0-289495①

SANDIA REPORT

SAND93-0788 • UC-706

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Printed August 1994

Voltages Across Assembly Joints Due to Direct-Strike Lightning Currents

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

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Voltages Across Assembly Joints Due to Direct-Strike Lightning Currents

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Abstract

An extensive set of direct-strike lightning tests has been carried out on a set of facsimile assembly joints of the kinds employed in the design of nuclear weapon cases. Taken as a whole, the test hardware included all the conceptual design elements that are embodied, either singly or in combination, in any specific assembly joint incorporated into any stockpiled weapon. During the present testing, the effects of all key design parameters on the voltages developed across the interior of the joints were investigated under a range of lightning stroke current parameter values. Design parameter variations included the types and number of joint fasteners, mechanical preload, surface finish tolerance and coatings, and the material from which the joint assembly was fabricated. Variations of the simulated lightning stroke current included amplitude (30-, 100-, and 200-kA peak), rise time, and decay time. The maximum voltage observed on any of the test joints that incorporated proper metal-to-metal surface contact was 65 V. Typical response values were more on the order of 20 V. In order to assess the effect of the presence of a dielectric coating (either intentional or as a result of corrosion) between the mating surfaces of a joint, a special configuration was tested in which the mating parts of the test assembly were coated with a 1-mil-thick dielectric anodizing layer. First strokes to these test assemblies resulted in very narrow voltage spikes of amplitudes up to 900 V. The durations of these spikes were less than 0.1 μ s. However, beyond these initial spikes, the voltages typically had amplitudes of up to 400 V for durations of 3 to 5 μ s.

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Voltages Across Assembly Joints Due to Direct-Strike Lightning Currents

1.0 Introduction

The electrical consequences of direct-strike lightning currents over the exterior of a weapon case were investigated as part of the Stockpile Lightning Analysis and Test Program (SLAT) [1]. The motivation for these tests stemmed from the concern that impedances as low as milliohms across assembly joints can result in the development of hundreds of volts across the interior surfaces of the joints. If sufficiently high voltages were to appear from such a mechanism, the possibility would exist for arcing to internal components. Furthermore, if a low impedance arc path were to be formed in this manner, it could carry thousands of amperes into the interior of the weapon. Should interior cables become involved in the arc path, they could transmit voltages throughout the weapon topology, which could conceivably result in deleterious secondary arcing at points physically removed from the joint. Moreover, if a multiple-point ground should become inadvertently established through this mechanism, very large currents could be injected into small gauge conductors, for example within circuitry, resulting in their explosive vaporization.

In order to investigate this potential lightning interaction mechanism and quantify practical bounds on the effects it might produce, a set of experiments was conducted by Department 2753 using the Sandia Lightning Simulator (SLS) in which voltages produced by lightning test currents were measured across the interiors of controlled joints in experimental hardware. The test items incorporated canonical features fundamental to all types of assembly joints of practical interest in nuclear weapon designs and included provisions that allowed a systematic variation of certain mechanical parameters during the testing. In this way, practical upper bounds on the voltages were established for each type of joint, and sensitivities of the responses to design and loading variations were empirically established. The experimental data base will also be valuable in supporting the development and validation of analytical models applicable to assembly joints in general.

An associated issue concerns the magnitude of voltages that can be produced by lightning between the tip of a fastener that penetrates to the interior of a weapon and its surrounding interior surface. The question is whether this voltage can be high enough to cause arcing to the interior surface, and, if so, under what conditions. Additional experiments were conducted to investigate this phenomenon.

1.1 Objectives

The specific objectives of these experiments were

1. Determination of practical upper-bound voltages that can be developed across the interior surfaces of facsimile assembly joints by non-penetrating lightning currents flowing on otherwise electrically tight cylindrical configurations;
2. First-order characterization of the sensitivity of such voltages to parameters such as surface area and roughness, mechanical preload, and amplitude of the applied test current; and
3. Determination of practical upper-bound voltages that can occur between the tips of penetrating fasteners and their surrounding surfaces interior to a weapon.

1.2 General Description of Experiments

At lightning frequencies, the two basic mechanisms by which voltages are developed across assembly joints are inductive and resistive. Figure 1-1 shows a test object that incorporates a simple butt joint, in which the response is due primarily to contact resistance (though some gap may exist due to machining quality and, therefore, some inductive component) between the mating surfaces. The magnitude and sensitivity of the gap voltage was evaluated as a function of surface roughness, finish (bare metal and dielectric anodizing coating), loading pressure, and material (aluminum or ferrous steel). Sensitivity to the amplitude and rate of rise of the applied test current and effects due to joint conditioning from multiple exposures were also investigated.

The primary coupling mechanism in the joint shown in Figure 1-2 is inductive, due to concentrated current flow between cylinder halves through the fastening bolts [2]. The sensitivity of the response voltage of this type of joint was investigated as a function of the number of bolts and the fit tolerances between the halves.

The flange and bolt joint shown in Figure 1-3 combines both resistive and inductive coupling features in a balance that depends on such variables as the number and types of fasteners and their tightness. This joint therefore represents the next logical level of complexity for testing and modeling. Variations included intentional shimming to accentuate the inductive coupling component. Two types of fasteners were investigated: the one shown in Figure 1-3, in which the bottom flange receives the fastening screws in tapped holes, and a version in which the fasteners were bolts through clearance holes in both halves of the assembly that were secured by nuts.

Figure 1-1 Preloaded butt joint test object

Figure 1-2 Radial fastener slip joint test object

Figure 1-3 Flange joint test object

Taken as a set, these three types of joints conceptually cover virtually all practical assembly joints represented in the stockpile. For example, the tape joint shown in Figure 1-4 can be thought of as a uniformly loaded compression joint, similar in principle to, but presumably better than, the simple butt joint of Figure 1-1. The same is true of threaded, tapered spline, marmon, and interference-fit pinned joints. Separate test objects of each of the types shown in Figures 1-1 through 1-3 were constructed of aluminum and ferrous steel. Each of these materials is of direct interest with respect to weapons. Furthermore, the magnetic attributes of ferrous steel can lead to significant nonlinear effects under high amplitude lightning currents, and the data from steel objects will be valuable in the development of an understanding of the practical effects associated with the magnetic properties of steel weapon cases.

Figure 1-4 Tape joint design

The design of the test objects and the experimental procedures to be used are intended to allow the isolation and assessment of the various competing effects that come into play. Specified tolerances for surface flatness, fit, hole clearance, and bolt hole size are representative of selected weapon designs and were determined from general Sandia product specifications [3], weapon drawings, and discussions with numerous Sandia mechanical designers. Thicknesses of the test pieces and other features were selected to eliminate coupling contributions from current diffusion through the walls of the test objects and from current division associated with the compression stud shown in Figure 1-1.

The test object used for measuring voltages on penetrating fasteners was a version of the flange joint unit, which was modified as shown in Figure 1.5.

Illustrated in Figure 1-6 is the basic test configuration. During the testing of joints, the output electrode of the SLS was attached to the test object by means of multiple lengths of 1-in braided ground strap. The hard-wire connection precluded development of arcing to the test item, which was undesirable during these experiments; and the use of braid strap to make the connection provided stress relief and prevented the transmission of mechanical shock from the SLS to the test object during firing of the pulser. Attachment of the test current to the penetrating fasteners was via a short arc, which represents the worst-case attachment mode during natural lightning encounters. In each instance the test object was bonded to the front plate of the standard aluminum SLS instrumentation cylinder. Conventional positive current flow was from the test object to the output electrode of the machine, corresponding to the situation in which a negative cloud-to-ground flash attaches to an object on the ground. (On a global basis over ninety percent of all cloud-to-

Figure 1-5 Test object used for measuring voltages on penetration fasteners

Figure 1-6 Assembly joint lightning test configuration

ground lightning is of this type.) The current path back to the pulser ground was via a symmetric array of tubular copper conductors attached to the front plate of the instrumentation cylinder. In this way a symmetric longitudinal current density flow was maintained over the exterior and across the gap of the joint in the test object.

2.0 Summary of Results

Based on the data from the extensive testing of joints fabricated from aluminum and steel that was carried out during this investigation, the fundamental conclusions can be summarized in two succinct statements:

1. Voltages produced by direct-strike lightning currents flowing across properly designed and maintained assembly joints in nuclear weapon cases do not constitute a threat to weapon safety, and
2. Care must be exercised to ensure that bare metal-to-metal contact is designed into such joints and is preserved throughout the stockpile life of the weapon.

The typical voltage measured across the test joints with metal-to-metal surface contact was of the order of 20 V, and the overall maximum under those conditions was 65 V. This latter result was obtained on a radial joint test assembly made from steel, and it occurred under a simulated return-stroke current of 100-kA peak amplitude. Except under the most contrived of circumstances, this voltage would not cause deleterious arcing internal to a weapon case. On the other hand, voltage of that amplitude in combination with the development of an inadvertent multiple-point ground that bridges the joint, perhaps as a result of an accident scenario, might result in a very high current being driven through whatever conducting path is involved. The specific consequences of this type of low probability interaction, however, would have to be evaluated on a case-by-case basis.

The presence of an intervening layer of dielectric material of any sort between the surfaces of a joint destroys the metal-to-metal bonding and leads to the buildup of voltage across the joint until the dielectric strength of the insulating layer is exceeded sufficiently to result in breakdown. In general, a dielectric layer might be used intentionally, for example, for purposes of protecting against corrosion. However, to our knowledge there are no anodized surfaces employed in the assembly joints of any weapon in the stockpile. A dielectric layer might also occur inadvertently over a period of time as the result of severe oxidation or other corrosion processes.

This situation was simulated in a joint assembly in which the mating surfaces were coated with a 1-mil dielectric anodizing layer. The tests conducted on joints of this type resulted in narrow voltage spikes of up to 900-V peak amplitude and half-value duration times of less than 100 ns, followed by 500-V levels sustained for several microseconds. While evaluation of the practical consequences associated with that kind of relatively short voltage transient cannot be specified in general terms, prudence clearly dictates that this situation should be avoided in any joints that might possibly have to carry high currents.

The final objective of this study was to understand the mechanism responsible for producing the response voltages as well as their sensitivities to various design parameters. Since the set of joints that was tested was chosen to include the conceptual features embodied in any weapon assembly joint, a quantitative understanding of this set provides the basis for the analysis of virtually any design variation of interest in the nuclear weapon context. The results of companion analyses of the results presented in this report will be documented separately.

3.0 Test Environment

An illustration is given in Figure 3-1 of a composite simulated lightning flash current of the type that is available from the SLS. The current consists of two simulated return strokes with continuing current during the interstroke interval and following the final stroke. For reference, this test current is referred to as a "full-flash" simulation. The second return stroke and continuing current components can be either separately included or not as so chosen for any particular test. Peak amplitudes, rise times, full-width-to-half-maximum (FWHM) durations, and interstroke intervals can all be independently adjusted over fairly wide ranges that correspond to the distributions of their respective counterparts in real lightning.

Figure 3-1 Simulated full-flash current waveform available from the SLS. Return-stroke amplitudes and rise times, interstroke intervals, and the initial amplitude of the continuing current are each adjustable.

3.1 The Sandia Lightning Simulator

In the SLS, return-stroke currents are produced by one or more of its four individual Marx generators, which are housed in two separate tanks filled with insulating oil. These high voltage impulse generators can be operated in various combinations, and each feeds a common oil-filled transmission line connected to the machine output bushing. The unipolar waveform corresponding to real lightning is produced through the use of a laser-triggered shorting, or "crowbarring," switch across the Marx capacitors. The function of the switch is to short out the Marx voltage at or near the first peak of the otherwise underdamped oscillating machine output current. This results in a fast-rise current pulse corresponding to the resonant frequency of the Marx capacitance and the discharge circuit inductance, followed by a decaying tail that is governed by the L/R parameters of the output circuit of the machine and test load. The nominal ranges of output parameters that are available are peak amplitudes from 20 to 250 kA, FWHM from 25 to 200 μ s, and interstroke intervals from about 40 ms to a second. For loads with inductances less than about 3 μ H, 10-to-90 percent rise times from 0.5 to 2 μ s can be obtained. Figure 3-2a shows a typical simulated return-stroke current obtained from the SLS, and Figure 3-2b shows a sequence of return-stroke currents measured directly at the base of the lightning channel of a real flash, along with an expanded presentation of the first of the strokes on a faster time scale for comparison with Figure 3-2a. The ringing that appears just after the peak of the simulated return stroke is due to residual energy within the Marx capacitance and output circuit inductance following crowbarring.

Continuing current is provided from a large motor-generator set, the output of which is coupled into the simulator output circuit through a large pulse isolation inductor. Prior to the test shot, the set is spun up in the motor mode to a designated spin rate. Just before the shot, the set is switched to the generator mode and is then allowed to wind down under its own inertia during the course of the test event, producing an

approximately exponentially decaying output current. Initial continuing current values of up to 700 A can be obtained, corresponding to the ninety-ninth percentile severity in a natural lightning flash [4]. Figure 3-3 shows an example of continuing current produced by the SLS.

The total current applied to a test object is recorded by summing the outputs of three low impedance coaxial current viewing resistors (CVR) that are inserted into the current return path to pulser ground. The recording arrangement for these signals is shown in Figure 3-4. In addition, the rise rate of the applied return-stroke current was recorded directly during most of the present tests using a Rogowski coil placed around one of four symmetrically routed return-stroke current return conductors between the test object and pulser ground.

(a)

(b)

Figure 3-2 (a) Simulated lightning return-stroke current obtained from the SLS; (b) five return-stroke currents measured at the base of a real lightning channel (top), and expanded plot of the first stroke current (bottom)

Figure 3-3 Simulated severe continuing current obtained from the SLS

Figure 3-4 SLS output test current recording instrumentation

4.0 Test Instrumentation

Standard SLS data acquisition instrumentation was used throughout these experiments. Figure 4-1 shows the general configuration of each test. During testing, the voltage developed across each joint was measured directly at up to four individual test points around its inside circumference. As shown in Figure 4-2, the voltage was sensed via two pick-up wires (actually miniature 50- Ω coaxial cables) connected directly to the top and bottom halves of the assembly at approximately 0.5 inch from their respective mating surfaces. Each wire pair was arranged to minimize stray magnetic field coupling (i.e., loop areas) and was led out the back end of the test object into the interior of the aluminum instrumentation chamber, where the individual cables were attached via OSM connectors to the input ports of their respective fiber optic transmitters. By convention, the lead from the top half of the joint was always connected to the positive input port on the transmitter. The transmitters were operated in the differential mode, with a corresponding input impedance of 100 Ω . This impedance is many orders of magnitude greater than the joint impedance during the test event (typically on the order of milliohms), ensuring, therefore, that the measurement caused no perturbation due to electrical loading.

Shown in Figure 4-3 is a diagram of one channel of recording instrumentation. Two different fiber optic data links (FOLs) were employed depending on bandwidth requirements. Wide bandwidth measurements were made using NanoFast Model 300-2 or 300-2A FOLs, which have working 3-dB bandwidths extending from 10 to 160 Hz on the low end to 100 to 200 MHz on the high end, depending on model type and individual unit. Overall measurement bandwidth was always limited to a maximum of 100 MHz due to the minimum sampling interval of 5 ns that is available from the 7612D digitizing oscilloscopes.

Because of the long duration, low frequency nature of the continuing current components of lightning, valid measurements associated with these components require a low frequency recording capability that extends virtually to direct current (dc). For these types of records, a Dymec frequency modulated (FM) FOL with a bandwidth from dc to 400 kHz was used.

Figure 4-1 General test configuration for the measurement of voltages across various types of assembly joints

Figure 4-2 Installation of voltage sensing wire pairs at test points around the interior circumference of the test unit

The linear operating input signal range of the NanoFast transmitters is ± 0.1 V, the corresponding range of the Dymec is ± 0.7 V. Attenuation of the response voltages to within these ranges was obtained through a combination of $150\text{-}\Omega$ resistors inserted into each sensing line near its test point connection and additional attenuators at the transmitter inputs. The latter included both external attenuators physically inserted at the input ports and internal attenuation within the transmitter itself that can be remotely set from the data recording room. The external attenuators were of the $50\text{-}\Omega$ Narda OSM type and were paired to within 0.2 dB. The minimum detectable signal levels during these tests were approximately 10 to 20 mV on channels incorporating NanoFast FOLs and 3 to 4 mV on the Dymec channels.

Recorded on each test shot were the applied current from the SLS, various pulser diagnostic functions, and up to four responses of the test object. In most cases, the derivative of the applied current was recorded during each test shot. Each of the latter five signals was routed to two Tektronix digitizers, which were set to provide records at two sensitivities and two sweep rates (sampling rates). Figure 4-4 is an example of the instrumentation setup sheet that was used. Such a sheet was filled out for each shot configuration to assist in preparing and double-checking the instrumentation room prior to each shot. Additionally, the data acquisition system automatically maintains a record of all instrumentation settings for each test. This record, an example of which is shown in Figure 4-5, was archived along with the data from each test shot

Figure 4-3 Standard data recording channel for assembly joint voltage measurements

for documentation purposes and for use in cross-checking against the setup sheet as required. Both the setup sheet and the archived record reflect all sensor gauge factors, channel attenuation, and digitizer settings that are necessary for scaling the recorded signals and plotting them in their respective engineering units.

4.1 Calibration

Calibrations were carried out and their results were archived regularly throughout the testing, usually at a minimum of once at the beginning of each test day. The procedure involved injecting a known voltage signal into the sensor end of the channel and comparing it with the plotted result as recorded through the entire channel. The input signal was either periodic or was a single pulse as obtained from a source that was under valid calibration certification by the Sandia Standards Laboratory (SSL). Three variations of this procedure were employed. In the first, the calibration signal was applied directly to each of the input ports of the fiber optic transmitter, either singly or in a differential mode across both ports. In the second technique, the calibration signal was applied across the input ends of the two sensor leads to yield a full end-to-end calibration of the entire channel. Finally, for certain joint assemblies, an in situ end-to-end calibration was performed in which the input signal was applied directly across the two (isolated) halves of the test joint. The three calibration methods are diagrammed in Figure 4-6. The results of typical calibration checks are given for two channels in Figure 4-7. During these checks, the percentage agreement among the peak voltages recorded by the four sensor channels and the input signal was typically within ± 5 percent. If the peak responses varied by more than 10 percent, the gains of the various FOLs were adjusted to bring them within a five-percent tolerance with respect to the calibration signal, an accuracy that was accepted as being more than sufficient for the purposes of these measurements. With the assurance of this kind of overall recording accuracy, no calibration corrections were applied during data processing, although, since all the calibration records were archived, that option has been preserved.

SHOT ID: 2530, STROKE SEQUENCE: FIRST 200kA, CCG None, DELAY 60 ms, SECOND 30kA

Figure 4-4 Example instrumentation setup sheet

SHOT#N2530

30-APR-92 15:22:21

#	UN	CHANNEL 1					CHANNEL 2					SECONDS/D	T	F	ZERO	XOP
		CAB	ATTEN	V/D	POS	OP	CAB	ATTEN	V/D	POS	OP					
1	1	27	100	.2	3.5	M	27	100	.5	3.5	M	2U	1	1	0	
2	2	28	100	.2	3.5	M	28	100	.5	3.5	M	2U	1	1	0	
3	3	30	100	.2	3.5	M	30	100	.5	3.5	M	2U	1	1	0	
4	4	31	100	.2	3.5	M	31	100	.5	3.5	M	2U	1	1	0	
5	5	29	100	.2	0	M	29	100	.1	0	M	1U	1	1	0	
6	6	27	100	.1	3.5	M	27	100	.2	3.5	M	2U	1	1	0	
7	7	28	100	.1	3.5	M	28	100	.2	3.5	M	2U	1	1	0	
8	8	30	100	.1	3.5	M	30	100	.2	3.5	M	2U	1	1	0	
9	9	31	100	.1	3.5	M	31	100	.2	3.5	M	2U	1	1	0	
10	10	29	100	.2	0	M	29	100	.1	0	Z	1U	1	1	0	
11	11	17	2	.2	3.5	M	17	2	.2	3.5	M	10U	1	1	0	
12	11	17	2	.2	3.5	M	17	2	.2	3.5	M	100U	1	1	0	
13	12	17	2	.05	3.5	M	17	2	.05	3.5	Z	10U	1	1	0	
14	15	27	100	.2	3.5	Z	28	100	.2	3.5	Z	10M	1	1	0	NY
15	16	30	100	.2	3.5	Z	31	100	.2	3.5	Z	10M	1	1	0	NY
16	43	99	1	1	0		1	1	0			1S	1	1	0	

SHOT#N2530

30-APR-92

15:22:21

#	UN	CHANNEL 1				CHANNEL 2			
		IDENTITY	GAUGE	Y-UNITS	DATA0	IDENTITY	GAUGE	Y-UNITS	DATA0
1	1	TP1A	4	V		TP1B	4	V	
2	2	TP2A	4	V		TP2B	4	V	
3	3	TP3A	4	V		TP3B	4	V	
4	4	TP4A	4	V		TP4B	4	V	
5	5	I-DOTA	1875	A/S		IDOT-B	1875	A/S	
6	6	TP1AS	4	V		TP1BS	4	V	
7	7	TP2AS	4	V		TP2BS	4	V	
8	8	TP3AS	4	V		TP3BS	4	V	
9	9	TP4AS	4	V		TP4BS	4	V	
10	10	I-DOTAS	1875	A/S		I-DOTBS	1875	A/S	
11	11	N_CVRSUM	78220.4	A		N_CVRSUM	78220.4	A	
12	11	N_CVRSUM	78220.4	A		N_CVRSUM	78220.4	A	
13	12	S_CVRSUM	78220.4	A		S_CVRSUM	78220.4	A	
14	15	TP1L1	4	V		TP2L2	4	V	
15	16	TP3L1	4	V		TP4L2	4	V	
16	43	CAMAC	1			CAMAC	1		

Figure 4-5 Example instrumentation setup record as archived by the SLS data acquisition system

Figure 4-6 Three instrumentation calibration techniques employed during the present testing

Figure 4-7 (a) Calibration input signal applied to the input ends of two sensor pairs, and (b) and (c) the resulting recorded responses of the two channels

The current derivative (I-dot) sensor that was used is a T&M Model P-8502-2 Rogowski coil. It was placed around one of the four symmetric return current conductors between the test object and pulser ground to provide a direct measurement of the derivative of the test current for use during data analysis and modeling. This sensor was calibrated as shown in Figure 4-8, with results as shown in Figure 4-9. The injected current pulse from the Velonex pulser, as measured by the Pearson pulse current probe indicated in Figure 4-8 and recorded on one channel of the Tektronix 7612D, is displayed in Figure 4-9a. The derivative, as detected by the I-dot probe, is given in Figure 4-9b. Finally, in Figure 4-9c, the result of a numerical integration of the derivative signal of Figure 4-9b is shown for comparison with the original input current pulse.

The values of all attenuators used during this testing were individually determined as shown in Figure 4-10. Any time attenuators were inserted into the recording channels, they were selected as a pair with no more than 0.2-dB difference in their values.

All the auxiliary equipment used during any of the calibration checks discussed above was verified to have been under current and valid calibration certification by the SSL.

Figure 4-8 Arrangement for verifying the calibration factor and performance of the I-dot sensor

(a)

(b)

(c)

Figure 4-9 (a) Calibration test current from the Velonex 587 of Figure 4-8, (b) recorded current derivative signal from the I-dot sensor, and (c) Numerical integration of the derivative signal shown in (b)

Figure 4-10 Arrangement for calibrating Narda 50-Ω signal attenuators

5.0 Preloaded Butt Joint

The geometry of the test cylinder is shown in Figure 5-1. The design of the assembly permitted measurement of voltages across the joint on the inside of the test item as functions of variations in mechanical preload, surface finish, surface coating, the material of the assembly, and peak current of the simulated incident lightning current.

Mechanical preload was adjusted by means of the nut indicated in Figure 5-1, the torque on which was translated into compressive force on the joint via the 0.5-in steel rod along the center axis of the assembly. Testing was performed under two levels of compressive load. In the first, the nut was tightened by hand to the minimum torque required simply to maintain alignment of the two halves of the joint while in the horizontal position. The corresponding torque value was determined by torque wrench to be 1 ft-lb. In the second condition, the nut was tightened to 30 ft-lb of torque, which, qualitatively speaking, was very tight. The plan was that, should the data indicate significant dependence on compression, the applied torque would have then been calibrated in terms of joint preload pressure in a mechanical laboratory test cell. As discussed below, however, the test data exhibited no significant dependence on preload at the two indicated levels.

Figure 5-1 Assembly joint test object A: preloaded butt joint

Another variation during testing included surface finish; the effects of 32 and 125 micro-inch finishes were evaluated. These finish specifications represent the extremes permitted Sandia weapon designers under the applicable general design specification standard [3]. Flatness was not varied; in all cases, the test assembly joints were fabricated to a 0.005-in flatness tolerance, typical of Sandia weapon design practice. The effects of joint conditioning on the response voltages due to multiple strokes and continuing current were also investigated.

Anodizing, which results in a dielectric coating of joint surfaces, is not employed in weapon assembly joints. However, in order to bound the effects of a corrosion or oxide layer in a joint of this type, anodized aluminum joints were tested. In these cases, the anodized layer was a nominal 0.001-in thick on each part and was applied per Sandia specification [5].

Nine separate butt joint assemblies were tested, with an average of nine shots being conducted on each one. In most cases, four responses were recorded on each test object, along with the applied test current, its derivative, and various SLS pulser diagnostic quantities. The test results are summarized and discussed in Section 5.2.

5.1 Assembly Procedures

The assembly of the test item was conducted according to the following general procedure. The lower half of the test item was attached to the front plate of the instrumentation chamber, and the voltage sensor lead pairs from each fiber optic transmitter were then connected to their respective attachment points on each half of the item. Each lead was provided with an O-lug terminal, which was attached to the test point by means of a 6-32 cap screw. (Refer to Figure 4-2.) In all cases, electrical continuity across these connections was checked and confirmed to be $0.2\ \Omega$ or less. Next, the values of the series 150- Ω attenuation resistors were also checked. In the early stages of testing, the sensor lead pairs were twisted together, in principle thereby reducing coupling of penetrating magnetic fields into the sensor lead circuit. However, subsequent characterization of noise pickup indicated that this precaution was unnecessary. Since the twisting of the leads was cumbersome and tended to produce mechanical strain near the attachment points, this practice was abandoned; for the bulk of the testing, the leads were left untwisted. At this stage of assembly, one or more of the instrumentation calibration procedures described in Section 4.1 were carried out.

The two halves of the joint assembly were next aligned with the aid of an auxiliary cylinder machined to slip snugly over the exterior of the test item. Once aligned, the torquing nut on the compression stud was adjusted to the desired level by means of a torque wrench, and the alignment cylinder was removed. At this point, the instrumentation chamber front plate, with the test object fully installed thereon, was secured to the instrumentation chamber by means of thirteen 1/4-20 screws. The four copper-tube conductors for the return current back to the simulator were attached to the front of the instrumentation chamber, and the input end of the test item was connected to the simulator output terminal by means of four lengths of 1-in braided ground strap.

Disassembly following the test was carried out in the reverse order. During disassembly, the values of the 150- Ω series resistors and the contact resistances of the test point connections were checked each time prior to their removal from the test object. A test log was maintained throughout, and all significant visual observations were noted. Numerous documentary photographs were taken and archived along with plots of the data from each test shot.

5.2 Test Results

Table 5-1 summarizes all the variations of all the parameters that were made during the tests. The principle results are

1. Measured peak voltages with durations exceeding several hundred nanoseconds across joints with bare metal surfaces (either aluminum or steel) never exceeded 25 V under any of the combinations of parameter values that were tested;
2. Peak voltages, with durations exceeding several hundred nanoseconds, as high as 500 V were observed across joints with anodization coatings;
3. Voltage spikes of durations less than several hundred nanoseconds, were observed with amplitudes as high as 900 V on first shots to joints with anodized surfaces;
4. The response amplitudes and waveforms were substantially independent of all test variations except the presence of anodizing layers; and
5. No synergistic or otherwise cumulative effects on peak voltage resulted from exposure to double-stroke flash simulations or the inclusion of intervening continuing current.

From a practical viewpoint, the two major conclusions regarding the butt joints and supported by the test results are (1) dielectric films of any mating surfaces of assembly joints (due either to intentional design or to the effects of corrosion) must be precluded, and (2) voltages across butt joints with good metal-to-metal contact present no significant threat to weapons safety or, in all probability, to reliability.

Table 5-1.
Parameter Variations in Butt Joint Tests

	Preload (ft-lb)		Test Current (kA)		Surface Finish (μ -in)	
	1	30	30	200	32	125
Al, bare	---	---	---	X	---	X
Al, anodized	X	X	X	X	X	X
Steel, bare	X	X	X	X	X	X

Table 5-2 and Figures 5-2 through 5-4 summarize the results obtained on the butt joints in terms of the voltage measured on each exposure at a time of 1 μ s into the waveform. The choice of this time point in each response for comparison purposes was based on a combination of reasons. First, it was necessary to find a common point for comparison among several waveform types that differed primarily in their early portions before 1 μ s (discussed below in Section 5.2.1). Secondly, the behavior of some of the responses before the 1- μ s point was characterized by very narrow (<100-ns half-width) spikes. Since these types of narrow spikes contain relatively very little energy, they do not represent practical threats to weapon safety. Furthermore, the available measurement bandwidth was inadequate to resolve such narrow spikes completely.

Table 5-2.
Preloaded Butt Joint Voltage Summary

Joint Material	Surface Coating ¹	Torque (ft-lb.)	Surface Finish (μ-inch)	First Shot ²	Subsequent Shots ³	
				30-kA Response (Volts)	30-kA Response (Volts)	200-kA Response (Volts)
Aluminum	Y	1	32	239(250)	41(60)	327(480)
Aluminum	Y	30	32	237(250)	123(165)	381(500)
Aluminum	Y	30	32			380 ⁴
Aluminum	Y	1	125	303(310)	154(170)	308(460)
Aluminum	Y	30	125	225(230)	149(180)	320(425)
Aluminum	N	1	32	Not Applied	Not Applied	0.84(1.7)
Noise ⁵					7.8(20)	36(90)
Steel	N	1	32	3(4)	2.3(4.5)	8.7(24)
Steel	N	30	32	0.37(0.4)	0.35(0.4)	0.31(0.6)
Steel	N	1	125	3.1(4)	1.7(3)	3.5(13)
Steel	N	30	125	0.1(0.15)	0.09(0.1)	0.7(1.7)
Noise ⁶					1.3(1.5)	0.5(1)

¹ Anodized, Sandia specification 9904102, black coating, ~1-mil thick

² Average voltage at 1 μs of four test points, with maximum datum in parentheses

³ Average voltage at 1 μs from all corresponding subsequent 30- or 200-kA shots

⁴ 200-kA level shot to an assembly with pristine anodizing layer

⁵ Average voltage at 1 μs for all aluminum butt joints with surface coating

⁶ Average voltage at 1 μs for all steel butt joints (no coating)

Figure 5-2 Aluminum butt joint test results. Lines represent linear regression fits to the responses at the 1- μ s benchmark points on each waveform. For each combination of test joint parameters, the error bars extend from the maximum to the minimum voltages obtained at each of the nominal peak amplitudes (30 and 200 kA) of the applied test currents.

Figure 5-3 Steel butt joint test results

Figure 5-4 Summary of all butt joint responses

5.2.1 Discussion

The test results fall into three categories corresponding to (1) first strokes on joints with anodized surfaces, (2) subsequent strokes on the same joints, and (3) all strokes to joints with bare mating surfaces. Each response type is now discussed in turn. No significant response to continuing current was detected.

5.2.1.1 Anodized Aluminum Mating Surfaces, First Strokes. The responses obtained on initial shots on anodized aluminum joints are typified by the waveform shown in Figure 5-5. Each such response is characterized by one or more sharp spikes occurring during the approximately 1- μ s rise time of the applied current, sometimes with a preceding excursion of opposite polarity. This portion is followed by a drop to a fairly constant plateau of duration of the order of hundreds of microseconds and then a relatively precipitous drop to zero. These features are illustrated in Figure 5-5a, which shows the first 10 μ s of the response measured during Shot 2362, (peak current of 30-kA), and in Figure 5-5b, which is a plot of the full response.

It is postulated that this behavior can be interpreted in a manner consistent with the phenomenology reflected in Figure 5-6. Prior to exposure to the first test shot (or, equivalently, the first stroke in a real lightning flash), the two metal mating surfaces were confirmed to be electrically isolated from each other by the two layers of anodization (dielectric strength unknown). Because the capacitance across such a joint is of the order of a nanofarad, it is very small with respect to the pulser capacitance and, in effect, represents an open circuit. Since the output circuit of the simulator comprises a transmission line, when the pulser is fired a voltage that would ultimately achieve a value of twice the erected Marx generator voltage begins to develop across the joint gap. At some early point on the rising front of the voltage, however, the two layers of anodization break down at one or more spots, and a short arc (~ 0.002 inch) develops. The voltage across such a short arc is set almost entirely by the sum of the potential drops occurring at the cathode and anode electrode spots. For aluminum electrodes, this value is about 10 to 20 V [6].

Figure 5-5 Example response waveform from the first exposure of an aluminum butt joint with anodized surfaces (Test ID 2362); (a) early portion, and (b) full record. The applied test current was 30-kA peak.

Figure 5-6 Site of electrical puncture and resulting arc between anodized mating surfaces of a butt joint

Referring to Figure 5-5b, it can be seen that the level of the plateau portion of the response corresponds well with this range. In virtually all of our data, this plateau lasts for approximately 190 μ s for the 30-kA input current waveform and 650-700 μ s for the 200-kA waveform, which have different decay time constants. When the applied current falls below the level required to sustain the electrode potential drop characteristic of the aluminum electrode material, the arc self-quenches. From Figures 5-5 and 5-7, which show the responses to simulated 30- and 200-kA return-stroke waveforms, it can be seen that at the 190- μ s and 650- μ s points, respectively, just before the arc extinguishes, the voltage is about 10 V in both instances.

5.2.1.2 Anodized Surfaces, Subsequent Strokes. In some instances the responses recorded during subsequent shots on a given joint with anodized surfaces (i.e., any shot other than the first one) exhibited waveforms similar to that shown in Figure 5-5 and discussed above. By a ratio of about 3 to 1, however, the waveshapes were similar to that given in Figure 5-7. The main difference lies in the initial portion of the response within the first 3 μ s. This distinction appears to be associated with the fact that, during subsequent shots, the puncture hole through the anodizing layers already exists and contains air. This implies that the breakdown threshold required to initiate an arc would be lower than in the case of the first shot, during which the pristine dielectric anodizing layer (of dielectric strength higher than that of air) must first be punctured. It is speculated that during the first shots, the arc column is filled with vapor and debris from the heated anodization material, and that some time is necessary to sweep it out and establish a stable arc in the tunnel volume, after which time the characteristics of both first and subsequent shots become the same. In the subsequent shots, the arc path contains no debris from the burned anodization material, and the arc development takes place in the air trapped in the previously established tunnel, thereby resulting in a somewhat modified waveform during the early portion of the arc development.

As discussed above in connection with first shots to fresh joint assemblies, in the data for subsequent shots at both 30-kA and 200-kA peak currents, the time interval to the point at which the voltage collapses from the plateau level to zero is always about 190 μ s for the 30-kA strokes and about 600 μ s for the 200-kA strokes.

From Figure 5-2 it can be observed that the ratio of the mean response at 200 kA to that at 30 kA is approximately 2, while the ratio of 200 kA to 30 kA is 6.6. It is therefore clear that the peak voltage (at 1 μ s) is not directly proportional to the driving current. It is, rather, related to the existing arc voltage, which is substantially independent of current.

One apparent anomaly occurs in the data involving anodized surfaces. In Figure 5-2, there is a systematic increase in the responses associated with 32-micro-inch finishes at the 30 ft-lb torque level over those acquired at 1 ft-lb of torque. Intuition suggests that the tighter the joint is compressed, the smaller should be the voltage developed across it. However, referring to Figure 5-6, it can be seen that air at ambient atmospheric pressure becomes trapped in the existing puncture channel during reassembly of the joint following inspection. What may be happening is that this air becomes somewhat compressed for the case in which the assembly halves are more tightly joined. This change in gas pressure may be causing a shift on the Paschen curve, which, in effect defines the breakdown potential between planar electrodes as a function of the pressure of the intervening gas and the distance between the electrodes. Another possible variable could be differences in the anodization thickness between samples. In any event, since the overall data clearly confirm the inappropriateness of coated mating surfaces, no further effort was made to verify this proposed explanation quantitatively.

5.2.1.3 Non-anodized Surfaces, All Strokes. Figures 5-3 and 5-4 clearly illustrate that the voltages occurring across joints comprised of bare mating surfaces are only a fraction of those obtained on the joints with anodized surfaces. For all but very loosely assembled joints, the voltages are negligible (<5 V) and in some instances barely exceed the measurement noise. An example response is shown in Figure 5-8. This waveform can be quite well reproduced under the assumption that the joint impedance predominantly consists of a contact resistance of about 6 $\mu\Omega$.

Figure 5-7 Response waveform from an aluminum butt joint with anodized surfaces (Test ID 2376). The applied peak test current was 200 kA. This joint was previously exposed to three 30-kA strokes.

Figure 5-8 Non-anodized stainless steel butt joint waveform (Test ID 2557). The applied peak current was 200 kA.

6.0 Radial Screw Joint

A drawing of the radial screw (slip) joint used during these tests is shown in Figure 6-1. As with the butt joint, the design permitted measurements of the voltage across the interior of the joint at up to four locations. The upper half fits into the lower and is secured by a number of equi-spaced set screws around the outer circumference. Design parameter variations that were tested included the number of fasteners, fit tolerances between the two halves (set by the inclusion of mylar spacers), and the type of material (aluminum or steel).

The set screws (1/4-20) were steel and were torqued to 2 ft-lb in each instance. Mylar strips of 0.005-in thickness were placed along the horizontal and vertical interface surfaces, as indicated in Figure 6-1. The vertical spacer was provided with holes at each screw location to allow direct electrical contact between the screw and the inner piece of the joint. This arrangement ensured that the current was carried across the joint entirely by the fasteners. At least one joint of each type of material was tested with the horizontal mylar spacer removed so as to allow a natural random contact around the flat mating surfaces of the two pieces. Listed in Table 6.1 are the variations that were tested, along with the identification assigned to each configuration. Surface flatness was not varied; and, in all cases, the joints were fabricated to a 0.001-in flatness tolerance, typical of Sandia weapon design practice [3].

Six separate radial joint assemblies were tested, and an average of ten shots was carried out on each one: four at 30 kA, four at 200 kA, and two at 100 kA. Typically, the responses at each of the four test points were recorded using two digitizers to provide appropriate resolution of both the early and late-time portions of the response waveforms. In addition, the applied test current and its derivative were recorded, along with the usual set of pulser performance diagnostics. The test results are summarized and discussed in Section 6.2.

Figure 6-1 Radial screw joint assembly test item

Table 6-1.
Radial Joint Parameter Test Variations

Joint ID	Material Type	Number of Screws	Insulator Strips
B1	Aluminum	4	Yes
B2	Aluminum	8	Yes
B3	Aluminum	8	Horiz. Removed
B _S 1	Steel	4	Yes
B _S 2	Steel	8	Yes
B _S 3	Steel	8	Horiz. Removed

6.1 Assembly and Test Procedures

The lower half of the joint was first attached to the front plate of the instrumentation chamber. The test point sensor leads were then installed on each half of the joint assembly, and their electrical continuity was checked and confirmed to be below 0.2 Ω . At the same time, the 150- Ω series attenuator resistors were verified to be within $\pm 5\%$ of nominal. The assembly was next positioned in front of the instrumentation chamber and the sensor leads were connected to their respective FOLs. At this point in the process, an end-to-end calibration was carried out by applying a voltage pulse from the Velonex 587 across the two halves of the joint and recording the response through the entire measurement channel. Further details of this process are given in Section 4.1, and typical results are shown in Figure 6-2. The 5-mil-thick mylar spacer strips were then installed and the two halves of the joint were mated and secured by tightening the screws to the designated torque of 2 ft-lb.

The test procedure was carried out in general accordance with the experiment plan [4]. A 30-kA simulated return-stroke current was first applied, and then the joint was disassembled and inspected. The inspection included checks of the electrical continuity of the voltage sensor leads, measurement of the sensor resistors, photography, and the recording of general observations. The joint was then reassembled and two additional 30-kA shots were carried out, followed by disassembly and re-inspection. This procedure was repeated for three 200-kA and two 100-kA shots. Noise measurements, with the two sensor pickup leads of a given pair connected to the same terminal point on the joint, were recorded at both the 30-kA and 200-kA input levels. The noise shots were generally carried out following the 100-kA shots.

6.2 Results

Figures 6-3 through 6-5 are representative of the typical waveforms obtained during all the radial joint tests. The first peak occurs within two to three tenths of a microsecond and is a narrow spike in appearance. A second broader main peak occurs at approximately one microsecond into the waveform. These peaks are evident in the early time plots in each figure. The first, spiked peak appears to be related to the derivative of the fine structure on the applied current waveform, which tends to change somewhat from shot to shot. The second peak, which occurs at approximately one microsecond, was more consistently observed on all the voltage waveforms and is discussed below. Because of its deterministic nature and consistency, this second peak was chosen as the benchmark comparison point among the responses of all the joint variations. This is the same benchmark that was selected for use in the comparisons among the butt joint data, which are discussed in Section 5.2.

Figure 6-2 Typical calibration waveforms recorded during the radial screw joint tests; (a) calibration input signal applied across the input ends of sensor lead pairs, (b) and (c) the resulting responses as recorded through two different complete instrumentation channels

Figure 6-3 Typical response voltages obtained on an aluminum test object (top) due to the applied test current (bottom)

Figure 6-4 Comparison of the effect of the number of set screws (B1 and B2) and of the mylar insulating layer (B2 and B3) on aluminum assemblies for 200- kA test currents. (Refer to Table 6-1.)

Figure 6-5 Comparison of the effect of the number of set screws (B_{S1} and B_{S2}) and of the mylar layer (B_{S2} and B_{S3}) on steel assemblies for 200-kA test currents. (Refer to Table 6-1.)

The effects of the variations of the joint parameters on the response voltages can be observed in the waveforms shown in Figure 6-4 and 6-5. The results of varying the number of ferrous alloy set screws in an aluminum joint are shown in Figures 6-4 and 6-6. At the 200-kA peak current level at which the data in Figure 6-4 were taken, the response voltage decreased from approximately 25 V down to 8 or 9 V when the number of screws was increased from 4 to 8, a result that is consistent with the addition of parallel paths through the increased number of screws across the gap of the joint. Removal of the horizontal mylar strips appeared to result in only minor modification of the responses. As can be seen from Figure 6-6, what change occurred was indeed in a direction consistent with the creation of additional parallel paths across the joint and, hence, a slight reduction in average voltage response. This same trend also occurred in the data from the steel joint, as shown in Figures 6-5 and 6-7. The response levels were, under the same input conditions, higher for the steel test objects than they were for the aluminum ones, a consequence of the increased inductance associated with the higher permeability of steel and lower conductivity of steel.

The peak responses obtained during the radial joint tests are listed in Table 6-2 and are given graphically in Figure 6-6. The primary observations are summarized as follows and are discussed further in Section 6.2.1.

1. The voltage developed across the joint is approximately proportional to the number of screws provided to carry the current,
2. Random contact between the two flat mating surfaces provides additional parallel current paths across the joints and decreases the voltage by an additional 25 percent or so,
3. The joints made from steel produced responses that are higher than those of their aluminum counterparts for the same test input currents, and
4. Joints made of steel show a higher response voltage under a 100-kA drive than they do under 200-kA.

Table 6-2.
Radial Screw Joints Voltage Summary

Joint Material	Number of Screws ¹	Contact Surface Insulated	30-kA Response ² (Volts)	100-kA Response (Volts)	200-kA Response (Volts)
Aluminum	4	Y	6.7(13)	24(26)	34(58)
Aluminum	8	Y	2.1(3.5)	4.3(7.5)	8.3(10)
Aluminum	8	Vertical only	1.6(2.5)	6.3(7)	7.6(8.5)
Noise ³			0.46(0.5)		1.9(5)
Steel	4	Y	9.9(18)	50(65)	41(58)
Steel	8	Y	3.8(4.5)	11(13)	14(16)
Steel	8	Vertical only	3.8(4)	10(13)	11(16)
Noise ³			2.1(9)		3.7(10)

¹ Screws torqued at 2 ft-lb

² Average voltage at 1 μ s, with maximum datum in parenthesis

³ Average voltage at 1 μ s, for all aluminum or steel joints

(a)

(b)

Figure 6-6 Summary of measured voltages (at 1 μ s) across radial screw joints assemblies under all test variations; (a) aluminum, and (b) steel

Figure 6-7 Comparison of all measured voltages (at 1 μ s) obtained on aluminum and steel radial screw joint test assemblies

6.2.1 Discussion

The basic model of the radial screw joint is the series inductance and resistance of the parallel combination of set screws, shunted by the capacitance between the two parts or the assembly. This shunt capacitance is on the order of several nanofarads, so its effect can be ignored even at the highest frequencies of interest (say 1 MHz, which roughly corresponds to a rise time of 1 μ s). The model for the voltage across the joint therefore reduces to

$$V_j(t) = I(t)R + L[di(t)/dt], \quad (6.1)$$

where $I(t)$ is the applied test current.

In Figure 6-8, the top trace is the applied test current of shot 2775, the middle trace is the directly recorded derivative of that current, and the bottom trace is the measured joint response. According to eqn. 6-1, at those points in time that the derivative is zero ($t \sim 2.5, 5,$ and 7.5μ s), the magnitude of the response voltage is just IR . Since $I(t)$ is known, R follows. Once R is known, L can be deduced, since the values of all the other parameters of eqn. 6.1 are known.

As mentioned in Section 6.1, two effects related to the magnetic properties of steel were observed. The first is the fact that, all other design and input current parameters being equal, the steel test unit yielded higher responses than did the aluminum unit. This follows directly from an increased effective inductance across the gap due to the higher permeability of the steel. Secondly, as indicated in Figure 6-6b, higher responses were observed on the steel test unit at 100-kA input currents than at 200 kA. This was not the case for aluminum, the results of which are shown in Figure 6-6a. The explanation for this is related to the nonlinearity of the permeability μ of the steel as a function of the current through it [e.g., 7]. From a practical viewpoint, however, the maximum voltage observed during the present test was 65 V, which, except for highly contrived circumstances, would not imply any threat to nuclear safety.

Figure 6-8 a) Input test current, (b) derivative of test current, and (3) recorded response of an aluminum radial screw joint test assembly, Shot 2774

7.0 Flange Joint

The design and dimensions of the flange joint assembly are shown in Figure 7-1. As with the two previously discussed joints, this design permitted measurements of the voltage across the interior of the joint at up to four locations. It also allowed the evaluation of effects due to two different types of fastener techniques, the presence of an insulating layer between the mating surfaces of the two halves, and the type of material from which the assembly was made.

The first fastener design consisted of 1/4-20 stainless steel countersunk screws that penetrated the top flange through clearance holes and screwed directly into tapped holes in the bottom flange. In the second technique, 1/4-20 stainless steel bolts penetrated through clearance holes in both flanges and were secured with washers and nuts. In both approaches, eight equi-spaced steel fasteners were used, each torqued uniformly to 50 in-lb.

The purpose of including a 0.005-in-thick mylar insulating layer between the mating surfaces of the assembly was to ensure that all current was carried across the joint by the fasteners, thereby representing the worst-case situation for such a joint. However, at least one aluminum and one steel joint assembly were also tested without a mylar spacer so as to allow natural contact between the mating surfaces. Table 7-1 lists the variations that were tested, along with the identification assigned to each configuration. Surface flatness was not varied; and, in all cases, the joints were fabricated to a 0.001-in flatness tolerance, typical of Sandia weapon design practice [3].

Figure 7-1 Flange joint assembly test item

Table 7-1.
Flange Joint Parameter Variations*

Joint ID	Material Type	Fastener Type	Mylar Insulator
C1	Aluminum	Bolts	Yes
C2	Aluminum	Bolts	No
C3	Aluminum	Screws	Yes
C4	Aluminum	Screws	No
C _s 1	Steel	Bolts	Yes
C _s 2	Steel	Bolts	No
C _s 3	Steel	Screws	Yes
C _s 4	Steel	Screws	No

* It should be noted that gaps in cylindrical bolt joints are always large compared to these planar joints, so the mylar case is a better model for these types of weapon joints.

Seven different assemblies were tested, and an average of ten shots were carried out on each: four at 30 kA, four at 200 kA, and two at 100 kA. Configuration C_s4 was not tested, since the previous results from the other cases in which there were no mylar spacers were essentially the same as the noise shots.

Typically, four voltage measurements were recorded during each test shot. Two digitizers were assigned to each test point to provide resolution of both the early- and late-time portions of the voltage waveforms. In addition, the applied test current and its derivative were recorded, along with the usual set of pulser performance diagnostics. The test results are summarized and discussed in Section 7.2.

7.1 Assembly and Test Procedures

The procedures used to install the voltage sensors and to assemble and mount the joint onto the instrumentation chamber were similar to those described in Section 6.1 for the radial screw joint. A digital multi-meter was used to verify that the contact resistances of the sensor O-lugs were all less than 0.2 Ω and that the sensor resistors were within ± 5 percent of their nominal 150- Ω values. After the voltage sensor leads were connected to their respective FOL transmitters, an end-to-end calibration was carried out by applying a voltage pulse from the Velonex 587 across the two isolated halves of the joint and recording the responses through each entire measurement channel. Further details of this process are given in Section 4.1, and typical results are shown in Figure 7.2. The two halves of the joint were then mated and secured by tightening the fasteners (bolts or screws) to the designated torque of 50 in-lb.

The test procedure was carried out in general accordance with the experiment plan [4]. A 30-kA simulated return-stroke current was first applied, and then the joint was disassembled and inspected. The inspection included checks of the electrical continuity of the voltage sensor leads, measurement of the sensor resistors, photography, and the recording of general observations. The joint was then reassembled and two additional 30-kA shots were carried out, followed by disassembly and re-inspection. This procedure was repeated for three 200-kA and two 100-kA shots. Noise measurements were recorded at both the 30-kA and 200-kA shot levels. The noise shots were generally carried out following the 100-kA shots.

(a)

(b)

(c)

Figure 7-2 Typical calibration waveforms recorded during the flange joint tests; (a) calibration input signal applied across the isolated halves of the assembly, (b) and (c) results recorded through two different complete instrumentation channels

7.2 Results

Figures 7-3 through 7-5 are representative of the typical voltage waveforms obtained during all the flange joint tests. The waveform characteristics are very similar to those of the radial screw joint discussed in Section 6.2. The first peak occurs within two to three tenths of a microsecond and is a narrow spike in appearance. A second broader main peak occurs at approximately one microsecond into the waveform. These peaks are evident in the early time plots in each figure. The first spiked peak appears to be related to the derivative of the fine structure on the early portion of the applied current waveform, which tends to change from shot to shot. The second peak, which occurs at approximately one microsecond, was more consistently observed on all the voltage waveforms and is discussed below. Because of its deterministic nature and consistency, this second peak was chosen as the benchmark comparison point among the measurements of all the joint design variations. This is the same benchmark that was selected for use in the comparisons among the butt and radial screw joints, discussed in the previous two sections.

Figure 7-3 Typical voltage measurements on an aluminum flange joint (top) and associated test current (bottom)

The effects due to the variation of fastener design can be observed in Figure 7-4, for aluminum, and in Figure 7-5, for steel. Both figures correspond to the situation in which the mylar spacer was included between mating surfaces. At the 200-kA peak current level at which the data in Figure 7-4 were taken, the response voltage increased, from approximately 8 to 35 V in this example, when bolts were used instead of screws. Similar results from steel assemblies are shown in Figure 7-5. With all other factors being equal, an increase in response due to the different types of fasteners from about 13 to 47 V occurred in this example. In no case did the results of post-shot inspections reveal evidence of arcing having occurred at any points of contact between the fasteners and the surrounding surfaces of the joint pieces. This increase is probably due to the bolt inductance in the bolt hole.

The effect of the material of the assembly can be seen in Figures 7-6 and 7-7, as well as from the values listed in Table 7-2. In general, other factors being equal, the responses of the steel joints were somewhat higher than those of the aluminum assemblies. This behavior is similar to the corresponding results obtained on radial screw joints, and it is probably related to the increased joint inductance associated with the higher permeability of steel over aluminum.

In both aluminum and steel joints, removal of the insulating mylar layer resulted in responses that were only slightly higher, on average, than those that occurred during noise shots. The noise measurements were conducted with the two ends of the voltage sensor for each test point connected to the same attachment point, usually on the "upstream" half of the joint. During the noise shots, the joints were secured with the usual eight fasteners and no mylar layer.

Figure 7-4 Comparison of the effect of screws versus bolts as fasteners for aluminum flange joint assemblies incorporating mylar spacers

Figure 7-5 Comparison of the effect of screws versus bolts as fasteners for steel flange joint assemblies incorporating mylar spacers

The primary observations from the flange joint tests are summarized as follows and are discussed further in Section 7.2.1.

1. For joints with a 0.001-in mylar spacer between their mating surfaces, the bolt-and-nut fastener combination led to higher response voltages than did the screw-and-tapped-hole design. Other factors being equal, the increases were approximately a factor of 5 higher in aluminum and a factor of 3.5 higher in steel assemblies;
2. Without mylar spacers, the responses of flange joints made of either aluminum or steel were, on average, only slightly higher than those of the noise shots;
3. The flange joints made from steel developed voltages that were approximately 80 percent higher than on aluminum assemblies with screw fasteners and 30 percent higher on those with bolts;
4. There were no indications that arcing had occurred at any point along the surface where the screws or bolts made contact with the joint flange; and
5. The highest voltage observed during any of the tests on flange joints was 55 V, which involved a case in which the mylar spacer was included. With no mylar present, all responses were less than 11 volts, which is only marginally higher than the corresponding measurement noise floor.

(a)

(b)

Figure 7-6 Summary of measured voltages (at 1 μ s) for the flange joint assemblies under all test variations; (a) aluminum, and (b) steel

Figure 7-7 Comparisons of all measured voltages (at 1 μ s) for both aluminum and steel flange joint assemblies

Table 7-2.
Flange Joints Voltage Summary

Joint Material	Screws or Bolts ¹	Contact Surface Insulated	30-kA Response ² (Volts)	100-kA Response (Volts)	200-kA Response (Volts)
Aluminum	Screws	Y	1.4(1.5)	5.9(7.5)	7.2(9.5)
Aluminum	Screws	N	0.6(1)	2.5(4.5)	3.3(5.5)
Aluminum	Bolts	Y	5.8(7)	30(33)	35(45)
Aluminum	Bolts	N			0.7(1.5)
Noise ³			0.4(1.3)		1.0(2)
Steel	Screws	Y	4.3(8)	10(12)	13(15)
Steel	Screws	N	1.5(2.5)	5.1(8.5)	6.4(11)
Steel	Bolts	Y	10(11)	37(42)	46(55)
Noise ³			0.83(2.5)		2.8(7)

¹ The number of screws or bolts used was eight; each was torqued to 50 inch-lb

² Average voltage at 1 μ s, with the maximum datum in parenthesis

³ Average voltage at 1 μ s

7.2.1 Discussion

The voltage developed across the flange joint has waveform characteristics very similar to those of the radial screw joint discussed in Section 6.2. As in the radial joint response waveform, there are two distinct features. The first is the spiked peak which occurs within the first few tenths of microseconds of the waveform, and the second is the relatively smooth and continuous peak which occurs at approximately one microsecond.

Similarly to the radial screw joint (Section 6.2.1), the voltage across the flange joint can be given as

$$V_j(t) = I(t)R + L[dI(t)/dt], \quad (7.1)$$

where $I(t)$ is the applied test current.

Given in Figure 7-8 is a quite typical example of an applied test current, its derivative, and the resulting voltage measured across an aluminum joint. As was discussed in Section 6.2.1, the equivalent joint resistance can be determined from eqn. 7.1 and Figure 7-8 at the points at which dI/dt is zero. Determination of L then follows, since the values of all the other parameters in eqn. 7.1 are known.

Figure 7-8 Typical results obtained on a flange joint; (a) applied test current, (b) its derivative, and (c) joint response voltage

8.0 Fastener Penetration

Voltage measurements were made between the tips fasteners penetrating through 0.5-in aluminum and the surrounding interior surface of the material. The barrier itself was comprised of the body of one of the aluminum test assemblies previously employed during the flange joint tests. In one case a 1/4-20 countersunk screw was threaded into a tapped hole and allowed to penetrate to the interior of the assembly. In the second configuration a countersunk 1/4-20 bolt penetrated through a clearance hole, with a washer and nut on the interior side of the case. The fasteners, washer, and nut were all steel. The interior end of each fastener was provided with a 4-40 tapped hole to accommodate the attachment of its sensor lead. These features are illustrated in Figure 8-1.

Each fastener was coated with Locktite 242 and was torqued to 50 in-lb. To ensure electrical isolation between the lead on the end of the screw and the surrounding surface, a small collar of 0.005-in mylar was fitted around the attachment.

Figure 8-1 Penetrating fasteners on a flanged joint test assembly

8.1 Assembly and Test Procedures

The flange joint was assembled using threaded screws and no mylar insulation between mating surfaces. Locktite was then applied to each of the penetrating fasteners. The screw and bolt were inserted and torqued to 50 in-lb. Next, the voltage sensors were attached to the interior ends of the fasteners. The positive lead of each sensor was connected directly to the end of its designated fastener, and the negative lead was connected to the surrounding surface by means of a tapped 6-32 hole located within 0.5 in of the tip of the fastener. Additionally, two noise sensor pairs were installed with their ends connected to the termination points of the respective negative leads of each fastener measurement. These provided noise characterizations that were carried out simultaneously with the actual test shots. A digital multi-meter was used to verify that all sensor lead contact resistances were less than 0.2 Ω and that the sensor resistors were within ± 5 percent of their nominal 150- Ω value. The joint was mounted to the instrumentation chamber front-plate and the sensor leads were connected to their associated FOL transmitters.

Prior to the assembly described above, an in situ calibration was performed, during which plastic fasteners were substituted for the steel ones. The plastic fasteners had thin metal screws through their centers, which provided the connection points for the Velonex 587 calibration source. The results were typical of those previously discussed in connection with the tests on the various joints and agreed to within 5 percent of the input pulses.

During testing, attachment of the input current to the fastener head was made in each case via a 0.25-in arc from the pointed tip of a tungsten rod electrode. Photographs were taken before and after each shot to show the actual location of each attachment point.

8.2 Results

For all practical purposes, no distinction could be made between the fastener voltages and the noise measurements. Eight shots were taken, with no intervening perturbation of the fasteners, yielding a total of 32 measurements, including the noise characterizations. On average, the peak recorded signal was 0.05 V, which is only a factor of about 2.5 above the fiber optic system noise floor. Figure 8-2 gives an example of the results that were obtained.

It should be pointed out that these were not intended to be exhaustive tests and that the barrier involved was quite thick (0.5 in). The direct application of these results is limited to certain configurations in bomb-type weapons in which the specifics of these tests relate somewhat closely to the actual conditions. Within these limits, the present results confirm that the threat of arcing to interior cabling is negligible.

Figure 8-2 Typical voltage measurements obtained on penetrating screw and bolts

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