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Measured Voltages and Currents Internal to Closed Metal Cylinders Due to Diffusion of Simulated Lightning Currents

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Abstract

One mechanism for the penetration of lightning energy into the interior of a weapon is by current diffusion through the exterior metal case. Tests were conducted in which simulated lightning currents were driven over the exteriors of similar aluminum and ferrous steel cylinders of 0.125-in wall thickness. Under conditions in which the test currents were driven asymmetrically over the exteriors of the cylinders, voltages were measured between various test points in the interior as functions of the amplitude and duration of the applied current. The maximum recorded open-circuit voltage, which occurred in the steel cylinder, was 1.7 V. On separate shots, currents flowing on a low impedance shorting conductor between the same set of test points were also measured, yielding a maximum current of 630 A, again occurring across the interior of the steel cylinder. Under symmetrical exterior drive current conditions, a maximum end-to-end internal voltage of 4.1 V was obtained, also in the steel cylinder, with a corresponding current of 480 A measured on a coaxial conductor connected between the two end plates of the cylinder. Data were acquired over a range of input current amplitudes between about 40 and 100 kA. These data provide the experimental basis for validating models that can subsequently be applied to real weapons and other objects of interest.

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1.0 Introduction

The basic mechanisms for the penetration of lightning energy into weapons are being systematically investigated by Department 2753 as part the Stockpile Lightning Analysis and Test (SLAT) program. One mechanism of interest is the diffusion of lightning currents from the exterior surface through the walls of apparently well shielded metallic enclosures. If excessive, voltages and currents induced inside an enclosure in this way could cause potential concerns for weapon safety.

Some previous analytical and laboratory work has been done to quantify this coupling process. Models were developed [1-3] and validated against laboratory data for cylindrical aluminum geometries. Here the response quantity of interest was the current flowing on end-to-end wires inside closed aluminum cylinders under conditions of axially symmetric flow of current on the exterior of the structure [4]. Voltages and currents were also measured across the inside diameter of a closed cylinder due to attachments of simulated lightning currents to the sides of the cylinder. Under those conditions, the exterior current distribution is strongly asymmetric. Those particular tests were performed in the context of a specific weapon assessment [5], which involved complicating factors related to geometry and the magnetic properties of the steel test object. At that time, the lack of a validated model capable of handling these additional factors, combined with limited opportunities for further testing, left the preliminary results obtained under asymmetric drive conditions only partially understood.

The purpose of the present experiments was to investigate the diffusion process more fully under controlled laboratory conditions. Identical test objects of aluminum and ferrous steel were tested, each under both symmetric and asymmetric attachments of simulated incident lightning currents. Various diagnostic voltages and currents inside the test cylinders were measured. These included open-circuit voltages and "short-circuit" currents,¹ which were measured across the inner diameter of the empty cylinders. The response voltages are not only useful for purposes of validating analytical models; they also provide a measure of the possibility for internal arcing. Similarly, short-circuit currents between the same points provide an indication of the maximum current that could flow in the event that an internal arc somehow did occur. The quantity measured during testing of the cylinders under symmetric attachment conditions was the current flowing on a wire connected along the longitudinal centerline of the cylinder between its two end plates. In each case, the responses were recorded as a function of the peak amplitude of the incident current. Some additional data points were also acquired for an incident current waveform with a narrower pulse width.

The tests were carried out in general accordance with the experiment plan of Reference 6 using the Sandia Lightning Simulator (SLS), located in Bldg. 888 in Albuquerque. The development of theoretical models and their comparison with these experimental data are to be separately documented.

¹ The term "short-circuit current" is used here in an approximate sense; in fact, what was measured was the current flowing on piece of 1/2-in braided ground strap connected between two test points across the inside diameter of the cylinder.

2.0 Objectives

The objectives of the experimental portions of the investigation were

1. Measurement under controlled laboratory conditions of the open-circuit voltages and short-circuit currents between various diagnostic test points inside closed cylinders due to diffusion of direct-strike lightning currents, and
2. Acquisition of a data base sufficient to support the development and validation of a general analytical model of diffusion-driven coupling in both nonmagnetic (aluminum) and magnetic (ferrous steel) cylindrical structures.

The overall objective of the combined experimental and analytical investigation was to develop a general capability to predict the reasonable upper bound values for currents and voltages inside weapon cases due to the diffusion of external lightning currents.

3.0 Experiment Description

3.1 Asymmetric Current Distribution

Figure 1 depicts the test cylinder design, defines the internal test point locations, and shows the arrangement of the measurement instrumentation. The details of the cylinder design are given in Figure 2. Each cylinder was 36 inches in length, had an outside diameter of 6 in, and a wall thickness of 0.125 in. The aluminum and steel cylinders were identical except for the material (6061-T6 aluminum and ASTM A513 steel). The end pieces were machined to a 0.005-in flatness tolerance and were secured by six 10-32 cap screws. In this way, appreciable field coupling through the end cap joints, which might otherwise contaminate the desired diffusion data, was prevented.

Each cylinder was connected to the output of the SLS as indicated in Figure 3. The tubular conductors that attached to the cylinder were slotted and clamped to the studs on the cylinder with small hose clamps. A photograph of the details of the connection of the cylinder to the pulser is shown in Figure 4. This arrangement permitted the injection and extraction of the simulated lightning currents precisely at the designated points on the test cylinders. The tests were conducted in the large coaxial fixture normally employed in the facility for purposes of producing magnetic field environments corresponding to nearby lightning. This fixture is approximately 5 feet in radius and 17 feet long. The test current flows down the center conductor from the SLS and returns to pulser ground via 16 copper tubing conductors arrayed uniformly around the circumference of the coaxial test volume. The symmetry of this arrangement and the 5-ft standoff distance of the return path conductors from the fixture's centerline combine to minimize any disruption of the current distribution on the test cylinder due to the magnetic field of the return current. Any such disruption would be difficult to quantify and would complicate the diffusion model validation process.

Measurements corresponding approximately to the open-circuit voltage and short-circuit currents across the inner diameter of the cylinder between the various test point combinations defined in Figure 1 were recorded as functions of the amplitude and duration of the applied simulated lightning return-stroke currents. The voltage between the two test points was sensed by means of the arrangement diagrammed in Figure 5. The dielectric turnbuckle provided the means for applying adequate pressure on the pointed tips of the sensor probes to ensure positive metal-to-metal contact with the wall of the cylinder. During the measurements of the response currents, the ends of the 1/2-in braided wire conductor were held in contact with the cylinder wall as shown in Figure 6. The longitudinal displacement between the various test point pairs is given in Table 1.

Figure 1 Arrangement of instrumentation inside test cylinders for the measurement of
 (a) voltages and (b) currents due to diffusion of external lightning currents

Figure 4 Connection of the terminals of the test cylinder to the SLS

Figure 5 Probe arrangement for the sensing of voltages across the inside diameter of the cylinder due to the diffusion of externally attached lightning currents

Figure 6 Probe arrangement for the sensing of current flowing on a low impedance conductor between points on the inside wall of the cylinder due to the diffusion of externally attached lightning currents

Table 1.
Longitudinal Distances Between Test Points

TP	$\ell(\text{in})$
1-2	0
1-3	9
1-4	18

It was originally planned to record the responses under both simulated return-stroke and continuing currents. However, it was found that the responses corresponding to continuing currents were too low to be measured and were therefore certainly too low to be of practical interest. From that point on, continuing current was eliminated from the testing.

3.2 Symmetric Current Distribution

The experimental configuration used to obtain data on aluminum and steel cylinders under conditions of symmetric exterior current flow is shown in Figure 7. Two types of measurements were made. During one sequence of tests, the voltage developed between the end of the coaxial 1/4-in copper tubing center conductor and the output endplate of the cylinder was recorded. This voltage corresponds to the open-circuit end-to-end voltage between the end plates. In a second series of shots, the center conductor was connected to the input of a coaxial viewing resistor (CVR) and the current on the conductor was measured at the output end of the test cylinder. Figure 8 is a photograph of the steel cylinder positioned on the coaxial test structure ready for testing. The amplitude of the incident test current was varied over the range of about 40 to 100 kA.

Figure 7 Modified cylinder and instrumentation for measuring (a) currents on a coaxial conductor and (b) end-to-end open circuit voltages inside a cylinder due to the symmetric flow of externally attached lightning currents

Figure 8 Steel cylinder positioned in the coaxial test structure attached to the SLS

4.0 Instrumentation

The voltages between various test point combinations were measured directly as shown in Figure 1a. Lead pairs were attached between the test points and the inputs to the fiber optic transmitter, which was operated in the differential mode. The leads were made of miniature 50- Ω coaxial cables. In order to minimize stray coupling, they were physically tied tightly together up to a point as close to the test points as possible. Since the 100- Ω differential-mode input impedance of the fiber optic transmitter was very much larger than the equivalent source impedance to which the sensor leads were attached, the instrumentation presented no significant electrical loading to the test points. The measurement of the response currents on the braid was accomplished using a Pearson Model 110A current viewing transformer (CVT), as shown in Figure 1b.

During the symmetric-drive experiments, the current on the center conductor was detected using a T&M Research 5-m Ω coaxial CVR, Model F4K-8N.

Due to the low frequency nature of the diffusion process, the rise times and decay times of the responses are much slower than those of the applied test current. The data transmission and recording channel configuration that was used for these low frequency measurements is shown in Figure 9, the key feature of which is the Dymec fiber optic data link. As indicated in Figure 10, this link has a 3-dB bandwidth from d.c. to 400 kHz into a 50- Ω load, which is more than adequate for the accurate transmission of the signals from this experiment.

Recording of the applied test current was performed in the manner that is standard at the SLS facility, as is described below.

4.1 Calibration

All instrumentation used to record the test responses was either currently under valid Sandia Standards Laboratory (SSL) calibration certification status or was calibrated during the course of the testing against test sources that were under valid SSL status. In addition, *in situ* end-to-end calibration checks of each recording channel from the inputs to the fiber optic transmitter were conducted periodically during the course of the testing as shown in Figure 11. Calibrations of the CVT and CVR sensors were conducted individually against a separate CVR that was under valid SSL certification.

Figure 9 Data recording instrumentation channel

Data from first prototype
Input amplitude = 0.7 V peak

Figure 10 Measured bandwidth of the Dymec fiber optic data transmission channel

Figure 11 Arrangement for the calibration and performance checkout of the data recording instrumentation channel

5.0 Facility Description and Test Environment

The SLS consists of four independent Marx generators contained in two separate tanks filled with insulating transformer oil (Figure 12). These high voltage impulse generators can be operated in various combinations, and each feeds a common oil-filled transmission line to the machine output bushing. Typically, the machine is configured to provide either a single simulated return-stroke current pulse of peak amplitude from 20 to 200 kA, with a nominal 10-to-90 percent rise time of 0.5 to 2.1 μ s, or else to provide a simulated two-stroke flash comprised of a sequence of two return-stroke pulses with independently controllable amplitudes and adjustable interstroke period of up to hundreds of milliseconds. Continuing current can be independently added to the output current as required by test objectives. During the present tests, only single return strokes were simulated, and, as discussed in Section 3.1, no continuing currents were applied.

The unipolar waveform characteristic of natural lightning is obtained through the use of a laser triggered shorting, or "crowbar," switch across the Marx capacitors. The function of the crowbar switch is to short out the Marx bank at or near the first current peak of the otherwise underdamped oscillating machine output current. This results in a unipolar current pulse with a fast rise to peak, followed by a slowly decaying exponential tail that is governed by the inductance and resistance of the output circuit of the simulator and the test load.

Figure 12 The Sandia Lightning Simulator

Return-stroke simulation in terms of peak current, rise time and/or rise rate, and decay time is controlled through a combination of the installation of selected components internally in the tanks, adjustment of Marx capacitor charging voltage, and adjustment of the crowbar switch timing. However, these are each relatively coarse adjustments resulting, in some cases, in only a limited range of achievable values and an inherent minor shot-to-shot variation in each of the output parameters. A more detailed description of the SLS is given in Reference 7.

The machine output current through the test object is detected by a combination of three calibrated low inductance, $1\text{-m}\Omega$ coaxial CVR's inserted into the return current path to machine ground. As shown in Figure 13, the detected signals are transmitted to the shielded instrumentation room via specially shielded coaxial cables and are there recorded on Tektronix 7612D digitizers. Figure 14 shows a typical simulated return-stroke current available from the SLS. The 275-kHz ringing superimposed on the first $30\text{ }\mu\text{s}$ of the current is due to residual energy in the Marx bank portion of the circuit following crowbarring. The amplitude of the return-stroke current applied to the test cylinders was varied from about 40 to 100 kA. The latter represents the safe operating upper limit of the simulator when driving the coaxial fixture described above in Section 3. In the present tests, rise time of the applied current was not critical, since only the low frequency content of the applied current penetrates to the inside the cylinder.

Figure 13 Standard SLS instrumentation for the recording of applied test lightning currents

Figure 14 Typical return-stroke current obtained from the SLS

6.0 Data

6.1 Asymmetric Current Drive

The data acquired under asymmetric drive conditions are summarized in Tables 2 and 3 for aluminum and steel cylinders, respectively. In those tables, the "N" and "S" prefixes on the shot numbers identify the Marx section of the SLS that was used during each shot, N for north and S for south. The significance of this item lies in the fact that the waveforms and available amplitudes from each of these sections are different. The south tank is set up for testing at median levels of lightning severity, in terms of peak amplitude, rise time, and decay time. The north tank is configured to produce return-stroke currents corresponding to the more severe ranges of lightning parameter distributions. Typical output currents of each type that were employed during the course of the present tests are shown in Figure 15.

Since the early portion of the drive currents do not contribute significantly to the diffusion-driven responses, it is adequate for analysis purposes to approximate the input currents as simple decaying exponentials of the form

$$I(t) = I_0 \exp(-\alpha t),$$

where I_0 is as defined in Figure 14. The decay constants of the currents from the north and south tanks are approximately 370 and 90 μ s, respectively.

The slowly varying nature of the responses in the vicinity of their peaks makes the reading of their times to peak subject to inaccuracy. Therefore, the interval to the point of 90-percent peak amplitude was chosen as the comparison benchmark because it could be determined with more accuracy. The values listed under the "Time to 90% Peak" columns in each table correspond to the interval referenced to the start of the applied test current, as detected by a magnetic field derivative sensor located within the coaxial test volume. (Refer to Figure 9.)

Table 2.
Diffusion-Driven Responses, Aluminum Cylinder
(Asymmetric Drive Current)

Test Point Pair		Shot Number	I ₀ ¹ (kA)	V _{peak} ² (V)	I _{peak} ³ (A)	Δt (μs) (90% of Peak)
1-2	V	N2708	102.5	0.365	---	84
		N2709	102.5	0.385	---	82
		N2836	91.1	0.371	---	80
		N2837	70.9	0.282	---	88
		N2838	41.1	0.157	---	84
		S2378	47.5	0.151	---	60
		S2379	48.9	0.130	---	64
	I	N2706	101.0	---	260.0	170
		N2707	96.7	---	260.0	174
		N2845	72.2	---	162.0	164
		N2846	41.1	---	94.8	160
		S2728	51.5	---	72.8	118
		S2729	41.7	---	56.4	118
1-3	V	N2722	100.0	0.660	---	84
		N2723	98.3	0.673	---	84
		N2711	51.2	0.317	---	
		N2712	47.3	0.306	---	
		N2839	63.6	0.439	---	80
		S2381	50.4	0.261	---	62
		S2382	43.0	0.216	---	64
	I	N2692	62.0	---	230.9	178
		N2693	67.3	---	242.9	186
		N2694	60.0	---	219.6	182
		N2695	80.0	---	302.3	188
		N2696	128.8	---	515.2	186
		N2697	88.7	---	345.5	186
1-4	V	S2730	37.0	---	79.5	122
		N2724	94.0	1.33	---	84
		N2725	86.0	1.17	---	82
		N2840	67.3	0.94	---	84
		N2841	40.5	0.537	---	80
		S2383	45.2	0.442	---	64
		S2384	45.8	0.446	---	64
		S2727	50.9	0.498	---	64
	I	N2701	95.0	---	459.9	184
		N2702	88.7	---	416.3	176
		N2842	40.5	---	160.1	164
		N2843	64.2	---	263.9	180
		S2732	40.9	---	99.7	127

¹ Peak amplitude of the applied test current

² Peak internal open-circuit voltage recorded between the indicated test point pair

³ Peak current recorded on the braided conductor between the indicated point pair

Table 3.
Diffusion-Driven Responses, Steel Cylinder
(Asymmetric Drive Current)

Test Point Pair		Shot Number	I ₀ ¹ (kA)	V _{peak} ² (V)	I _{peak} ³ (A)	Δt (μs) (90% of Peak)
1-2	V	N2760	91.0	0.962	---	124
		N2831	46.0	0.384	---	180
		N2833	71.0	0.900	---	132
		N2835	100.0	1.332	---	144
		S2735	43.8	0.063	---	88
		S2736	43.1	0.062	---	86
	I	N2743	77.8	---	379.2	197
		N2820	105.7	---	523.9	284
		N2821	47.5	---	192.2	280
		N2822	33.9	---	93.5	320
		S2741	40.6	---	20.3	137
1-3	V	N2757	84.0	1.21	---	230
		N2758	53.6	0.57	---	178
		N2759	91.9	1.57	---	188
		S2737	41.1	0.063	---	82
	I	N2750	46.0	---	203.7	340
		N2751	65.7	---	427.8	350
		N2752	83.0	---	627.7	312
		N2753	89.1	---	743.0	310
		N2754	40.0	---	128.0	338
		S2740	40.9	---	19.6	278
1-4	V	N2756	66.8	1.70	---	164
		N2826	77.9	2.30	---	204
		N2827	45.0	0.80	---	240
		N2829	46.0	0.80	---	204
		N2830	50.0	0.90	---	200
		S2738	40.8	0.12	---	88
	I	N2745	73.5	---	630.3	275
		N2747	60.0	---	486.8	304
		N2823	41.7	---	215.2	376
		N2824	50.0	---	356.1	348
		S2739	39.8	---	27.8	388

¹ Peak amplitude of the applied test current

² Peak internal open-circuit voltage recorded between the indicated test point pair

³ Peak current recorded on the braided conductor between the indicated point pair

Figure 15 Example SLS output currents as applied during the present tests

The peak response voltages and currents recorded inside the aluminum cylinder are plotted in Figures 16 and 17 as functions of the peak amplitude I_0 of the applied test current. The waveform of the test current associated with all of the data in those figures is the type labeled N2708 in Figure 15. The input current waveforms scale linearly with the peak amplitude over the range employed in the present testing. The corresponding data set acquired on the steel cylinder is presented in Figures 18 and 19.

Example voltage and current waveforms obtained between TP's 1 and 4 (Figure 1) at nominal input peak current levels at both ends of the test range are shown in Figure 20. The test current waveform applicable to all of the data given in that figure corresponds to the north tank version shown in Figure 15. Comparisons of the differences in responses obtained in each type of cylinder under the two different waveforms of Figure 15 are given in Figure 21. In each case, the peak amplitude of the input current was nominally 40 kA. The data of Figures 20 and 21 illustrate the effects of both the amplitude and the duration of the applied current. Finally, a comparison is shown in Figure 22 of the responses of the aluminum and steel cylinders under the shorter duration waveform shown in Figure 15 with a peak amplitude of 40 kA.

Figure 16 Peak amplitudes of the response voltages obtained between different test point pairs during asymmetric diffusion tests on the aluminum cylinder

Figure 17 Peak amplitudes of the response currents obtained between different test point pairs during asymmetric diffusion tests on the aluminum cylinder

Figure 18 Peak amplitudes of the response voltages obtained between different test point pairs during asymmetric diffusion tests on the steel cylinder

Figure 19 Peak amplitudes of the response currents obtained between different test point pairs during asymmetric diffusion tests on the steel cylinder

(a)

(b)

(c)

(d)

Figure 20 Example response waveforms obtained between Test Points 1 and 4 inside the test cylinders due to asymmetrically applied test currents of peak amplitudes near the upper and lower ends of the range employed during the present tests. (a) Voltages and (b) currents in the aluminum cylinder; (c) voltages and (d) currents in the steel cylinder.

Figure 21 Example response waveforms obtained between Test Points 1 and 4 inside the test cylinders due to asymmetrically applied test currents of the two types shown in Figure 15. (a) Voltages and (b) currents in the aluminum cylinder; (c) voltages and (d) currents in the steel cylinder.

(a)

(b)

Figure 22 Comparison of (a) voltages and (b) currents obtained in aluminum and steel cylinders due to an applied test current of approximately 40-kA peak obtained from the south tank (similar to S2378 in Figure 15)

6.2 Symmetric Current Drive

The data measured under axially symmetric drive current flow on the exterior of the test cylinders are summarized in Table 4. The same data sets are plotted in Figures 23 and 24, in which the nonlinear character of the responses in the steel test object are quite evident. This behavior is a consequence of the nonlinear nature of the magnetization curve associated with steel, which is a function of the local current density within the material.

Table 4.
Diffusion-Driven Responses for Aluminum and Steel Cylinders
(Symmetric Exterior Drive Current)

Material		Shot Number	I_0^1 (kA)	V_{peak}^2 (V)	I_{peak}^3 (A)
Aluminum	V	N2866	37.0	1.20	---
		N2867	46.7	1.50	---
		N2868	66.7	1.96	---
		N2869	81.5	2.31	---
		N2870	96.0	2.59	---
	I	N2871	100.0	---	274
		N2872	83.4	---	225
		N2873	71.7	---	190
		N2874	46.5	---	125
		N2875	36.8	---	97
Steel	V	N2848	43.4	0.4	---
		N2849	66.2	1.37	---
		N2850	86.2	3.12	---
		N2851	93.7	4.06	---
		N2852	66.6	1.75	---
		N2853	69.0	1.93	---
		N2854	62.2	1.53	---
		N2855	41.9	0.59	---
	I	N2857	38.5	---	50
		N2858	41.0	---	55
		N2859	60.5	---	138
		N2861	74.8	---	230
		N2862	84.6	---	312
		N2863	87.4	---	336
		N2864	104.5	---	480

¹ Peak amplitude of the applied test current

² Peak internal open-circuit voltage recorded between coaxial center conductor and end plate of cylinder as shown in Figure 7.

³ Peak current recorded on the coaxial center conductor as shown in Figure 7.

Figure 23 Peak amplitudes of end-to-end open-circuit voltages obtained on aluminum and steel test cylinders under symmetric test current conditions

Figure 24 Peak amplitudes of current flowing on a coaxial conductor between the ends of the aluminum and steel test cylinders under symmetric test current conditions

7.0 Conclusion

Tests were conducted in which simulated lightning currents were asymmetrically applied to and extracted from aluminum and steel walled closed cylinders. The maximum voltages measured between test points located on the internal surface of the aluminum cylinder was 1.3 V for an applied simulated lightning current of 94-kA peak amplitude. The corresponding value for the steel cylinder was 1.7 V, obtained under a 67-kA peak amplitude applied current. In each case, the test points were located diametrically opposite from each other on the interior walls, but were displaced longitudinally by a distance of 18 in. The highest currents measured on a braided conductor connected between the same test points were 460 A and 630 A for aluminum and steel, respectively.

Under axially symmetric current flow over the exterior of the cylinders, the maximum end-to-end open-circuit voltage measured between the interior end plates of the 36-in long measurement volume was 2.6 V for aluminum and 4.1 V for steel, both responses being recorded under drive currents of approximately 95-kA peak amplitude. Maximum currents flowing on the short-circuited copper tube center conductor were 274 A and 480 A in the aluminum and steel cylinders, respectively.

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