NASA Technical Memorandum 84554

EFFECTS OF SIMULATED LIGHTNING ON COMPOSITE AND METALLIC JOINTS

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October 1982

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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ABSTRACT

An investigation of effects of simulated lightning strikes and currents on aircraft bonded joints and access/inspection panels has been conducted. Tests were conducted on both metallic and composite specimens. The evaluation also included tests on metal fuel feed-through elbows in graphite/epoxy structures. Sparking threshold and residual strength of single-lap bonded joints and sparking threshold of access/inspection panels and metal fuel feed-through elbows are reported.

INTRODUCTION

Aircraft electrical safety is an increasing concern because small general aviation fixed and rotary wing aircraft are flying more frequently in instrument conditions as a result of the development of relatively inexpensive, highly sophisticated avionics. Increased instrument flying increases exposure of aircraft to thunderstorm activity and the probability of lightning strikes. Therefore, the aircraft must be capable of sustaining lightning strikes without incurring significant damage to the structure or avionics. The kinds of damage produced by lightning strikes on aircraft are described in reference 1.

The introduction of advanced composites as an aircraft structural material has also stimulated interest in aircraft lightning protection. Composite material properties are compared to aluminum in table 1. The electrical properties of composites and metals are significantly different. Both Kevlar/epoxy and glass/epoxy are dielectric materials and, where needed, a safe electrical path must be provided for protection.

The results of a strike on a general aviation aircraft is shown in figure 1 and indicates the need to ensure electrical safety in all aircraft designs and fabrication methods. The lightweight fiberglass wing tips on the aircraft in figure 1 represent a general class of wing tip construction used on single and light twin engine aircraft. Navigation lights are mounted on these dielectric wing tips. As indicated by the damage shown in figure 1, adequate paths for the current associated with the lightning strike were not

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provided. The effects of some other lightning strikes are described in detail in references 2 and 3. Some of the problems associated with lightning strikes to helicopters are discussed in reference 4.

The aircraft strike zones (fig. 2) are described in reference 5 and differ from those specified by the FAA in reference 6. Reference 7 provides a detailed discussion of the strike zones in references 5 and 6 and of the need for more refinement in the definition of strike zones.

The energy delivered by a lightning current is a function of the resistivity and several other properties of the material through which it flows. Graphite/epoxy, for example, will try to absorb orders of magnitude more energy than aluminum. The absorption of this energy may cause a significant temperature rise and physical damage. This characteristic has led to questions about its application in aircraft structures that might become part of a lightning strike current path. Two investigations of the effects of simulated lightning strikes and high currents on graphite/epoxy structures, including bolted and bonded joints, are reported in references 8 and 9. Damage caused by simulated strikes to unprotected graphite/epoxy is reported along with some protection schemes designed to protect the structure from strikes with the ability to deliver energy, or "action integral", up to 2.0×10^6 $\text{Amperes}^2 \cdot \text{second}$ (refs. 8 and 9). This represents a very severe strike.

The purpose of this paper is to report experimental data that characterizes the sparking damage to adhesively bonded structural joints and the sparking threshold currents of joints and access/inspection panels in fuel tanks. Composite and metallic specimens, representative of typical designs for joints and access/inspection panels in general aviation wing fuel-cell structures, were fabricated. Tests were performed to determine the behavior of the specimens when exposed to high current and voltage levels associated with lightning strikes. The research was conducted by Langley Research Center and Lightning Technologies, Inc.

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TEST SPECIMENS

Several test specimen configurations were evaluated. The intent was to test representative designs of typical joints and access/inspection panels for aircraft wing fuel-cell structures fabricated from both aluminum and graphite/epoxy materials. Tests were conducted to determine the minimum, or threshold, current levels that would cause sparking through or across bonded joints and sparking through the fuel tank sealant on attachments for both access/inspection panels and metal fuel lines through composite structures.

SINGLE-LAP BONDED JOINTS

Aluminum Adherends. - The specimens were 1.00 in. (2.54 cm) wide with an overlap of 0.50 in. (1.27 cm) (see fig. 3). Two sets of specimens were fabricated from sheared aluminum. One set was not deburred and was bonded using normal fabrication techniques which do not control bondline thickness. The adherends were bonded together with the burred surfaces facing each other. This orientation caused most of the specimens to be conductive across the joint. Nominal bondline thickness ranged from 0.001 to 0.009 in. (0.002 to 0.023 cm). The first eight adhesive systems listed in table 2 were used to bond this set of specimens.

The second set of specimens was fabricated with deburred adherends and only one adhesive system, AF-126-2 (see table 2). The purpose was to evaluate the effect of bondline thickness. The specimens were bonded in a press with stops to obtain nominal bondline thicknesses of 0.005, 0.010, 0.015, and 0.020 in. (0.013, 0.025, 0.038, and 0.051 cm).

Graphite/epoxy adherends. - Two sets of specimens were fabricated. Each specimen in the first set was 2.00 in. (5.08 cm) wide with an overlap of 0.25 in. (0.64 cm) as indicated in figure 3. Such a small overlap is not sufficient for bondline shear strength tests so the specimens were used only for voltage/current sparking threshold evaluations. Nominal bondline thicknesses were 0.003, 0.007, 0.010, 0.015, and 0.020 in. (0.008, 0.018, 0.025, 0.038, and 0.051 cm). A non-conductive adhesive, EA-9628 (see table 2), was used to bond the specimens. The adherends consisted of 4 plies of T300/934 fabric with an orientation of [+45, 0, 90, -45].

Each specimen in the second set was 2.00 in. (5.08 cm) wide with an overlap of 0.75 in. (1.90 cm). The adherends were fabricated with 16 plies of T300/5208 tape with an orientation of $[0, \pm 45, 90]_{2S}$. The adherends were molded to predetermined angles in the overlap area and will be discussed later in this paper. A conductive adhesive, EA-934 (see table 2), was used to bond the specimens. Nominal bondline thickness ranged from 0.003 to 0.005 in. (0.008 to 0.013 cm).

ACCESS/INSPECTION PANELS

Aluminum skins. - Each specimen consisted of a full size fuel cell access/inspection panel, the associated splice ring, and a portion of the outer skin (fig. 4). Three combinations of riveted and bonded splice-to-skin attachment designs were fabricated. All dome nuts and joint edges on the fuel side were sealed with fuel cell sealant similar to that applied to the interior of aircraft wings.

Graphite/epoxy skins. - The specimens consisted of strips of laminate bolted together with one dome nut fastener instead of an entire access/inspection panel. The two laminates were electrically insulated except through the fastener (fig. 5). The specimens were designed to permit a determination of the current that one fastener could conduct without sparking. It was assumed that the data can then be extrapolated to the complete access/inspection panel.

FUEL FEED-THROUGH ELBOWS

Metal fuel feed-through elbows used in aircraft fuel lines were mounted on a graphite/epoxy laminate (fig. 6). Fuel tank sealant was applied around the bulkhead flanges of the elbows. The specimen represents metal fuel line attachments through wing ribs or other aircraft structures. Each elbow mounted on the panel was used as an individual test specimen to determine sparking threshold.

TEST PROCEDURES

The range of test currents used to evaluate, for the first time, the effects on the structural strength and to determine the sparking threshold of the bonded joints was 0.035-50 kA. Test currents used to evaluate the access/inspection panels and fuel feed-through elbows were varied to determine the level of current required to spark through the fuel cell sealant.

SINGLE-LAP BONDED JOINTS

Aluminum adherends. - Each specimen was mounted in the test circuit shown in figure 7(a). The circuit was critically damped and produced the desired waveform shown in figure 7(b). The waveform simulates that of a lightning strike and was used to conduct tests at current levels of 1 and 5 kA. The test equipment did not have the capability of producing the same waveform at higher current levels. Therefore, the resistor was removed from the circuit before tests were conducted at 10 and 50 kA. With the resistor removed, the oscillating current waveform shown in figure 7(c) was produced.

Graphite/epoxy. - The specimens were tested in the electrical circuit shown in figure 7(a), except the resistor was removed because the resistance of the specimens was sufficient to nearly critically damp the circuit (fig. 7(d)). Each composite joint was enclosed and a camera was used to obtain photographic evidence of sparking. These tests were conducted over a current range of 0.035 to 5.6 kA to determine sparking and structural damage thresholds.

After exposure to a test current, each single-lap bonded joint specimen was mechanically tested to failure in tension. The failure loads were used to calculate the residual shear strength of the bonded joints.

ACCESS/INSPECTION PANELS

Aluminum skins. - Using the test circuit shown in figure 8, an electric spark was struck to the panel. The current was conducted through the mechanically fastened or bonded splice to the skin (refer to figure 4(a)). The internal surface, or fuel side, of the panel was enclosed and a camera was used to photograph any sparking. The procedure was used to determine the sparking threshold for a simulated lightning swept stroke attachment to the access/inspection panel.

Graphite/epoxy skins. - The specimens were tested in a circuit similar to the one shown in figure 7(a) except the resistor was removed. Each specimen was mounted in an enclosure and the sparking at the fastener was photographed.

FUEL FEED-THROUGH ELBOWS

Each metal elbow was tested in a circuit similar to the one shown in figure 7(a). The test portion of the panel was positioned in an enclosure and a photograph was taken to determine sparking. Current was introduced into the composite laminate, conducted across the composite-elbow interface, and exited through the metal elbow.

TEST RESULTS AND DISCUSSION

SINGLE LAP BONDED JOINTS

Aluminum adherends. - Test results for the first set of specimens (the ones not deburred and with bondline thickness not controlled) are presented in figure 9. Tests were conducted at current levels of 2, 10, 20, and 100 kA/in.^{2} (0.31, 1.55, 3.10, and 15.50 kA/cm^2). Tensile tests conducted on specimens exposed to no current and to 2 kA/in.^{2} (0.31 kA/cm^2) showed no shear strength degradation for all the adhesives tested. A current density of 2 kA/in.^{2} (0.31 kA/cm^2) represents the normally expected lightning threat. Some of the adhesive systems tested experienced no damage at current densities as high as 24 kA/in.^{2} (3.72 kA/cm^2). Other adhesives were significantly degraded at a current density of 10 kA/in.^{2} (1.55 kA/cm^2). Damage was caused by sparking through the adhesive as shown in figure 10. All specimens tested at a current density of 100 kA/in.^{2} (15.50 kA/cm^2) were totally destroyed. With the facing burs, most of the joints were electrically conductive. Even so, the specimens experienced external sparking, from the end of one adherend to the surface of the other adherend, at all current levels.

The second set of specimens with aluminum adherends (the ones deburred and with controlled bondline thicknesses) experienced no appreciable strength degradation through the entire current density range (fig. 11). The specimens with the thickest bondline did, however, experience a slight decrease in strength at test current levels of 1 and 50 kA. There was no tendency for sparking to occur through the adhesive. All the specimens sparked externally from the edge of one adherend to the surface of the other adherend at all test current levels.

Graphite/epoxy adherends. - The first set of specimens (the ones with an overlap of only 0.25 in. (0.64 cm)) experienced external sparking at current levels between 0.215 and 0.450 kA as shown in figure 12. There was no evidence of sparking through the adhesive; therefore, no shear strength degradation should have been caused by the current. The sparking occurred across the joint from the edge of one adherend to the surface of the other adherend.

The data obtained for the second set of specimens (the ones with an overlap of 0.75 in. (1.91 cm)) are presented in figure 13. In order to isolate any effect of overlap angle on the test results, the data were normalized to baseline shear strength data for specimens with the same overlap angles. The curve is drawn through individual data points. For the test range of 0-2 kA/in.^{2} (0-0.31 kA/cm^2), the scatter in the data is typical of bonded joint tests. At a current density of 3.75 kA/in.^{2} (0.58 kA/cm^2), however, structural damage was induced in the joint as indicated by a 30 percent decrease in the joint shear strength.

ACCESS/INSPECTION PANELS

Aluminum skins. - The sparking threshold determined for these specimens is shown in figure 14. As indicated in the figure, there is considerable scatter in the sparking threshold of similar specimens. Safety dictates, however, that the minimum observed sparking current values be of primary importance. For the rivet patterns tested, no sparking through the fuel tank sealant occurred below approximately 40 kA. For the limited number of tests performed, 40 kA was the minimum sparking current observed. More tests are required to statistically determine the minimum sparking threshold. Except for the single row of rivets, which did not exhibit sparking throughout the range of test currents, the rivet pattern did not significantly affect the sparking threshold. Figure 15 shows the location of sparking and damage in aluminum access/inspection panels. For the test configuration with the splice bonded to the skin, a strike or restrike with a current level higher than 40 kA could cause sparking past the "O" ring seal which would destroy the fuel tank integrity (fig. 15(c)).

Graphite/epoxy skins. - Tests were conducted to determine the threshold for sparking through the fuel tank sealant on the fuel side of dome nut fasteners (fig. 16(a)). Figure 16(b) is a plot showing sparking threshold for the fasteners and fuel tank sealants evaluated. Figure 16(b) indicates that there is considerable scatter in the data. Some specimens sparked at 5 kA whereas other specimens did not spark at the highest test current of 17 kA. For the configuration tested, an individual dome nut fastener, treated with fuel tank sealant conducted up to 5 kA of current without sparking. Although two different sealants were evaluated, it is beyond the scope of this paper to dicuss the relative merits thereof.

FUEL FEED-THROUGH ELBOWS

The threshold for sparking through the fuel tank sealant on the metal fuel feed-through elbows was determined. Sparking through the fuel tank sealant at one of the test specimens is shown in figure 17(a) and the sparking data are presented in figure 17(b). There is considerable scatter in the data ranging from a low sparking current of 10 kA to a high current of 40 kA at which one specimen did not spark. The minimum sparking threshold observed was 10 kA.

SUMMARY OF RESULTS

An investigation of the effects of simulated lightning strikes and currents on bonded joints and access/inspection panels has been conducted. Tests were conducted on both metallic and composite specimens. The evaluation also included tests on metal fuel feed-through elbows attached to graphite/epoxy structures. The results of this investigation are as follows:

1. At normally expected current densities there was no significant degradation in strength of the bonded aluminum joints.

2. All the single-lap bonded joints sparked.

3. A conductive adhesive on graphite/epoxy did not prevent sparking and showed significant strength degradation at a current density of 3.75 kA/in.^{2} (0.58 kA/cm^2).

4. The minimum sparking threshold observed for aluminum access/inspection panels was 40 kA.

5. The minimum sparking threshold observed for graphite/epoxy access/inspection panels was 5 kA per fastener.

6. The minimum sparking threshold observed for graphite/epoxy access/elbows on a graphite/epoxy panel was 10 kA.

The investigation reported herein represents a first attempt to obtain data on the effects of lightning currents on joints; however the need for electrically safe structures is highlighted. Although the strength of adhesive joints was not significantly degraded by the lightning currents, the development of design guidelines to prevent sparking across joints and fasteners requires additional study.

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9. Craft, W. L.: Volpe, V.; Schwenk, H.; Robb, J.; Hanawalt, B.; Kunz, K.; Dastin, S.; and Carri, R.: Protection Optimization for Advanced Composite Structures. AFWAL-TR-81-30309, May 1981.

TABLE I. - Material properties for three composites and aluminum.

MATERIAL	PROPERTIES			
	STRENGTH, KSI (MPa)	MODULUS PSI (GPa)	DENSITY LB/IN.^{3} (KG/M^3)	RESISTIVITY OHM-IN. (OHM-CM)
GRAPHITE/EPOXY	225* (1,551)	18 X 10^6 (124)	0.055 (1.52 X 10^3)	35.4 - 43.3 X 10^{-6} (0.9 - 1.1 X 10^{-4})
KEVLAR/EPOXY	270* (1,862)	11 X 10^6 (76)	0.050 (1.38 X 10^3)	2.0 x 10^{15} (5.0 x 10^{15}) **
GLASS/EPOXY	200* (1,379)	6 X 10^6 (41)	0.070 (1.94 X 10^3)	0.8 x 10^{15} (2.0 x 10^{15}) **
ALUMINUM	55 (379)	10 X 10^6 (69)	0.101 (2.80 X 10^3)	1.1 X 10^{-6} (2.8 X 10^{-6})

* UNIDIRECTIONAL STRENGTH VALUE

** DIELECTRIC MATERIAL (NON-CONDUCTOR)

TABLE II. - Composite materials and adhesives used to fabricate test specimens.

MANUFACTURER	DESIGNATION
AMERICAN CYANAMID	FM-400
AMERICAN CYANAMID	FM-61
AMERICAN CYANAMID	FM-1000.04
AMERICAN CYANAMID	HT-424
NARMCO	MB-1113
CIBA-GEIGY	R7114.06
3-M	AF-126-2
HYSOL	EA-9602.3
HYSOL	EA-934
HYSOL	EA-9628
NARMCO	T300/5208
FIBERITE	T300/934

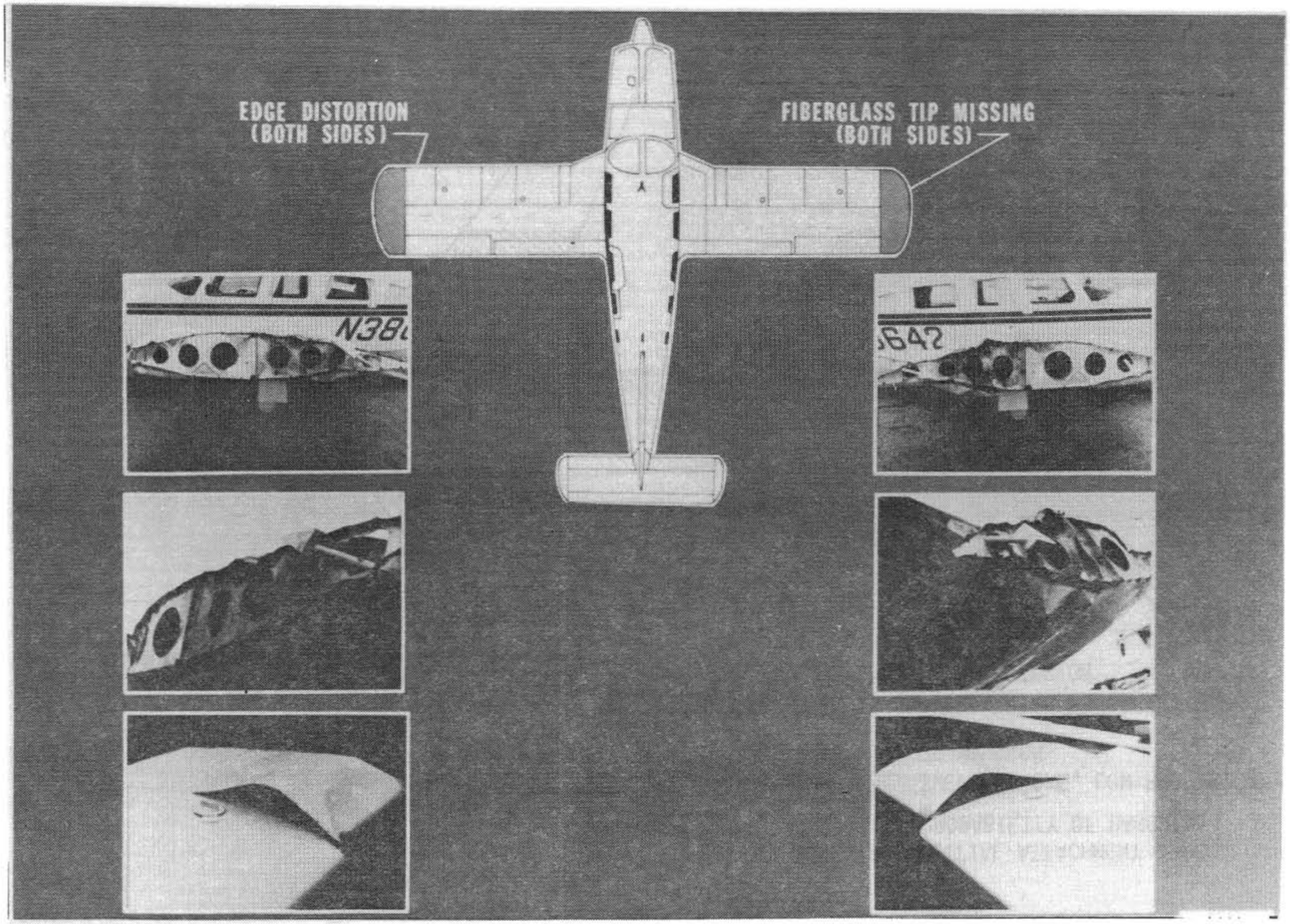


Figure 1. - Lightning damage to a general aviation aircraft.

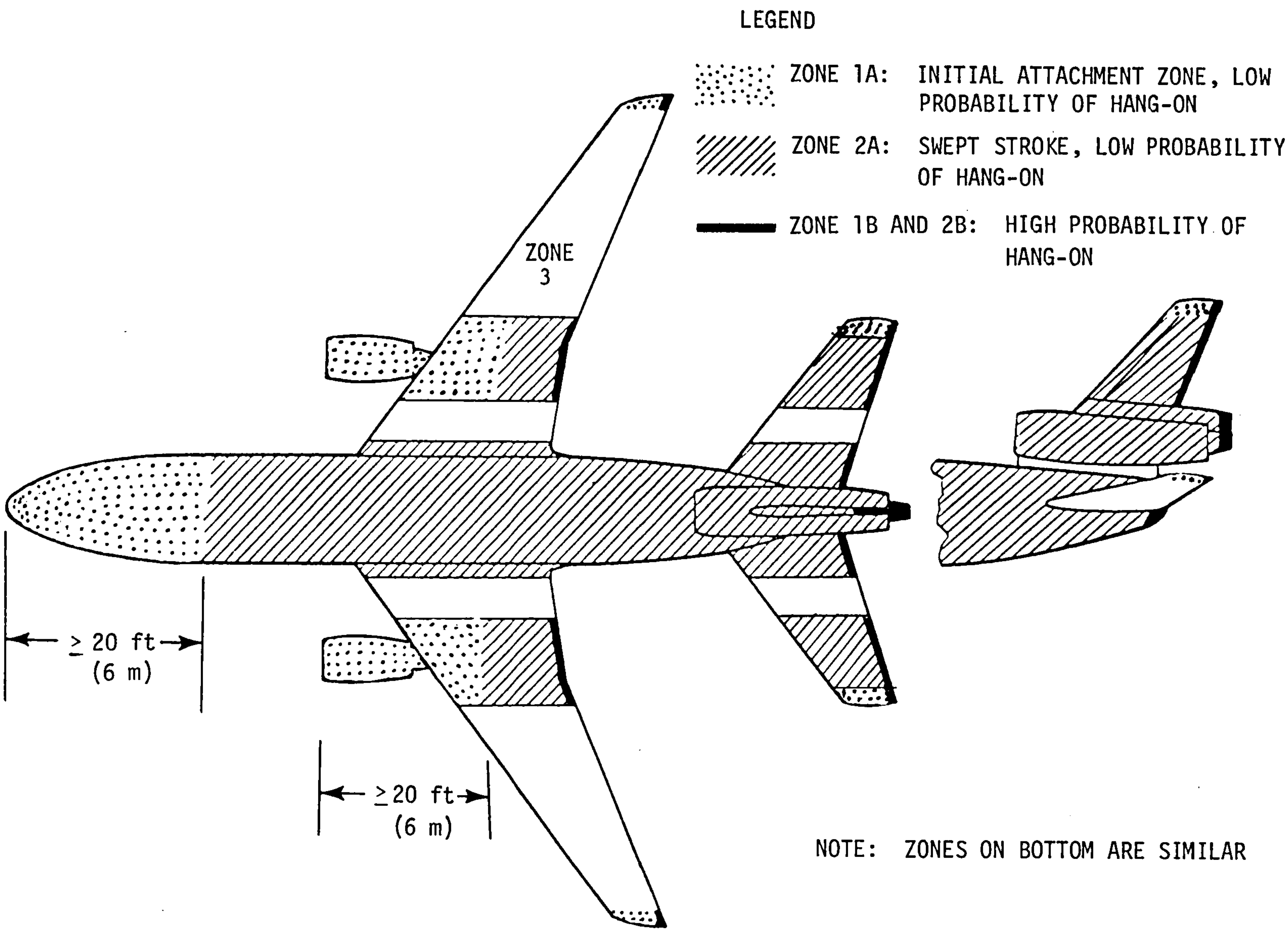
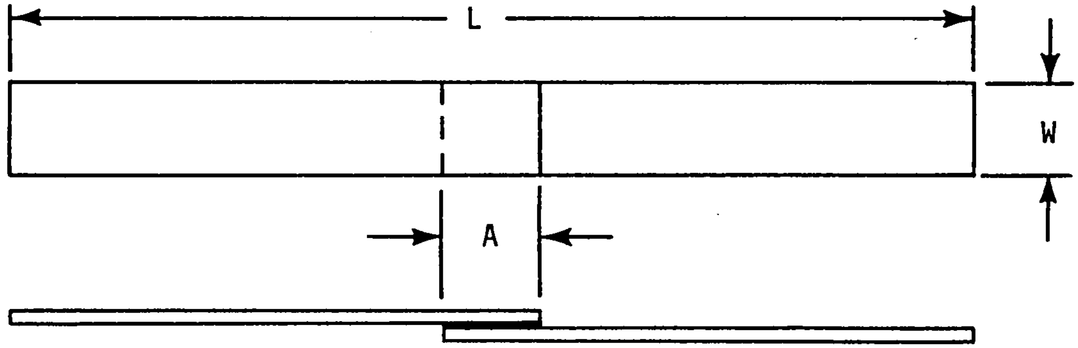
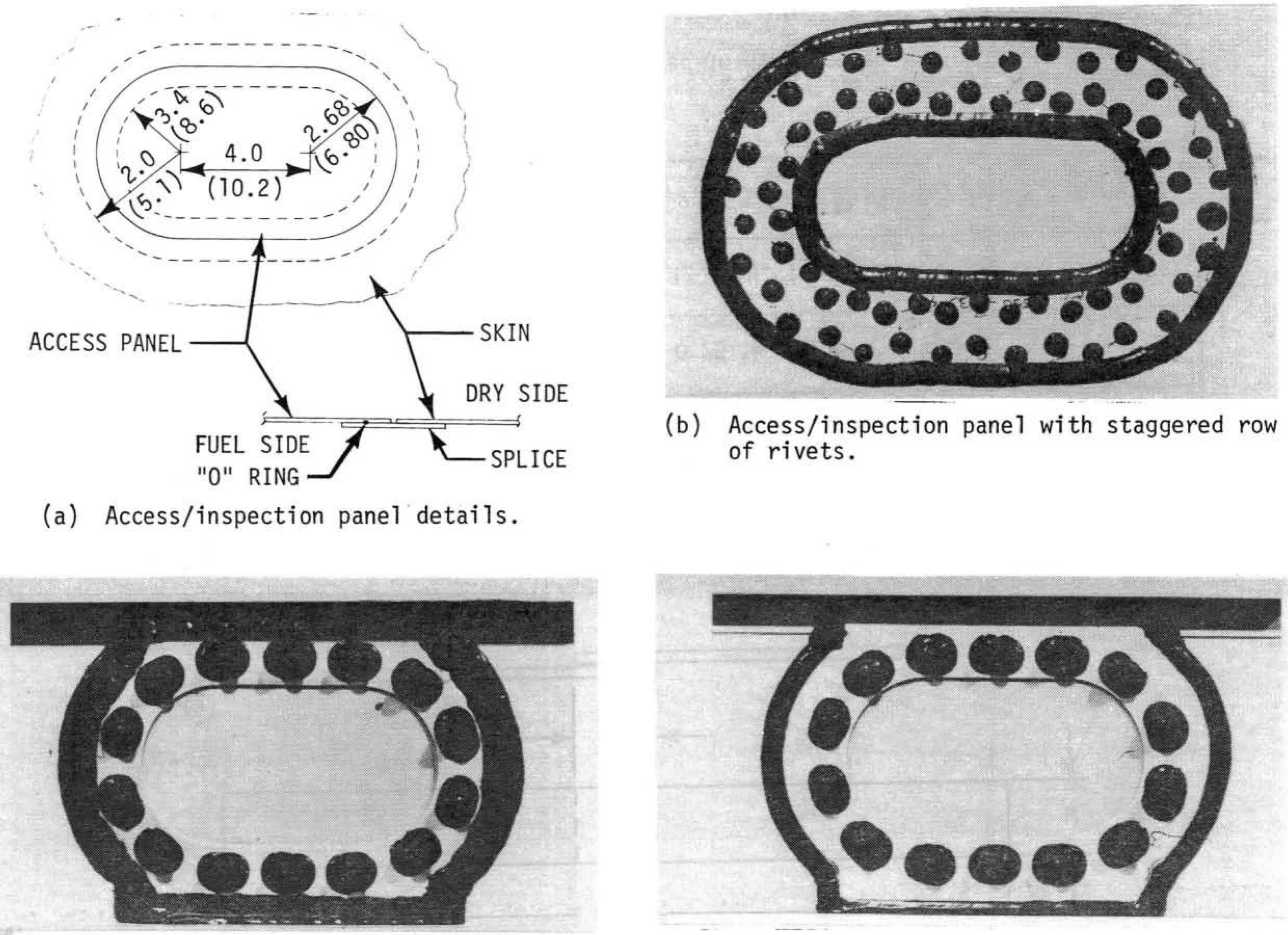


Figure 2. - Aircraft lightning attachment zones.



	ALUMINUM		GRAPHITE/EPOXY	
	BURRED	DEBURRED	SHORT OVERLAP	LONG OVERLAP
A	0.50 IN. (1.27 CM)	0.50 IN. (1.27 CM)	0.25 IN. (0.64 CM)	0.75 IN. (1.90 CM)
L	7.0 IN. (17.8 CM)	9.0 IN. (22.9 CM)	12.0 IN. (30.5 CM)	11.0 IN. (27.9 CM)
W	1.00 IN. (2.54 CM)	1.00 IN. (2.54 CM)	2.00 IN. (5.08 CM)	2.00 IN. (5.08 CM)

Figure 3. - Single-lap bonded joint specimen.



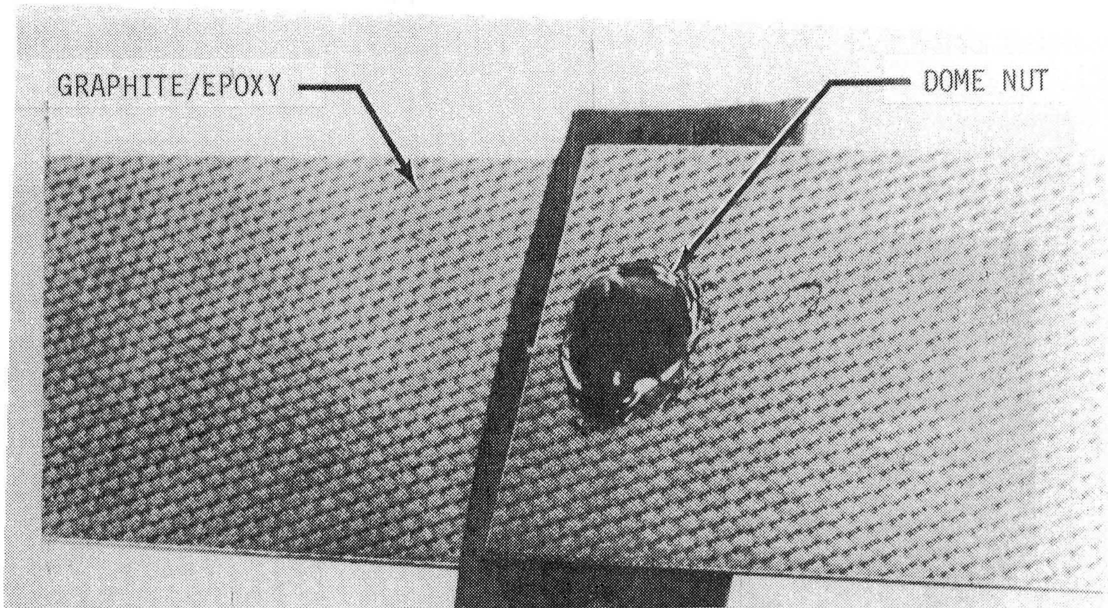
(a) Access/inspection panel details.

(b) Access/inspection panel with staggered row of rivets.

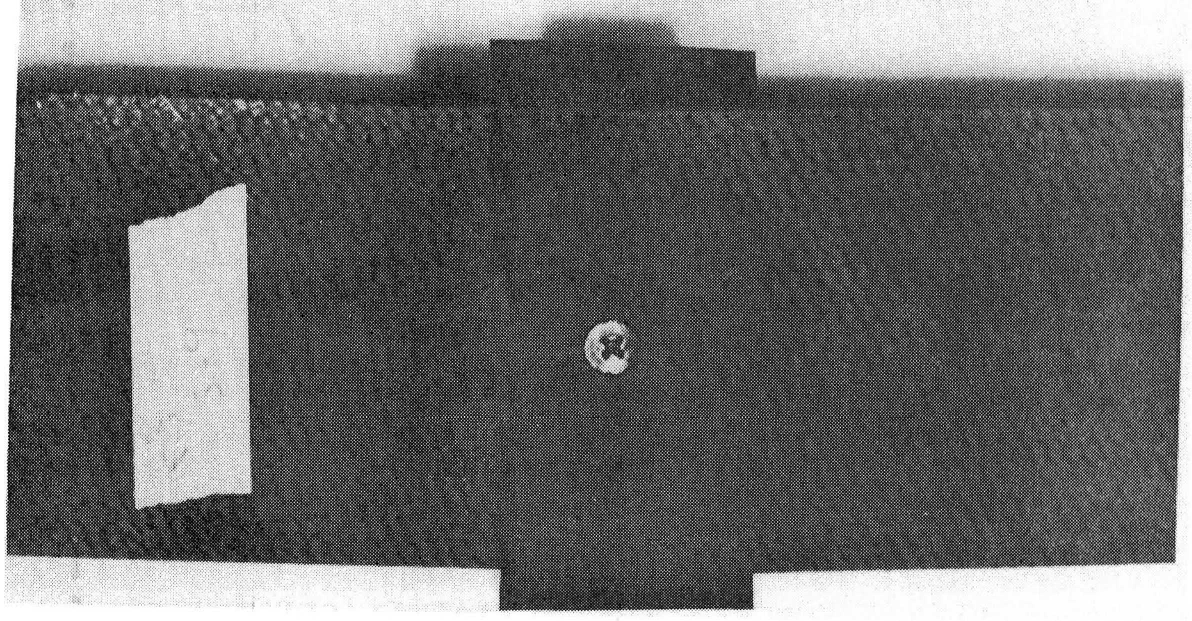
(c) Access/inspection panel with single row of rivets.

(d) Access/inspection panel with splice bonded to skin.

Figure 4. - Aluminum access/inspection panels. Dimensions are given in inches (centimeters).

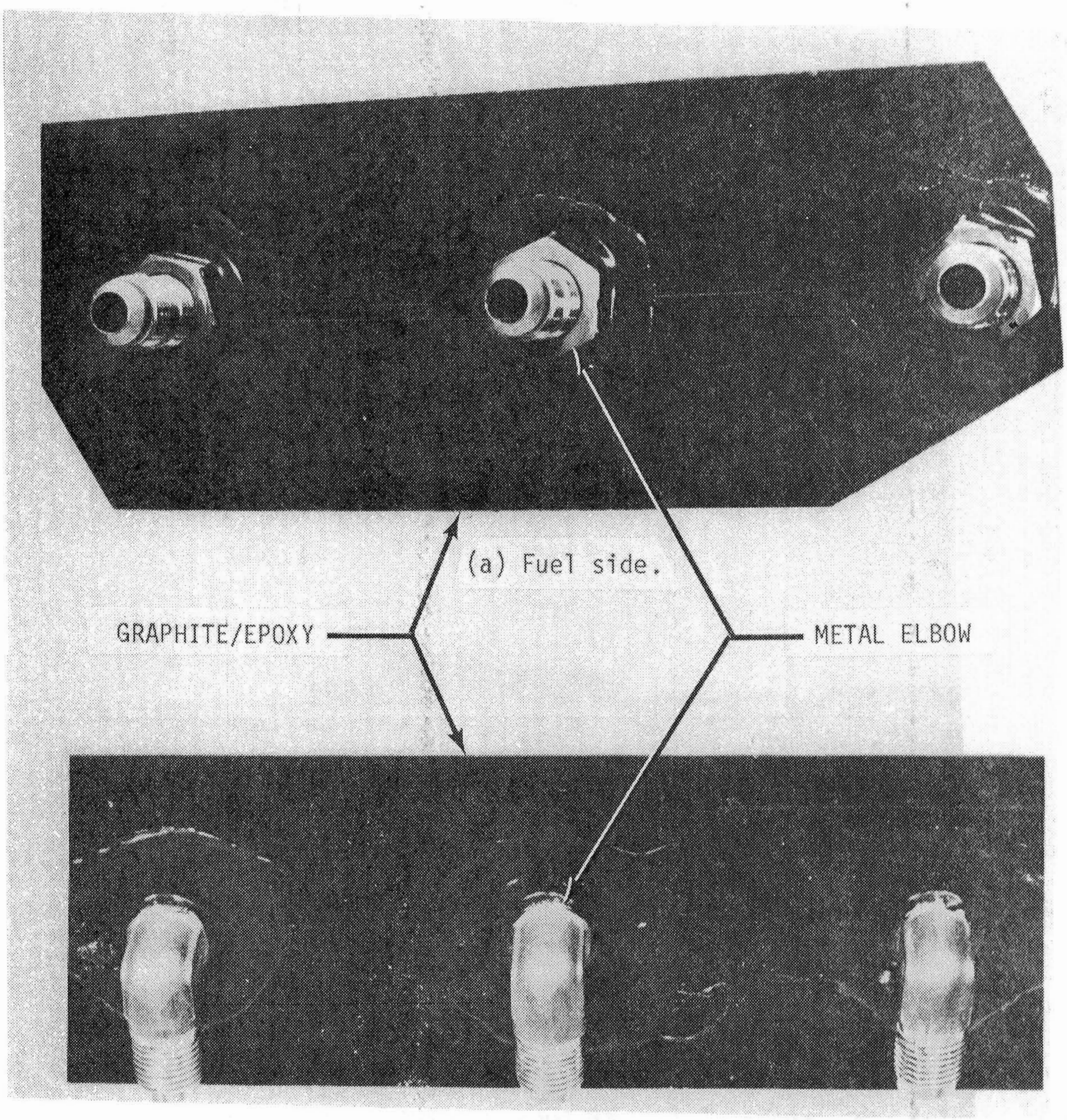


(a) Fuel side.



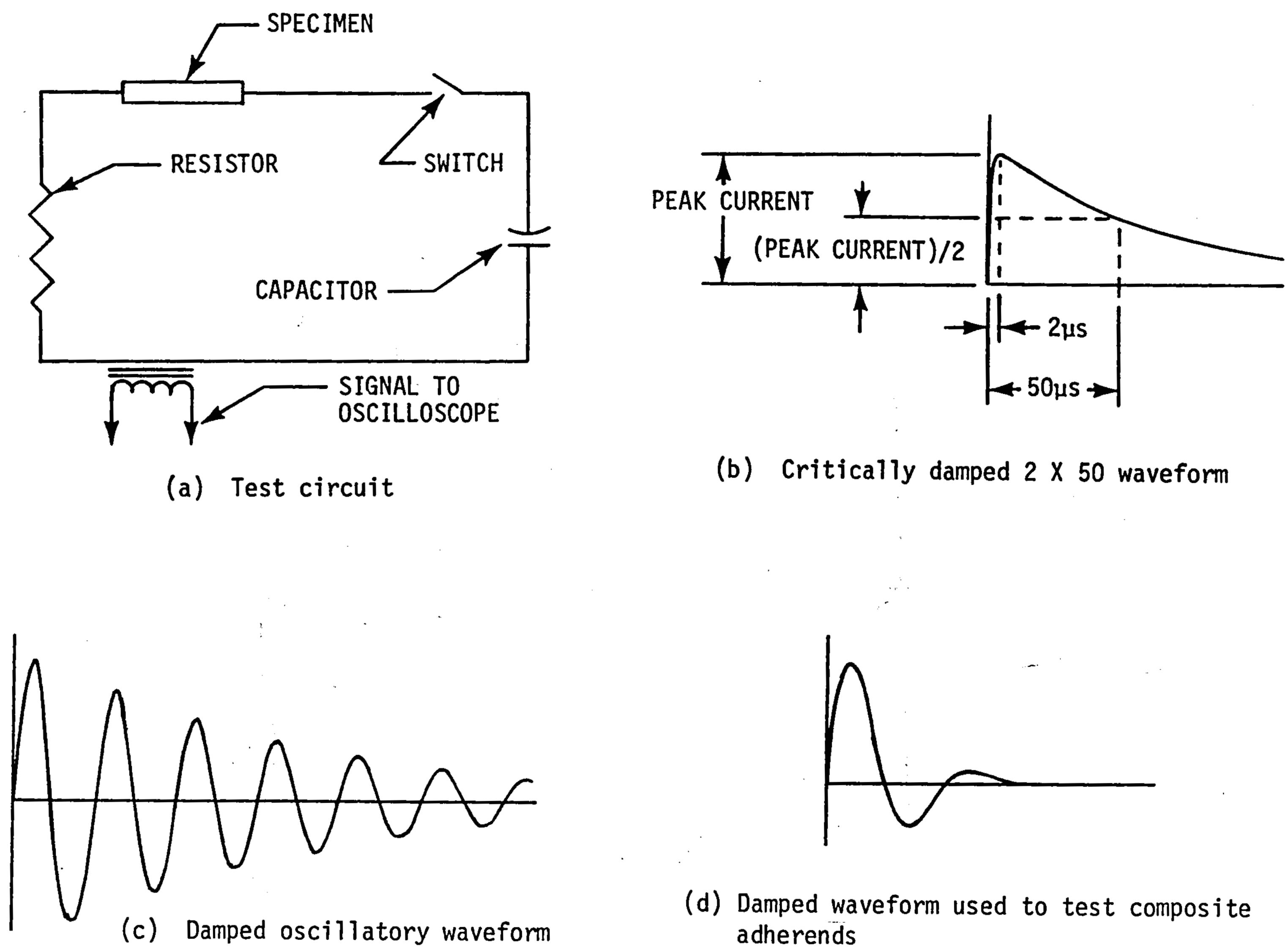
(b) Dry side.

Figure 5. - Graphite/epoxy access/inspection panel specimen.



(b) Dry side.

Figure 6. - Metal fuel feed-through elbow specimens.



(a) Test circuit

(b) Critically damped 2 X 50 waveform

(c) Damped oscillatory waveform

(d) Damped waveform used to test composite adherends

Figure 7. - Circuit and waveforms used for tests on single-lap bonded joint specimens.

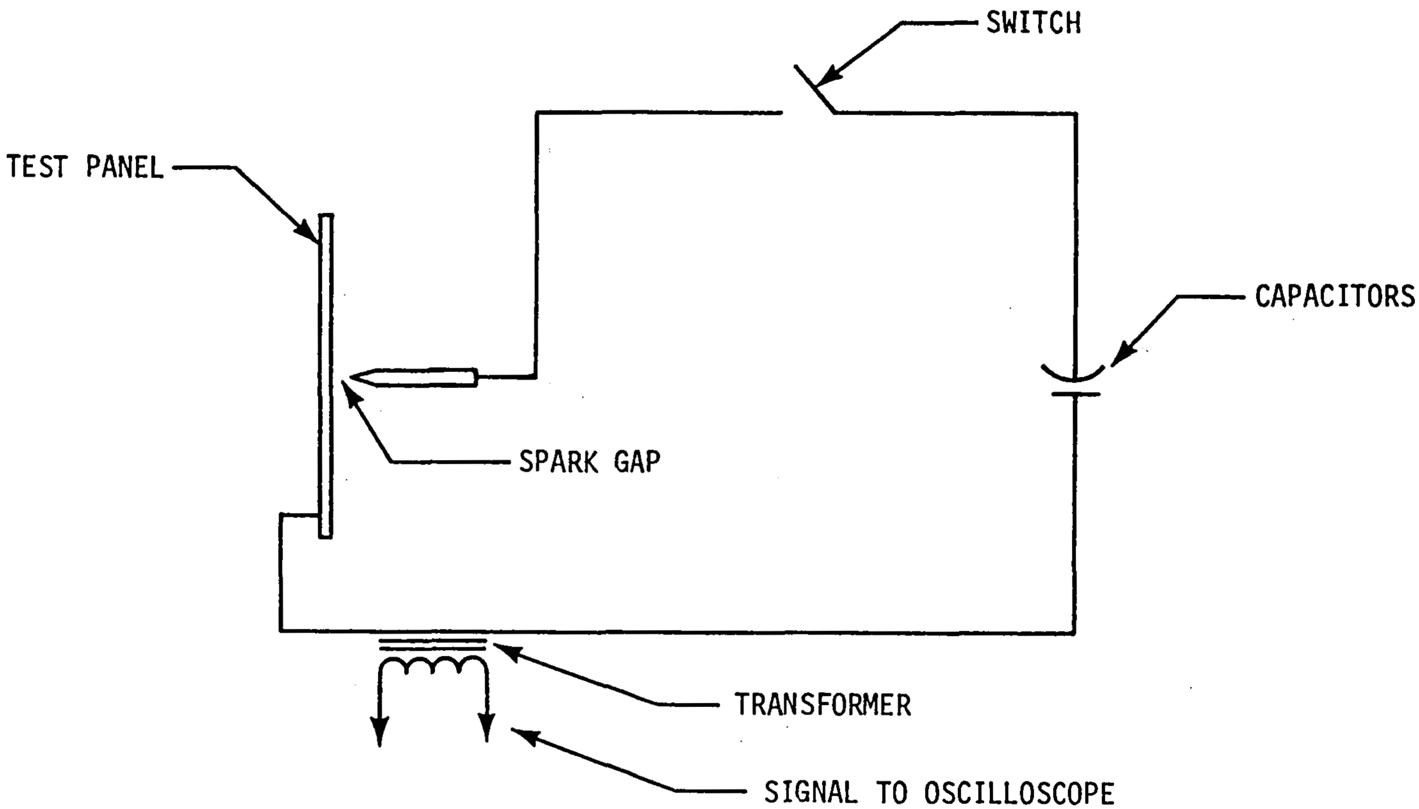


Figure 8. - Circuit used to test aluminum access/inspection panels.

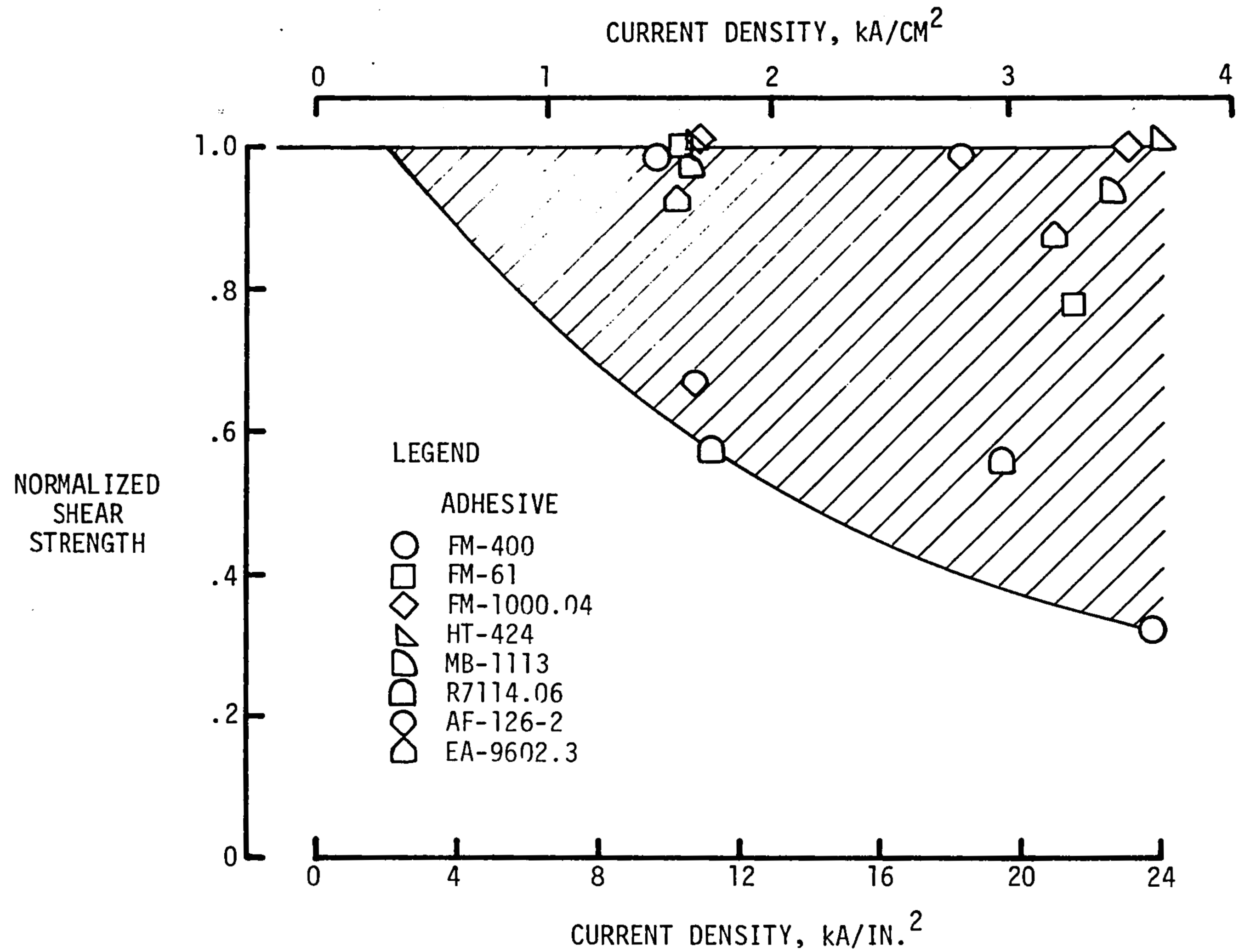


Figure 9. - Effect of current density on shear strength of aluminum single-lap joint specimens.

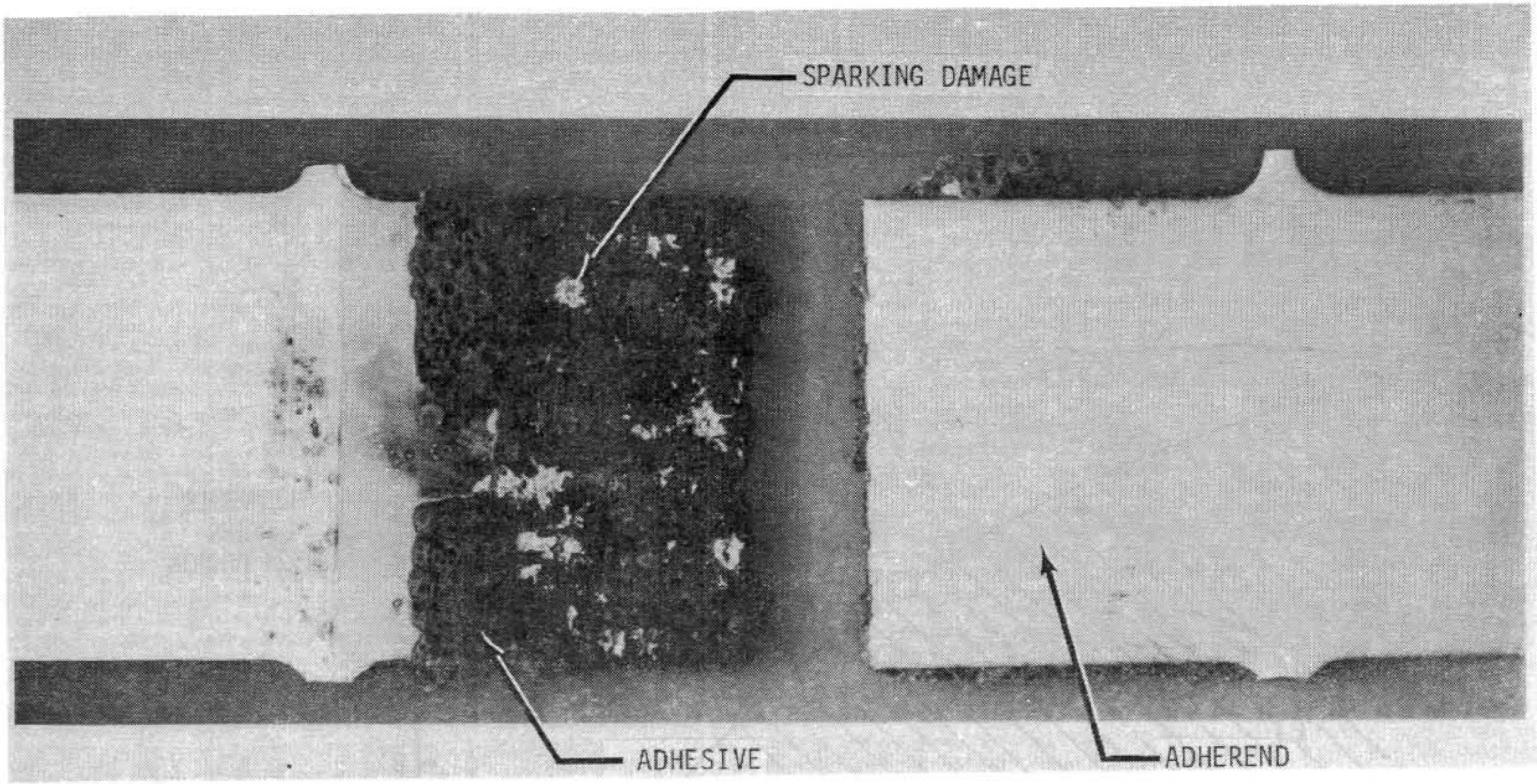


Figure 10. - A failed aluminum single-lap bonded joint specimen.

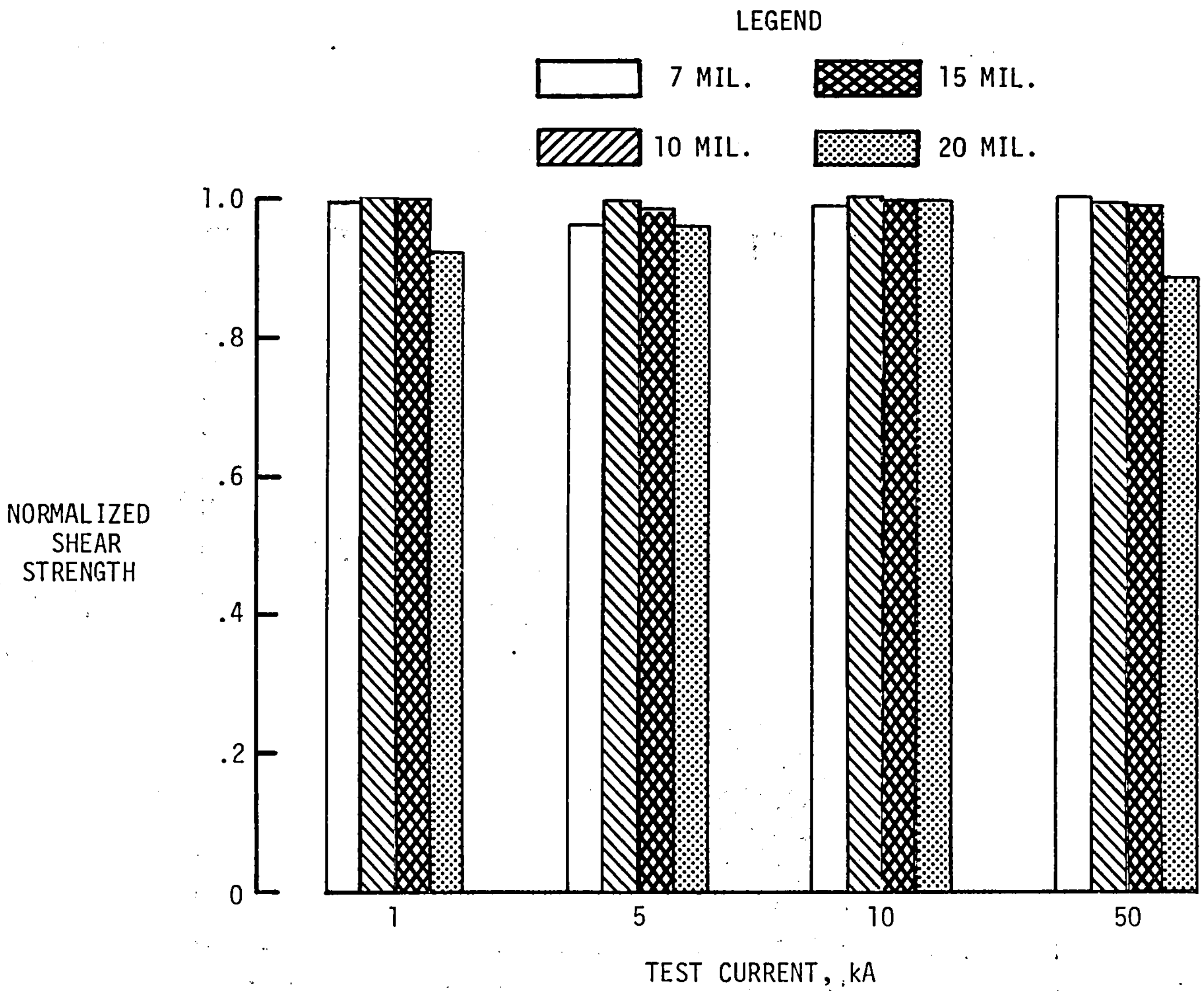


Figure 11. - Effect of bondline thickness on shear strength of aluminum single-lap joint specimens.

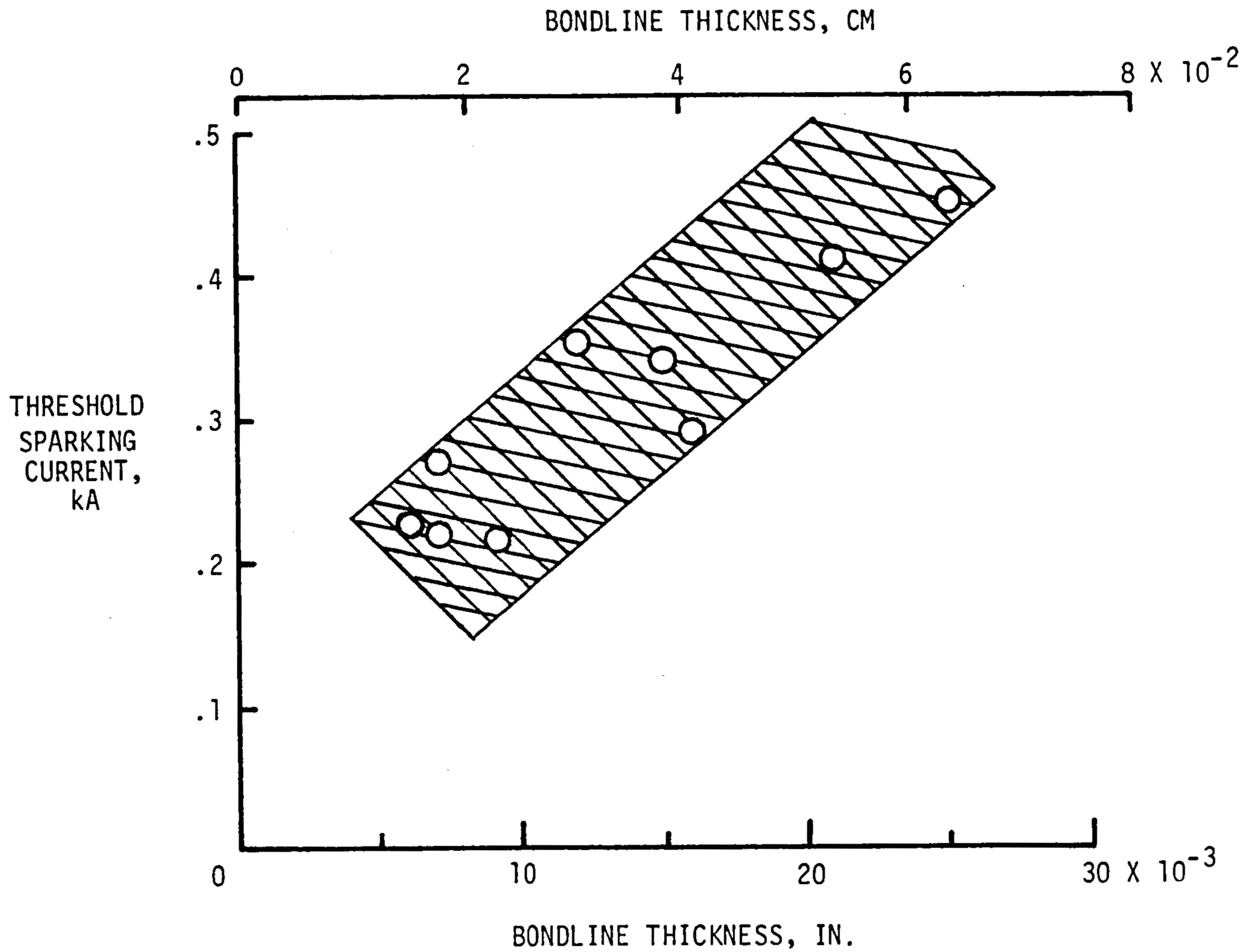


Figure 12. - Sparking threshold as a function of bondline thickness for graphite/epoxy single-lap joint specimens.

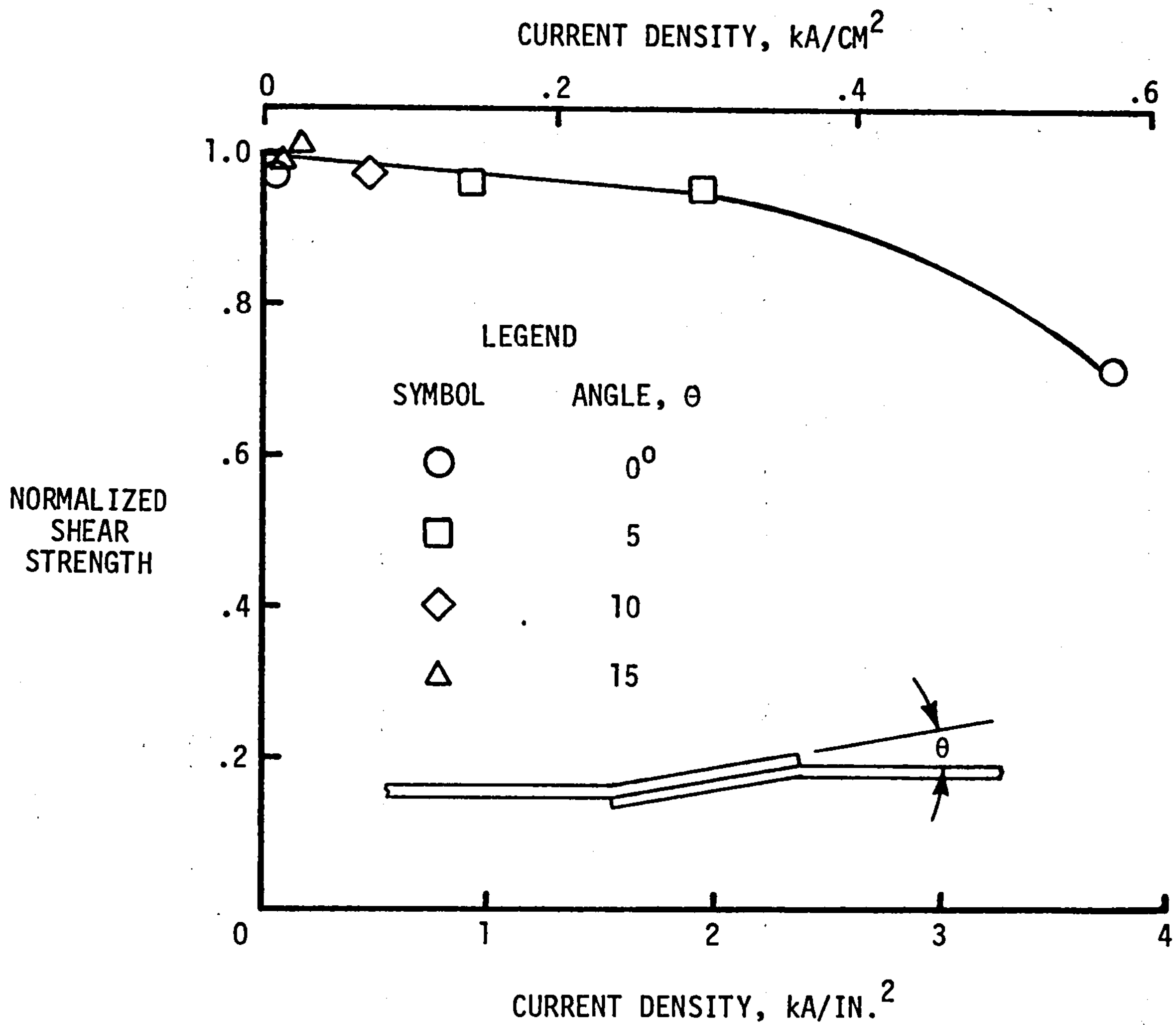


Figure 13. - Effect of current density on the shear strength of graphite/epoxy single-lap bonded joint specimens.

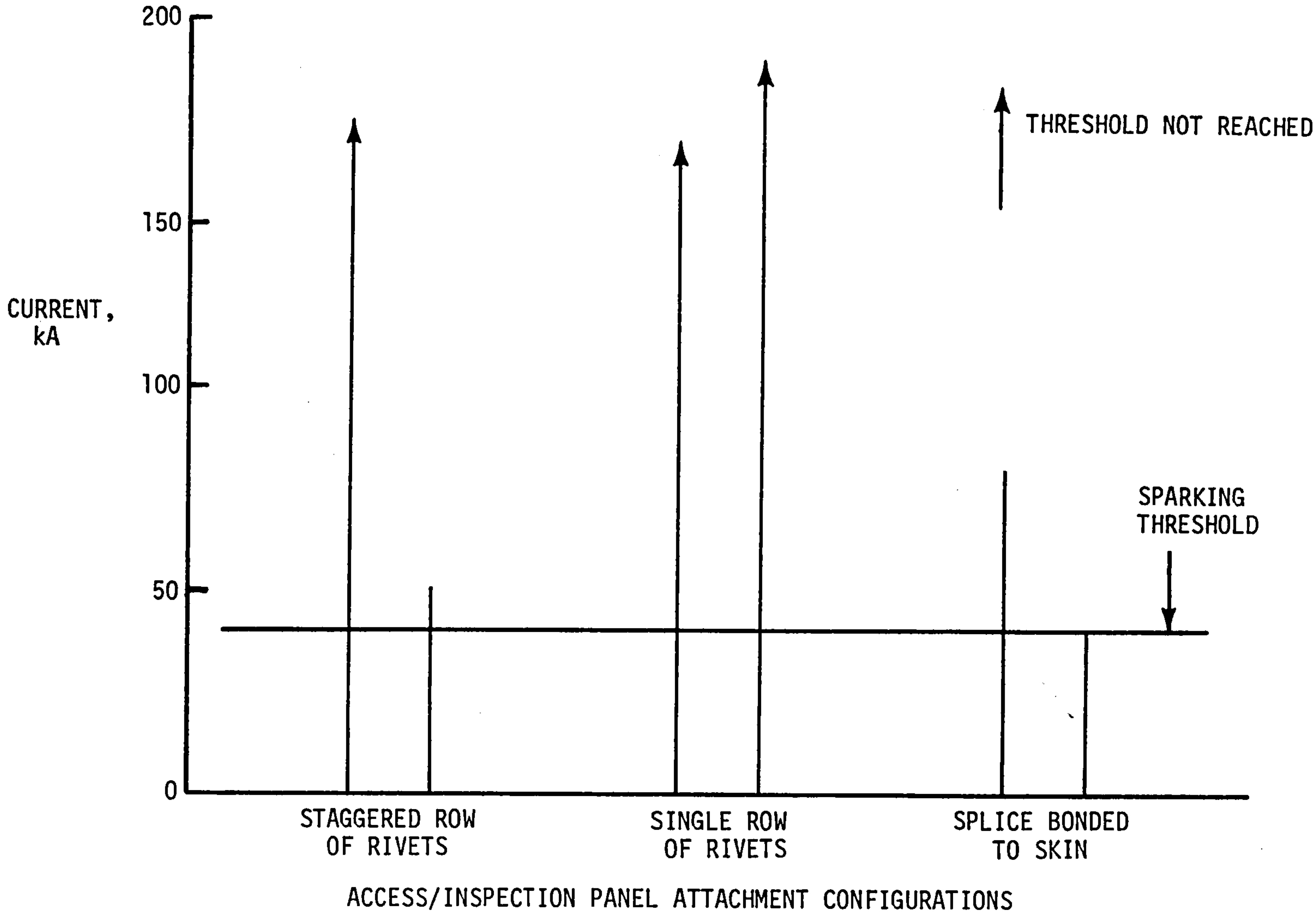
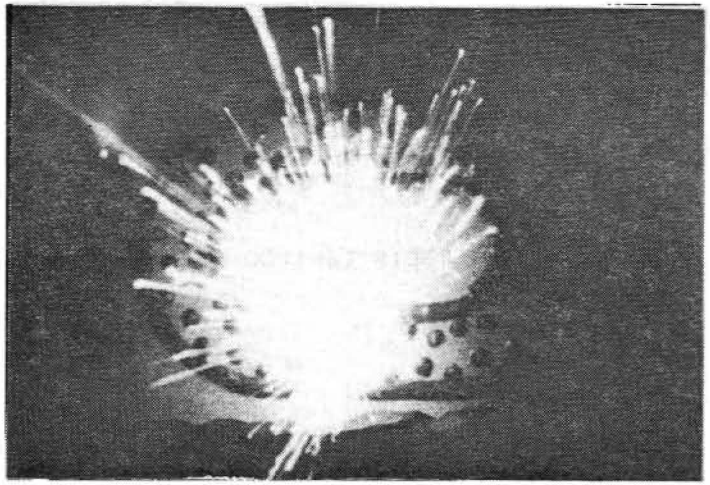
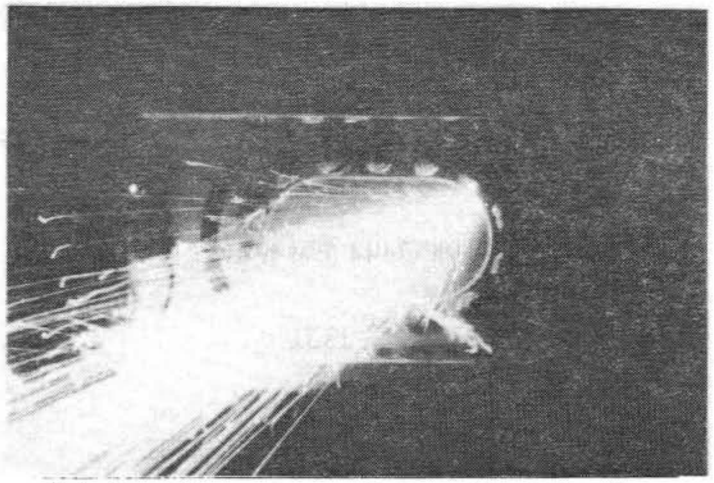


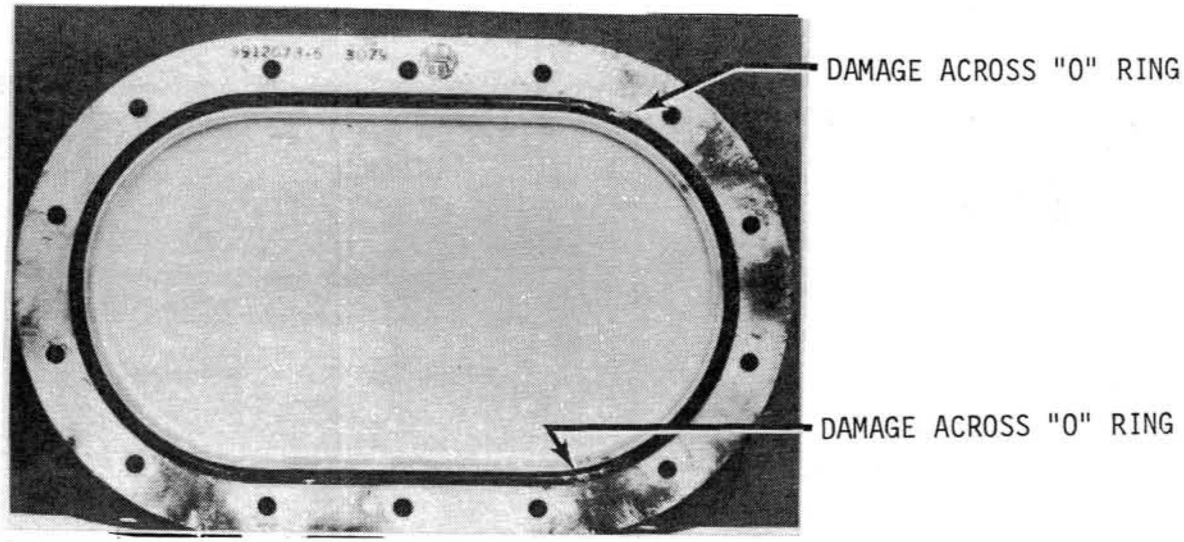
Figure 14. - Sparking threshold for the aluminum access/inspection panels.



(a) Sparking at Panel-to-splice rivet
(Staggered row of rivets design)

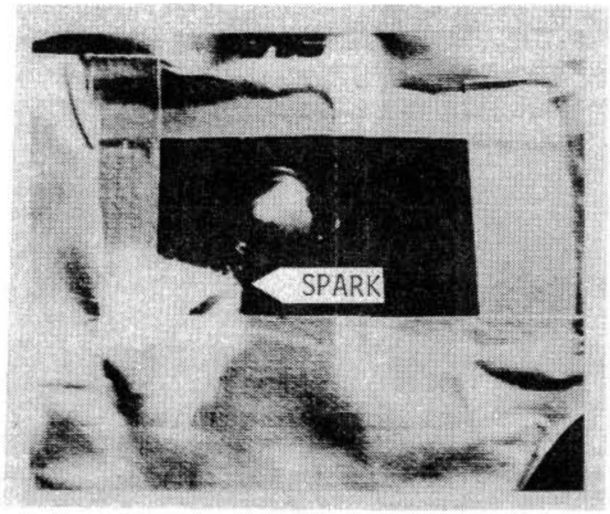


(b) Sparking at panel-to-skin interface
(Bonded splice-to-skin design)

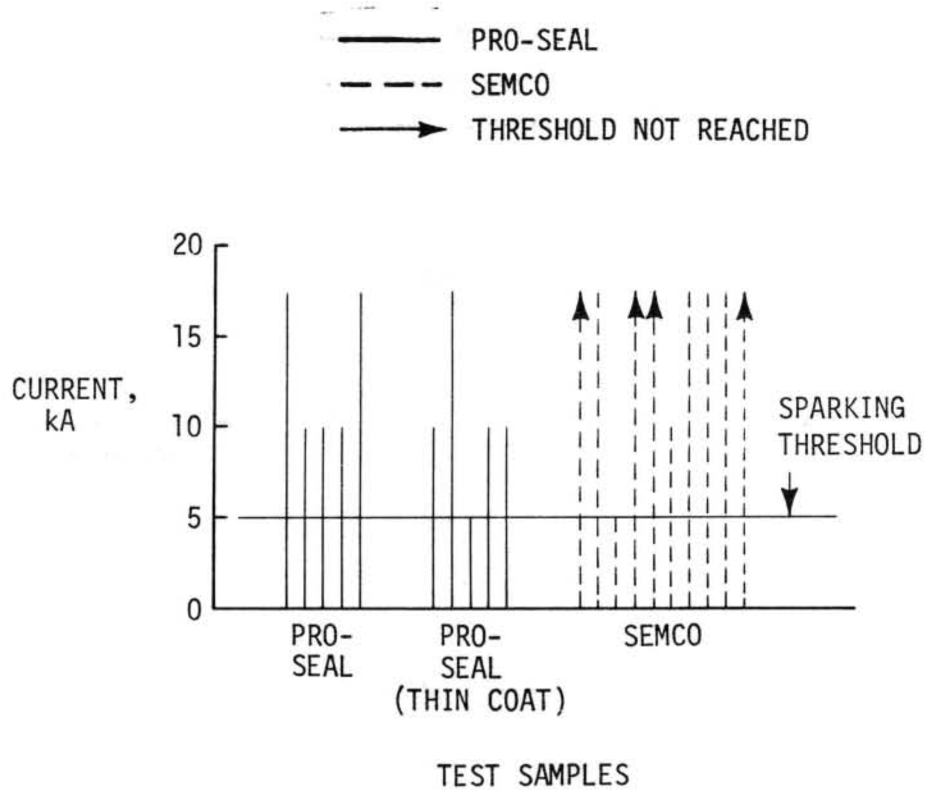


(c) Sparking damage of bonded splice-to-skin panel

Figure 15. - Sparking and damage of aluminum access/inspection panels.

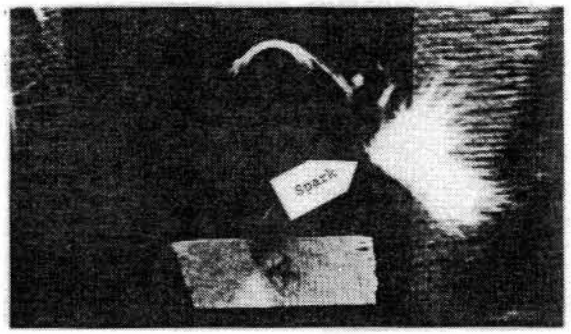


(a) Spark on fuel side.

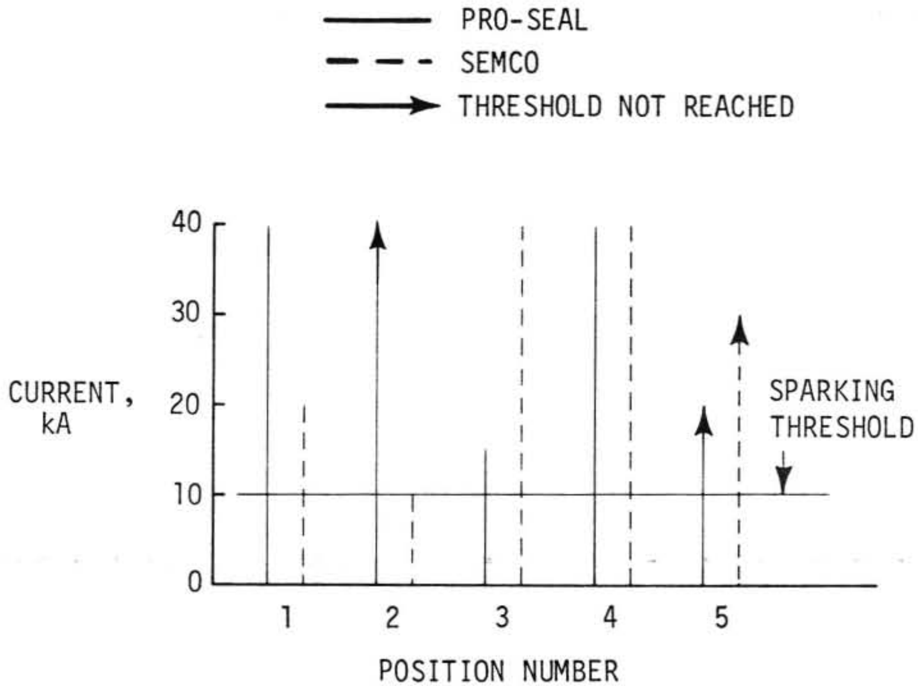


(b) Sparking threshold.

Figure 16. - Sparking and sparking threshold for access/inspection panel dome nut on graphite/epoxy structure.



(a) Spark on fuel side.



(b) Sparking threshold.

Figure 17. - Sparking and sparking threshold for metal fuel feed-through elbows on graphite/epoxy structure.

1. Report No.
NASA TM 84554

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Effects of Simulated Lightning on Composite and Metallic Joints

5. Report Date
October 1982

6. Performing Organization Code
505-33-33-01

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8. Performing Organization Report No.

10. Work Unit No.

9. Performing Organization Name and Address

NASA Langley Research Center
Hampton, VA 23665

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 66045

14. Sponsoring Agency Code

15. Supplementary Notes

*Lightning Technologies, Inc.
Pittsfield, MA 01201

This paper was presented at the Army Symposium on Solid Mechanics, 1982, September 21-23, 1982 at Cape Cod, MA.

16. Abstract

An investigation of effects of simulated lightning strikes and currents on aircraft bonded joints and access/inspection panels has been conducted. Tests were conducted on both metallic and composite specimens. The evaluation also included tests on metal fuel feed-through elbows in graphite/epoxy structures. Sparking threshold and residual strength of single-lap bonded joints and sparking threshold of access/inspection panels and metal fuel feed-through elbows are reported.

17. Key Words (Suggested by Author(s))
Aircraft Structures
Lightning
Composites
Bonded Joints
Bolted Joints

18. Distribution Statement

Unclassified-Unlimited
Subject Category 24

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Uncalssified

21. No. of Pages
28

22. Price
A03