted using a nominal charge transfer of 350 C (1C = 1 Ampere X 1 second). The 350 C represents the expected charge transfer from an extreme lightning strike—or 1% frequency of occurrence—and is selected from Uman, et al., "Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence (Second Revision)," 2010 [2]. Lightning flash event parameters describing extreme 1% frequency of occurrence and (median) 50% values shown below from Uman (2010) [2], were first established by Fisher and Uman in 1989, are applicable to the military theater, and are used for our experiments as the primary lightning physics reference to set test parameters representative of natural cloud-to-ground lightning. The CCG used in these tests produced square current pulses at three different current levels with three different current durations (Table 3-1). A plot of the typical square current pulse (300 A, 1.167 seconds) and the corresponding charge transfer is shown in Figure 3-13. Continuing current, time to burnthrough, and charge transfer were collected for each test.

ABNORMAL LIGHTNING ENVIRONMENTS

A lightning strike directly to the warhead or to equipment associated with the warhead is considered a credible possibility. The lightning could be of either the cloud-to-ground or cloud flash (intracloud, intercloud, or cloud-to-air) type. Extreme (1% frequency of occurrence) and median (50%) values are given below for those cloud-to-ground flash parameters considered to constitute the most important threats to the weapon. Corresponding cloud flash parameters fall within the envelope defined below and are therefore not separately listed.

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b. Time to Peak (μs)	0.1-15	3
c. Max. Rate of Current Rise (kA/μs)	400	150
d. Time to Decay to Half Peak (μs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150

FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
e. Action Integral [$\int I^2 dt$] (A^2s)	$3x10^6$	$5x10^4$

[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

[2]Continuing currents can occur between individual strokes, following the final stroke in a flash, or both.

Table 3-1. CCG Parameters

Amperes	Seconds	Charge Transfer (C)
300	1.167	350
400	0.875	350
500	0.700	350

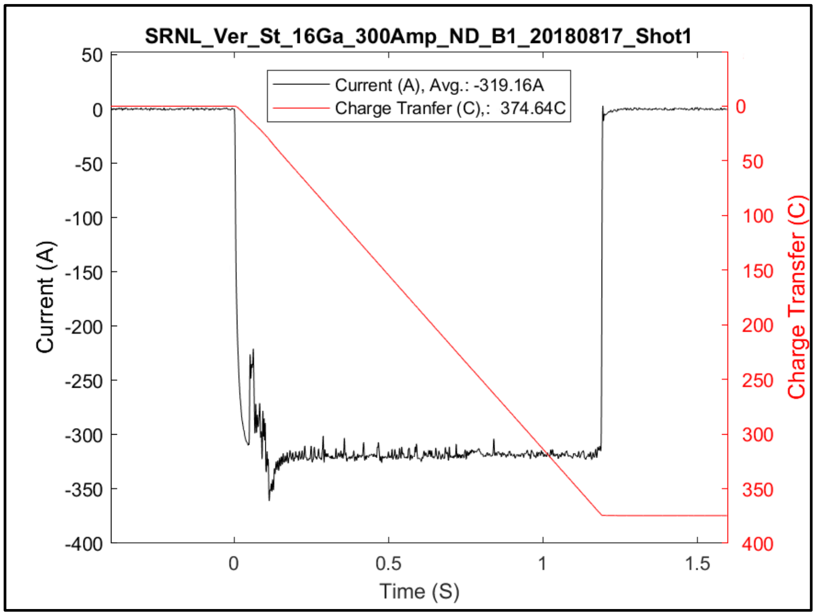

Figure 3-13. Typical CCG square current pulse (black) and imparted charge transfer to test object (red).

The coupons were tested in vertical and horizontal configurations with two electrode configurations. In the vertical orientation the force of gravity is parallel to the surface of the coupon, and in the horizontal orientation the force of gravity is normal to the surface of the coupon. The purpose for varying the orientation was to simulate lightning arc attachment to surfaces of either orientation that may occur to either lid or sidewall attachment in typical 55-gallon drum outdoor storage, and to investigate the influence of gravity on the burnthrough process, namely its effect on the melt pool. The removal of molten metal by the force of gravity could perhaps accelerate the burnthrough process by exposing the underlying solid base metal to the arc temperatures at a faster rate.

Measurements of hole sizes for both the coupons and 55-gallon drums were made with either calipers or a precision gauge-pin set at 0.001 inch resolution. Unless otherwise stated in the tables in this report, the hole measurements were made with gauge-pins. The burnthrough holes are not perfectly round and some holes may be larger in one axis than in other axes, or they may have had a piece of slag or debris that only allowed a smaller pin to fit the hole. Reported hole measurements should be read as approximations.

The scope of the tests covered in this report did not include the accounting of either dynamic arc impedances or causes for observed arc wander in some tests. The explanation for any non-linearity observed was not investigated. A few tests included measurements of both arc voltage and CCG current to illustrate differences in arc impedance for direct and indirect (using the polytetrafluoroethylene diverter tip) electrode configurations. Figure 3-14 shows the voltage and current measurements for a 519 A, 700 ms test on a 16-gauge coupon with a direct electrode. Using Ohm's law (R=V/I), the arc impedance can be calculated and is shown along with the voltage and current in Figure 3-15, which is a shorter time segment of the x-axis (0 to 0.7 second) from Figure 3-14. The arc impedance varies with the changes in voltage and current. In this test, the dynamic arc impedance is relatively stable for most of the 0.7-second pulse, with some variation near 0 and 0.7 second.

Figure 3-16 and Figure 3-17 show the voltage and current measurements for a 519 A, 700 ms test on a 16-gauge coupon with an indirect electrode.

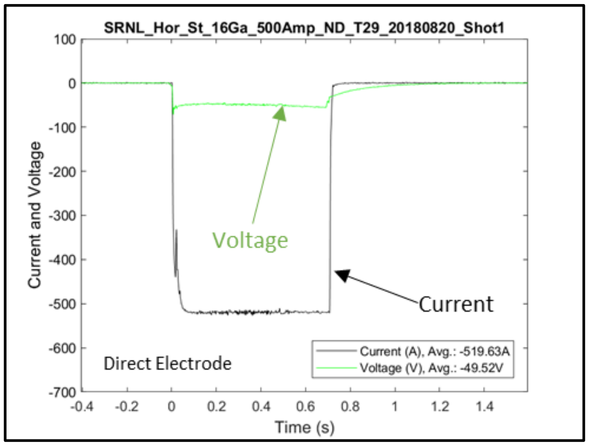

Figure 3-14. Direct electrode 50 V and 500 A.

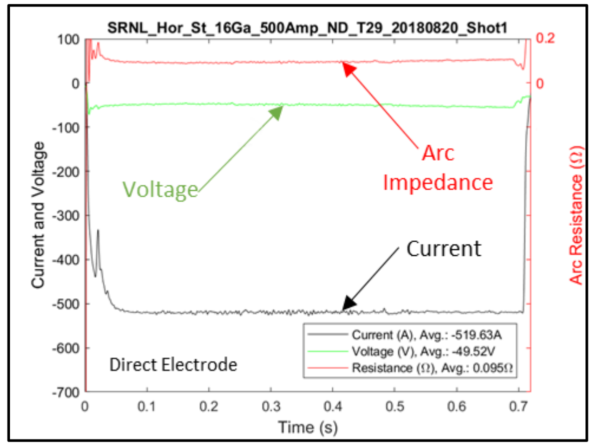

Figure 3-15. Direct electrode impedance (red).

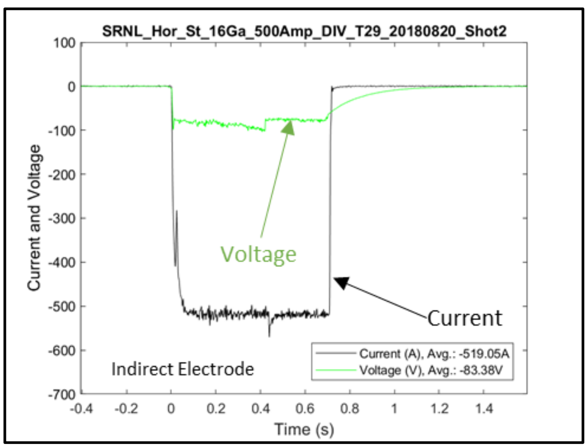

Figure 3-16. Indirect electrode 50 V and 500 A.

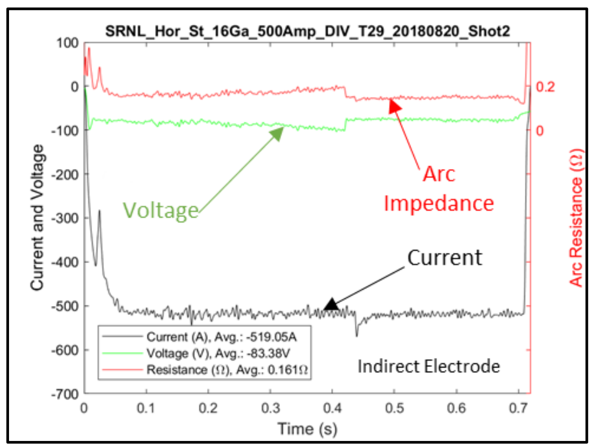

Figure 3-17. Indirect electrode impedance (red).

In this indirect electrode test, the dynamic arc impedance is more pronounced than similar tests with a direct electrode. It is also interesting to note that the average arc impedance with the direct electrode test shown in Figure 3-15 was 0.095 ohm (Ω) and produced a hole size of 0.588 inch, while the average arc impedance with the indirect electrode test shown in Figure 3-17 was 0.161 Ω and only produced a hole size of 0.376 inch. A review of Figure 3-11 shows a longer arc length with the indirect electrode that suggests a per unit length increase in arc impedance, so an approximately 69% increase in arc impedance for the indirect electrode configuration seems consistent with the visible arc path increase. The perturbation in the waveforms in Figure 3-17 at approximately 0.44 second could be the result of the arc momentarily wandering away from the arc root, which occasionally was seen in video captures. Figure 3-18 shows a photo of a burnthrough hole produced with a stable arc root, one that did not wander away from the major hole diameter. By contrast,

Figure 3-19 shows a burnthrough hole produced with the arc root wandering away from the major diameter of the hole. Arc wandering diverts the arc plasma heat away from the primary attachment point, which led to smaller diameter holes where burnthrough occurred.

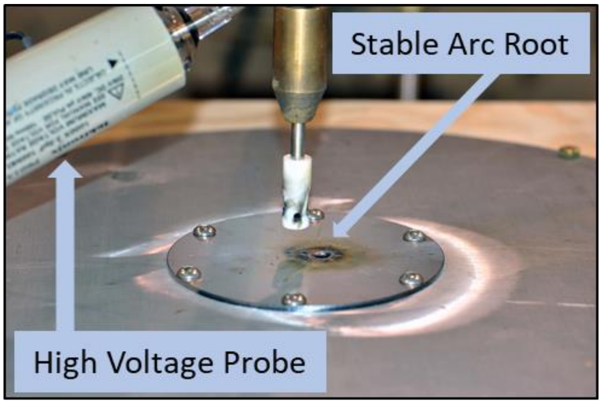

Figure 3-18. Stable arc root.

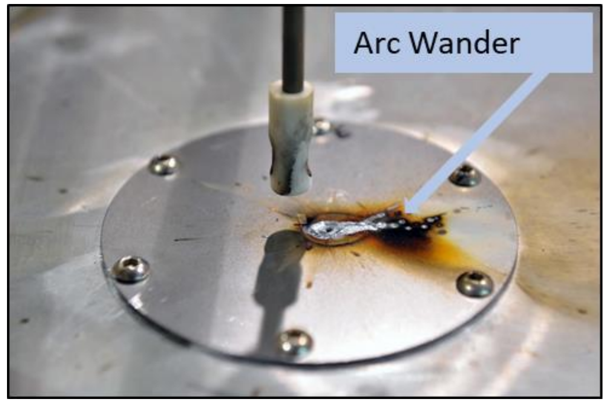

Figure 3-19. Arc wander.

3.1.5. Vertical Coupon Tests with Direct Electrode

Table 3-2 shows the test results for vertically oriented coupons with average currents of 312 A, 420 A, and 520 A using a direct electrode. The data is plotted in Figure 3-20 and Figure 3-21, which show hole sizes and burnthrough times (time to first light), respectively. None of the 7-gauge coupons achieved burnthrough. All other coupons (16-gauge, 12-gauge, and 10-gauge) burned-through, although one anomaly occurred with the 10-gauge coupon tested with 312 A. Photometric (high-speed video) data for the 10-gauge coupon did not evidence a "first light" appearance on the rear camera recording during the CCG current square wave interval, but after the test a hole measuring 0.018 inch was observed. A possible explanation for this could be that the molten metal that was present and ready to burnthrough finally opened due to stresses in the metal as it cooled after the CCG was de-energized and the cameras switched off. The 16-gauge coupons representative of the TRU drum lid and rib thickness all burned through for the 350 C charge transfer, but the absorbed charge required to burn through the coupon (first light) is inversely proportional to current level.

In general, given the same charge transfer—our 350 C target, for example—thinner gauge samples will burnthrough quicker and should have larger holes than thicker gauges. A plot of steel gauges versus hole sizes obtained using a direct electrode and a vertically oriented coupon are shown in Figure 3-20. Under ideal application of the current (arc plasma) to a variety of coupon thicknesses with the same alloy, it is expected that a linear relationship between hole size and gauge thickness should exist. This near linear relationship can be seen in the 312 A and 420 A data. One anomaly in the 520 A data for the 12-gauge coupon shows a hole diameter similar to the 10-gauge coupon. Possible reasons for such anomalies include dynamic arc impedance and arc root wander. Figure 3-21 is a plot of the time to first light versus gauge thickness using a direct electrode with vertically oriented coupons. Again, a linear relationship between time to first light and gauge thickness should exist and is observed for the 312 A and 420 A data. The 520 A data has a non-linear data point potentially caused by dynamic arc impedance or arc wander.

Table 3-2. Alloy 1008 Carbon Steel Coupons with Vertical Direct Electrode

Date	Shot #	Material Gauge	CCG Measured Time (s)	Measured Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
15-Aug-18	4	16	1.200	312	374	0.601	0.5520	172
15-Aug-18	5	12	1.191	312	371	0.251	1.0597	331
15-Aug-18	6	10	1.200	312	374	0.018	No data	No data
15-Aug-18	7	7	1.200	312	374	0.000	None	None
15-Aug-18	8	16	0.907	420	381	0.603	0.2659	112
15-Aug-18	9	12	0.914	420	384	0.377	0.5617	236
16-Aug-18	7	10	0.910	418	380	0.230	0.7674	321
15-Aug-18	11	7	0.900	420	378	0.000	None	None
16-Aug-18	1	16	0.710	520	369	0.640	0.1477	77
16-Aug-18	2	12	0.714	520	371	0.243	0.6554	341
16-Aug-18	3	10	0.714	520	371	0.243	0.5533	288
16-Aug-18	4	7	0.714	520	371	0.000	None	None

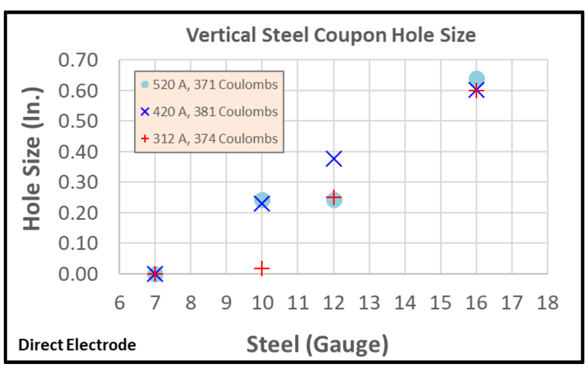

Figure 3-20. Vertical steel coupon hole size.

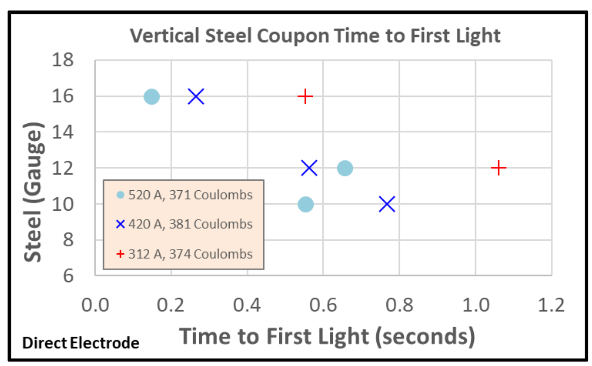

Figure 3-21. Time to first light.

3.1.6. Horizontal Coupon Tests with Direct Electrode

Table 3-3 shows the test results for horizontally oriented coupons with average currents of 324 A, 422 A, and 521 A, using a direct electrode. The data is plotted in Figure 3-22 and Figure 3-23, which show hole sizes and burnthrough times (time to first light), respectively. A comparison of average drive currents for these tests and those in Table 3-2, show that they are less than 3% different. Consistent with the vertical coupon tests, no burnthrough of the 7-gauge coupons was observed. For the 10-gauge coupons subjected to 324 A and 522 A currents, we measured burnthrough holes of 0.028 inch and < 0.015 inch, respectively, although photometric cameras did not record a first light hole opening visible during the high-speed framing interval. A similar anomaly occurred for a 12-gauge coupon at 324 A drive, which opened a 0.104 inch-diameter hole, but this apparently

Table 3-3 Horizontal Coupon with Direct Electrode

Date	Shot #	Material Gauge	CCG Measured Time (s)	Measured Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
21-Aug-18	11	16	1.198	324	388	0.578	0.6921	224
21-Aug-18	12	12	1.186	324	384	0.104	No data	No data
21-Aug-18	13	10	1.186	324	384	0.028	No data	No data
21-Aug-18	14	7	1.186	324	384	0.000	None	None
21-Aug-18	10	16	0.907	424	385	0.564	0.2146	91
21-Aug-18	6	12	0.902	420	379	0.335	0.8103	340
21-Aug-18	7	10	0.905	420	380	0.000	None	None
21-Aug-18	9	7	0.894	424	379	0.000	None	None
20-Aug-18	1	16	0.718	518	372	0.588	0.1524	79
21-Aug-18	4	12	0.718	522	375	0.149	0.6889	360
21-Aug-18	2	10	0.718	522	375	< 0.015	No data	No data
21-Aug-18	3	7	0.718	522	375	0.000	None	None

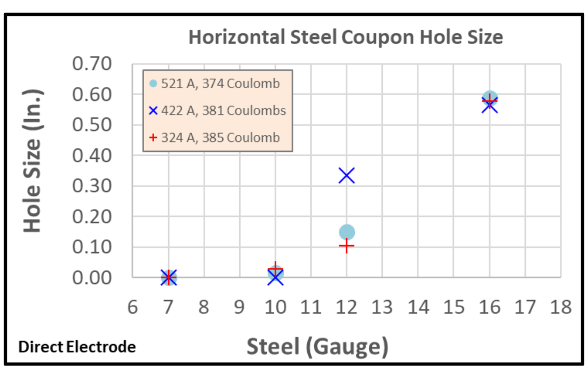

Figure 3-22. Horizontal steel coupon hole size.

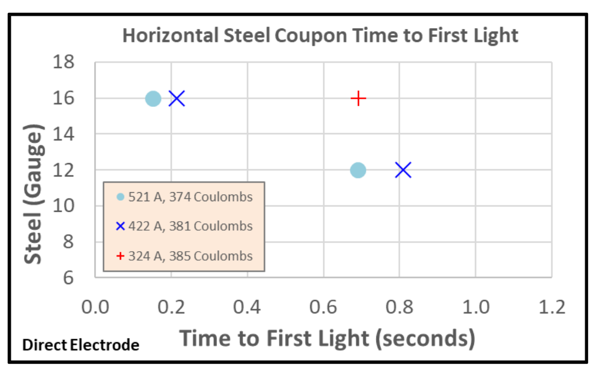

Figure 3-23. Time to first light.

opened post-test after the current and cameras were switched off. Burnthrough of the 16-gauge coupons representative of the 55-gallon TRU drum lid and side-wall thicknesses was recorded on video with all three different current levels initiating first light, with higher currents requiring less charge transfer to open the coupon.

Figure 3-22 and Figure 3-23 are plots of the data collected using a direct electrode and horizontally oriented coupons to determine hole size and time to first light, respectively. Both plots show good linearity for these data sets.

3.1.7. Comparison of Vertical and Horizontal Coupon Tests with Direct Electrode

A comparison of the data for the direct electrode configuration on vertically and horizontally oriented coupons shows that average drive currents for the nominal 300 A, 400 A, and 500 A tests are within 3.85%, 0.60%, and 0.19%, respectively. Similarly, the charge transfer correlated from time to first light for the nominal 300 A, 400 A, and 500 A drive currents were within 3.09%, 0.04%, and 0.89%, respectively. The average charge transfer for all tests was 377.5 C, with a standard deviation of 5.4 C, which demonstrates the consistent application of both the current and charge transfer across the test series. This corresponds well with the largely linear trends in the data.

Comparison of the hole sizes of the vertically and horizontally oriented 16-gauge coupons tested with the direct electrode configuration shows an approximately 6.2% smaller hole size on average for the horizontal configuration. As mentioned above, the removal of molten metal down the vertical plane by the force of gravity may accelerate the burnthrough process by exposing the underlying solid base metal to the arc plasma and its temperatures at a faster rate versus heat transfer through the molten metal pool, which creates an access barrier to the arc plasma to reach the still-intact base metal. In the vertical coupon orientation, gravity acts to pull the molten metal downward and away from the melt pool, which exposes new base metal and allows the arc plasma to interact more with the perimeter of the melt pool, thus increasing the diameter of the melt pool and the eventual burnthrough hole diameter. In the horizontal configuration, gravity pulls downward on the melt pool volume equally, and the arc plasma is more centrally located and interacts with minimal dynamic removal of the base metal, thus producing a smaller melt pool and eventual hole size on burnthrough events. Nevertheless, the relatively small difference noted in hole size data suggests that either configuration could be used with confidence to assess burnthrough processes. However, due to the slightly more stable melt pool observed in the photometric data, a horizontal configuration may reasonably simplify any computer-generated models of burnthrough processes.

3.1.8. Horizontal Coupon Tests with Indirect Electrode

Table 3-4 shows the test results for horizontally oriented coupons with average currents of 324 A, 422 A, and 521 A, using an indirect electrode. The data is plotted in Figure 3-24 and Figure 3-25, which show hole sizes and burnthrough times (time to first light), respectively. No burnthrough of 7-gauge and 10-gauge coupons was observed. Burnthrough occurred for 12-gauge coupons with 420 A and 522 A drives, but no burnthrough occurred at the 326 A level.

Figure 3-24 and Figure 3-25 are plots of the data collected using an indirect electrode and horizontally oriented coupons to determine hole size and time to first light, respectively. Both plots show good linearity for the data sets. The 16-gauge coupon burnthroughs are notably varied in cumulative charge transfer calculated at first light.

Table 3-4 Horizontal Coupon with Indirect Electrode

Date	Shot #	Material Gauge	CCG Measured Time (s)	Measured Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
22-Aug-18	1	16	1.170	326	381	0.366	0.2367	77
22-Aug-18	2	12	1.170	326	381	0.000	None	None
22-Aug-18	3	10	1.170	326	381	0.000	None	None
22-Aug-18	4	7	1.170	322	377	0.000	None	None
21-Aug-18	20	16	0.880	424	373	0.292	0.5786	245
21-Aug-18	21	12	0.880	420	370	0.041	0.8423	354
21-Aug-18	22	10	0.880	420	370	0.000	No data	No data
21-Aug-18	23	7	0.880	420	370	0.000	None	None
20-Aug-18	2	16	0.700	518	363	0.376	0.1814	94
20-Aug-18	3	12	0.700	522	365	0.242	0.4823	252
20-Aug-18	4	10	0.700	522	365	0.000	None	None
21-Aug-18	19	7	0.700	522	365	0.000	None	None

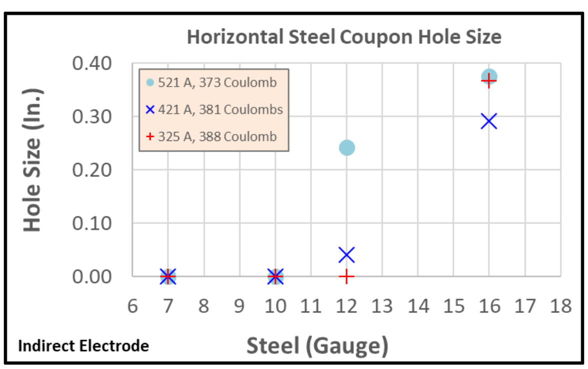

Figure 3-24. Horizontal steel coupon hole size.

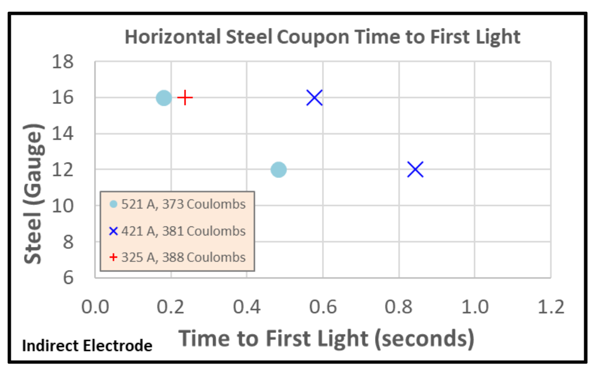

Figure 3-25. Time to first light.

3.1.9. Comparison of Horizontal Coupon Tests with Direct and Indirect Electrodes

A comparison of 16-gauge, horizontally oriented coupons using direct and indirect electrodes showed significant differences in hole size, with the indirect electrode producing hole sizes approximately 59.8% smaller than the direct electrode. The burnthrough holes produced with the direct electrode (Table 3-3) had an average hole size of 0.577 inch with a standard deviation of 0.012 inch. The indirect electrode (Table 3-4) produced an average hole size of 0.345 inch with a standard deviation of 0.046 inch. The higher standard deviation in hole size with the indirect electrode may be due to dynamic arc impedance and arc root wander.

3.1.10. Coupon Tests from Painted TRU Lids Versus Uncoated 1008 Alloy Steel

Tests on bare 1008 alloy steel and coated/painted 1008 alloy steel coupons cut from 55-gallon TRU drums were tested to compare the effect of the coating/paint on hole size and burnthrough times. Table 3-5 shows the data for these tests. These tests were conducted using a direct electrode to maximize burnthrough hole size and a vertically oriented coupon to simulate later tests with 55-gallon drums, where the barrels were laid on their side so that drive currents could be injected horizontally onto the lids of the barrels, making the lids vertically oriented on the test rig. In the "Material Gauge" column, "BL" stands for Barrel Lid. As with all other tests, a 0.015 inch copper starter wire initiated current onto the coupons. For the painted coupons, a small area was sanded down to bare metal to attach the starter wire, since the incident voltage from a natural lightning strike would easily arc through the paint on a barrel. There was very little difference in hole sizes between painted and unpainted coupons. The average hole size for unpainted coupons was 0.615 inch, while the average hole size for painted coupons was 0.620 inch. The average hole size for all coupons was 0.618 inch, with a standard deviation of 0.018 inch. The wide variation noted among times to first light for painted and unpainted coupons is an unexplored anomaly.

Figure 3-26 and Figure 3-27 show the outside and inside coatings for the post-test TRU waste drum lid coupons. All three coupons showed good consistency, having the same nominal hole size as shown in Table 3-5. The coating around the perimeter of the inside surface of the coupons was removed to minimize contact impedance at the interface of the coupon holder to allow uniform current distribution from the center of the coupon to the perimeter, leading via copper bus bars to the CCG ground.

Figure 3-28 and Figure 3-29 are plots of hole size versus charge transfer, and time to first light versus charge transfer, respectively. There was no significant difference in hole sizes between painted and unpainted coupons. Variation in time to first light likely is due to dynamic arc impedance or arc wander. Here, again, all 16-gauge coupons representative of the TRU drum lid and rib thickness burned through with the absorbed charge required to achieve first light greater at low currents, with lid coupon BL3-16 a slight data variant.

Table 3-5. Vertical 1008 Alloy and TRU Barrel Lid Coupons with Direct Electrode

Date	Shot #	Material Gauge	CCG Measured Time (s)	CCG Measured Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
15-Aug-18	4	Bare 16	1.200	312	374	0.601	0.5520	172
15-Aug-18	8	Bare 16	0.907	420	381	0.603	0.2659	112
16-Aug-18	1	Bare 16	0.710	520	369	0.640	0.1477	77
17-Aug-18	1	BL1-16	1.191	320	381	0.640	0.7030	225
17-Aug-18	2	BL2-16	0.906	418	379	0.608	0.2414	101

Date	Shot #	Material Gauge	CCG Measured Time (s)	CCG Measured Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
17-Aug-18	3	BL3-16	0.718	518	372	0.613	0.2367	123

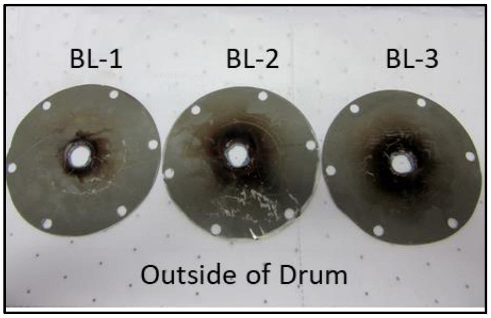

Figure 3-26. TRU waste drum lid coupons (painted exterior).

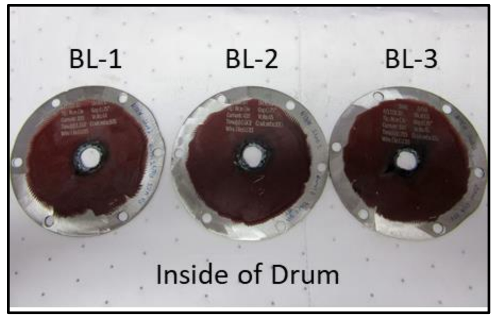

Figure 3-27. TRU waste drum lid coupons (painted interior).

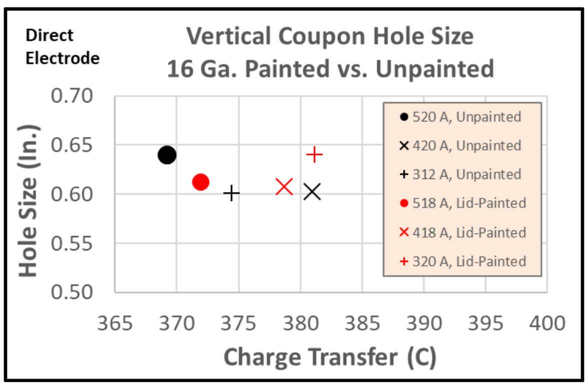

Figure 3-28. Vertical coupon hole size.

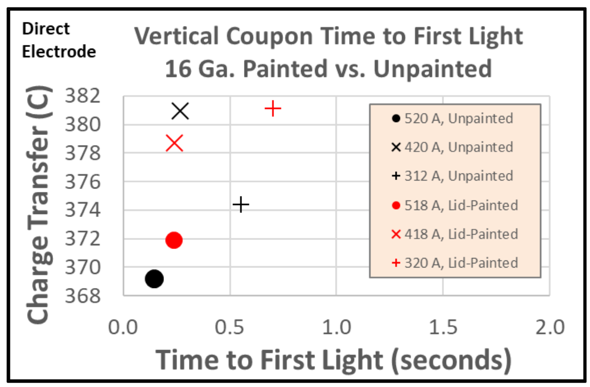

Figure 3-29. Time to first light.

3.2. Barrel Test Setup and Configuration

Skolnik CQ5508 and TRU waste 55-gallon drums ("CQ5508L" hereafter)—the main subject of these tests—are made of 1008 steel alloy and have representative thicknesses of 16-gauge for the main body, bottom, and lid. The closure ring that girdles and clamps the barrel lid to the barrel main body, and which compresses the EPDM gasket, is 12-gauge. The coupon tests above included samples of 16- and 12-gauge 1008 steel alloy, both coated/painted and bare, to simulate the effects of the continuing current component of lightning on these surface features of 55-gallon drums, creating prospective points of ground leader origin and subsequent attachment for cloud-to-ground lightning. The burnthrough tests on the CQ5508 and TRU waste drums were performed at the SLS. The 55-gallon steel drum tests were performed on Skolnik CQ5508 and Skolnik CQ5508L-SRNL99, Rev A5 TRU Waste drums, with all materials under test identical to those seen in the drawing depicted in Figure 3-30, except the exterior paint color selection.

The CQ5508 drum is a generic, painted, carbon steel drum representative of wider industrial use, and the TRU waste drum is a pedigreed, lined drum used for staging low-level TRU waste across the Department of Energy (DOE) complex. Figure 3-31 depicts the three different simulated lightning attachment points for all drums subject to test at the SLS: (1) the center of the lid, (2) the drum cover clamp ring, and (3) an exterior rib (rolling hoop).

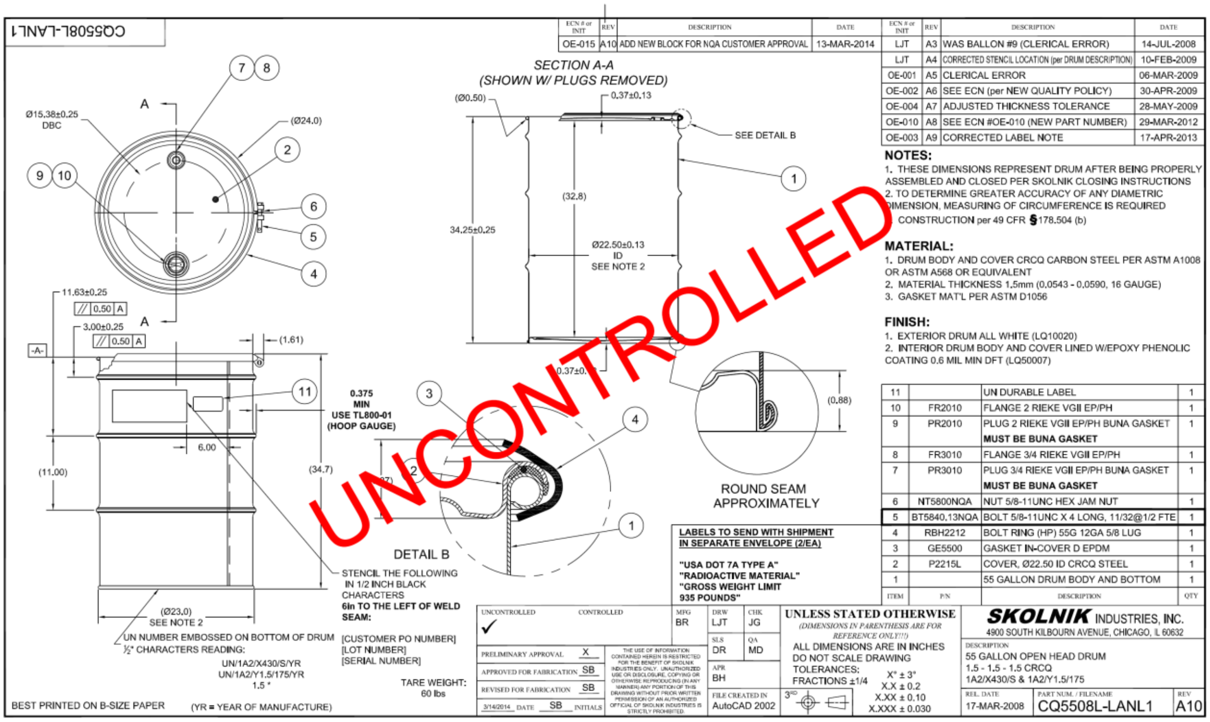

Figure 3-30. Skolnik CQ5508L.

Figure 3-31. Lightning attachment points for 55-gallon drums.

For all barrel burnthrough tests, a 0.25 inch-diameter tungsten electrode was used with the tip of the electrode positioned 0.75 inch from the barrel attachment point, creating a short arc path to simulate a lightning channel in air. To be consistent with prior coupon tests, initial electrical contact was made between the electrode output of the SLS CCG and the barrel by using a 0.015 inch-diameter copper starter wire. A small area of the paint on the barrels was removed to enable a low-resistance attachment of the starter wire. The SLS CCG drive current arced to the barrel and returned to earth ground on the 0.5 inch-diameter copper buss bars (current return conductors) attached to the bottom of the barrel. A spare barrel clamp ring with ¼-20 bolts welded to the clamp ring provided a convenient low-resistance means to connect the return conductors to each barrel under test at its bottom end. The clamp ring/barrel interface was sanded to remove paint from both surfaces to provide good current contact. Photometric data (high-speed video) was collected to capture burnthrough times at the three separate attachment points on the barrels, using the same configuration described in Section 3.1. Figure 3-32 shows the photometric layout used for the barrel tests.

A Lexan shield was attached to the bottom of the barrel with horseshoe magnets (shown in Figure 3-33) to protect personnel and equipment from molten steel ejected during the burnthrough process. A large diameter hole was cut into the bottom of the barrel for photometric viewing of the interior of the barrel to determine time to first light—the elapsed time from CCG switching until burnthrough was first observed on video.

Figure 3-34 shows photos of a test on a TRU waste drum with the attachment point near the center of the lid (top left) and in close-up (top right). Post-test external and internal damage to the drum lid are shown in the bottom left and bottom right photos.

Figure 3-35 shows photos of a test on a TRU waste drum with the attachment point on the clamp ring. The attachment point is shown in the left photo, and the post-test damage is shown in the right photo.

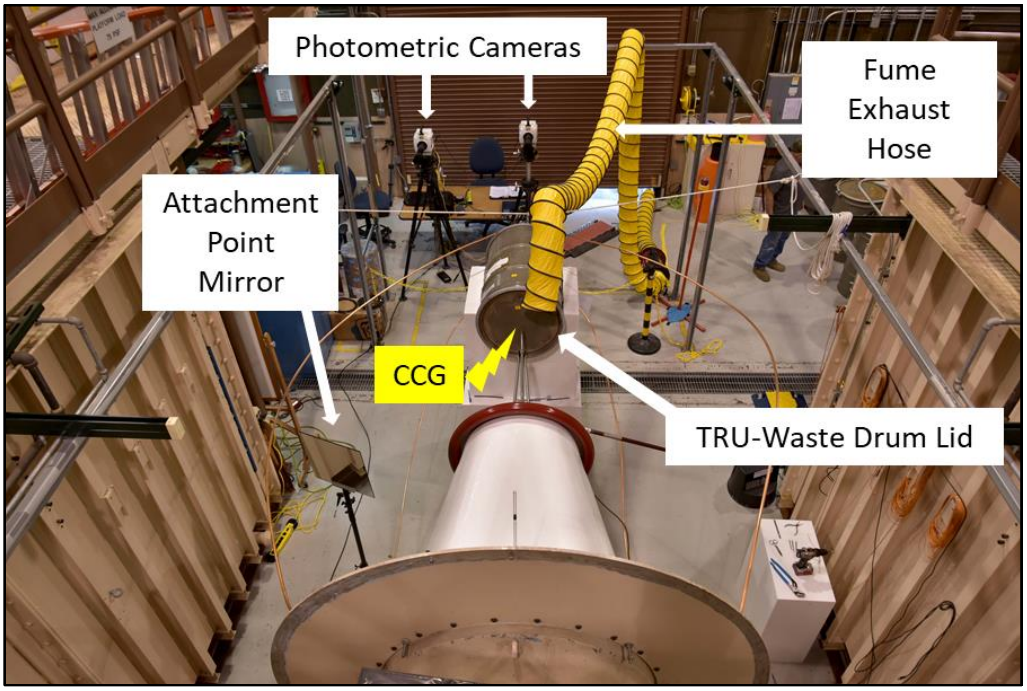

Figure 3-32. Photometric setup for barrel tests.

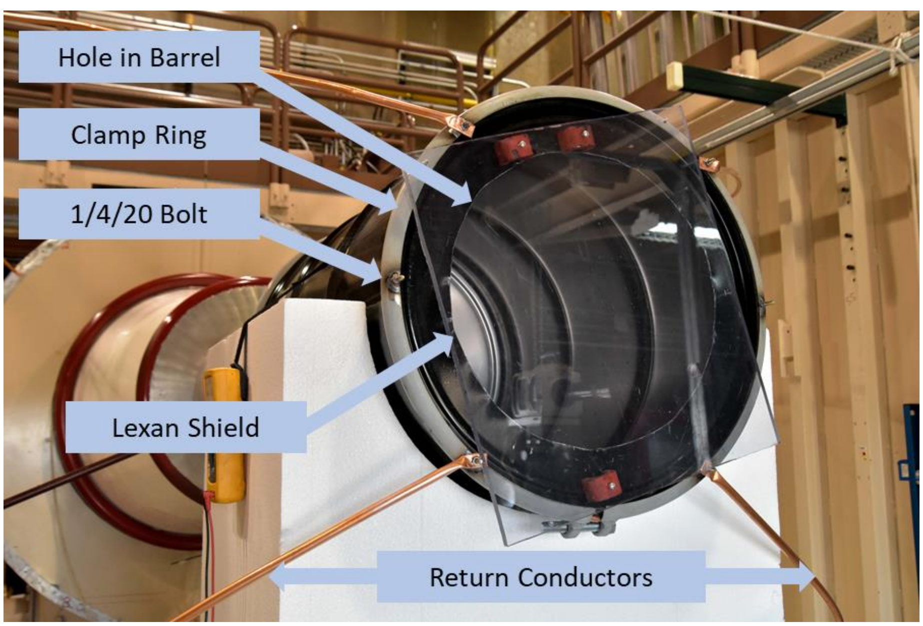

Figure 3-33. Large diameter hole cut in bottom end for photometric viewing.

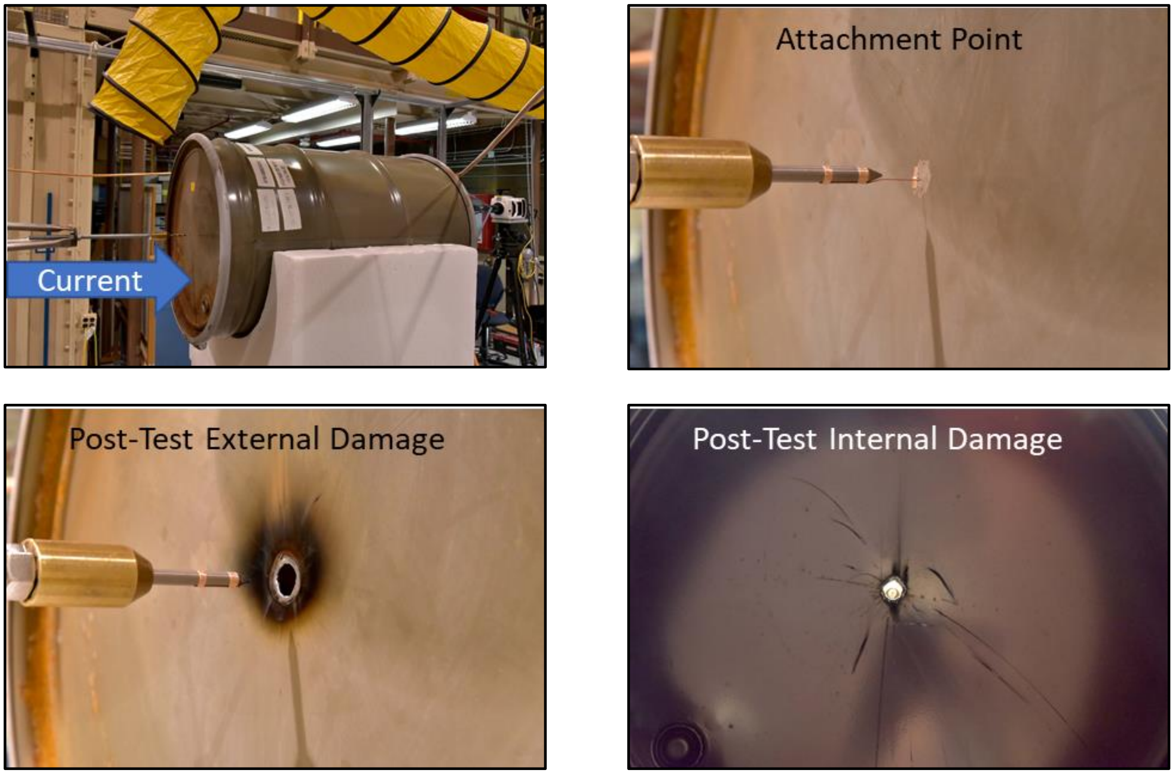

Figure 3-34. Attachment to TRU waste drum lid.

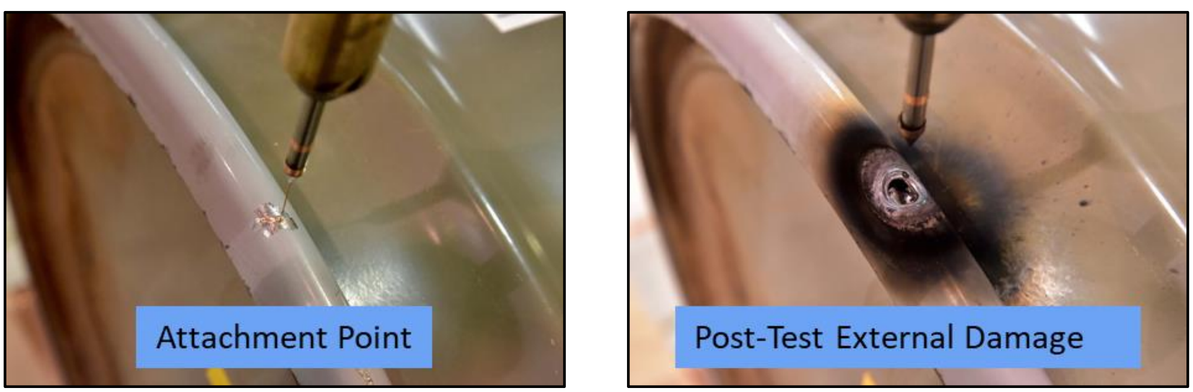

Figure 3-35. Attachment to TRU waste drum closure ring.

Figure 3-36 shows photos of a test on a generic CQ5508 drum with the attachment point on a rib on the side of the barrel. Note that the test on the rib followed a test on the closure ring. Damage to the closure ring from the previous closure ring test can be seen in these photos and was not caused by the test on the rib. The starter wire attachment on the rib is shown in the top photo. Post-test external and internal damage to the drum are shown in the bottom left and bottom right photos.

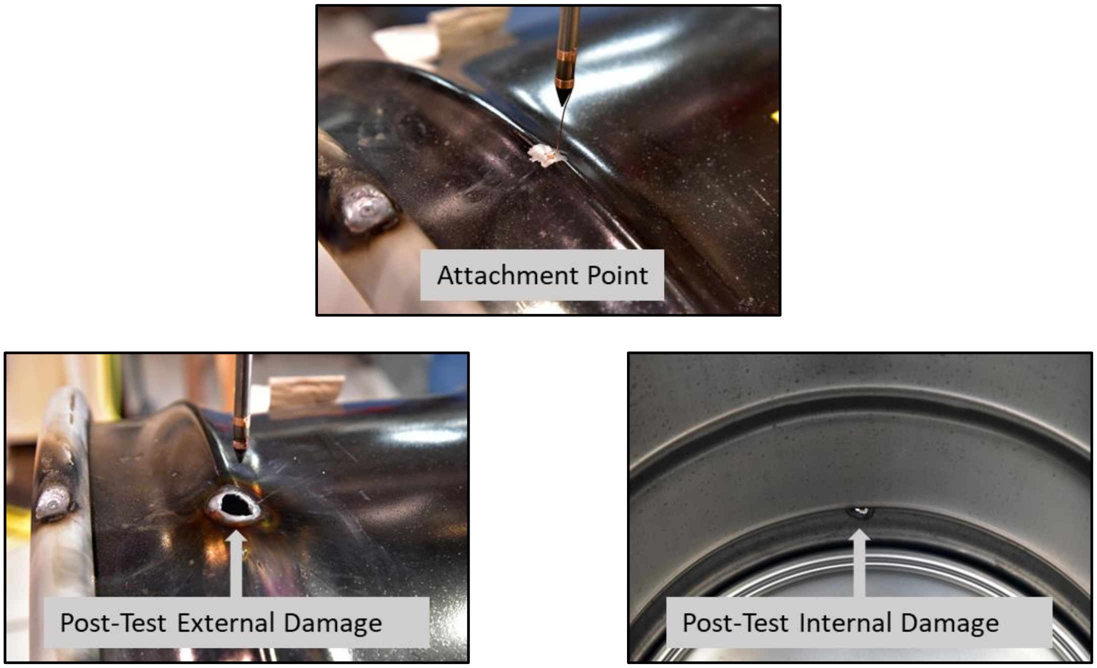

Figure 3-36. Attachment point to CQ5508 drum rib.

3.2.1. Barrel Test Data

Lightning burnthrough data was collected on Skolnik CQ5508 and Skolnik TRU Waste (CQ5508L-SRNL99, Rev A5) drums. The 55-gallon drums were tested with the direct electrode configuration in horizontal and vertical orientations. The approximately 6% difference in hole sizes during coupon tests with indirect and direct electrode configurations mentioned above, coupled with the fact that the direct electrode configuration produced the most damage, drove the decision to test the drums without the polytetrafluoroethylene divertor tip (indirect electrode) used in earlier coupon tests. The lids were tested in the vertical orientation, and the closure ring and rib were tested in the horizontal orientation. For comparison, all tests were conducted using a nominal charge transfer of 350 C (1C = 1 Ampere X 1 second), using only nominal 500 A currents with 0.7 second continuing current durations and absent any return stroke pulses from the Marx generator banks. A plot of the typical square current pulse and corresponding charge transfer used to test CQ5508 and CQ5508L barrels is shown in Figure 3-37.

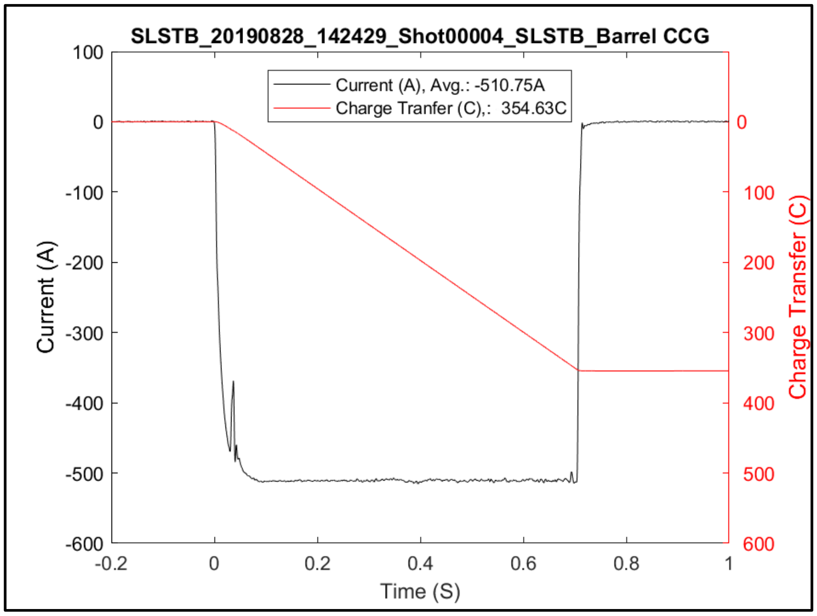

Figure 3-37. Typical CCG current profile used for barrel tests delivering 350C total charge transfer to simulate an extreme lightning strike.

3.2.1.1. Barrel Lid Test Data

Results for burnthrough tests on CQ5508 and CQ5508L lids are shown in Table 3-6 Hole sizes for the lid tests were not as consistent as the hole sizes seen in the 16-gauge coupon tests. For the lid tests, the average hole size was 0.5547 inch, with a standard deviation of 0.0471 inch. There were no significant differences in hole sizes between the two barrel types. The average hole size for the16-gauge steel coupons was 0.615 inch, with a standard deviation of 0.022 inch Table 3-6 shows that the range of hole sizes fits within the range of hole sizes for the 16-gauge coupon tests, which supports the decision that the use of coupons for testing was a reasonable approach to bound the burnthrough hole size for minimal cost, compared with using 55-gallon drums for all tests. Times to first light for the 16-gauge drum lid tests were significantly shorter than the 16-gauge steel and painted steel coupons reported above. The reason for the variation was not determined but could have been caused by differences in test configurations. For example, the coupon test rig metal hardware and closer-proximity copper return conductors may have provided a heat conductor or heat sink for the small coupons that required longer times to burn through the coupon. Another possible explanation is that the paint on the exterior surface and interior epoxy coating of the large diameter barrel lids may have provided thermal insulation that confined the heat to regions near the arc root that promoted shorter times to first light.

Table 3-6. Carbon Steel (CQ5508) and TRU (C15508L) Drum Lid Tests

Date	Shot #	Test Area	Type/#	CCG Time (s)	CCG Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
28-Aug-19	3	Lid	CQ5508/6	0.708	512	362	0.635[1]	0.0540	28
28-Aug-19	4	Lid	CQ5508/5	0.708	511	361	0.531	0.0454	23
28-Aug-19	5	Lid	CQ5508/4	0.704	512	360	0.580	0.1391	71
28-Aug-19	6	Lid	CQ5508/3	0.704	512	360	0.517	0.0587	30
28-Aug-19	7	Lid	CQ5508/2	0.708	512	362	0.579	0.0530	27
28-Aug-19	8	Lid	CQ5508/1	0.712	512	364	0.553	0.0413	21
28-Aug-19	9	Lid	CQ5508L/1	0.708	512	362	0.533	0.0943	48
28-Aug-19	10	Lid	CQ5508L/2	0.708	512	362	0.603[1]	0.0687	35
28-Aug-19	11	Lid	CQ5508L/3	0.700	512	358	0.615[1]	0.0791	40
28-Aug-19	12	Lid	CQ5508L/4	0.708	512	362	0.501	0.0356	18
29-Aug-19	1	Lid	CQ5508L/5	0.708	512	362	0.490	0.0461	24
29-Aug-19	2	Lid	CQ5508L/6	0.708	512	362	0.519	0.0699	36

[1] Hole size measured with calipers and not gauge-pins.

3.2.1.2. Barrel Closure Ring Attachment Test Data

Results for burnthrough tests on CQ5508 and CQ5508L closure rings are shown in Table 3-7. Although burnthrough of the closure ring was evident in several tests, no burnthrough of the barrel lid behind the closure ring occurred. As a result, no time to first light was recorded. Hole sizes for the closure ring tests were more consistent in hole size than those seen in the 12-gauge coupon tests. For the closure ring tests, the average hole size for both the CQ5508 and CQ5508L closure rings was 0.3124 inch, with a standard deviation of 0.0425 inch. There was no significant difference in hole sizes between either barrel type. For comparison, the hole sizes for the 12-gauge coupons were 0.196 inch, with a standard deviation of 0.122 inch. The reason for the larger hole sizes seen with the drum closure rings compared to those measured on the 12-gauge coupons was not determined. One hypothesis is that perhaps the barrel lid behind the closure ring provided a more consistent arc root attachment after burnthrough of the closure ring. Since no burnthrough of the barrel lid or sidewall occurred, no first light was observed by the camera on the inside of the barrel.

Table 3-7 Carbon Steel (CQ5508) and TRU (C15508L) Drum Closure Ring Tests

Date	Shot #	Test Area	Type/#	CCG Time (s)	CCG Current (A)	Total Charge Transfer (C)	Ring Hole Size (inches)	Time to First Light (s)
29-Aug-19	3	Ring	CQ5508/1	0.712	512	365	0.263[2]	-
29-Aug-19	5	Ring	CQ5508/2	0.712	512	365	0.370[2]	-
29-Aug-19	7	Ring	CQ5508/3	0.712	512	365	0.279[2]	-
29-Aug-19	9	Ring	CQ5508/4	0.712	512	365	0.321[2]	-
29-Aug-19	11	Ring	CQ5508/5	0.712	512	365	No Hole	-
29-Aug-19	13	Ring	CQ5508/6	0.708	512	362	No Hole	-
29-Aug-19	15	Ring	CQ5508L/1	0.712	512	365	0.329[2]	-
29-Aug-19	17	Ring	CQ5508L/2	0.712	512	365	No Hole	-
29-Aug-19	19	Ring	CQ5508L/3	0.712	511	364	No Hole	-

[2] Hole size in clamp ring only. No burnthrough to barrel interior.

3.2.1.3. Barrel Closure Rolling Hoop (Rib) Attachment Test Data

Results for burnthrough tests on CQ5508 and CQ5508L ribs are shown in Table 3-8. Hole sizes for the rib tests were slightly smaller (approximately 14.6%) on average than the hole sizes seen in the 16-gauge horizontal coupon tests with a direct electrode. For the rib tests, the average hole size was 0.5038 inch with a standard deviation of 0.0157 inch. The hole sizes for the 16-gauge coupons were 0.5777 inch, with a standard deviation of 0.0121 inch. Times to first light for the 16-gauge drum rib tests were significantly shorter than the 16-gauge steel and painted steel coupons reported previously. The reason for the variation was not determined but could have been caused by heat sink differences in test configurations, as noted above. We note good consistency among the charge transfer values calculated to be required to obtain first light at the rib, slightly more so than the variation noted in the above lid tests at the same current level.

Table 3-8 Carbon Steel (CQ5508) and TRU (C15508L) Drum Rib Tests

Date	Shot #	Test Area	Type/#	CCG Time (s)	CCG Current (A)	Total Charge Transfer (C)	Hole Size (inches)	Time to First Light (s)	Charge Transfer at First Light (C)
29-Aug-19	4	Rib	CQ5508/1	0.712	512	364	0.512	0.0463	24
29-Aug-19	6	Rib	CQ5508/2	0.708	512	362	0.529	0.0613	31
29-Aug-19	8	Rib	CQ5508/3	0.712	512	364	0.508	0.0499	26
29-Aug-19	10	Rib	CQ5508/4	0.708	512	362	0.494	0.0606	31
29-Aug-19	12	Rib	CQ5508/5	0.712	512	364	0.486	0.0586	30
29-Aug-19	14	Rib	CQ5508/6	0.708	512	362	*	0.0553	28
29-Aug-19	16	Rib	CQ5508L/1	0.712	512	364	0.494	0.0490	25
29-Aug-19	18	Rib	CQ5508L/2	0.706	511	361	*	0.0597	31
29-Aug-19	20	Rib	CQ5508L/3	0.712	511	364	*	0.0527	27

*Sent to SRNL before measurement was made.

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4. SUMMARY OF TESTS

The feasibility of attributing inherent lightning protection to 55-gallon carbon steel (1008 alloy) transuranic (TRU) waste drums acting as a containment barrier was investigated by lightning simulation tests conducted at the Sandia Lightning Simulator (SLS) at Sandia National Laboratories (SNL). These TRU drums protect Department of Energy (DOE) waste contaminated with alpha-emitting transuranic radionuclides and are staged throughout the complex prior to shipment to the Waste Isolation Pilot Project (WIPP) for permanent storage below ground. The SLS trials were focused on simulated lightning continuing current tests on steel coupons with similar thicknesses to those used in 55-gallon generic carbon steel and pedigreed 55-gallon TRU waste drums, to ultimately assess containment breach by lightning burnthrough at three different lightning attachment points: (1) a drum lid, (2) a closure ring, and (3) on a structural rib. All tests were conducted using nominal 300 Ampere (A), 400 A, and 500 A continuing currents that produced nominal charge transfers of 350 Coulombs (C) to simulate an extreme lightning event (assessed 1% frequency of occurrence).

Coupon tests evaluated direct and indirect electrode configurations. The indirect electrode configuration represents cloud-to-ground direct lightning arc root attachment. The direct electrode configuration represents the scenario of lightning-induced arcing between two metal objects. Both types of configurations could occur in lightning interactions outdoors, the latter with stacked drums, which potentially could result in metal vapors or spallation from a first drum struck in free air bridging onto a second drum below or adjacent to the first in the lightning travel path to ground.

Direct electrode burnthrough tests using vertical and horizontal coupon configurations with 300 A, 400 A, and 500 A continuing currents with an average of 375 C of charge transfer, produced expected linear trends in hole size and burnthrough times. Tests on horizontally oriented coupons produced slightly smaller hole sizes on average than vertically oriented coupons. The relatively small difference in hole sizes seen in the 16-gauge coupons suggests that either configuration could be used to simulate burnthrough processes on a carbon steel drum lid or side rib (rolling hoop). However, due to the slightly more stable melt pool observed in the photometric data, a horizontal configuration may be better suited to validate any computer-generated models of burnthrough processes.

A comparison of 16-gauge, horizontally oriented coupons using direct and indirect electrodes showed significant differences in hole sizes, with the indirect electrode producing hole sizes approximately 59.8% smaller than the direct electrode. This observed deviation in hole size with the indirect electrode may be due to the higher average dynamic impedance (longer arc) seen with the indirect electrode configuration and arc path or arc root wander visible in select high-speed video captures.

Tests on coupons harvested from barrel lids demonstrated no significant difference in hole sizes between the painted cutouts and unpainted 1008 steel coupons. Observed variation in time to first light is likely due to dynamic arc impedance or arc wander.

Results for burnthrough tests on CQ5508 and CQ5508L lids showed no significant difference in hole sizes between the two types of barrels. The difference in hole sizes between the 16-gauge drum lids and 16-gauge bare steel and barrel lid coupons showed an approximately 11% smaller hole for the barrel lids.

Results for burnthrough tests on CQ5508 and CQ5508L closure rings showed there was no significant difference in hole sizes between the two types of barrels. The difference in hole sizes between the 12-gauge closure rings and 12-gauge bare steel coupons showed an approximately 60%

smaller hole for the coupons. The reason for the difference in hole sizes between the closure rings and 12-gauge coupons is indeterminate. One hypothesis is that perhaps the barrel rib behind the closure ring provided a more consistent arc root attachment or acted as thermal barrier that reflected heat towards the closure ring after the burnthrough of the closure ring. Burnthrough of the closure ring was evident in several tests, but no burnthrough of the barrel lid behind the closure ring occurred in any tests, which maintained drum content containment integrity.

Results for burnthrough tests on CQ5508 and CQ5508L barrel ribs showed hole sizes slightly smaller (approximately 14.6%) on average than the hole sizes seen in the 16-gauge horizontal coupon tests with a direct electrode. The reason for this difference is indeterminate, but test rig configurations and the test article size could have been a factor.

Times to first light (containment breach) for the 16-gauge drum lid and drum rib tests were significantly shorter than the 16-gauge steel and painted steel coupon test results presented in this report. The reason for the variation was not determined but may have been caused by differences in test fixture configurations. For example, the smaller coupon test rig configuration hardware between the coupon and the copper return leads may have provided a heat sink for the coupon that required longer burnthrough times for the test coupons. Another possible explanation is that the paint on the surfaces of the large diameter barrel lids may have provided thermal insulation that confined the heat to regions near the arc root and promoted shorter times to first light.

5. CONCLUSIONS

We found sheet metal burnthrough (drum containment breach) to occur for simulated lightning attachment to carbon steel (1008 alloy) transuranic (TRU) waste drums placed in a test rig at the Sandia Lightning Simulator when a 350 Coulomb (C) charge was transferred from a tungsten electrode across a 0.75 inch arc in free air to the drum lid at its center or the upper rolling hoop side rib, each made of 1.5 millimeter painted carbon steel with an epoxy interior liner. The 350 Coulomb charge is considered an extreme—a 1% frequency of occurrence—direct strike lightning event in military specifications used as a baseline for the lab tests. In every test on 16-gauge carbon steel thicknesses—both coupons and barrel attachment points—burnthrough was achieved. Higher continuing currents required a lower charge transfer to achieve burnthrough.

Coupons and barrel closure rings, which are both 12-gauge steel, experienced burnthrough in most, but not all, tests. Subsequent burnthrough of the lid beneath the closure ring did not occur in any barrel tests. Burnthrough of 10-gauge coupons was achieved using a direct electrode in both vertical and horizontal coupon orientations. No burnthrough of 10-gauge coupons was achieved with the indirect electrode configuration. No burnthrough of 7-gauge coupons was achieved with either the direct or indirect electrode configuration.

Containment breach of 55-gallon TRU waste drums by lightning burnthrough was achieved at two of the three proposed test locations, which suggests a vulnerability to lightning exists for direct strike lightning attachment to bare metal at these locations in an extreme lightning event.

Lightning interaction or heating of drum contents and the potential for radiation contamination of areas surrounding TRU waste drums was not investigated for this report, which tested empty drums, including holes cut for camera visibility of the burnthrough event during high-speed video captures of each test.

We note the closure ring assembly protected the drum lid and sidewall sheet metal beneath from containment breach, with the electrode placed 0.75 inch from the ring to simulate cloud-to-ground lightning attachment in free air. This feature may provide an inherent air terminal protective feature for drum contents, if lightning attachment occurs solely at this closure ring from a stepped leader originating from this drum edge feature. Lightning phenomenology retains many unknown processes, and multiple attachment points could breach the containment where bare lid or side sheet metal is exposed to an arc root, as noted.

We further note that our tests were focused on an extreme lightning event and did not investigate the probability of holding containment in median lightning events, and further did not take into account local lightning climatology important to assign direct strike probabilities for Safety Basis calculations specific to Department of Energy field sites.

This research was conducted with funding from the US Department of Energy. Support by Sharon Steele, Office of Chief Defense Nuclear Safety, is gratefully acknowledged.

REFERENCES

[1] Electromagnetic Environmental Effects Requirements for Systems, MIL-STD-464C , Department of Defense Interface Standard, 1 December 2010.

[2] M. A. Uman,V. A. Rakov, J. O. Elisme, D. M. Jordan, C.J. Biagi, J. D. Hill., "Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence (Second Revision)", LLNL-SR-458333, September 2010.

[3] M. Tanaka and J.J. Lowke, *Predictions of weld pool profiles using plasma physics*, J. Phys. D.: Appl. Phys. 40 R1, 2007.

[4] M. Caldwell and L.E. Martinez, *The Sandia Lightning Simulator: recommissioning and upgrades*, EMC 2005 International Symposium, 368-371 Vol. 2, 2005.

Appendix A. CQ5508 DATA SHEET

SKOLNIK

INDUSTRIAL PACKAGING FOR CRITICAL CONTENTS

ITEM CQ5508 : OPEN HEAD CARBON STEEL DRUM

Skolnik Carbon Steel Drums have proven to be a durable and heavy-duty package for storage and transportation. Suitable for packaging a variety of contents, including hazardous materials, they are available in open and tight head configurations, in sizes from 5-110 gallons, including the Workhorse 55 Gallon Drum. Manufactured of ASTM grade carbon steel, Skolnik Carbon Steel Drums can be customized to suit unique needs and size requirements.

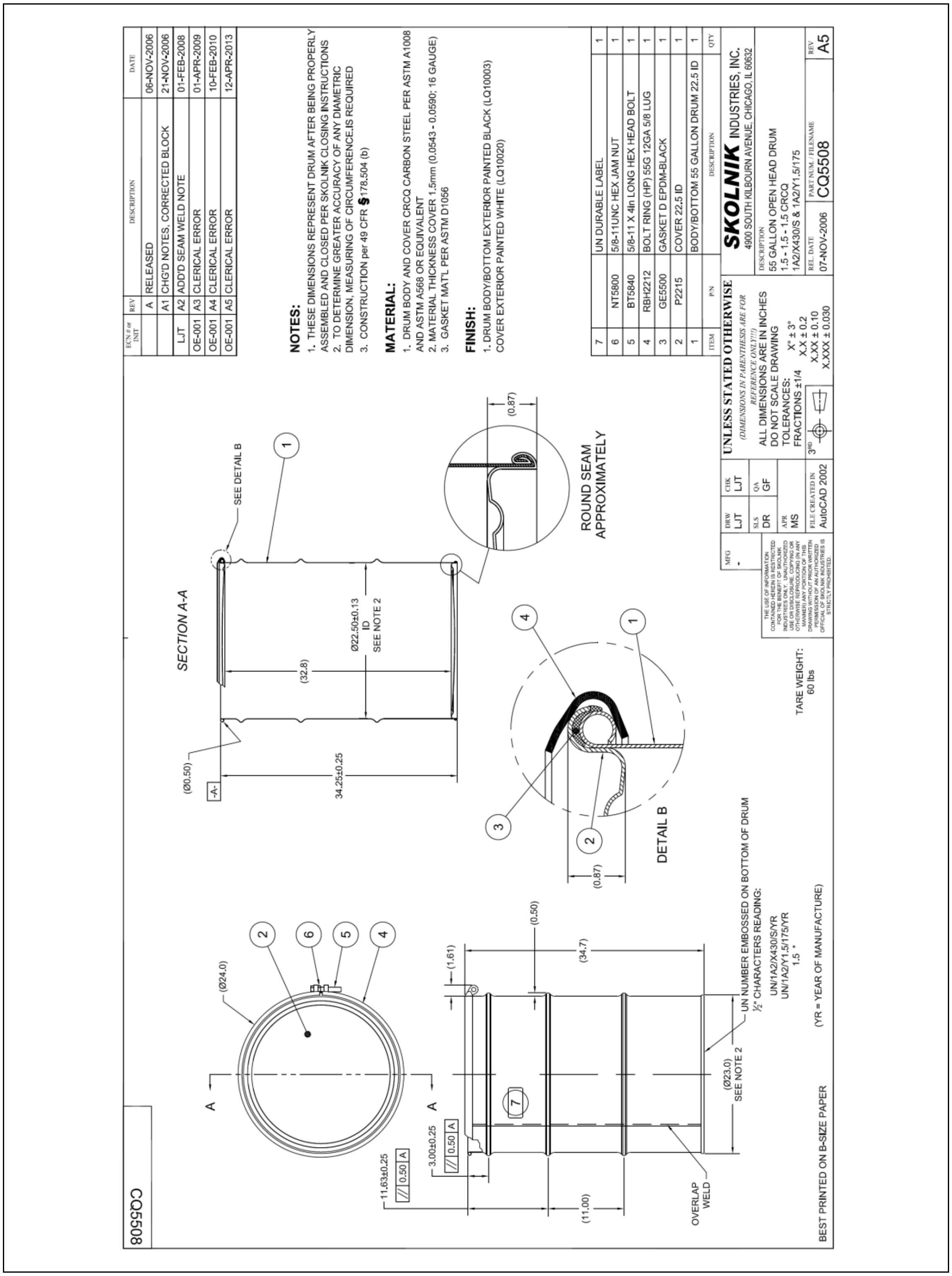
Part Number	CQ5508
Volume	55 US Gallons
Style	Open Head
Material	Carbon Steel
UN Solid	1A2/X430/S
UN Liquid	1A2/Y1.5/175
Thickness (tp/bd/bt)	1.5/1.5/1.5
Fittings and/or Gasket	EPDM
Closure	Bolt Ring
Exterior Color	Black with White Cover
Interior Color	N/A
Weight	60.00 Lbs
Inside Diameter	22.50 Inches
Inside Height	32.80 Inches

Skolnik Industries, Inc.
4900 S. Kilbourn Avenue
Chicago, IL 60632-4593 USA

1.800.441.8780 CUSTOMER SERVICE
1.773.735.0700 MAIN OFFICE
1.800.441.8780 OUTSIDE U.S.
1.773.735.7257 FAX

skolnik.com
skolnikwine.com
sales@skolnik.com

Appendix B. CQ5508 DRAWING



Appendix C. CQ5508 EXTERIOR PAINT LQ10003 ,MSDS

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                                                              Page   1 of   8
-----------------------------------------------------------------------------
          SECTION 1 - CHEMICAL PRODUCT AND COMPANY IDENTIFICATION
-----------------------------------------------------------------------------
  001
CHEMICAL PRODUCT IDENTIFICATION:
  PRODUCT IDENTIFICATION. . . : 4WB-5659EX  PL
  PRODUCT CLASS . . . . . . . : WATER BASED ENAMEL
  TRADE NAME. . . . . . . . . : 701 BLACK WR LEC
  PRODUCT USE . . . . . . . . :

  FORMULA IDENTIFICATION. . . : 4WB-5659EX
  FORMULA VERSION NUMBER. . . :    7

PREPARED BY . . . . . . . . . :
DATE OF ISSUE . . . . . . . . : 02/21/2012
LAST REVISION DATE. . . . . . : 01/09/2012

MSDS PREPARED FOR . . . . . . :




CONTACT INDIVIDUAL. . . . . . :

MSDS LAST PREPARED. . . . . . :


MANUFACTURER IDENTIFICATION  :
  NAME. . . . . . . . . . . . : IVC INDUSTRIAL COATINGS, INC.
  ADDRESS  . . . . . . . . . . . : BRAZIL LIQUID PLANT
                                   1825 E. National Ave.


                                   BRAZIL               IN  47834

  TELEPHONE  . . . . . . . . . . : 812-442-5080
  EMERGENCY CONTACT  . . . . . . : CHEM-TEL
  EMERGENCY TELEPHONE. . . . . . : 1-800-255-3924
  INTERNATIONAL EMERGENCY. . . . : 00-1-813-248-0585

-----------------------------------------------------------------------------
          SECTION 2 - COMPOSITION, INFORMATION ON INGREDIENTS
-----------------------------------------------------------------------------
  1
 CAS#  108-01-0
DIMETHYLAMINOETHANOL
                                                         LEL      1.60
-----------------------------------------------------------------------------
  2
 CAS#  111-76-2
ETHYLENE GLYCOL MONOBUTYL ETHER
                    VAPOR PRESSURE:     .040 MMHG @ 68F  LEL      1.10
EXPOSURE LIMIT:
   ACGIH TLV/TWA:        25.00
   ACGIH TLV/STEL:       75 PPM
```

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

OSHA PEL/TWA:	50
OSHA STEL:	75 PPM
LC50:	INHALATION 700 PPM IN 7 HR (RAT)
LD50:	SKIN 220 MG/KG (RABBIT) ORAL 470 MG/KG (RAT)
SARA STATUS:	THIS MATERIAL IS A SARA 313 REPORTABLE

3
CAS# 123-42-2
DIACETONE ALCOHOL
VAPOR PRESSURE: .080 MMHG @ 68F LEL 1.80
EXPOSURE LIMIT:

ACGIH TLV/TWA:	50
ACGIH TLV/STEL:	75
OSHA PEL/TWA:	50
OSHA STEL:	75

4
CAS# 5131-66-8
2-PROPANOL-1-BUTOXY
VAPOR PRESSURE: .600 MMHG @ 68F LEL 1.10
EXPOSURE LIMIT:

---

5 SECONDARY BUYTL ALCOHOL
CAS# 78-92-2
2-BUTANOL
VAPOR PRESSURE: 12.000 MMHG @ 68F LEL 1.70
EXPOSURE LIMIT:

ACGIH TLV/TWA:	100 PPM (303 MG/M3)
OSHA PEL/TWA:	100 PPM (305 MG/M3)
SARA STATUS:	THIS MATERIAL IS A SARA 313 REPORTABLE

****
This product is not considered a carcinogen under OSHA regulations
****

SECTION 3 - HAZARDS IDENTIFICATION

HMIS Information Health - 1 Flammability - 1
Reactivity - 0 Personal Protective Equipment - X

HAZARD INDEX: 4= Severe 3= Serious 2= Moderate 1= Slight 0= Minimal
*= Chronic health Hazard

HMIS ratings involve data and interpretations that may vary from company to company. They are intended only for rapid, general identification of the magnitude of the specific hazard. To deal adequately with the safe handling of this material, all the information contained in this MSDS must be considered.

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

SECTION 4 - FIRST AID MEASURES

EYE CONTACT: Flush with luke warm water for 15 minutes. Seek Medical attention.

SKIN CONTACT: Flush with copious amounts of luke warm water. Remove contaminated clothing promptly. Seek medical attention.

INHALATION: Remove exposed individual to fresh air. Restore breathing if required. Seek medical attention.

INGESTION: Rinse mouth immediately. Give exposed individual 6 to 8 ounces of liquid.
(NEVER GIVE ANYTHING BY MOUTH TO AN UNCONCIOUS PERSON)
Do NOT induce vomiting unless advised by a physician.
Seek medical attention immediately.

Remove contaminated clothing immediatly and do not wear it until it has been properly laundered.

MEDICAL EXAMINATIONS:
Comprehensive preplacement and biennial medical examinations to be directed toward, but not limited to the liver, kidney, gastrointestinal disorders, skin irritation, and the central nervous system, may be considered.

SECTION 5 - FIRE FIGHTING MEASURES

FIRE AND EXPLOSIVE PROPERTIES OF THE CHEMICAL:

Flammability Classification . . . . . . :
Flashpoint (F). . . . . : 150.0
Explosion Level . . . . : Low - 1.1
High - 11.9
Flammability Limits . . . . : Lower - -N/A
Higher - -N/A

Auto-Ignition Temperature. . . . . . . : -N/A

EXTINGUISHING MEDIA:
USE CO2, DRY CHEMICAL, FOAM, or ALCOHOL FOAM

FIRE-FIGHTING PROCEDURES AND EQUIPMENTS:
Water spray may be used to cool closed containers to prevent pressure buildup and possible autoignition or explosion when exposed to extreme

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

heat. Water may be ineffective in extinguishing a paint fire, therefore, use caution not to spread flames with stream of water.
If water is used, fog nozzles are preferable.

Clear fire area of unprotected personnel. Do not enter confined space without helmet, face shield, bunker coat, gloves, rubber boots, and a positive pressure NIOSH-approved self-contained breathing apparatus.

OTHER:
Liquid and vapor states of this substance are dangerous fire hazards and moderate explosion hazards when exposed to heat or flames.

Thermal decomposition in the presence of air may yield carbon monoxide, carbon dioxide and/or various hydrocarbons.

SECTION 6 - ACCIDENTAL RELEASE MEASURES

CLEAN-UP:
Stay upwind and away from spill or leak unless wearing appropriate protective equipment. Stop and/or contain discharge if it may be done safely. Keep all sources of ignition away. Ventilate area of spill. Use non-sparking tools for cleanup. Cover with inert material to reduce fume. Keep out of drains, sewer, or waterways. If large spill call spill response teams. Contact fire authorities. Notify local health and pollution agencies.

Do NOT flush to sewer, watershed, or waterway.

CONTAINMENT:

SECTION 7 - HANDLING AND STORAGE

HANDLING:

Keep product containers cool, dry, and away from sources of ignition. Use and store this product with adequate ventilation. Do NOT smoke in storage areas.

Sprinkler fire protection is desirable in areas of storage, handling, and use.

SPECIAL COMMENTS:

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

SECTION 8 - EXPOSURE CONTROLS, PERSONAL PROTECTION

EYE PROTECTION:
Avoid contact with eyes. Wear goggles if there is a likelihood of contact with the eyes.

Contact lenses pose a special hazard; soft lenses may absorb irritants and all lenses concentrate them.

Eyewash stations and safety showers should be readily available in use and handling area.

RESPIRATORY PROTECTION:
Use ventilation as required to control vapor, dust, and fumes. Avoid prolonged or repeated breathing of vapors. If exposure exceeds TLV, use a NIOSH approved respirator to prevent overexposure.

SKIN PROTECTION:
Protective gloves are required for prolonged or repeated contact. Wear resistant gloves such as natural rubber, neoprene, buna N, or nitrile. An apron should be worn to avoid skin contact.

Wash hands thoroughly before eating and using washroom.

SPECIAL COMMENTS:
Personnel should avoid inhalation of vapors. Presonal contact with the product should be avoided. Should contact be made, remove saturated clothing and flush affected skin areas with water. Containers of this material may be hazardous when emptied. Since emptied containers retain product residues (vapor, liquid, and/or solid), all hazard precautions given in this sheet must be observed.

NOTICE - Reports have associated repeated and prolonged occupational overexposure to solvents with permanent brain and nervous system damage Intentional misuse by deliberately concentrating and inhaling the contents may be harmful or fatal.

SECTION 9 - PHYSICAL AND CHEMICAL PROPERTIES

Physical Appearance . . . . : OPAQUE BLACK
Odor . . . . : MILD AMMONIA

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

Odor Threshold	-N/A
Physical State	LIQUID
pH	-N/A
Vapor Pressure	12.00
Vapor Density	4.60
Boiling Range	Lower - 211.0 Higher - 343.0
Freezing Point	-N/A
Melting Point	-N/A
Water Solubility	MISCIBLE
VOC (lbs/gal) less water and exempt.	2.783
VOC (lbs/gal) Actual as Supplied	1.403
VOC (g/L)	333.48
Evaporation Rate	1.200 (n-Butyl Acetate = 1)
Volatile by Weight	64.7782
Volatile by Volume	68.7880
Weight per Gallon	8.5456 LB/GL
Coeff of Water-Oil Distribution	-N/A
Mechanical Impact Explosion	-N/A
Static Electricity Explosion	-N/A

SECTION 10 - STABILITY AND REACTIVITY

INCOMPATIBILITIES:
This raw material is incompatible with strong oxidizing agents, strong mineral acids, alkali metals, and halogens.

STABILITY/DECOMPOSITION:
Stable; hazardous decomposition not expected; thermal decomposition may produce toxic oxides of carbon and/or nitrogen.

CONDITIONS TO AVOID:
Avoid exposure to sparks, open flame, hot surfaces, and all sources of heat and ignition.

POLYMERIZATION:
Hazardous polymerization will not occur.

SECTION 11 - TOXICOLOGICAL INFORMATION

EYE EFFECTS:
This product is severly irritating to eyes, Exposure may cause extensive

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corneal injury.

SKIN EFFECTS:
This product may casue skin irritation and drying/defatting or cracking, and dermatitis on repeated or prolonged exposure to skin.

ORAL EFFECTS:
Ingestion of this product can result in irritation in the mouth, stomach, and digestive tract. Symptoms can include sore throat, abdominal pain, nausea, vomiting, and diarhea. Vomiting may cause aspiration resulting in chemical pneumontis.

INHALATION EFFECTS:
headaches, nausea,dizziness, and vomiting may occur from inhalation

This product is irritating to the upper respiratory tract.

OTHER:
Vapors of this product may cause irritation of the eyes, nose, throat, upper respiratory tract, mucous membranes, and skin.

Pulmonary edema may develop with inhalation of high concentrations of this material.

Chronic overexposure to this product may cause kidney and liver injury.

Overexposure to this material (or its components) has been suggested as a cause of the following effects in laboratory animals, and may aggravate pre-existing disorders of these organs in humans: liver abnormalities.

Prolonged exposure could cause CNS depression.

SECTION 12 - ECOLOGICAL INFORMATION

ECOTOXICOLOGICAL INFORMATION/ENVIRONMENTAL FATE:

No definitive information available on environmental impact if product is released to the environment.

SECTION 13 - DISPOSAL CONSIDERATIONS

IVC INDUSTRIAL COATINGS, INC.
MATERIAL SAFETY DATA SHEET

4WB-5659EX
701 BLACK WR LEC

Dispose of product in accordance with applicable local, county, state, and federal regulations.

SECTION 14 - REGULATORY INFORMATION

This product contains the following toxic chemicals subject to the reporting requirements of Section 313 of the Emergency Planning and Community Right-To-Know Act of 1986 and of 40 CFR 372:

ETHYLENE GLYCOL MONOBUTYL ETHER
CAS# 111-76-2 PCT BY WT: 7.0020

2-BUTANOL
CAS# 78-92-2 PCT BY WT: 4.0210

FEDERAL REGULATIONS:

The OSHA Hazard Communication Standard 1910.1200 and the Workplace Hazardous Materials Information System (WHMIS) require that the information contained on these sheets be made available to your workers. Instruct your workers to handle this product properly.

TSCA (Toxic Substance Control Act): All components of this product are listed on the TSCA Inventory.

CA PROPOSITION 65:
WARNING: This product contains a material known in the state of California to cause cancer.

SECTION 15 - OTHER INFORMATION

THE INFORMATION CONTAINED HEREIN IS INFORMATION RECEIVED FROM OUR RAW MATERIAL SUPPLIERS AND OTHER SOURCES AND IS BELIEVED TO BE RELIABLE. THIS DATA IS NOT TO BE TAKEN AS A WARRANTY OR REPRESENTATION FOR WHICH I.V.C. INDUSTRIAL COATINGS, INC. ASSUMES LEGAL RESPONSIBILITY.

IVC INDUSTRIAL COATINGS INC

SAFETY DATA SHEET

Publish Date 30-Apr-2015 **Revision Date** 30-Apr-2015 **Version** 1

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product identifier
Product Name SKOLNIK 201 GRAY WHITE WR LEC

Other means of identification
Product Code 1WB-5658
Synonyms None

Recommended use of the chemical and restrictions on use
Recommended Use For professional use only.
Uses advised against Not Applicable

Details of the supplier of the safety data sheet
Manufacturer Address
IVC Industrial Coatings, Inc.
Brazil Liquid Plant
1825 E. National Ave.
Brazil, IN 47834

Emergency telephone number
Emergency Telephone Chem-Tel 1-800-255-3924

2. HAZARDS IDENTIFICATION

Classification

OSHA Regulatory Status
This chemical is not considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.122)

Skin corrosion/irritation	Category 2
Serious eye damage/eye irritation	Category 2
Flammable liquids	Category 4

Label elements

Emergency Overview
Warning

Hazard statements
Causes skin irritation
Causes serious eye irritation
Combustible liquid

Appearance OPAQUE WHITE **Physical state** Liquid **Odor** SLIGHT AMINE

Precautionary Statements - Prevention
Wash face, hands and any exposed skin thoroughly after handling
Wear protective gloves/protective clothing/eye protection/face protection
Wear eye/face protection
Keep away from heat/sparks/open flames/hot surfaces. — No smoking

Precautionary Statements - Response
Specific treatment (see .? on this label)
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
If eye irritation persists: Get medical advice/attention
IF ON SKIN: Wash with plenty of soap and water
If skin irritation occurs: Get medical advice/attention
Take off contaminated clothing and wash before reuse
In case of fire: Use CO_2, dry chemical, or foam for extinction

Precautionary Statements - Storage
Store in a well-ventilated place. Keep cool

Precautionary Statements - Disposal
Dispose of contents/container to an approved waste disposal plant

Hazards not otherwise classified (HNOC)
Other Information
• May be harmful if swallowed
Unknown Acute Toxicity 60.385929% of the mixture consists of ingredient(s) of unknown toxicity

3. COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name	CAS No.
DIMETHYLAMINOETHANOL	108-01-0
DIACETONE ALCOHOL	123-42-2
2-PROPANOL-1-BUTOXY	5131-66-8
ETHYLENE GLYCOL MONOBUTYL ETHER	111-76-2
AMORPHOUS SILICON DIOXIDE	7631-86-9
2-BUTANOL	78-92-2

4. FIRST AID MEASURES

First aid measures

General advice If symptoms persist, call a physician.

Eye contact Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. If symptoms persist, call a physician. Rinse thoroughly with plenty of water for at least 15 minutes, lifting lower and upper eyelids. Consult a physician. Immediately flush with plenty of water. After initial flushing, remove any contact lenses and continue flushing for at least 15 minutes. Keep eye wide open while rinsing.

Skin Contact Wash off immediately with plenty of water for at least 15 minutes. If skin irritation persists, call a physician. Immediate medical attention is not required. Wash off immediately with soap and plenty of water while removing all contaminated clothes and shoes.

Inhalation If symptoms persist, call a physician. Immediate medical attention is not required. Move to fresh air in case of accidental inhalation of vapors.

Ingestion Immediate medical attention is not required. Rinse mouth. Drink plenty of water. Do NOT induce vomiting. Never give anything by mouth to an unconscious person. Call a physician.

Self-protection of the first aider Use personal protective equipment as required.

Most important symptoms and effects, both acute and delayed

Symptoms May cause allergy or asthma symptoms or breathing difficulties if inhaled. May cause allergic skin reaction. Drowsiness. Dizziness.

Indication of any immediate medical attention and special treatment needed

Note to physicians Treat symptomatically.

5. FIRE-FIGHTING MEASURES

Suitable extinguishing media
Carbon dioxide (CO_2). Foam. Dry chemical.

Unsuitable extinguishing media Caution: Use of water spray when fighting fire may be inefficient.

Specific hazards arising from the chemical
Thermal decomposition can lead to release of irritating and toxic gases and vapors.

Explosion data
Sensitivity to Mechanical Impact None.
Sensitivity to Static Discharge None.

Protective equipment and precautions for firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions, protective equipment and emergency procedures

Personal precautions Use personal protective equipment as required. Avoid contact with eyes and skin. Remove all sources of ignition. Evacuate personnel to safe areas. Keep people away from and upwind of spill/leak.

Environmental precautions

Environmental precautions Prevent entry into waterways, sewers, basements or confined areas. Do not flush into surface water or sanitary sewer system. Prevent further leakage or spillage if safe to do so. Prevent product from entering drains. See Section 12 for additional ecological information.

Methods and material for containment and cleaning up

Methods for containment Prevent further leakage or spillage if safe to do so.

Methods for cleaning up Use personal protective equipment as required. Take up mechanically, placing in appropriate containers for disposal. Avoid creating dust. Clean contaminated surface thoroughly. Soak up with inert absorbent material. Dam up. Pick up and transfer to properly labeled containers. Sweep up and shovel into suitable containers for disposal. After cleaning, flush away traces with water. Take precautionary measures against static discharges.

7. HANDLING AND STORAGE

Precautions for safe handling

Advice on safe handling Ensure adequate ventilation, especially in confined areas. Use personal protective equipment as required. Use with local exhaust ventilation. Do not breathe dust/fume/gas/mist/vapors/spray.

Conditions for safe storage, including any incompatibilities

Storage Conditions Keep container tightly closed. Keep out of the reach of children. Keep containers tightly closed in a cool, well-ventilated place. Keep in properly labeled containers.

Incompatible materials None known based on information supplied.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Control parameters

Exposure Guidelines .
NIOSH IDLH Immediately Dangerous to Life or Health

Other Information Vacated limits revoked by the Court of Appeals decision in AFL-CIO v. OSHA, 965 F.2d 962 (11th Cir., 1992).

Appropriate engineering controls

Engineering Controls Showers
Eyewash stations
Ventilation systems.

Individual protection measures, such as personal protective equipment

Eye/face protection Tight sealing safety goggles. Face protection shield.

Skin and body protection Wear protective gloves and protective clothing.

Respiratory protection If exposure limits are exceeded or irritation is experienced, NIOSH/MSHA approved respiratory protection should be worn. Positive-pressure supplied air respirators may be required for high airborne contaminant concentrations. Respiratory protection must be provided in accordance with current local regulations.

General Hygiene Considerations When using do not eat, drink or smoke. Wash contaminated clothing before reuse. Regular cleaning of equipment, work area and clothing is recommended.

9. PHYSICAL AND CHEMICAL PROPERTIES

Information on basic physical and chemical properties

Physical state	Liquid		
Appearance	OPAQUE WHITE	**Odor**	SLIGHT AMINE
Color	No information available	**Odor threshold**	No information available

Property	Values	Remarks • Method
pH	Not Applicable	
Melting point/freezing point	Not Applicable	
Boiling point / boiling range	99 °C / 211.0 °F	
Flash point	66 °C / 150.0 °F	
Evaporation rate	1.200	
Flammability (solid, gas)	Not Applicable	
Flammability Limit in Air		
Upper flammability limit:	Not Applicable	
Lower flammability limit:	Not Applicable	
Vapor pressure	Not Applicable	
Vapor density	4.60	
Specific Gravity	1.26	
Water solubility	MISCIBLE	
Solubility in other solvents	Not Applicable	

Partition coefficient	Not Applicable
Autoignition temperature	Not Applicable
Decomposition temperature	Not Applicable
Kinematic viscosity	Not Applicable
Dynamic viscosity	Not Applicable
Explosive properties	Not Applicable
Oxidizing properties	Not Applicable

Other Information

Softening point	Not Applicable
Molecular weight	Not Applicable
VOC Content (lbs/gal)	3.077
VOC Content (g/L)	368.716
VOC Content (lbs/gal) Actual as Supplied	1.836
Density	Not Applicable
Bulk density	Not Applicable

10. STABILITY AND REACTIVITY

Reactivity
No data available

Chemical stability
Stable under recommended storage conditions.

Possibility of Hazardous Reactions
None under normal processing.

Conditions to avoid
Heat, flames and sparks. Extremes of temperature and direct sunlight.

Incompatible materials
Incompatible with strong acids and bases. Incompatible with oxidizing agents.

Hazardous Decomposition Products
None under normal use conditions. Thermal decomposition can lead to release of irritating and toxic gases and vapors.

11. TOXICOLOGICAL INFORMATION

Information on likely routes of exposure

Product Information

Eye contact	Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. If symptoms persist, call a physician. Rinse thoroughly with plenty of water for at least 15 minutes, lifting lower and upper eyelids. Consult a physician. Immediately flush with plenty of water. After initial flushing, remove any contact lenses and continue flushing for at least 15 minutes. Keep eye wide open while rinsing.
Skin Contact	Wash off immediately with plenty of water for at least 15 minutes. If skin irritation persists, call a physician. Immediate medical attention is not required. Wash off immediately with soap and plenty of water while removing all contaminated clothes and shoes.
Inhalation	If symptoms persist, call a physician. Immediate medical attention is not required. Move to fresh air in case of accidental inhalation of vapors.
Ingestion	Immediate medical attention is not required. Rinse mouth. Drink plenty of water. Do NOT induce vomiting. Never give anything by mouth to an unconscious person. Call a physician.

Information on toxicological effects

Symptoms Inhalation of high vapor concentrations may cause symptoms like headache, dizziness, tiredness, nausea and vomiting. Disorientation.

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Skin corrosion/irritation Irritating to skin.
Serious eye damage/eye irritation Irritating to eyes.
Corrosivity Not Applicable.
Sensitization May cause sensitization by inhalation and skin contact.
Germ cell mutagenicity No information available.
Carcinogenicity .

Chemical Name	ACGIH	IARC	NTP	OSHA
ETHYLENE GLYCOL MONOBUTYL ETHER	A3			

ACGIH (American Conference of Governmental Industrial Hygienists)
A3 - Animal Carcinogen
IARC (International Agency for Research on Cancer)
Group 2B - Possibly Carcinogenic to Humans
OSHA (Occupational Safety and Health Administration of the US Department of Labor)
X - Present

Reproductive toxicity No information available.
STOT - single exposure No information available.
STOT - repeated exposure No information available.
Chronic toxicity May cause adverse effects on the bone marrow and blood-forming system. May cause adverse liver effects. Avoid repeated exposure.
Target Organ Effects blood, Central nervous system, Eyes, Hematopoietic System, kidney, liver, lungs, Respiratory system, Skin.
Aspiration hazard No information available.

Numerical measures of toxicity - Product Information

The following values are calculated based on chapter 3.1 of the GHS document .
ATEmix (oral) 3843 mg/kg
ATEmix (dermal) 7650 mg/kg
ATEmix (inhalation-dust/mist) 12.1 mg/l
ATEmix (inhalation-vapor) 116 mg/l

12. ECOLOGICAL INFORMATION

Ecotoxicity

Persistence and degradability
No information available.

Bioaccumulation
No information available.

Chemical Name	Partition coefficient
DIMETHYLAMINOETHANOL	-0.55
DIACETONE ALCOHOL	1.03
ETHYLENE GLYCOL MONOBUTYL ETHER	0.81
2-BUTANOL	0.6

Other adverse effects No information available

13. DISPOSAL CONSIDERATIONS

Waste treatment methods

Disposal of wastes Disposal should be in accordance with applicable regional, national and local laws and regulations.

Contaminated packaging Do not reuse container.

US EPA Waste Number U140 U165

This product contains one or more substances that are listed with the State of California as a hazardous waste.

14. TRANSPORT INFORMATION

DOT Not regulated

15. REGULATORY INFORMATION

US Federal Regulations

SARA 313
Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA). This product contains a chemical or chemicals which are subject to the reporting requirements of the Act and Title 40 of the Code of Federal Regulations, Part 372

Chemical Name	CAS No.	Weight-%	SARA 313 - Threshold Values %
ETHYLENE GLYCOL MONOBUTYL ETHER -	111-76-2	6.4063	1.0
2-BUTANOL -	78-92-2	2.744	1.0

SARA 311/312 Hazard Categories

Acute health hazard	Yes
Chronic Health Hazard	No
Fire hazard	No
Sudden release of pressure hazard	No
Reactive Hazard	No

CWA (Clean Water Act)
This product does not contain any substances regulated as pollutants pursuant to the Clean Water Act (40 CFR 122.21 and 40 CFR 122.42)

CERCLA
This material, as supplied, does not contain any substances regulated as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302) or the Superfund Amendments and Reauthorization Act (SARA) (40 CFR 355). There may be specific reporting requirements at the local, regional, or state level pertaining to releases of this material

US State Regulations

U.S. State Right-to-Know Regulations

Chemical Name	New Jersey	Massachusetts	Pennsylvania
DIMETHYLAMINOETHANOL	X	X	X
ETHYLENE GLYCOL MONOBUTYL ETHER	X	X	X
DIETHYLENE GLYCOL MONOMETHYL ETHER	X	X	X
DIACETONE ALCOHOL	X	X	X
TITANIUM DIOXIDE	X	X	X
AMORPHOUS SILICON DIOXIDE 7631-86-9	X	X	X
ISOBUTANOL	X	X	X
2-BUTANOL	X	X	X
NAPHTHALENE 91-20-3	X	X	X
1,2,4 - TRIMETHYL BENZENE	X	X	X

U.S. EPA Label Information
EPA Pesticide Registration Number Not Applicable

Canada

This product has been classified in accordance with the hazard criteria of the Controlled Products Regulations (CPR) and the SDS contains all the information required by the CPR

16. OTHER INFORMATION

NFPA	**Health hazards** 2	**Flammability** 0	**Instability** 0	**Physical and Chemical Properties** -
HMIS	**Health hazards** 1	**Flammability** 1	**Physical hazards** 0	**Personal protection** X

Revision Date 30-Apr-2015
Revision Note
No information available
Disclaimer
The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

End of Safety Data Sheet

Appendix E. TRU CQ5508L INTERIOR PAINT RESCO 958 DARK RED

PAGE 1 OF 5

	11/03/97
DATE REVISED	10/31/00
CURRENT AS OF	09/24/08

MANUFACTURER:

Universal Chemicals & Coatinos Inc
1975 Fox Lane
Elgin, Illinois 60123

EMERGENCY PHONE: (847) 931-1700
CHEMTREC: (800) 424-9300

SECTION I - PRODUCT IDENTIFICATION

FORMULA : 6- 95-400-C
PRODUCT NAME : RESCO 958 DARK RED
CHEMICAL CLASS : ORGANIC COATING
HMIS NUMBER : 2 2 0

SECTION II - HAZARDOUS INGREDIENTS

INGREDIENT DESCRIPTION	TLV	LEL	VAPOR PRESSURE (mm Hg)
ETHYLENE GLYCOL ETHER	25 ppm	1.10	.80
n-BUTYL ALCOHOL	50 ppm	1.40	7.00
2-PROPOXYETHANOL		1.26	1.30

SEE SECTION "X" FOR MORE REGULATORY INFORMATION & MATERIALS, IF APPLICABLE.

TRACE ELEMENTS

SECTION III - PHYSICAL DATA

BOILING RANGE : 148 to 550 (deg F)
VAPOR DENSITY : 3.72
VAPOR PRESSURE: .0 (mm Hg)
WATER SOLUBLE : OIL
APPEARANCE : RED LIQUID
ODOR : MILD ODOR

WEIGHT/GALLON : 9.31 - 9.71
VOC (LB/GAL) : 3.390
SOLIDS BY WEIGHT: 38.5 - 42.5 %
SOLIDS BY VOLUME: 28.5 - 32.5 %

SECTION IV - FIRE AND EXPLOSION HAZARD DATA

DOT CLASSIFICATION: PAINT
FLASH POINT : 139 (deg F) T.C.C. LEL: 1.00 UEL: 15.80
EXTINGUISHING MEDIA:
Foam. carbon dioxide. dry chemical. Do not use water. Water may spread fire.
SPECIAL FIRE FIGHTING PROCEDURES:
Exclude air/oxygen from fire.
UNUSUAL FIRE AND EXPLOSION HAZARDS:
Do not mix with acid or caustic materials.
Do not store near heat or heat surfaces.

SECTION V - HEALTH HAZARD DATA

AFFECTS OF OVEREXPOSURE:
Eye irritation, drying of skin. Excessive inhalation can cause headaches, dizziness, or nausea.
NOTICE: Reports have associated repeated and prolonged occupational over-exposure to solvents with permanent brain and nervous system damage. Intentional misuse by deliberately concentrating and inhaling the contents may be harmful or fatal.
EMERGENCY FIRST AID PROCEDURES:
Eye contact: Flush with water for at least 15 minutes and get medical attention.
Skin contact: Wipe off excess and wash with mild soap and apply skin cream.
Inhalation: Remove to fresh air and call a physician if necessary. If breathing is difficult, give oxygen.
TARGET ORGANS:
Over exposure to ingredients listed in Section II could result in adverse effects to:

liver. kidney, lymphoid system, skin, blood, eyes, respiratory system, central nervous system, GI tract, BLOOD

SECTION VI - REACTIVITY DATA

STABILITY: Stable
CONDITIONS TO AVOID:
Do not expose to heat or ignition sources.
INCOMPATABILITY:
Strong oxidizing agents. Natural rubber will soften and deteriorate.
HAZARDOUS DECOMPOSITION PRODUCTS:
Thermal decomposition may yield carbon monoxide, carbon dioxide, aldehydes and other chemicals.
HAZARDOUS POLYMERIZATION:
Will not occur.

SECTION VII - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED:
Eliminate all sources of ignition.
Small spill: Absorb with inert material. Collect into approved container and handle in accordance with local, state and federal regulations.
Large spill: Dike area and prevent material from entering drains, sewers or water ways. Pump into approved container and handle in accordance with local, state and federal regulations.
Highway spill: Contact Chemtrec - 800-424-9300
WASTE DISPOSAL METHOD:
Dispose of in accordance with local, state and federal regulations.

SECTION VIII - SPECIAL PROTECTION INFORMATION

RESPIRATORY PROTECTION:
Provide properly fitted OSHA approved respirators, unless air monitors demonstrates vapor/mist levels are below applicable limits.
VENTILATION:
LOCAL EXHAUST: Yes
SPECIAL : Air make-up recommended
MECHANICAL : Yes, explosion proof
OTHER : OSHA recommendations

----------Continued on page 4----------

SECTION VIII - SPECIAL PROTECTION INFORMATION (Continued)

PROTECTIVE GLOVES:
Yes - impervious type
EYE PROTECTION:
Yes - goggles or safety glasses (ANSI-Z-87.1---1968).
OTHER PROTECTIVE EQUIPMENT:
Eye bath and safety shower, plus impervious outerwear.
If painted surface is to be welded, care should be taken to prevent welder from inhaling fumes.

SECTION IX - SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORING:
Use with adequate ventilation. Avoid prolonged or repeated contact with the skin. Normally accepted grounding techniques are to be employed during all phases of handling and application to eliminate sparks due to static discharge.
FOR INDUSTRIAL USE ONLY.

SECTION X - MISC. REGULATORY INFORMATION

SECTION 313 SUPPLIER NOTIFICATION
This product contains the following toxic chemical(s) subject to the reporting requirements of Section 313 of the Emergency Planning and Community Right-To-Know Act of 1986 and of 40 CFR 372:

Chemical Name	CAS Number	Percent by weight
ETHYLENE GLYCOL ETHER	111-76-2	9.62
n-BUTYL ALCOHOL	71-36-3	2.73
2-PROPOXYETHANOL	2807-30-9	5.23

SECTION X - MISC. REGULATORY INFORMATION (Continued)

HAZARDOUS AIR POLLUTANTS - (HAPs)

This product contains the following chemical(s) which are on the list of hazardous air pollutants (HAPs) under Section 112(b) of the Clean Air Act.

Chemical Name	CAS Number	Maximum % by weight
XYLENE (MIXED ISOMERS)	1330-20-7	.94
2-PROPOXYETHANOL	2807-30-9	5.23

LBS OF HAPS PER GALLON: .58
LBS OF HAPS PER SOLID GALLON: 2.00

CANADA

The hazardous components of this product are listed on the Canada Domestic Substances List (DSL) or otherwise comply with CEPA new substances notification requirements. EXCEPT FOR ITEMS LISTED BELOW:

Chemical Name	CAS No.	Percent by weight

The information contained herein is correct to the best of our knowledge. It is offered in good faith, but not to be construed as a warranty expressed or implied as to the performance or results. This information should be used only as a guide and Universal Chemicals & Coatings, Inc. assumes no liability, since the conditions of use of our products are beyond our control. It is the users responsibility to determine the suitability of any material for a specific purpose and adopt such safety precautions as may be necessary. Nothing contained herein should be construed as a recommendation to use this product in conflict with Federal, State or Local regulations or existing patents.

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