

5

VOLUME V

ADA 127911

DOCUMENT NUMBER

QTR-2191-001

REV. N/C

TITLE

QUALIFICATION TEST REPORT FOR
450 GALLON CRASHWORTHY FUEL TANK
FOR
U.S. AIR FORCE H-53 HELICOPTER

TEST PERFORMED BY

FIBER SCIENCE DIVISION

CONTRACT NUMBER

F09603-79-C-1642-P20002

PREPARED BY

RICHARD R. LYMAN
C.A. PATNODE, JR.
JAMES O. CRUMBAKER

APRIL 2, 1982

FIBER SCIENCE DIVISION
SALT LAKE CITY, UTAH 84116

PREPARED FOR

WARNER ROBINS ALC/MMSRCB
ROBINS AIR FORCE BASE, GEORGIA 31098

DTIC
ELECTE
MAY 11 1983
B

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

DTIC FILE COPY

83 04 06 013

APPENDIX B
QUALIFICATION TEST REPORTS

QTR-2191

SECTION N, Q, P, AND R

Admission For	
DATE: 6/24/81	☒
DATE: 7/1/81	☐
DATE: 7/1/81	☐
PER LETTER	
District: 7	
Admission Codes	
Admission and/or	
Dist	Special
A	



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTR-2191

DATE: 4/6/82

PAGE

OF

PAGES _____
ARE
MISSING
IN
ORIGINAL
DOCUMENT

APPENDIX "B"
QUALIFICATION TEST REPORT
QTR - 2191
SECTION N
FUEL VAPOR IGNITION TEST



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTR-2191-001

DATE: 4-6-82

PAGE

OF

Universal QTP-2191
Report No. Section "N"

Dynamic Science
Report No. 4111-81-071/1895
Revision

REPORT OF: Fuel Vapor Ignition Qualification
Tests of Fiber Science 450 Gallon
Filament Wound, Lightweight, Explo-
sion Proof, External Fuel Tank for
H-53 Helicopter.

TEST PERFORMED BY:

Dynamic Science, Inc.
1850 W. Pinnacle Peak Road
Phoenix, AZ 85027

TEST AUTHORIZED BY:

Fiber Science, Inc.
Salt Lake International Center
506 Billy Mitchell Rd.
Salt Lake City, UT 84116

Contract No. F09603-79-C-1642

	Date	Signature
Test Initiated	3/26/81	(contract award)
Test Completed	6/23/81	
Report Written By (DSI)	8/3/81	<i>James B. E.</i>
Supervisor	8/3/81	<i>E. E. E.</i>
FSI Test Engineer		
Supervisor		
Government Repr.		
Final Release		

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 PURPOSE AND BACKGROUND	1
1.2 DESCRIPTION OF TEST SAMPLES	2
1.3 DISPOSITION OF TEST SPECIMEN	2
1.4 CONCLUSIONS AND RECOMMENDATIONS	2
1.5 REFERENCES	3
2.0 FACTUAL DATA	4
2.1 DESCRIPTION OF TEST APPARATUS	4
2.2 TEST PROCEDURE	4
2.3 TEST RESULTS	10
3.0 TEST DATA	12
3.1 TEST CONDITIONS	12
3.2 TEST RESULTS	12
APPENDIX A - PRESSURE DATA FILTERED AT 100 HZ	A-1
APPENDIX B - PRESENTATION OF PHOTOGRAPHS	B-1
APPENDIX C - FIBER SCIENCE, INC. DOCUMENT NUMBER QTP-2191 SECTION "N" QUALIFICATION TEST PROCEDURE H-53 TANK REQUIREMENTS FOR FUEL VAPOR IGNITION TEST	C-1
APPENDIX D - COMPLETE LISTING OF 35MM TEST PHOTOGRAPHS .	D-1

1.0 INTRODUCTION

1.1 PURPOSE AND BACKGROUND

The test described in this report is an Internal Fuel Vapor Ignition Qualification Test of the 450 Gallon Filament Wound, Lightweight, Explosion Proof, External Fuel Tank for the H-53 series helicopter.

The Internal Fuel Vapor Ignition Test is described in Paragraph 4.6.20 of Technical Exhibit ASD/ENFEA-75, October 1978:

"A tank suspended from integral pylon shall withstand the explosive pressures caused by rapid ignition of an N-Pentane/air mixture. The explosion shall produce a pressure peak rise of at least 6.5 atmospheres within 60 milliseconds. No structural damage is permitted."

However, Section 3.4.1.7.3 states:

"The tank shall contain the explosion pressures generated from fuel vapor ignition without catastrophic rupture."

This statement appears to modify Section 4.6.20 to the extent that some damage is permitted as long as it is not "catastrophic" in nature. The pass/fail criteria for this test is therefore somewhat ambiguous.

The explosion-proof external tank was originally suggested in Mishap Control No. WR76-022A.

This test was performed for Fiber Science, Inc. by Dynamic Science, Inc. at its test facility in Phoenix, Arizona. This report was prepared by Dynamic Science, Inc. excluding Section 1.4, "Conclusions and Recommendations," those portions of Data Sheet 2 requiring cross sectioning of the

tank, and those sections of Data Sheet 2 pertaining to Evaluation of Data, all of which were prepared by Fiber Science, Inc.

1.2 DESCRIPTION OF TEST SAMPLE

The sample tank used in this test was a prototype of the 450 gallon, Filament Wound, Lightweight, Explosion Proof, External Fuel Tank for the H-53 series helicopter. This tank was developed and fabricated by:

FIBER SCIENCE, INC.
Salt Lake International Center
506 Billy Mitchell Road
Salt Lake City, UT 84116

under Contract No. F09603-79-C-1642 from USAF Logistics Command, Warner Robins Air Logistics Center. The tank was designated by Fiber Science, Inc. as Part Number 2191-001A, Serial Number 0001, and was manufactured in April, 1981.

1.3 DISPOSITION OF TEST SPECIMEN

Following post-test examination by Dynamic Science, Inc., the test specimen was returned to Fiber Science, Inc. for further analysis.

1.4 CONCLUSIONS AND RECOMMENDATIONS

There was no visible damage to the tank structure. Both fuel and air fittings were blown from the tank. This was the result of an oversight on the part of all parties concerned, since to be truly representative of an actual aircraft installation, restrictive sockets representing the aircraft valve into which these fittings are installed should have been used for this test. The blowoff of the fittings would not have occurred had restrictive valve adaptors been used.

1.5 REFERENCES

1. Technical Exhibit ASD/ENFEA-78, October 1978.
2. Mishap Control No. WR76-022A
3. "Qualification Test Procedure, H-53 Tank, Requirements for Fuel Vapor Ignition Test," Fiber Science, Inc., Document No. QTP-2191 Section "N," December 1980.

2.0 FACTUAL DATA

2.1 DESCRIPTION OF TEST APPARATUS

Table 2-1 presents a summary of all instruments and equipment used for the collection of electronic data, the manufacturers' names, instrument serial numbers, ranges, accuracy, and dates of latest calibration. All non-electronic data (i.e., static measurements) were obtained through the use of standard measurement techniques.

2.2 TEST PROCEDURE

The requirements of the Internal Fuel Vapor Ignition Test are as stated in Section 1.1.

Section 2.2.1 describes the Internal Fuel Vapor Ignition Test Procedure. Section 2.2.2 describes the electronic data acquisition process. Section 2.2.3 describes photography.

2.2.1 Internal Fuel Vapor Ignition Test Procedure

The test procedure generally followed the outline given in Fiber Science, Inc. Document No. QTP-2191 Section "N," "Qualification Test Procedure, H-53 Tank, Requirements for Fuel Vapor Ignition Test," (Appendix C).

It was determined that there was small likelihood that a pressure rise to 6.5 atmospheres could be reached within 60 milliseconds using an N-pentane/air mixture and a single igniter. N-pentane is primarily a liquid below 97°F and flame front propagation is only on the order of one to two feet per second. For these reasons, the fuel was changed to acetylene, and a complex ignition system consisting of 17 electric matches at one foot intervals was developed.

TABLE 2-1. VAPOR IGNITION INSTRUMENTATION AND TEST EQUIPMENT SUMMARY						
Item	Model	Manufacturer	Serial Number	Range	Accuracy	Date of Last Calibration
Flow Meters	1110-09H3G1A 1110-07H2G1A	Brooks Instrument Division	8105H71343 8105H71342	0-10.4 CFM 0-1.7 CFM	± 0.1 CFM ± 0.01 CFM	6-05-81 6-05-81
Pressure Transducers	PA220TC-1.25M-350	Statham	1229 1239	0-1250 PSIA	$\pm 0.79\%$ $\pm 0.19\%$	5-11-81 5-11-81
Pressure Transducer	4-202-0002	Bell & Howell	6199	0-250 PSIG	$\pm 0.20\%$	5-14-81
Pressure Transducer	4-326-0008	CEC	13916	0-1500 PSIA	$\pm 0.22\%$	5-11-81
2000 PPS Camera	Hycam 41-004	Red Lake Laboratories	1228/2486 H1	20-11,000 PPS	Determined From Timing Marks	None
2000 PPS Camera	FASTAX WF-1	Wollensak	16-222	100-4,000 PPS	Determined From Timing Marks	None
100 Hz Camera Timing Generator	None	Dynamic Science	H1	100 Hz	Checked and recorded before use	1-12-81
120 Hz Camera Timing Generator	None	Dynamic Science	F1	120 Hz	From AC Source	None

TABLE 2-1. VAPOR IGNITION INSTRUMENTATION AND TEST EQUIPMENT SUMMARY (CONTD)						
Item	Model	Manufacturer	Serial Number	Range	Accuracy	Date of Last Calibration
Camera Timing Frequency Counter	MAX 100	Continental Specialties Corporation	17692	100 Hz-100 MHz	1 Hz (1% at 100 Hz)	3-16-81
Remote Signal Conditioning Module	M140	Edtron	7657	*	*	Cal Before Use
Instrumentation Tape Recorder	Sabre III	Sangamo	7153	*	*	1-28-81
Playback Tape Recorder	Sabre III	Sangamo	7628	*	*	1-28-81
FM Demodulators	GFD-15/TU01	Data Control Systems	1073501 thru 1073523	*	*	Cal Before Use
Butterworth Analog Filters	4122	Ithaco	25745 thru 25751	*	*	3-06-81
A/D Converter	DAS-6000	Phoenix Data, Inc.	85978	8 KHz Sample Rate	$\pm 0.03\%$	None
Computer	Eclipse S130	Data General	15903-1 359	-	$\leq 2.72\%$ **	None
*The Dynamic Science data acquisition system provides a flat, linear response up to 1 KHz with $\pm 5\%$ error. **Error due to propagation of truncation error through the FFT digital filter.						

Additional changes approved by Fiber Science, Inc. were as follows:

- The allowable pressure was modified from "at least 6.5 atm" to a 6-8 atm range.
- The fuel and air valves were installed and remained in the closed position for the test.

An acetylene/air ratio of 4.3 percent was determined to be the proper mixture to provide the desired pressure pulse. The tank and pylon were mated to the Fiber Science "Qualification Test Fixture" which was in turn attached to a steel A-frame fixture. The acetylene/air mixture was introduced into the tank through the nose of the tank. The fuel/air mixture was controlled through the use of regulators and flow meters. After twenty minutes, the valves at the tank nose and tail were closed, the instrumentation was turned on, and the igniters were fired. The tank was then purged of the combustion products. Figure 2-1 shows the Fuel Vapor Ignition Test setup.

2.2.2 Electronic Data Acquisition

The electronic data obtained in this test consisted of internal pressures at four locations, as shown in Table 2-2.

The individual transducers and other components of the data acquisition system are described in Table 2-1. Each transducer was attached to an Ectron differential amplifier within the Remote Signal Conditioning Module (RSCM) mainframe by an umbilical cable. After amplification, the transducer signals were converted to the frequency domain by the Voltage Controlled Oscillators within the RSCM mainframe. The information was then multiplexed and transmitted via hardline to the Sabre III instrumentation tape recorder for recording.

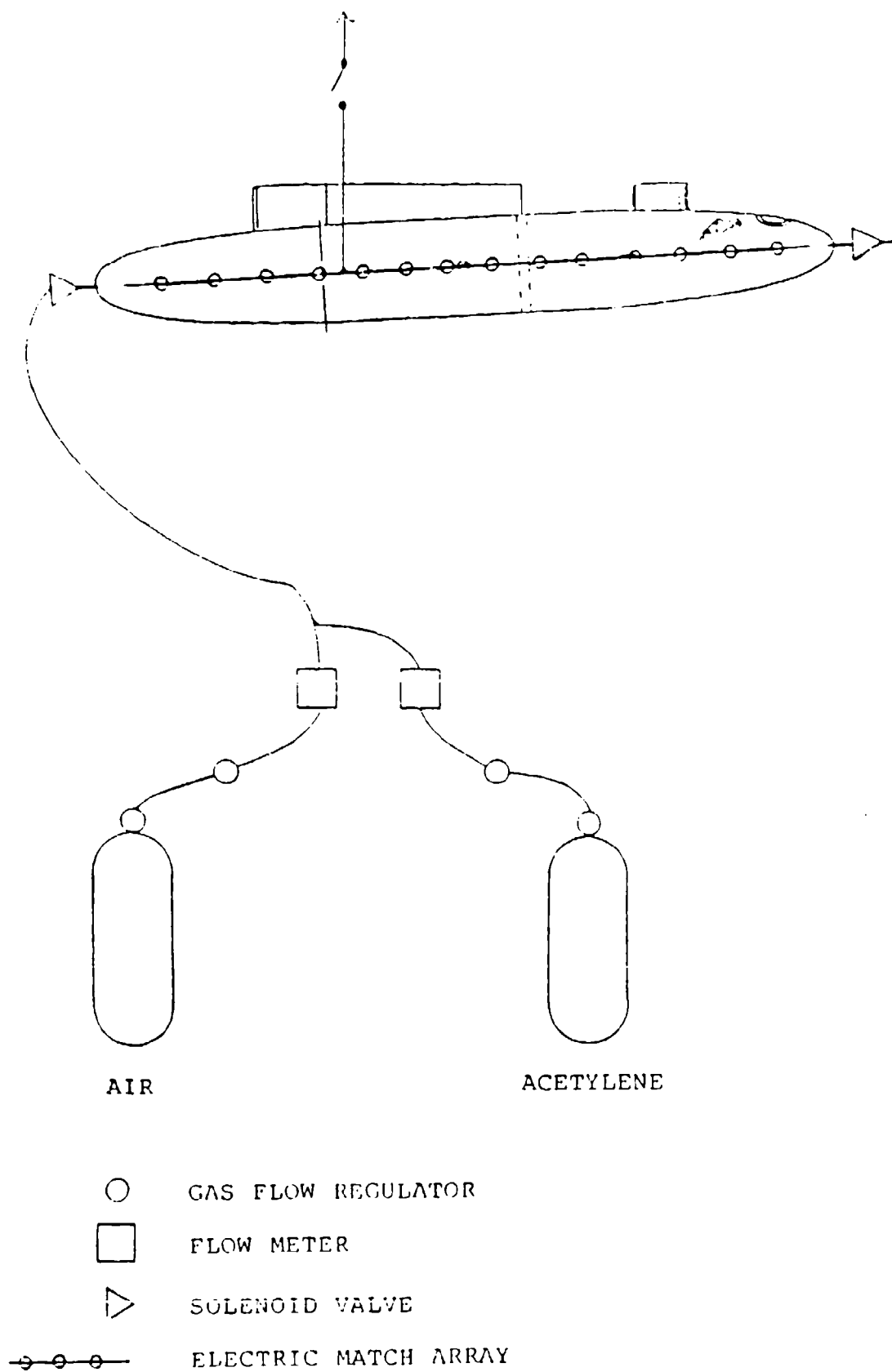
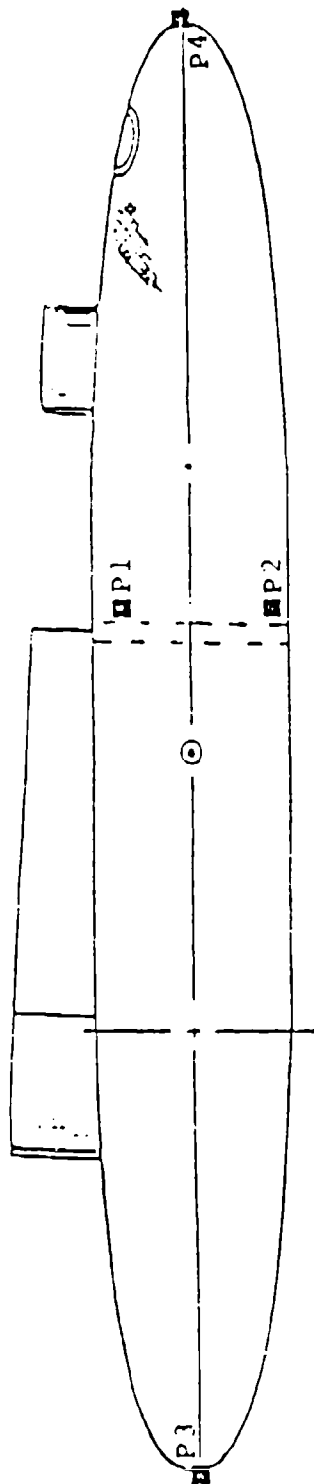


FIGURE 2-1. FUEL VAPOR IGNITION TEST ARRANGEMENT.



PRESSURE SENSOR LOCATIONS

TABLE 2-2. FUEL VAPOR IGNITION TEST INSTRUMENTATION		
Pressure Sensor Locations		Expected Ranges
Number	Description of Location	PSIA
P1	Through Aft Baffle Access Cover, Measures 6 Inches Below Top Q_L	<180
P2	Through Aft Baffle Access Cover, Measures 2 Inches Above Bottom Q_L	<180
P3	Nose Hole	<180
P4	Tail Hole	<180

The recorded, multiplexed signal was later played back and demodulated by the Data Control Systems demodulator. The demodulated signal was then filtered and digitized for processing and plotting on the Data General Sl30 Eclipse Computer.

2.2.3 Photographic Coverage

The Internal Fuel Vapor Ignition Test was recorded on 16 mm color film by two cameras as shown in Table 2-3. The event was filmed at 2,000 fps. In addition, 24 fps documentary footage and a complete set of 35 mm color slides were taken.

2.3 TEST RESULTS

No damage was observed to the tank shell, internal baffles, or internal plumbing, based on non-cross sectioning examination.

As there was no "catastrophic rupture," the tank appears to meet the specification requirements.

3.0 TEST DATA

3.1 TEST CONDITIONS

The test was set up according to the procedures set forth in Section 2.2. The tank was inadvertently mounted in a 6° nose-down position, but this attitude was deemed not critical to the test. Pre-test approval was obtained (Data Sheet 1) and the test proceeded.

A summary of test conditions is presented in Table 3-1.

3.2 TEST RESULTS

After the tank was filled with the acetylene/air mixture, the fill and vent lines were sealed, instrumentation was initiated, and the ignition system was fired. The resultant pressure pulses are presented as computer generated plots in Appendix A. The pressures recorded at the tank nose and just rear of the aft frame rose to approximately 100 psi (6.8 atm) within 55 msec, while the pressure at the tank tail rose to 138 psi (9.4 atm) in 44 msec. There is no ready explanation for the 138 psi reading, especially since it occurred within the same tank compartment as two of the other pressure sensor locations.

Analysis of the high-speed film revealed that, after ignition, a flame propagated first out the top of the fuel valve and then around the circumference of the valve. Part of the valve was blown off the tank and a column of hot gas vented out the fuel valve access. A flame then propagated out the top of the air valve followed by the air valve being blown clear of the tank. A column of hot gas was then vented through the air valve access.

Post-test examination at the test site revealed that the metal band clamps used to hold the flexible joint coupling in place had failed to securely hold the upper portion of the fuel and air valve in place and they ejected from the tank. It may have been that the clamps were not securely fastened around this joint. The phenolic fuel and air fittings cracked from ejection or subsequent impact with the ground. There was no failure of the mating half fittings which remained attached to the tank.

The metal honeycomb flame arrestor was blown out of the bulkhead fitting which connects the air line to the flexible joint coupling.

Damage to the tank is further described in the text of Data Sheet 2. Color photographs of the test are presented in Appendix B.

DATA SHEET 1. PRE-VAPOR IGNITION EXAMINATION

Testing Activity: Dynamic Science, Inc.

Tank Serial No.: 0001

Test Date: June 23, 1981

Activity Test Engineer: Terry Bjork

Fiber Science, Inc. Test Engineer: Richard R. Lyman

Government Representative: Hugh Hilliard

EXAMINATION OF PRODUCT:

Visual Inspection: Approved

Delaminations (Tap Test): Small (less than one inch square) (less than 16) delaminations in center section - appeared to be only in outside circumferential wrap - approval to proceed.

MOUNTING:

Aircraft Simulated Attachment Deviations If Any:

Apparent tank angle 6° nose down - approved to proceed.

ARRANGEMENT:

Approved Test Arrangement Including Ignition Device:

TABLE 3-1. VAPOR IGNITION TEST SUMMARY

Test Description: FSI 450 Gallon Vapor Ignition Qualifi-
cation Test

Tank Serial Number: 0001 Mfg. Date: April 1981

Test Number: T2-1

Number of Data Channels: 4

Number of Cameras: 2

Date: June 23, 1981 Time: 2:39 PM Temperature: 107°F

PRE-TEST DATA

Air Flow Rate: 10.4 cfm

Acetylene Flow Rate: 0.467 cfm

Acetylene/Air Ratio: 4.33

Required Pressure Pulse: 6.5 atm (95 psi), 60 msec

POST-TEST DATA

Actual Pressure Pulse:

Location 1 - 101 psi (6.9 atm), 55 ms

Location 2 - 104 psi (7.1 atm), 55 ms

Location 3 - 102 psi (6.9 atm), 56 ms

Location 4 - 138 psi (9.4 atm), 44 ms

Number of Ruptures: None

DATA SHEET 2. POST-VAPOR IGNITION EXAMINATION

VISUAL INSPECTION:

No apparent damage to tank shell. Both fuel and air coupling joints failed and the shutoff valve assemblies were blown clear of the tank. Nylon fitting of fuel level probe partially melted. Plastic cover of internal wires melted onto fuel plumbing.

DELAMINATIONS (TAP TEST):

Several new dead areas noted, primarily on rear section of tank.

(To be completed by Fiber Science.)

Internal Damage

Tank Shell _____

Frames _____

Baffles _____

Fittings _____

Tubing _____

(To be completed by Fiber Science.)

EVALUATION OF DATA

CAMERAS: _____

PRESSURE RECORDINGS: _____

INTERNAL DAMAGE: _____



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "N"

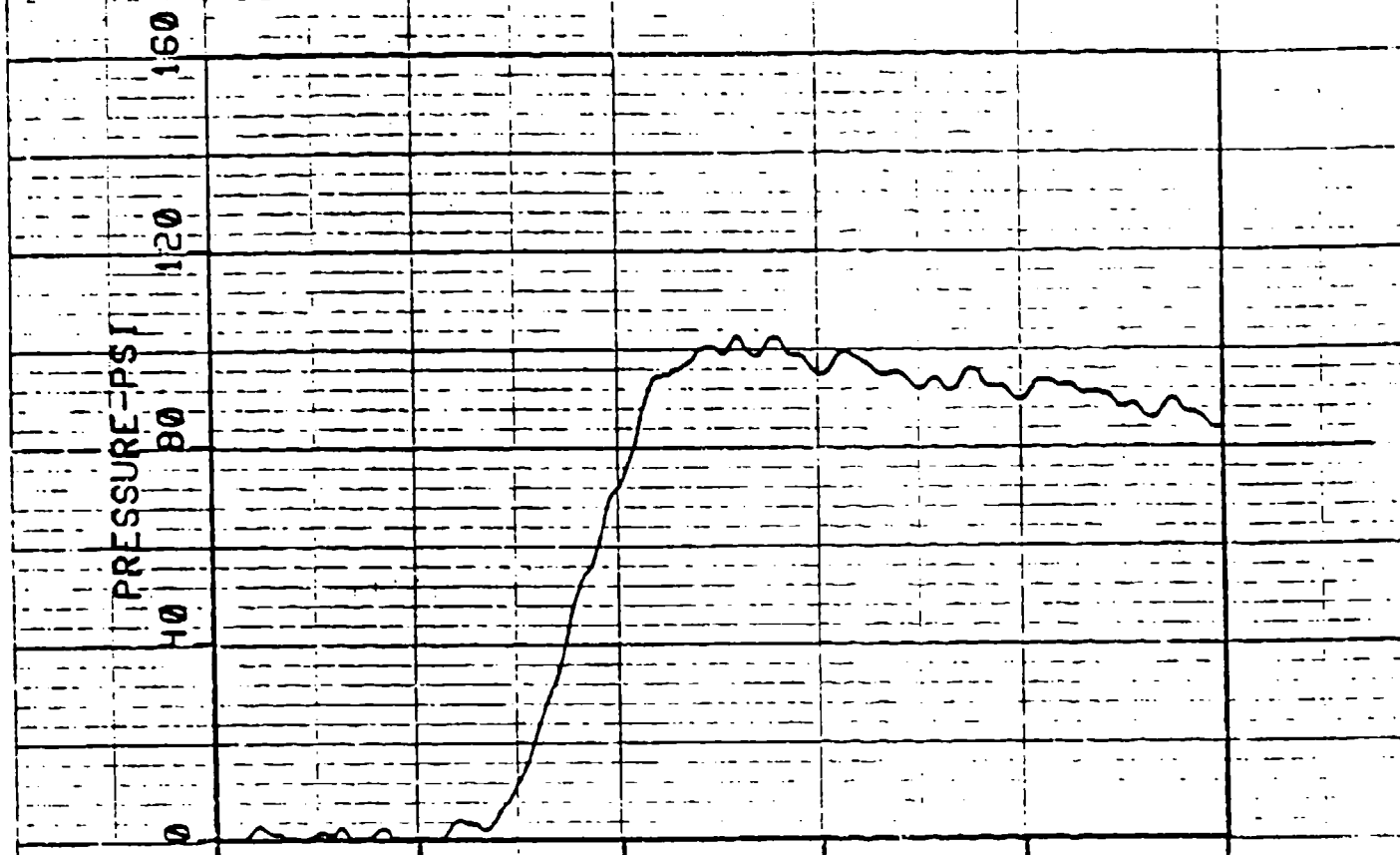
DATE 11/18/80

APPENDIX A

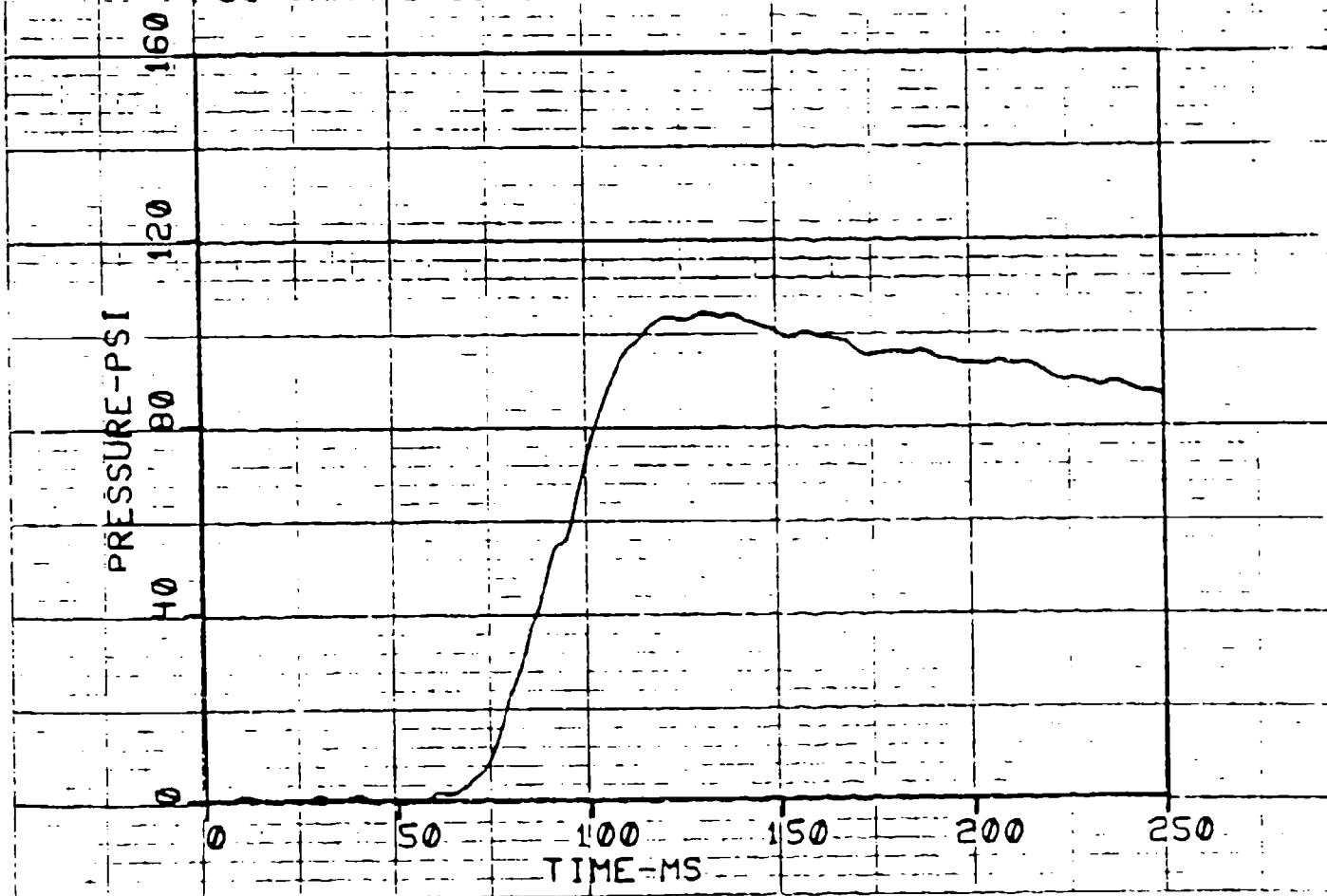
PRESSURE DATA FILTERED AT 100 HZ

NOTE: Initial delay of approximately 65 ms
due to relay response time and electric
match response time.

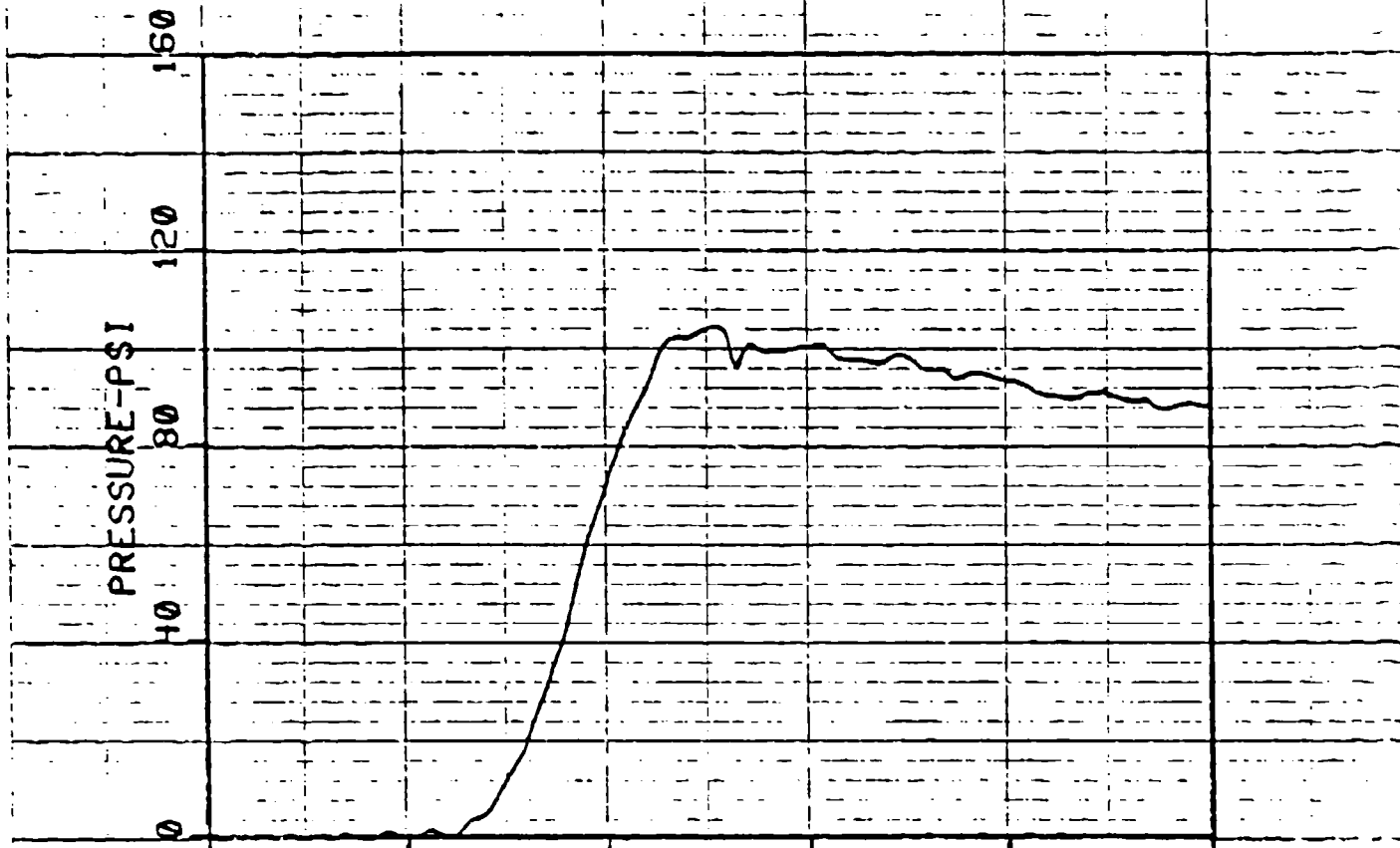
FSI TANK SN0001 VAPOR IGN. PRESSURE #1



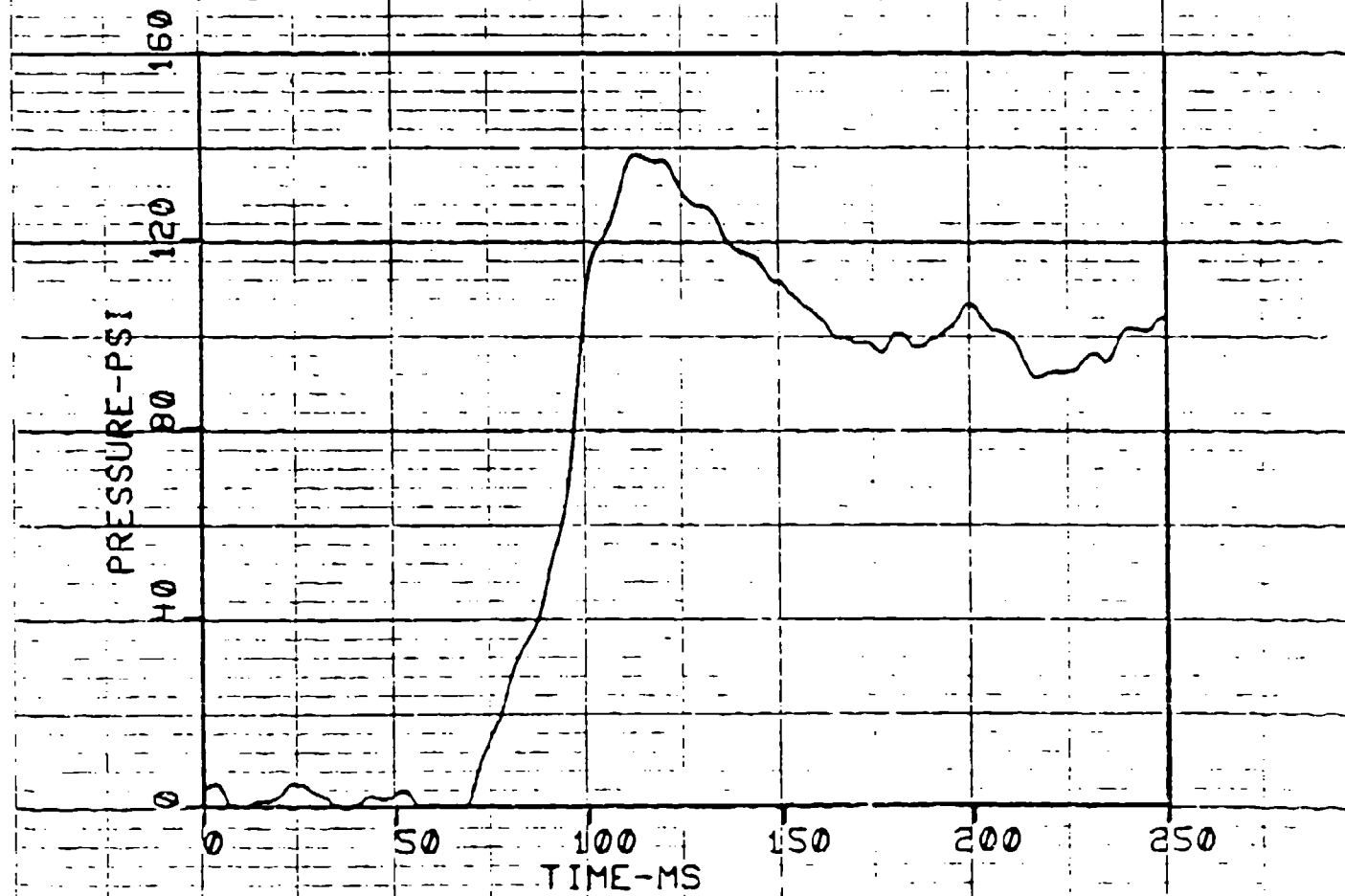
FSI TANK SN0001 VAPOR IGN. PRESSURE #2



FSI TANK SN0001 VAPOR IGN. PRESSURE #3



FSI TANK SN0001 VAPOR IGN. PRESSURE #4



APPENDIX B
PRESENTATION OF PHOTOGRAPHS



FIGURE B-1. PRE-TEST LEFT FRONT VIEW OF TANK.

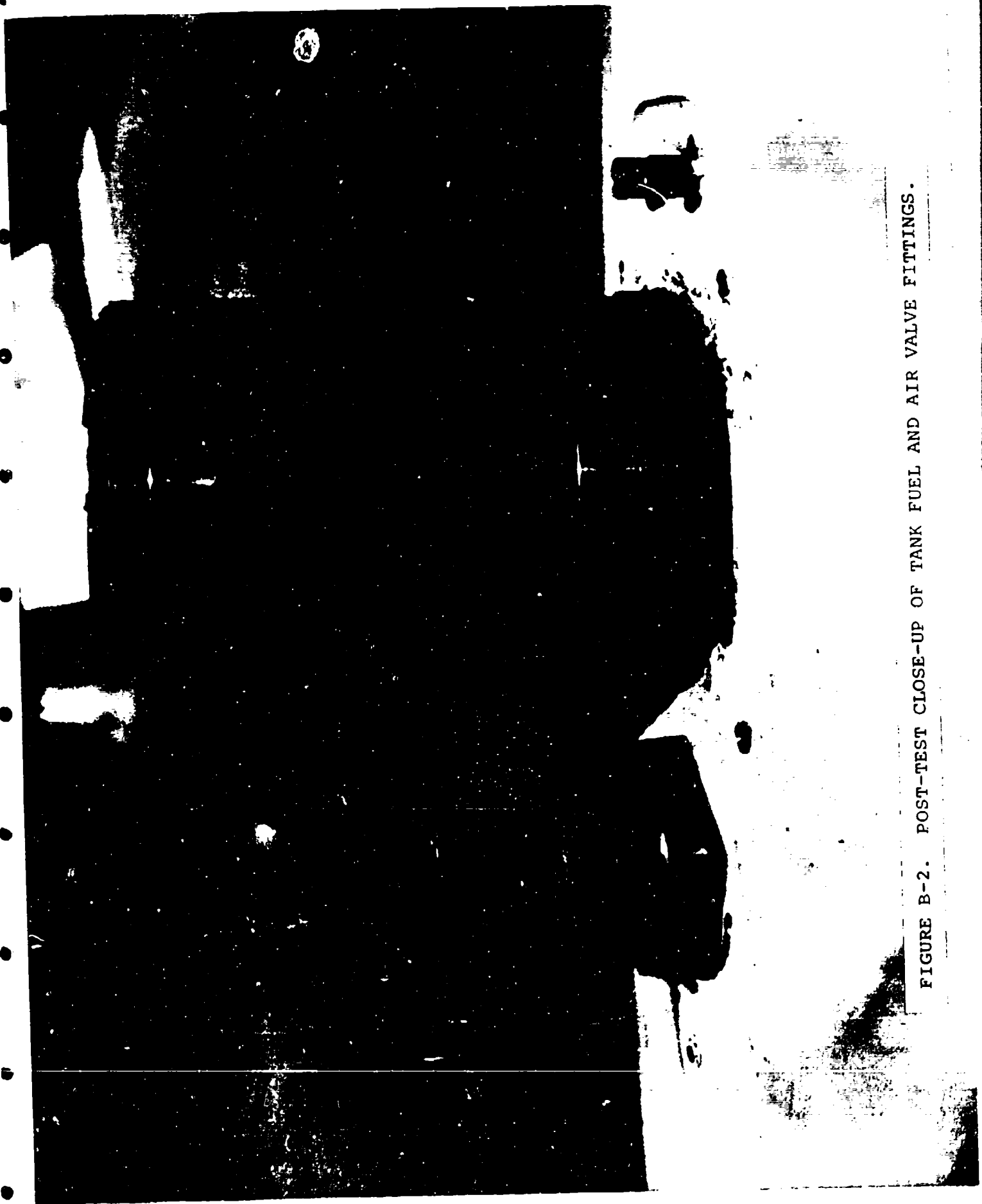


FIGURE B-2. POST-TEST CLOSE-UP OF TANK FUEL AND AIR VALVE FITTINGS.

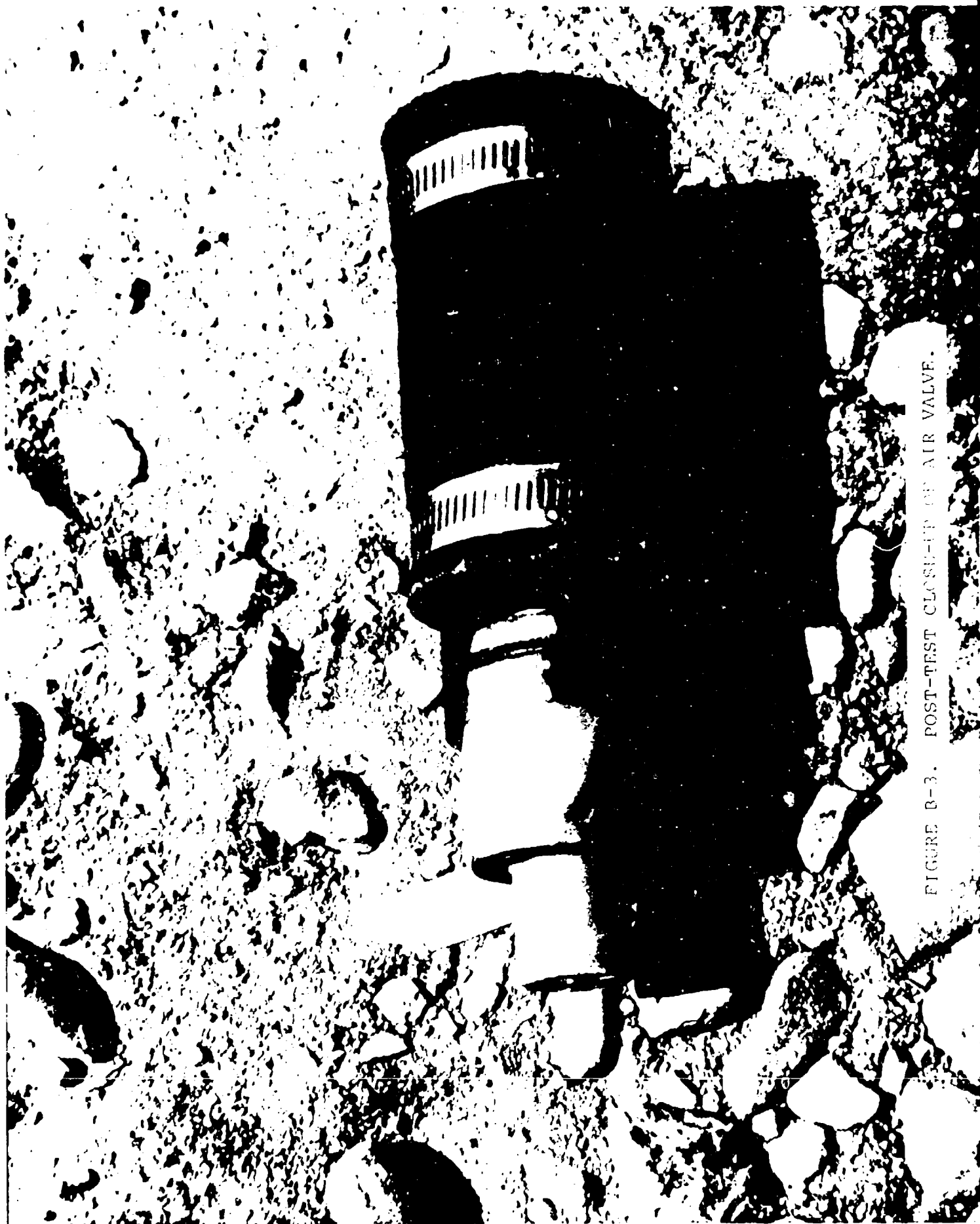


FIGURE B-3. POST-TEST CLOSE-UP OF AIR VALVE.



FIG. 1. CONNECTION OF NONE PRESSURE TRANSDUCER AND
VALVE TO VALVE.

APPENDIX C

FIBER SCIENCE, INC.

DOCUMENT NUMBER
QTP-2191 SECTION "N"

QUALIFICATION TEST PROCEDURE
H-53 TANK
REQUIREMENTS FOR FUEL VAPOR IGNITION TEST

APPENDIX D

COMPLETE LISTING OF
35MM TEST PHOTOGRAPHS

Test T2-1, SN0001

- B1-82: Pre-Test Right Side Overall View of Tank and Fixture
- B1-83: Pre-Test Rear Overall View of Tank and Fixture
- B1-84: Pre-Test Left Side Overall View of Tank and Fixture
- B1-85: Pre-Test Left Front View of Tank
- B1-86: Post-Test Right Side View of Tank
- B1-87: Post-Test Right Rear View of Tank
- B1-88: Post-Test Left Rear View of Tank
- B1-89: Post-Test Close-Up of Tank Fuel and Air Valve Fittings
- B1-90: Post-Test Close-Up of Fuel Valve
- B1-91: Post-Test Close-Up of Tank Air Fitting
- B1-92: Post-Test Close-Up of Tank Air Fitting
- B1-93: Post-Test Close-Up of Air Valve
- B1-94: Post-Test Close-Up Right Front View of Nose Fitting
- B1-95: Post-Test Close-Up Front View of Nose Fitting
- B1-96: Post-Test Close-Up Right Side View of Tail Fitting
- B1-97: Post-Test Close-Up Rear View of Tail Fitting

APPENDIX "B"
QUALIFICATION TEST REPORT
QTR - 2191
SECTION 0
GUNFIRE TEST



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTR-2191-001

DATE: 4-6-82

PAGE

OF

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78284

SwRI Project No. 02-6513
21 July 1981

GUNFIRE QUALIFICATION TEST IN 450 GALLON, FILAMENT WOUND,
EXTERNAL FUEL TANK P/N 2191-001 S/N 0006
FOR THE H-53 HELICOPTER

Prepared by
Patrick H. Zabel
and
John P. Riegel III

APPROVED

Alex B. Wenzel

A. B. Wenzel, Director
Department of Ballistics
and Explosives Sciences

Conducted for:

Fiber Sciences, Inc.
506 Billy Mitchell Road
Salt Lake City, Utah

Under Purchase Order A 3752
Authorized by Contract F09603-79-C-1542 from Air Logistics Center
Warner Robbins AFB, Georgia

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
1.1 Reason for Test	1
1.2 Description of Test Sample	2
1.3 Disposition of Test Specimen	2
1.4 Narrative Abstract, Conclusions and Recommendations	2
2. FACTUAL DATA	3
2.1 Description of Test Apparatus	3
2.2 Test Procedure	7
2.3 Test Results	8
2.3.1 Hydraulic Ram Pressures	10
2.3.2 Strain Measurements	10
2.3.3 High Frame Rate Motion Pictures	17
2.3.4 Examination of Test Specimen	17
2.3.5 Test Data	17
2.4 Evaluation of Test Results	17
2.5 Recommend Changes for a Retest	21
APPENDIX A, Test Data Sheets	
APPENDIX B, Pressure Instrumentation Brochures and Calibration Sheets	

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Test Installation	4
2	Instrumentation Locations, Impact Side	5
3	Instrumentation Locations, Exit Side	6
4	Hydraulic Ram Pressure Traces	11
5	Strains at Locations 1 and 2	12
6	Strains at Locations 3 and 4	13
7	Strains at Locations 5 and 6	14
8	Strains at Locations 7 and 8	15
9	Strains at Locations 9 and 10	16
10	Damage to Impacted Side	18
11	Damage to Exit Side	19
12	Close-up of Damage to Impacted Side	20
13	Pressure Transducer for Use in Liquids	22

1. INTRODUCTION

This report documents the Gunfire Test of the 450 Gallon, Filament Wound, External Fuel Tank for the H-53 Helicopter.

1.1 Reason for Test

This test was conducted to establish the performance characteristics of the 450 Gallon, Filament Wound, Lightweight, Explosion Proof, External Fuel Tank to the gunfire test requirements established in Technical Exhibit ASD/ ENEFA-78 dated October 1978. These test requirements are:

"3. REQUIREMENTS

"3.4 General Characteristics

"3.4.1 Design

"3.4.1.7 Survivability

"3.4.1.7.2 Gunfire Loads. In addition to the internal pressure load requirements listed in paragraph 3.4.1.3.6, the tank shall withstand the loads generated from the hydraulic ram and internal ignition pressure loads from an impact by a projectile. The projectile impact shall not yield an entrance or exit orifice wound larger than the projectile contact frontal area. Structural damage is permitted; however, leakage shall occur only from the entrance or exit.

"3.4.1.7.2.1 Hydraulic Ram. The tank shall contain without rupture the pressures generated from the hydraulic ram effect when full and impacted by a 14.5 mm (AP at distance of 75 feet).

" 4. QUALITY ASSURANCE PROVISIONS

"4.6 Test Methods

"4.6.2.1 Ballistic. The tank while suspended from the integral pylon, shall be subjected to the projectile specified in paragraph 3.4.1.7.2."

NOTE: The Soviets have not produced an AP (Armor Piercing) round since World War II. They now produce Armor Piercing Incendiary (API) or Armor Piercing Incendiary-Tracer (API-T) rounds.

1.2 Description of Test Sample

The tank tested was Fiber Science Incorporated (FSI) Part Number 2191-001, Serial Number 0006.

1.3 Disposition of Test Specimen

The test specimen was forwarded to another testing laboratory for another test in the qualification test series per FSI instructions.

1.4 Narrative Abstract, Conclusions and Recommendations

The Fiber Science 450 Gallon, Filament Wound, Lightweight, Explosion Proof, External Fuel Tank was subjected to a gunfire test. This test consisted of firing a Soviet 14.5 mm API-T projectile to impact the fuel tank at a velocity of 3468 ft/sec and at a near full tumble attitude. Ten biaxial strain gages were mounted on the tank. Four piezoelectric pressure transducers were installed. The impact resulted in an aperture in the impacted side of the tank which was larger than the impacting projectile presented area.

The excessive aperture size could have been caused by the excessive hydraulic ram pressure resulting from the greater than usual impact velocity, and by the presence of a hole in the tank wall used to mount the first pressure transducer.

We recommend that this test be considered invalid due to the higher than standard projectile velocity and due to the weakening of the wall from the hole made for the pressure transducer. A repeat test would be advisable.

2. FACTUAL DATA

2.1 Description of Test Apparatus

The test apparatus includes the Mann gun, the holding fixture, and the instrumentation.

The Mann gun consists of a single shot, smooth bore barrel; a breech mechanism; a muzzle-mounted tumble attachment; a mount with elevation and deflection mechanisms; and, a platform. The Mann gun is shown to the left in Figure 1.

The holding fixture consists of a cross piece with four legs, see Figure 1. The tank was attached to the holding fixture by a pylon made to Sargent-Fletcher Co. P/N 27-450-4400, which was in turn attached to the holding fixture by means of a special adapter, furnished by Fiber Science, Inc., which adapter simulated the aircraft pylon mounting arrangement.

The instrumentation included:

(1) a chronograph system consisting of a chronograph screen array, seen in Figure 1 between the Mann gun and the fuel tank, and three electronic counters located in the instrumentation room. The chronograph screens were two sheets of aluminum foil separated by waxed paper which when perforated by the metallic projectile closed an electric circuit. Three of these screens were mounted on wooden frames attached to a steel rack so that the screens were spaced exactly at four foot intervals. Each screen was wired in a circuit with a 9 volt battery to a start and/or stop input of an electronic counter. The electronic counters were Hewlett Packard Model 5315A Universal Counters. The screen closest to the Mann gun was connected to the start inputs of Counters 1 and 3. The center screen was connected to the stop input of Counter 1 and to the start input of Counter 2. The last screen was connected to the stop inputs of Counters 2 and 3. This screen was intended to provide redundancy in determining the projectile velocity. The first screen was located three feet from the muzzle of the Mann gun; the fuel tank was 16 feet from the Mann Gun muzzle. The screens were spaced within $\pm 1/8$ inch. The counters can determine the elapsed time within ± 0.0000002 sec. The data reduction technique used corrected for the change in projectile attitude at each screen encountered. The accuracy of the projectile velocity determination is ± 18 ft/sec.

A total of 10 biaxial strain gages were emplaced as shown on Figures 2 and 3. These were Micro-Measurement EA-13-125 TQ-350 biaxial strain gages. B&F Model 720 SG (10 each) and Honeywell Accudata 218 signal conditioning amplifiers were used to produce the signals recorded on an Ampex Model FR 1800 and an Ampex Model PR 2230 magnetic tape recorder. Strain gage locations 1 and 2 were along the tank side on a line parallel to the center line of the fuel tank and spaced 11.50 and 5.75 inches respectively rearward from the aim point, see Figure 2. The rest of the strain gage locations were placed along a plane passing through the aim point and perpendicular to the fuel tank centerline. These locations were 22.5 degrees apart with the No. 3 location 22.5 degrees below the aim point, No. 6 location at the bottom of the tank, and No. 10 location directly opposite the aim point, see Figure 3.

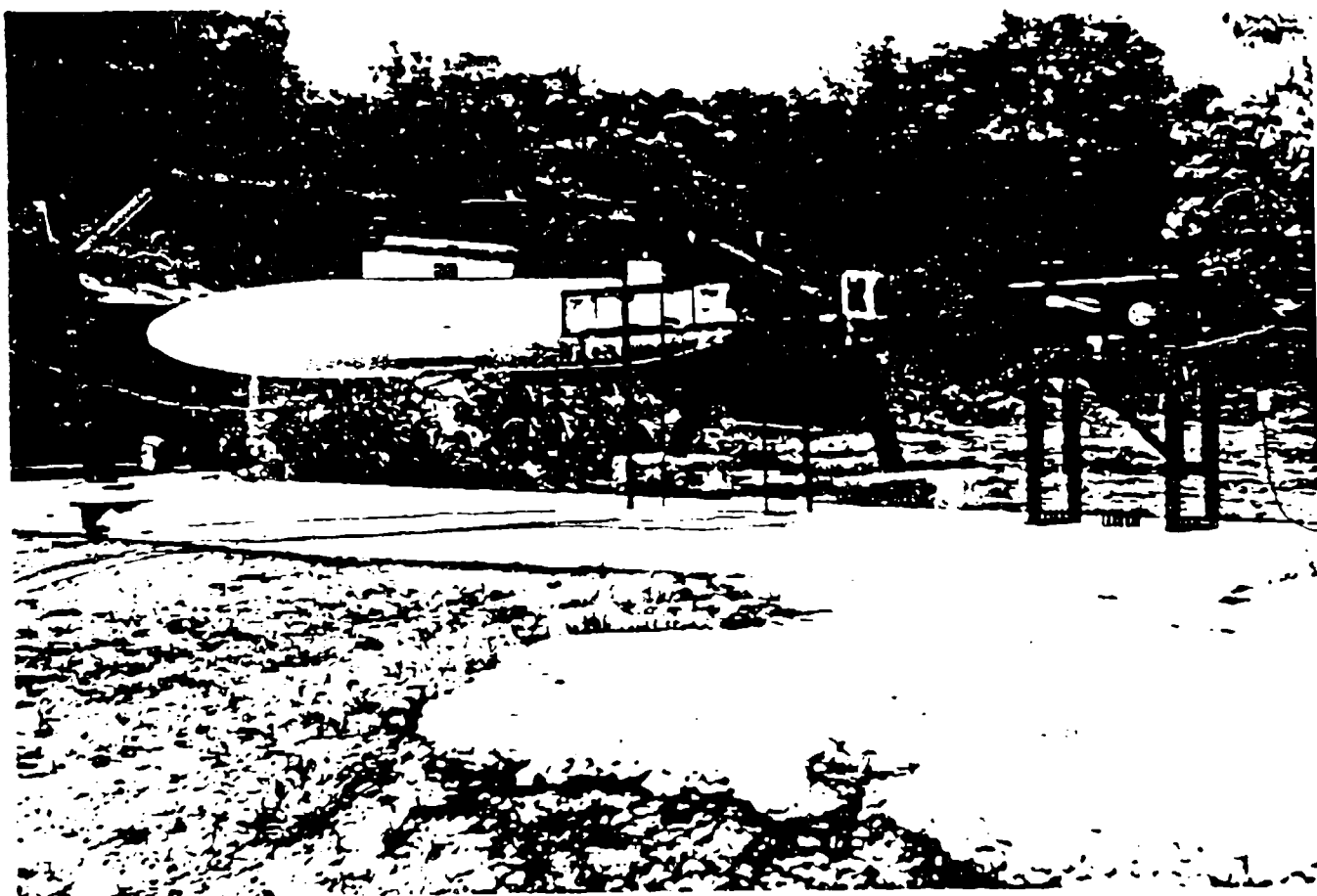


Figure 1. Test Installation

Right to Left: Mann Gun, Chronograph Screen Array, and Fuel Tank

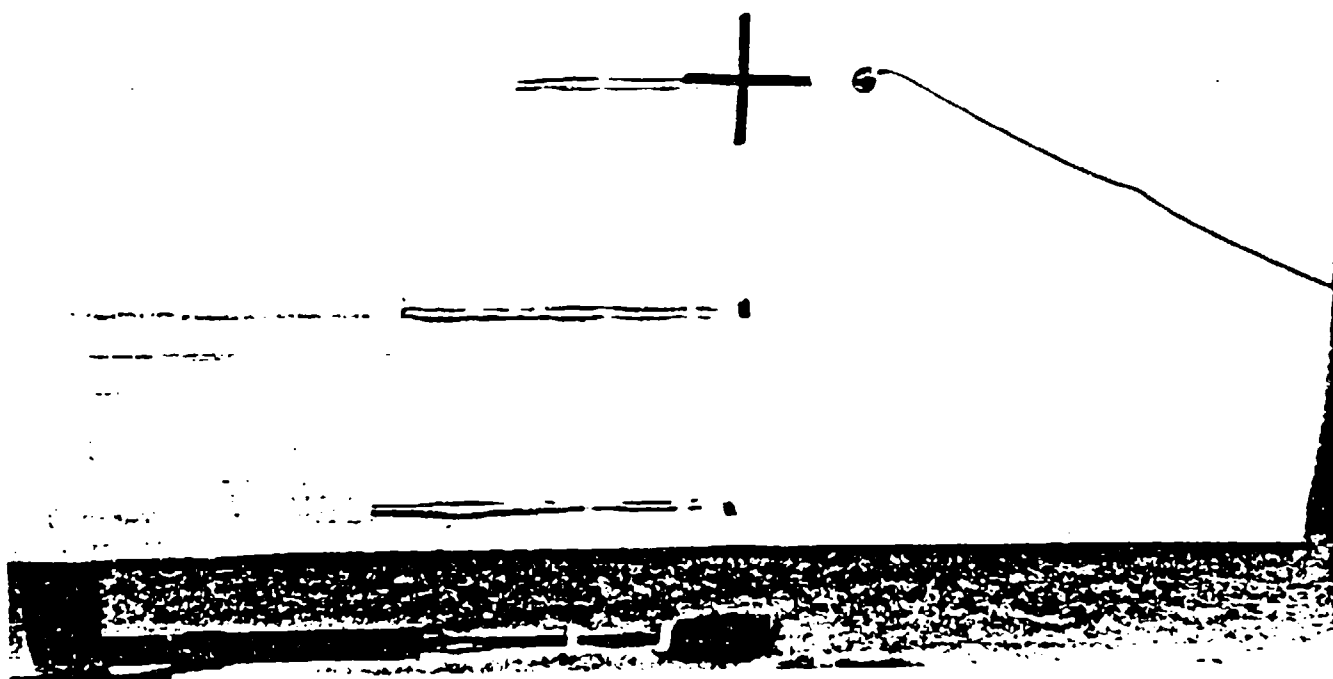


Figure 3. Instrumentation Locations, Exit Side

The cross is directly over Strain Gage Location 10 (S_{10}). Pressure Transducer 3 is adjacent. Strain Gage Locations S_9 , S_8 and S_7 can be seen. Strain Gage Location 6 and Pressure Transducer 2 are at the bottom of the tank.

Four PCB Model 102 A03 piezoelectric pressure transducers were emplaced as shown on Figures 2 and 3. The No. 1 pressure transducer was 3 inches forward of the aim point on the impact side of the fuel tank on the line parallel to the tank centerline. The No. 2 pressure transducer was 3 inches forward of the No. 6 strain gage location. The No. 3 pressure transducer was 3 inches forward of the No. 10 strain gage location. The No. 4 pressure transducer was within the fuel tank along the fuel tank centerline approximately two feet toward the tank rear from the anticipated trajectory. The diaphragm of pressure transducer 4 was facing the intersection of the anticipated trajectory and the fuel tank centerline. This transducer was in a fitting positioned by a tube through which the lead wires passed. The other three transducers were mounted in fittings which passed through the fuel tank wall with the transducer diaphragms facing the center line of the fuel tank. A PCB Model 494A06 Amplifier produced the signals recorded on the Ampex Model PR 2230 magnetic tape recorder.

The transducers have a range of 2 to 10,000 psi; the serial numbers are given in the data sheets, Appendix A. The rated accuracy of these transducers is indicated on the transducer data sheets in Appendix B.

High frame rate motion pictures were taken of the left side^{*} of the fuel tank from the left rear (the impacted side or "front" surface), and of the right side of the fuel tank from the right rear (the side from which the projectile would exit if a complete perforation is obtained or "rear" surface). The cameras used were a Hycam Model 41-0004 for the front surface and a Hycam Model K2004E for the rear.

2.2 Test Procedure

The tank was installed on the holder with the leading end pointed downward at a 2 degree angle. The target was 87 inches from the leading end of the tank and on the tank centerline. The Mann gun was located so that the muzzle was exactly 16 feet from the impact point on the fuel tank. The chronograph screen array was emplaced between the Mann gun muzzle and the fuel tank. The fuel tank was filled with water until no more water would enter the tank. This provided a trapped air bubble at the top of approximately 3 percent of the total tank volume. The high frame rate motion picture cameras were loaded.

The tumble attachment was adjusted to have the projectile rotate to a fully broadside attitude with the meplat upward at approximately 16 feet. The weapon was loaded with a Soviet 14.5 mm API-T projectile with a standard propellant load. The Mann gun is fired when a solenoid is activated. This solenoid is activated by a switch in the Hycam filming the front tank surface. This switch activates after the camera passes a designated length of film. The length of film is set to allow the camera to reach the desired frame rate before the event occurs. This switch was set for 150 feet of film which correlates with a 2500 frames per second rate. The magnetic tape recorders were started, then electric power was applied to the Hycam cameras. When the front-surface-viewing Hycam passed 150 feet of film, the Mann gun fired.

^{*}Directions assuming the observer is standing on the center of the fuel tank facing the direction an aircraft mounting this tank would travel.

When the area was declared safe, the test personnel and Fiber Science and government witnesses inspected the fuel tank.

2.3 Test Results

The center of the projectile impact was 1/2 inch below the line parallel to the tank centerline and on the intersection of the plane of the strain gage locations 3 through 10. (The cross drawn on the tank was approximately 3/4 inch toward the rear of the tank from the actual aim point.)

The projectile impact velocity at the tank surface was approximately 3468 ft/sec. Chronograph Screen 3 failed to function. The only velocity obtained was that between Chronograph Screens 1 and 2. This velocity was 3523 ft/sec. In two earlier checkout shots the velocities obtained were:

<u>Between Chronograph Screens</u>	<u>Interscreen Distance (ft)</u>	<u>Distance Correction Factors in Inches for Tumble Attitude</u>		<u>Time (sec)</u>	<u>Mean Velocity (ft/sec)</u>
		<u>At Lead Screen</u>	<u>At Tail Screen</u>		
Checkout Test No. 1					
1 and 2	4	1.612	1.522	.0011419	3509.5
1 and 3	8	1.612	1.069	.0022998	3498.2
2 and 3	4	1.522	1.069	.001580	3486.8
Checkout Test No. 2					
1 and 2	4	1.604	1.450	.0011349	3535.8
1 and 3	8	1.604	0.902	.0022859	3525.3
2 and 3	4	1.450	0.902	.0011510	3514.9
This Test					
1 and 2	4	1.606	1.402	.0011403	3522.8

Note that the rate of change of velocity per foot travelled for Checkout No. 1 was -5.625 ft/sec/ft and for Checkout No. 2 was -5.225 ft/sec/ft. Using the mean of these two values, -5.425 ft/sec/ft, the estimated projectile velocity 11 feet down range would be 3468 ft/sec.

The projectile attitude was established by the length of the silhouette left in the chronograph screens, the target, and, in the two checkout shots, in witness papers placed midway between each successive pair of chronograph screens. The attitudes at the various witnesses are given in Table 1. In an earlier program, we determined that near the fully tumbled attitude (an angular charge of 90 degrees or 270 degrees) the energy or momentum expended in perforating the witness can affect the rate of tumble. This is particularly true with targets which are usually more substantial than the witness papers or screens. Also silhouettes in witness papers at projectile attitudes near zero degrees are difficult to measure since the bullet ogive does not cut a neat hole at small attitudes with the méplat leading. Therefore, the most reliable tumble attitudes are those in witness sheets nearer to the target. Note that the rate of tumble per unit distance travelled between chronograph screens 2

Table 1. Projectile Attitudes During Tests

Witness	Silhouette length (in.)	Projectile Attitude θ (deg)	Distance From Muzzle d (ft)	Change in Attitude $\Delta\theta$	Change in Distance Δd	Rate of Change $\Delta\theta/\Delta d$	Using Chronograph Screens Only $\Delta\theta$	Δd	$\Delta\theta/\Delta d$
a. Fuel Tank Test 15 May 1981									
(Muzzle)	-	0	0						
Chr. Ser. 1	0.84 [*]	18.7	3	18.7	3.0	9.233	18.7	3	9.233
Chr. Ser. 2	1.67	39.0	7	20.3	4.0	5.075	20.3	4	5.075
Chr. Ser. 3	2.50	66.8	11	27.8	4.0	6.95	27.8	4	6.95
Target	2.49 [*]	113.3	16	46.5	5.0	9.30			
b. Check Out Test No. 1									
(Muzzle)	-	0	0						
Chr. Ser. 1	0.7 [*]	13.0	2	13.0	2.0	6.05	13.0	2	6.5
Paper A	0.90	20.3	4	7.3	2.0	3.65			
Chr. Ser. 2	1.30	30.2	6	9.9	2.0	4.95	17.2	4	4.3
Paper B	1.84	43.5	8	13.3	2.0	6.65			
Chr. Ser. 3	2.23	55.7	10	12.2	2.0	6.10	25.5	4	6.38
Target	3.31 ^{**}	-	14	-	4.0	-			
c. Check Out Test No. 2									
(Muzzle)	-	0	0						
Chr. Ser. 1	0.85 [*]	18.7	3.0	18.7	3.0	6.23	18.7	3	6.23
Paper A	1.11	25.8	5.0	7.1	2.0	3.55			
Chr. Ser. 2	1.54	35.8	7.0	10.0	2.0	5.00	17.1	4	4.28
Paper B	1.99	48.0	9.0	12.2	2.0	6.1			
Chr. Ser. 3	2.43	63.0	11.0	15.0	2.0	7.5	27.2	4	6.8
Target	2.69 [*]	80.0	15.5	17.0	4.5	3.78			

^{*} Questionable

^{**} Target yielded rendering measurement non-indicative of projectile attitude.

and 3 was 6.4 degrees/ft for Checkout 1, 6.8 degrees/ft for Checkout 2, and 6.95 degree for the tank test. These tumble rates are essentially equivalent. Using the rate of tumble for this test, the tumble attitude at impact was probably 101.6 degrees rather than the 113.3 degrees indicated by the silhouette in the fuel tank. However, the 113.3 degrees is more indicative of the projectile attitude when entering the water within the tank. At the attitude of 113.3 degrees, the area presented by the bullet would be approximately 1.3035 sq. in. This assumes that at near full tumble the area presented, A_{p_g} , is equal to $1/2$ the area presented base-on, A_{p_b} , times $\cos \theta$ plus the area presented side-on, A_{p_s} , times $\sin \theta$, or

$$A_{p_g} = \frac{1}{2} A_{p_b} \cdot |\cos \theta| + A_{p_s} \cdot |\sin \theta|.$$

Absolute values of the trigonometric functions are used to provide the proper signs for these two increments for tumble attitudes greater than 90 degrees. The projectile used has presented areas of $A_{p_g} = 1.36082$ sq in. and $A_{p_b} = 0.27155$ sq in.

The projectile used has a mass of approximately 0.0041151 slug. Thus the approximate kinetic energy of the projectile at impact was 24,746 ft-lb. The mass was determined by weighing a sample of 28 like projectiles. The standard deviation of this sample is 0.0000251 slug. The actual projectile used was not weighed.

2.3.1 Hydraulic Ram Pressures

The four hydraulic ram pressures measured are shown on Figure 4. This figure shows the pressures over the time span in which the fuel tank tore. The pressure spikes, both positive and negative, seen on P2 should be ignored. These spikes are probably due to either the transducer condition (sensing element contaminated with moisture) or are a characteristic of this type transducer, but do not represent true pressure inputs.

2.3.2 Strain Measurements

The strain measurements over the same time span of the pressures are shown on Figures 5, 6, 7, 8, and 9. These are separated into sets of strain gages located near pressure transducers 1, 2 or 3, which show the same trends. Positive strains are tension. Negative strains are compressions.

Note in Figure 5 that the circumferential strains in for Sets 1 and 2 have similar shapes even though the magnitudes vary. The same is true of the longitudinal strains. The circumferential strain at Location 2 exceeded the range of the amplifier and/or the tape recorder. These had been spanned to six times the greatest signal anticipated.

Note in Figure 6 that both the circumferential and longitudinal strains for Location 3 quickly settle to significantly lesser (compressive) strains. The tearing of the fuel tank noted in Figure 10 probably occurred shortly after the pressure shown at P1 arrived. Note the initial tensions at S3c and S3e which quickly changed to compressions. Note the same indication at S4c.

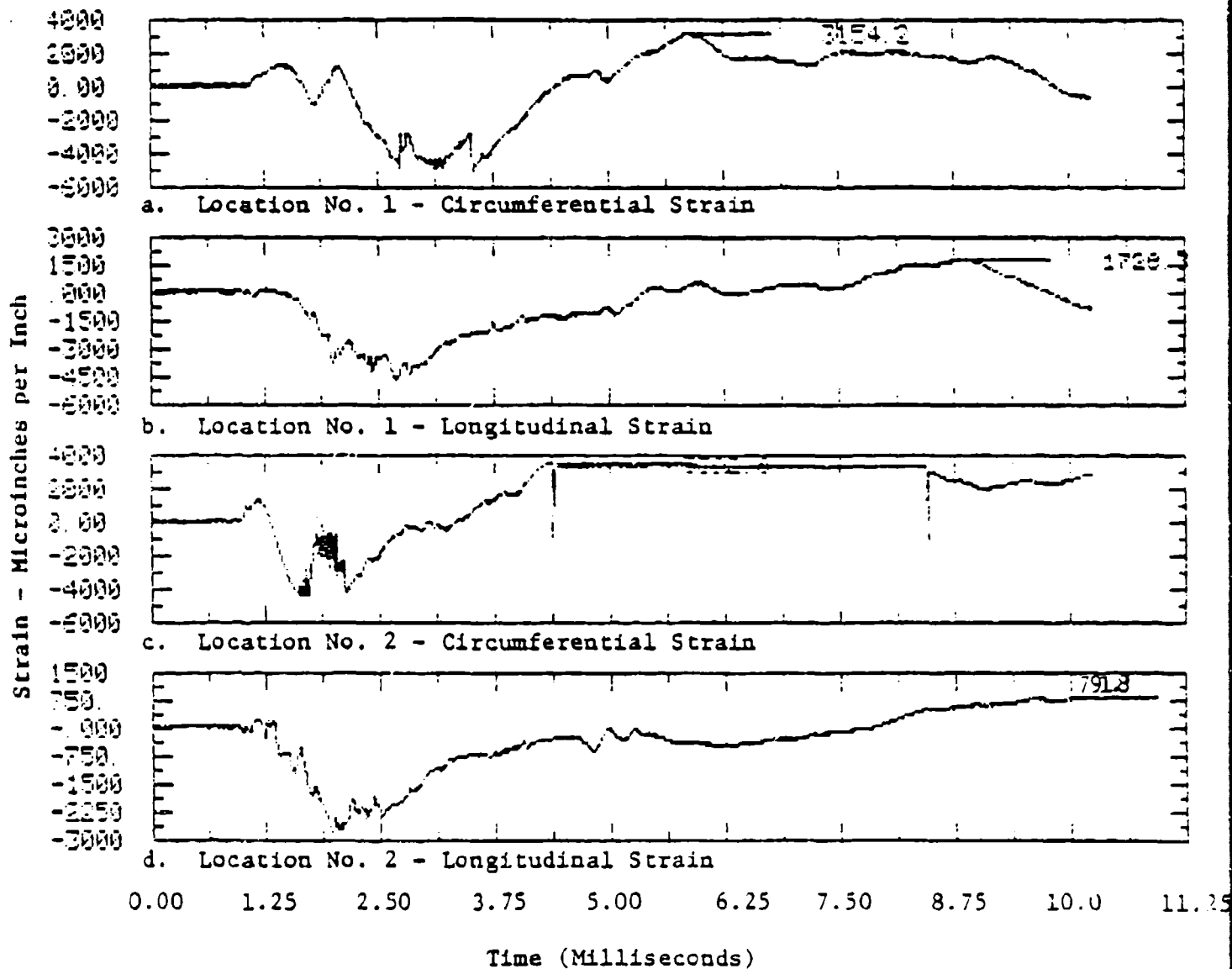


Figure 5. Strains at Locations 1 and 2

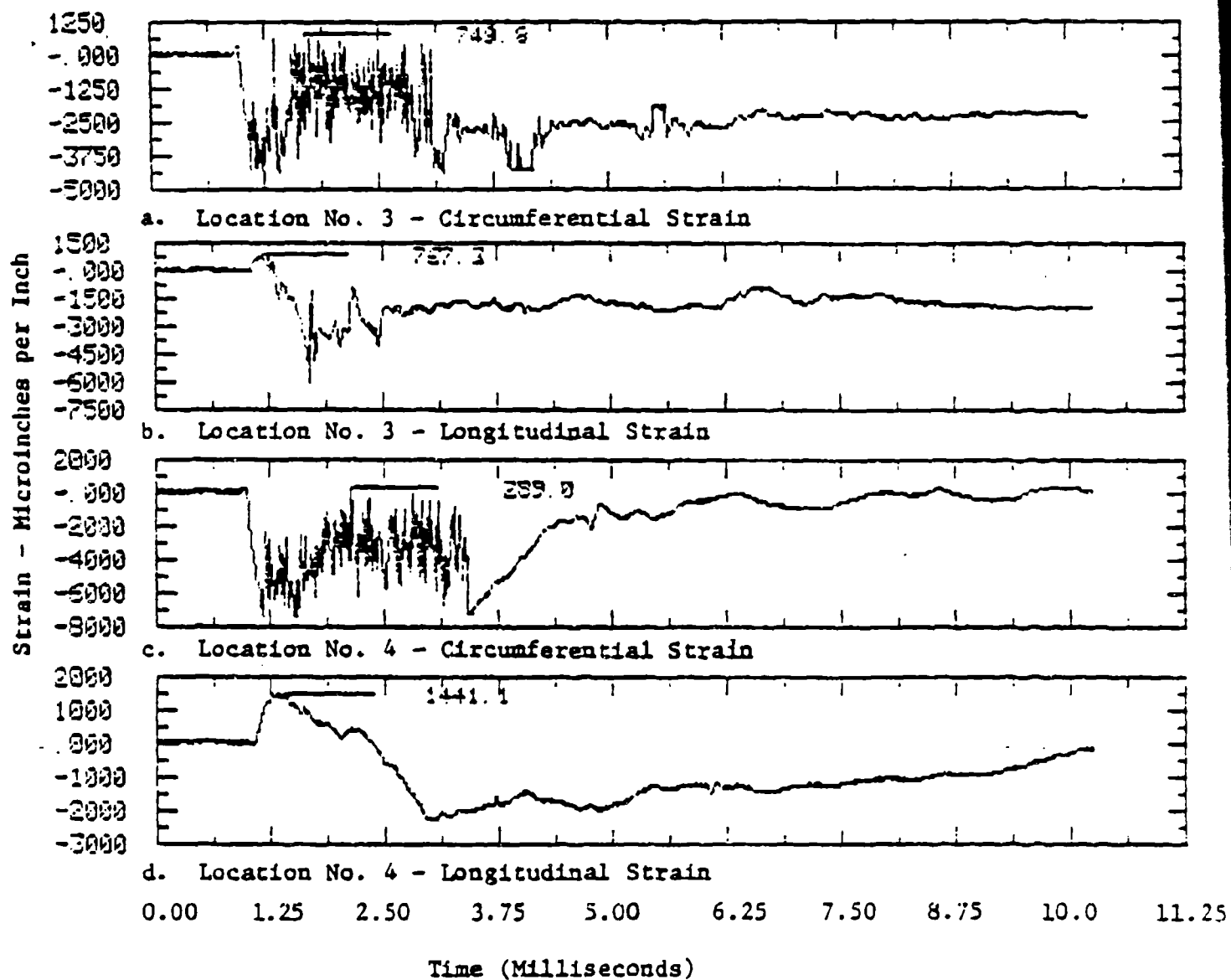


Figure 6. Strains at Locations 3 and 4

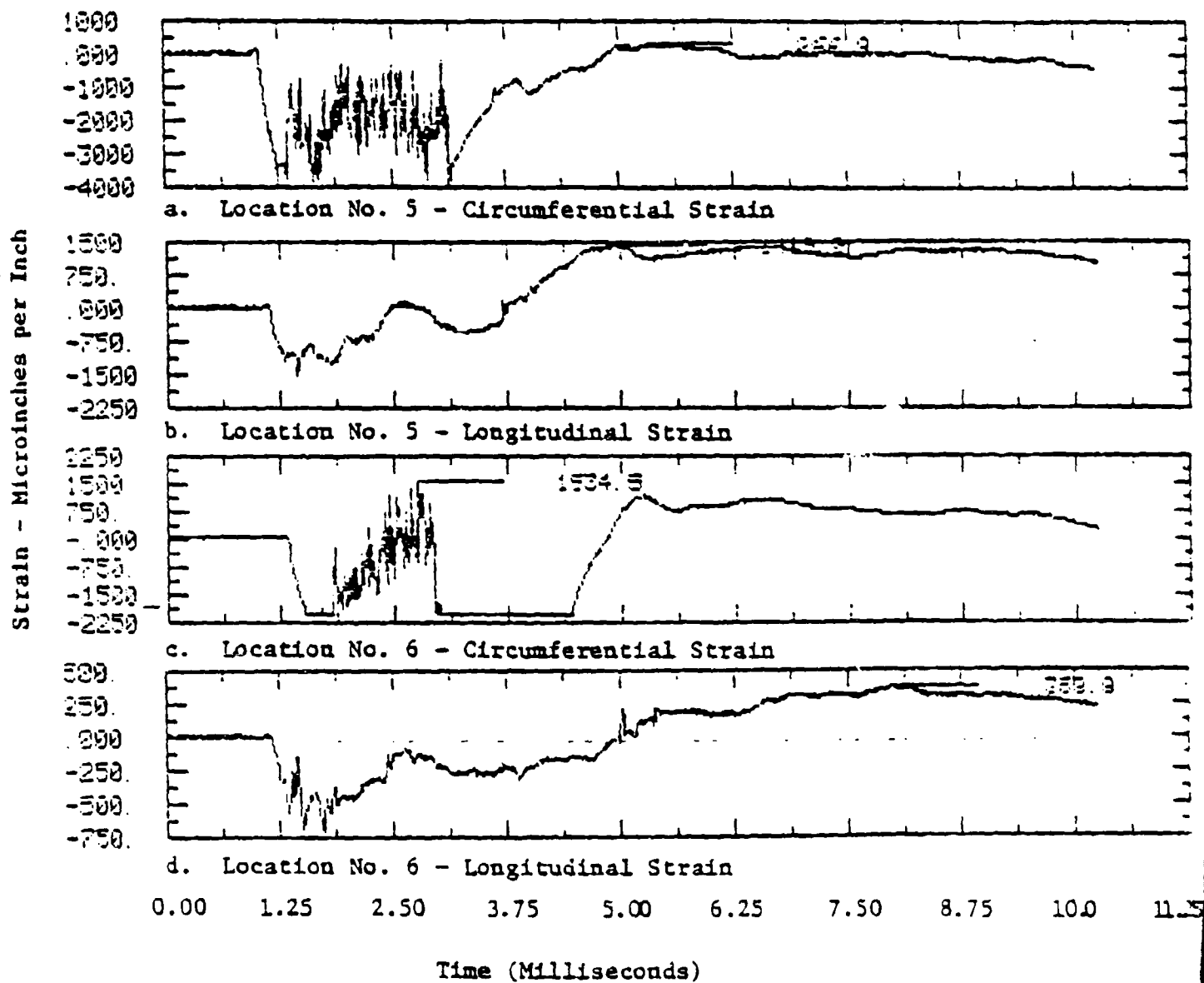


Figure 7. Strains at Locations 5 and 6

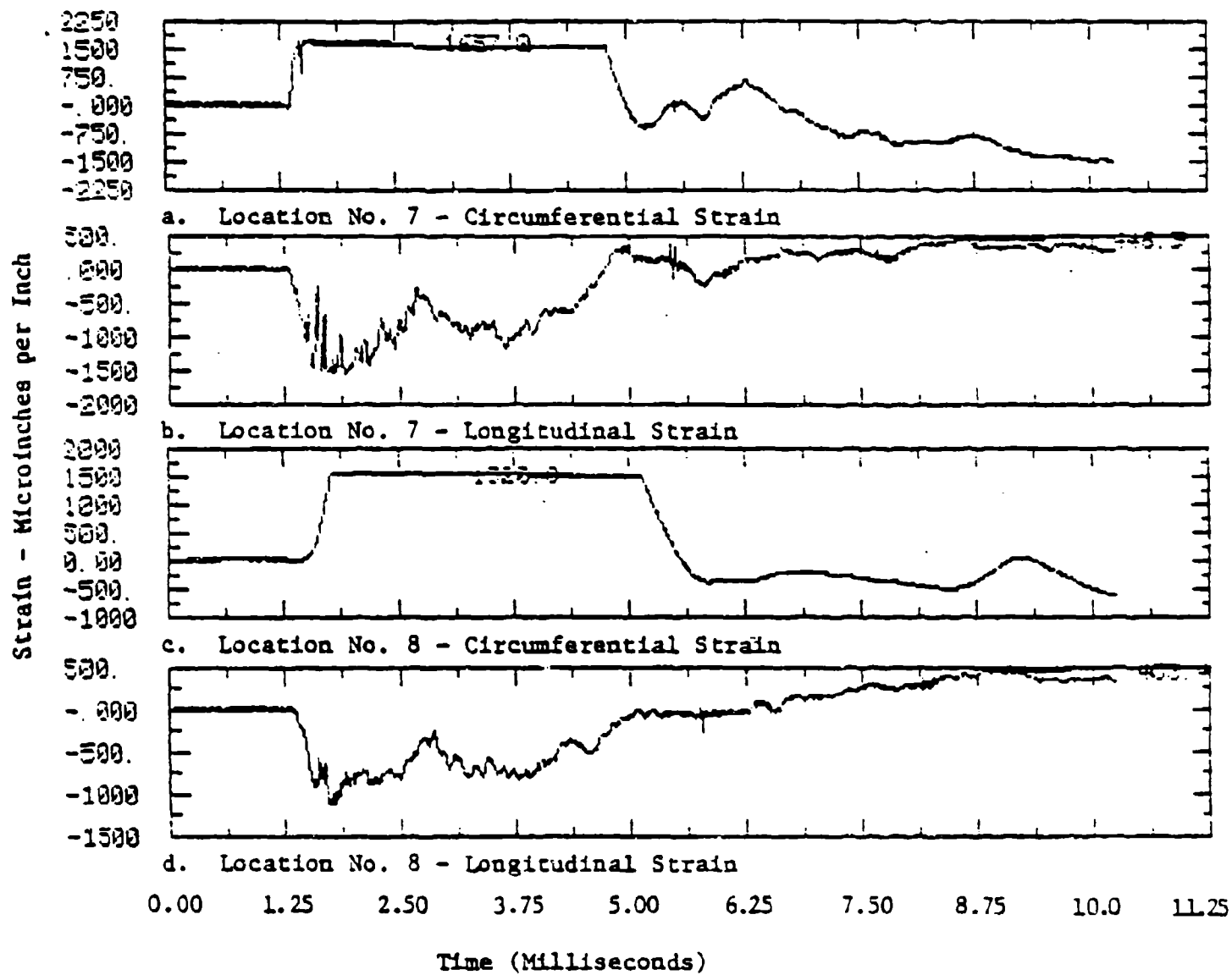


Figure 8. Strains at Locations 7 and 8

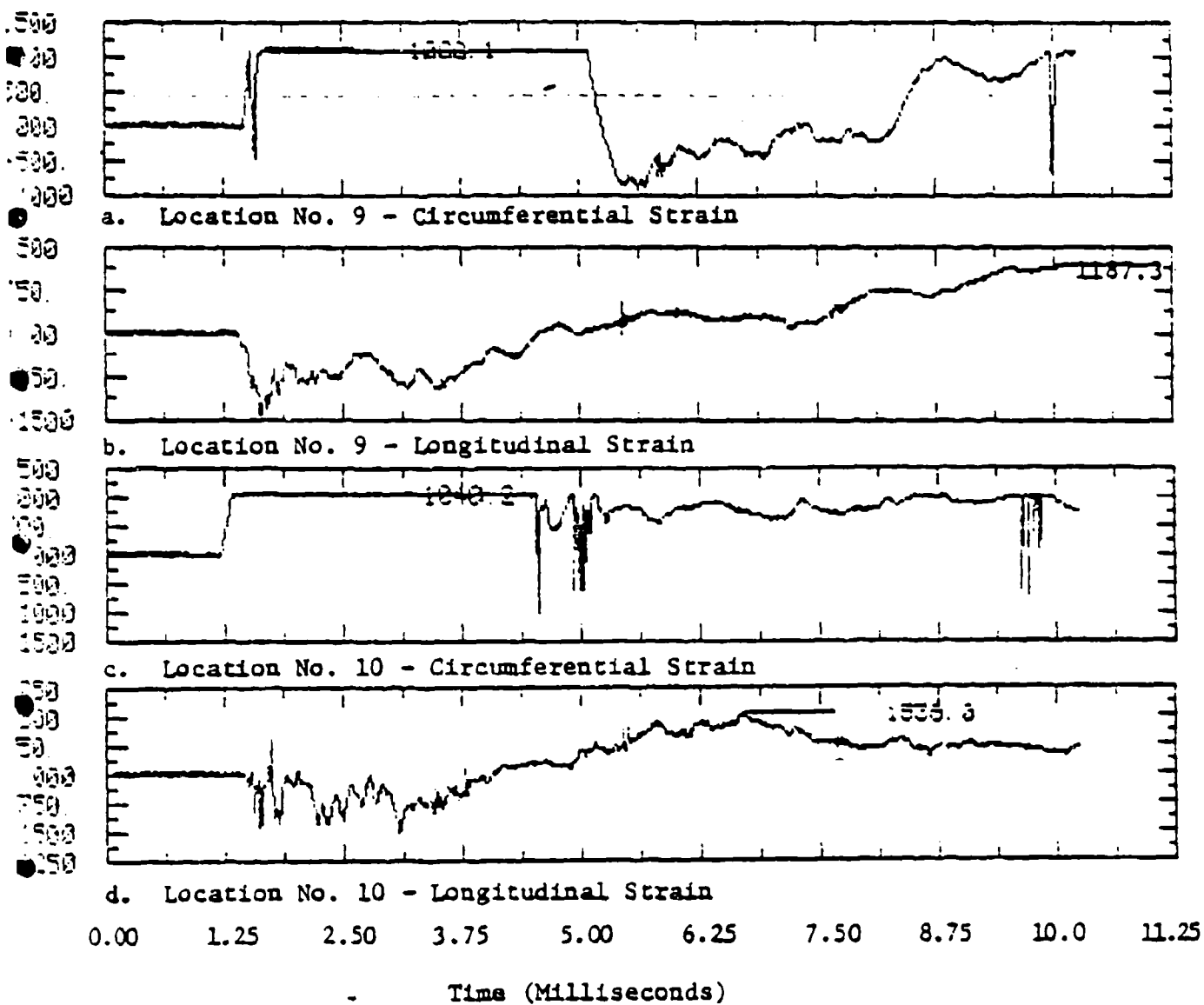


Figure 9. Strains at Locations 9 and 10

Strain Gages 3 were in an area three sides of which were bounded by tears in the composite layers.

The strain gages at locations 5, 6 and 7 (Figures 7 and 8) show characteristics similar to one another. The initial move to a compressive strain by the circumferential gages again indicate that the tank had torn before the hydraulic ram pressures became effective at these locations.

The strains at locations 8, 9 and 10 again are similar to one another (Figures 8 and 9).

All of these recordings are valid. The magnitude exceeded that anticipated by over an order of magnitude. The maximum microstrain is estimated to have been approximately 8000 microinches per inch.

2.3.3 High Frame Rate Motion Pictures

The frame rates achieved were 2185 fr/sec for the camera viewing the front surface and 2250 fr/sec for the camera viewing the rear surface of the fuel tank. These motion pictures were taken when the outside light level had dropped approximately 2 F-stops below that required. To compensate for this low light level the film processing was "pushed one stop." With the ASA 400 film used this forced processing resulted in a very high level of graininess in the pictures. We attempted to regain the second F-stop by over exposure in the making of the movie copy.

2.3.4 Examination of Test Specimen

The impacted side of the test specimen is shown on Figure 10 and the rear surface on Figure 11. Note that even though the hole in the impacted surface is larger than the projectile presented area at impact, that the flow through the resulting hole is considerably restricted by the numerous fiber ends partially blocking the aperture. This aperture was larger than desired due primarily to the hole in the tank wall bored for pressure transducer No. 1, see Figure 12. Had this hole not been bored in the tank wall the resulting aperture could have been that which was made by the impacting projectile.

The hole made in the rear surface was the size of the perforating fragment of the projectile, Figure 11.

None of the remainder of the tank suffered damage on the exterior surfaces. A "tap test" by the Fiber Science witness indicated no difference in the extent of delamination established before the test; however, the resonance of the surface over the apparent pre-test "delamination" indicated that the area was probably not delaminated.

2.3.5 Test Data

The test data sheets are located in Appendix A.

2.4 Evaluation of Test Results

Rated muzzle velocity for this particular cartridge in the weapon for which the round is made is 3281 ft/sec. This would provide an impact velocity

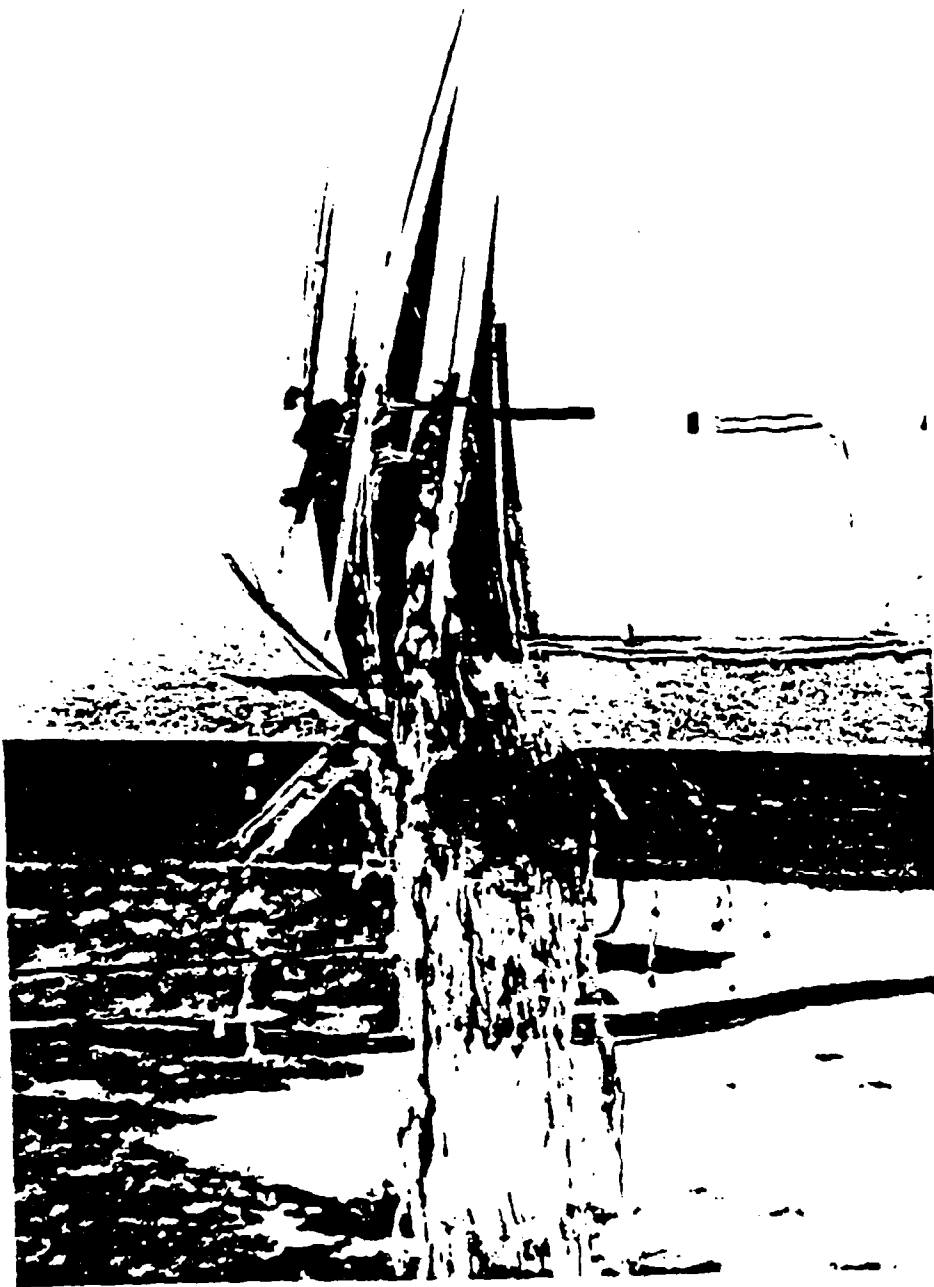


Figure 10. Damage to Impacted Side

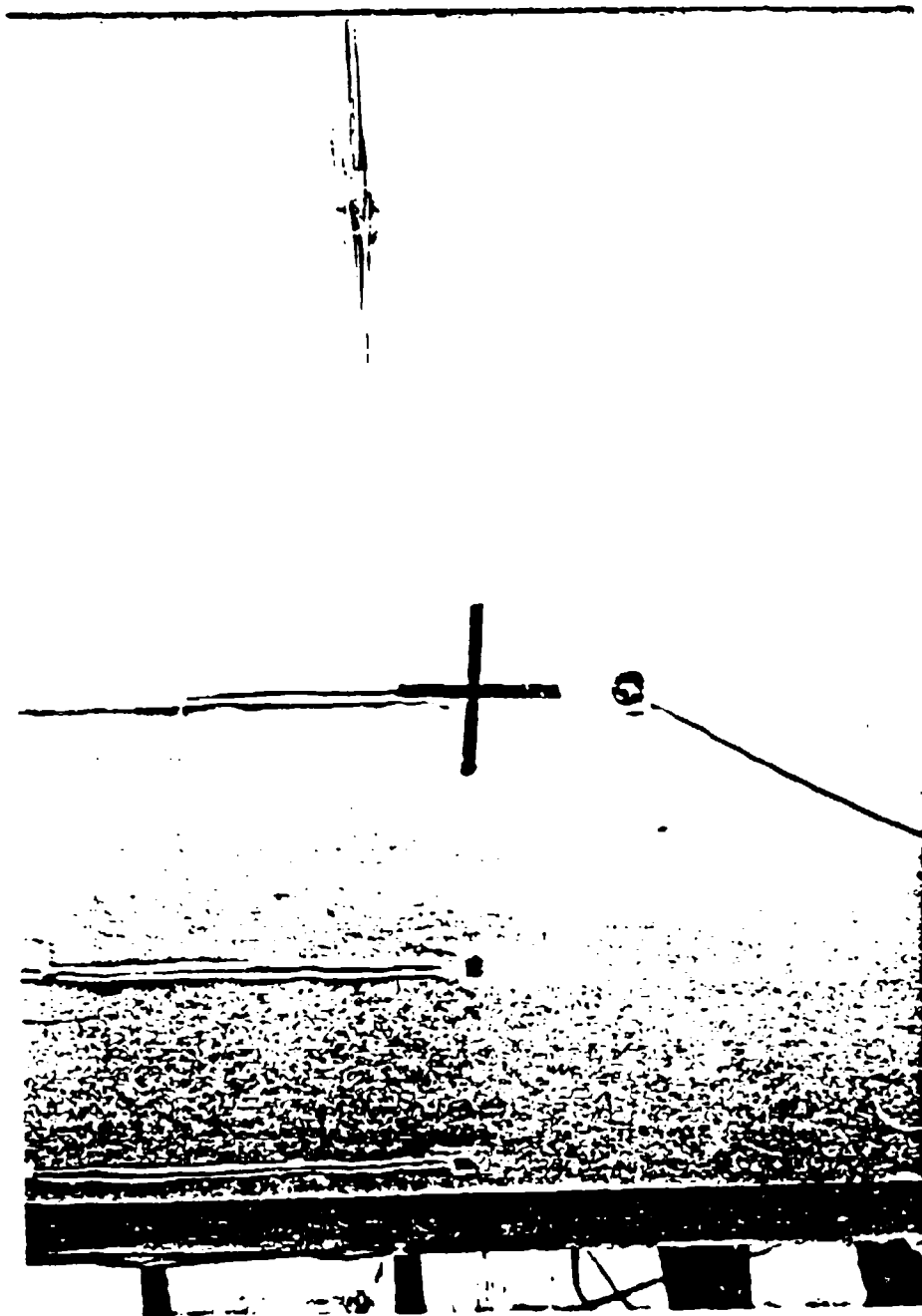
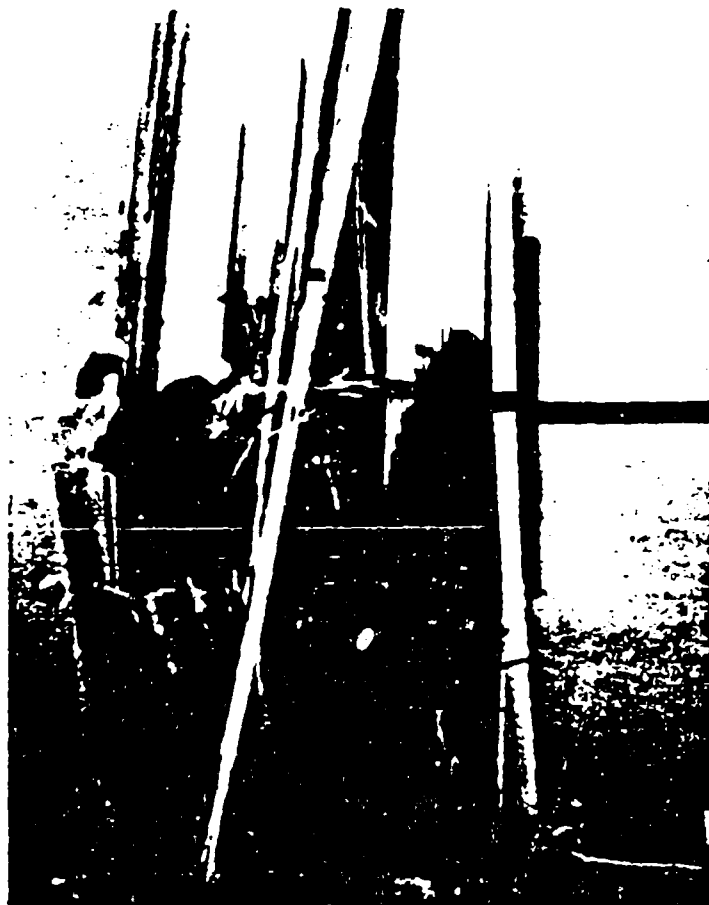


Figure 11. Damage to Exit Side

ole where
ressure Trans-
ucer No. 1 had
een mounted.



Impact
Location

Strain Gage
Location 3

Figure 12. Close-up of Damage to Impacted Side

Note that the composite material tear intersected the aperture made for Pressure Transducer 1 and that the Strain Gages at Location 3 were on a portion of the outer wrap which had lost longitudinal continuity.

under the conditions of this test of approximately 3226 ft/sec. The kinetic energy possessed by such a projectile would be 21,413 ft-lb. This is considerably under that delivered in this test; it is in fact, a 16 percent overload. This excessive kinetic energy which combined with the disruption of the filament winding strength resulting from the boring of the hole to mount the pressure transducer could be the cause of the excessive tearing of the side of the fuel tank.

Since the impact velocity and the resulting kinetic energy were greater than those logical for this test and since the hole bored for the No. 1 pressure transducer weakened the filament windings at a critical point, we recommend that this test be declared invalid. Repeat of this test would be in order.

The original intent in subjecting external fuel tanks to projectile impact tests was to assure that the fuel tank would not rip open, dumping the fuel or presenting a drastically different aerodynamic shape. The desire was to have a relatively slow pour through any hole and/or to maintain the basic aerodynamic shape of the fuel tank. This tank did meet those objectives. The fuel poured out of the hole made at the impact location, and the tanks aerodynamic shape was not drastically changed.

2.5 Recommended Changes for a Retest

We, at SwRI, have located some underwater explosion pressure transducers, Figure 13, which do not require a hole in the tank wall for proper determination of the incident pressure. We would propose to use this type of pressure transducer in a repeat test.

We are testing means which could be used to increase the illumination of the tank for the high frame rate motion pictures. We propose to use these light intensification techniques in future qualification tests.

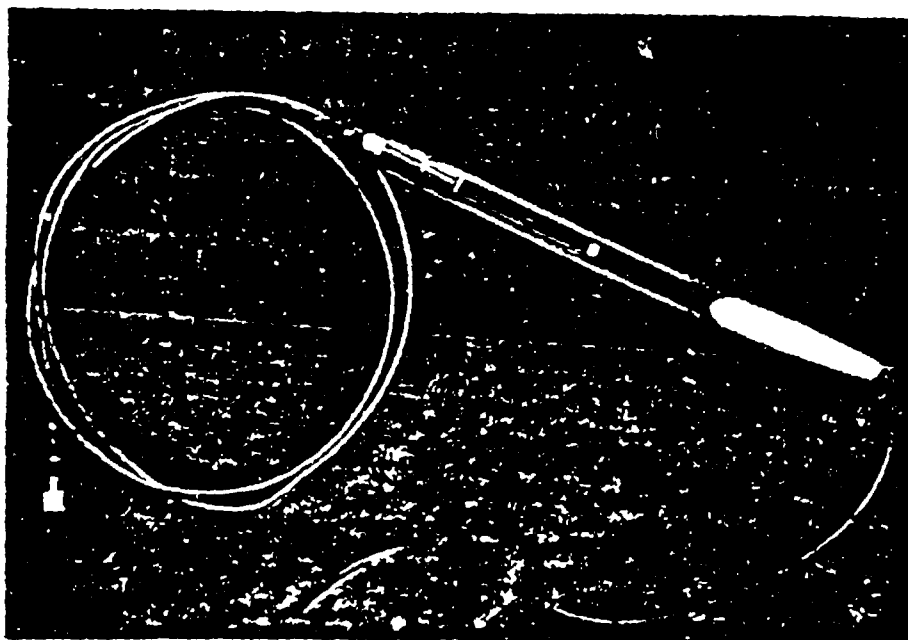


Figure 13. Pressure Transducer for Use in Liquids

APPENDIX A
Test Data Sheets

TEST DATA SHEET

QTR-2191 SECTION "O"

Testing Activity SWRT

Activity Test Engr. PATRICK H. ZABEL

Tank Serial No. P/N 2191-001
S/N 0006

F.S.I. Test Engr. RICHARD LYMAN

Test Date MAY 15, 1981

Government Rep. HUGH HILLIARD

EXAMINATION OF PRODUCT

Ref. Para. 4.1: Visual Inspection NO VISUAL DAMAGE

Delaminations (Tap Test) APPARENT DELAMINATION AREA
MARKED

MOUNTING

Ref. Para 4.2: Aircraft Simulated Attachment
Deviations If Any NONE

 FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "O"

ARRANGEMENT

Ref. Para. 4.3: Approved Test Arrangement (Ref. Figure 2 & ASD/ENFEA-78
Technical Exhibit.)

Testing Activity Approval

Approved By Patrick H. Jabel Date 15 May 1981

F.S.I. Test Engineer Approval

Approved By Richard J. Johnson Date 15 May 1981

Government Approval

Approved By Hugh Hilliard Date 15 May 81

Minimum of two signatures required.

INSTRUMENTATION

Ref. Para. 4.4.1: CHECK INSTRUMENTATION CALIBRATION

ITEM

CALIBRATION DATE

Gun (If Applicable)

NA

Cameras (If Applicable)

NA

Pressure Transducer Recorder

NA

Strain Gauge Recorder

NA

Timing Devices (Chronograph Counters)

18 Dec 80
23 Feb 81
23 Feb 81

Other Instruments:

1. _____

2. _____

3. _____

4. _____



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

11/18/80 11/18/80 11/18/80

Ref. Para 4.4.2:

CHECK PROPER INSTALLATION

<u>ITEM</u>	<u>REMARKS</u>
Gun	1P OK
Cameras	1P OK
Pressure Transducers	1P OK
Strain Gauges	1P OK
Recorders	1P OK
Other Instruments	OK CHRONOGRAPH COUNTERS
1. _____	_____
2. _____	_____
3. _____	_____
4. _____	_____

Ref. Para 4.4.3:

CHECK PROPER OPERATION

<u>ITEM</u>	<u>REMARKS</u>
Gun	1K OK
Cameras	1K OK
Pressure Transducers	1P OK
Strain Gauges	1P OK
Recorders	1P OK
Other Instruments	OK PROJECTILE CHRONOGRAPH
1. _____	_____
2. _____	_____
3. _____	_____
4. _____	_____



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

FUELING

Ref. Para 4.5:

FUEL TANK AT PROPER ATTITUDE

ITEM

REMARKS

Attitude (20° Nosedown)

OK

PAJ

Fill With 450 Gal. Water

OK

PAJ

Secure Filler Cap

OK

PAJ

GUNFIRE TEST

Ref. Para 4.6:

FIRE GUN WITH ALL INSTRUMENTATION SYNCHRONIZED

ITEM

OPERATION REMARKS

Gun

OK

PAJ

Cameras

OK

PAJ

Pressure Transducers

OK

PAJ

Strain Gauges

OK

Recorders

OK

Other Instruments

PROJECTILE CHRONOGRAPH

1. _____

PAJ

Screen No. 3 failed to

2. _____

stop Counters 2 and 3.

3. _____

4. _____



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

DATE: 11/18/80

PAGE 13 OF 16

POST GUNFIRE EXAMINATION

Ref. Para. 4.7:

EXAMINE TANK FOR THE FOLLOWING:

ITEM

REMARKS

Initial Round Area

Round Entrance Orifice Area

Approx. 4" x 2" = 8 in²

Exit Round Area
(If round can be retrieved
unmodified.)

Approx. 0.6" Dia. Penetrator
not found.

Round Exit Orifice Area

0.47 in²

Visual Inspection

Fibers cut and peeled
back approximately 1 foot both up and down
from perforation on impact face. Exit hole is
high on tank. Fibers cut and peeled back
approximately 6 inches from hole.

Delaminations (Tap Test) Conducted by the Fiber
Science Representative.



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

Ref. Para. 4.7:

Color Photographs

LOCATION

PHOTO NO.

Entrance

Exit

} SEE BELOW

() () () ()

() () () ()

Other Damage

LOCATION

PHOTO NO.

COLOR PHOTOGRAPHS OF ENTRANCE INCLUDE BOTH SLIDES AND POLAROID. THERE WERE THREE OR FOUR POLAROID'S FURNISHED AND THREE OR FOUR SLIDES INCLUDING THE BEFORE IMPACT CONDITION. SIMILARLY THERE WAS ONE EACH SLIDE AND POLAROID OF THE EXIT SURFACE BEFORE AND AFTER THE TEST.



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

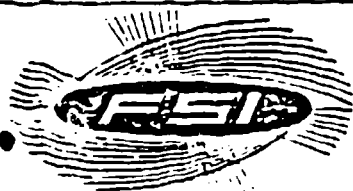
DATE: 11/18/80 PAGE 15 OF 16

EVALUATION OF DATA

CAMERAS: SIGNIFICANT DISTORTIONS OF THE FUEL TANK
WERE NOTED TO OCCUR WITHOUT RESIDUAL DAMAGE
AT LOCATIONS OTHER THAN THE IMPACT POINT.
A SPRAY OF FUEL EXITED THE VENT PORT.

PRESSURE RECORDINGS: THE INSIDE SURFACE OF THE FUEL TANK
SAW A PRESSURE IN THE NEIGHBORHOOD OF 1641 PSI NEAR
THE IMPACT LOCATION. THIS SAME APPROXIMATE PRESSURE
WAS BETWEEN THE IMPACT POINT AND STRAIN GAGE
LOCATION 3.

STRAIN RECORDINGS: THE FUEL TANK TORE BETWEEN THE
IMPACT POINT AND STRAIN GAGE LOCATION 3 UNDER
THE LOADING, APPARENTLY BEFORE SIGNIFICANT STRAINS
WERE RECORDED BY THE 3C AND 3R STRAIN GAGES.
SEVERE STRAINS WERE RECORDED ELSEWHERE WITHOUT
COMPOSITE FAILURE.



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "0"

DATE: 11/18/80 PAGE 16 OF 16

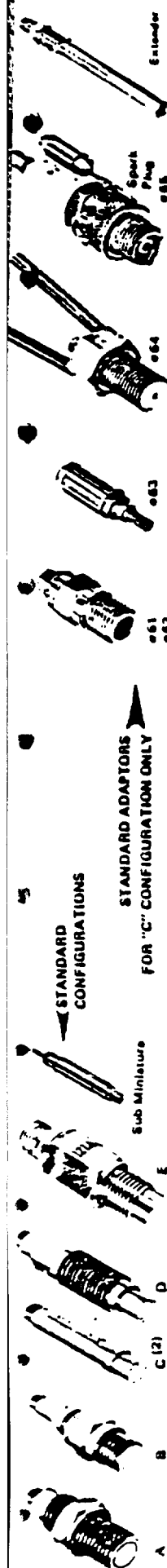
APPENDIX B

Pressure Instrumentation Brochures and Calibration Sheets

with built-in amplifiers⁽³⁾

Series 100

PIEZOTRONICS



DYNAMIC RANGE ⁽¹⁾		.01 to 100		2 to 1000		1 to 5000		2 to 10,000		10 to 80,000	
Application	pu	General Purpose	High Resolution	High Frequency	Industrial DEM	General Purpose	High Frequency	General Purpose	High Frequency	General Purpose	High Frequency
Frequency Tailored(s)				★			★		★		★
Acceleration Compensated											
Ground Isolated (A & B Configurations)											
Standardized Sensitivity (± 5%)											
Static Calibration											
MODEL NO. Config. A		101A	102A02	102A12							
MODEL NO. Config. B		101A05	102A05	102A15		101A04	102A04	101A02	102A03		
MODEL NO. Config. C ⁽²⁾		111A21	112A21	113A21		111A24	113A24	111A22	113A23		
MODEL NO. Config. D or E					121A (E)					108A02(D)	108A (D)
SENSITIVITY	mV/pu	40 ± 10	50 ± 10	20 ± 4	40 ± 20	5 ± 5	5 ± 25	1 ± 1	1 ± 5	5 ± 5	1 ± 1
Resolution	pu	.005	.004	.01	.005	.04	.04	.2	.4	.4	.2
Resonant Frequency	Hz	300,000	250,000	500,000 ⁽¹⁰⁾	200,000	400,000	500,000 ⁽¹⁰⁾	400,000	500,000 ⁽¹⁰⁾	300,000	500,000 ⁽¹⁰⁾
Rise Time	μsec	2	2	1*	3	1	1*	1	1*	2	1*
Time Constant ⁽⁶⁾	sec	1	1	1	1	100	100	500	1000	1000	2000
Low Frequency (5% down) ⁽⁶⁾	Hz	5	5	5	5	505	505	501	5005	5005	5003
Linearity ⁽⁷⁾	%	1	1	1	2	2	1	2	1	2	2
Range (for 5 volts out)	pu	125	100	250	125 ⁽¹¹⁾	1000	1000	5000	10,000	10,000	50,000
Range (for 10 volts out) ⁽⁴⁾	pu	250	200	500	250	2000	2000	10,000	20,000	20,000	100,000
Maximum Pressure	pu	1000	1000	1000	1000	10,000	10,000	15,000	20,000	20,000	125,000
Output Impedance	<ohms	100*	100*	100*	100*	100*	100*	100*	100*	100*	100*
Vibration/Shock ⁽⁸⁾	g	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000	2000/20,000
Acceleration Sensitivity	pu/g	.01	.002*	.002*	.02	.002*	.002*	.002*	.002*	.01	.004
Temperature Range ⁽¹⁰⁾	°F	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275	-100 + 275
Temperature Coefficient	%/°F	.03	.03	.03	.04	.03	.03	.03	.03	.03	.03
Fatigue Temperature	°F	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Case Material ⁽¹²⁾	SS	17-4PH	17-4PH	17-4PH	303	17-4PH	17-4PH	17-4PH	17-4PH	17-4PH	18-300 ⁽⁹⁾
Diaphragm Material ⁽¹²⁾		Invar	Invar	Invar	303/In	Invar	Invar	Invar	Invar	18-300 ⁽⁹⁾	18-300 ⁽⁹⁾
Connector		10-32	10-32	10-32	TMC	10-32	10-32	10-32	10-32	10-32	10-32

NOTES: (* denotes exceptional characteristic)

(1) Measures relative to initial or average level - Measures to full vacuum - Dynamic range 6000:1 independent of cable length.

(2) Installs interchangeably with .218 dia. quartz minipagers. 5/16-24 clamp nut is standard; 7 mm installation available.

(3) Power required 2 to 20 ma thru ce diode from ±18 to ±24V DC supply for ±5 volts output. Higher current drives long cables (>100 ft.).

(4) ±24V DC supply required for ±10V DC output.

(5) Near non-resonant response - suppressed ringing.

(6) Measures transients lasting a few % of time constant.

(7) % F.S. any calibrated range - zero based best straight line.

(8) Built-in amplifier withstands 100,000 g shock.

(9) Diaphragms are integral.

(10) Special models operate from -440°F to +325°F.

(11) Other ranges available.

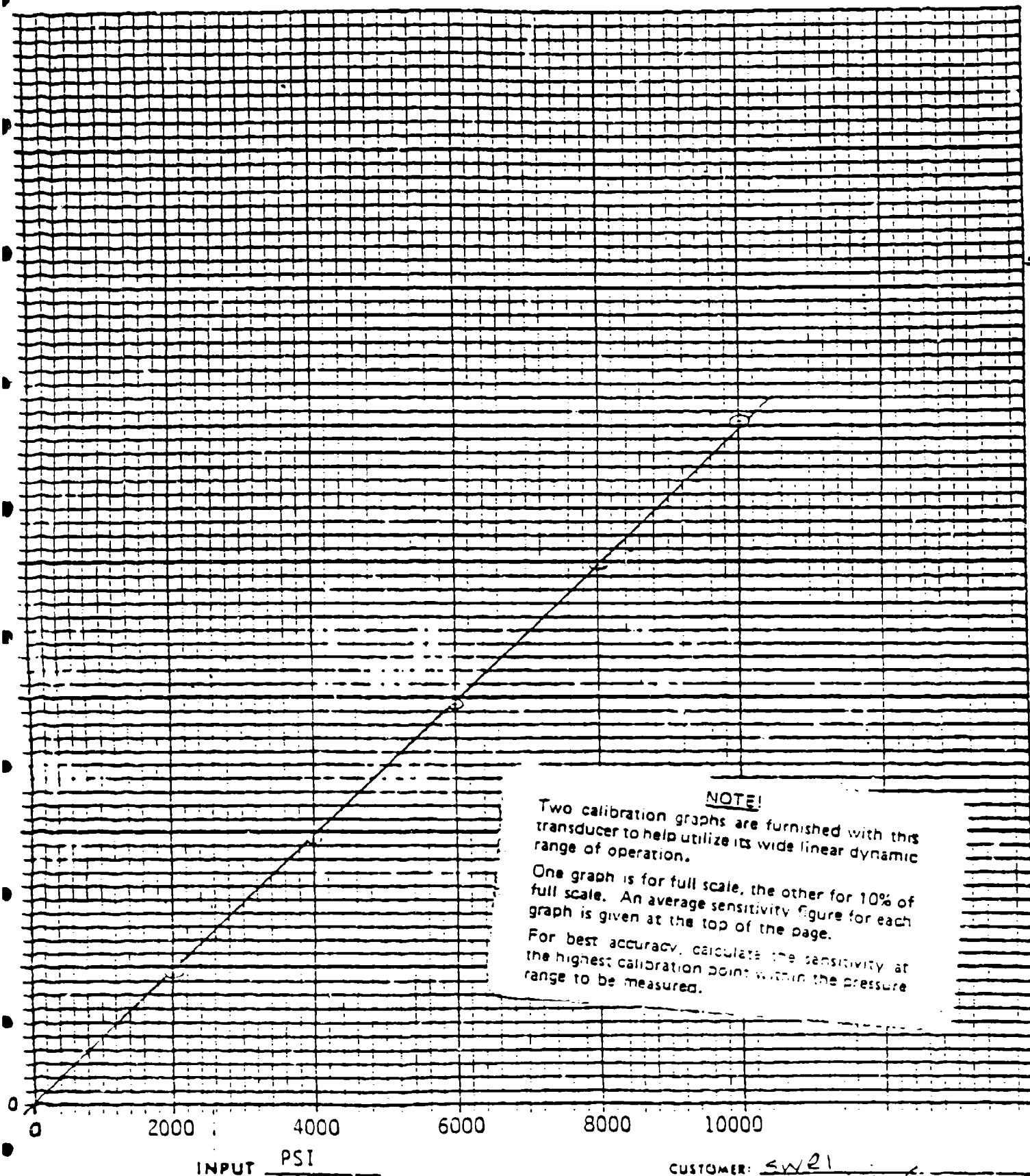
(12) Special diaphragm or case material available.

Options include other time constants, sensitivities, and configurations; signal conditioning, conformal diaphragm, ablative coating and welded hermetic sealing.

Model - 107A13
S/N 1143
Average Sensitivity * 0.499 mv/psi
Linearity ±1.0 %F.S.

Cal. Range 0-10,000 PSI
Input Time Constant 10N Sec
Rise Time 1 μ Sec
Natural Frequency 50 KHz
Output Impedance <100 Ohms

P.O. BOX JJ
BUFFALO, NEW YORK 14225
By T. Rippl
Date 11-6-80
*By comparison with reference
Standard per ISA 537.10



CUSTOMER: SW21
PO NO 107154 SW

I.C.P. TRANSDUCER DATA

P. O. BOX 33

BUFFALO, NEW YORK 14225

Model 112A13

Cal. Range 0-1000 PSI

Input Time Constant 112N Sec

S/N 1143

Rise Time 1 μ Sec

Average Sensitivity 0.475 mv/psi

Natural Frequency 50K KHz

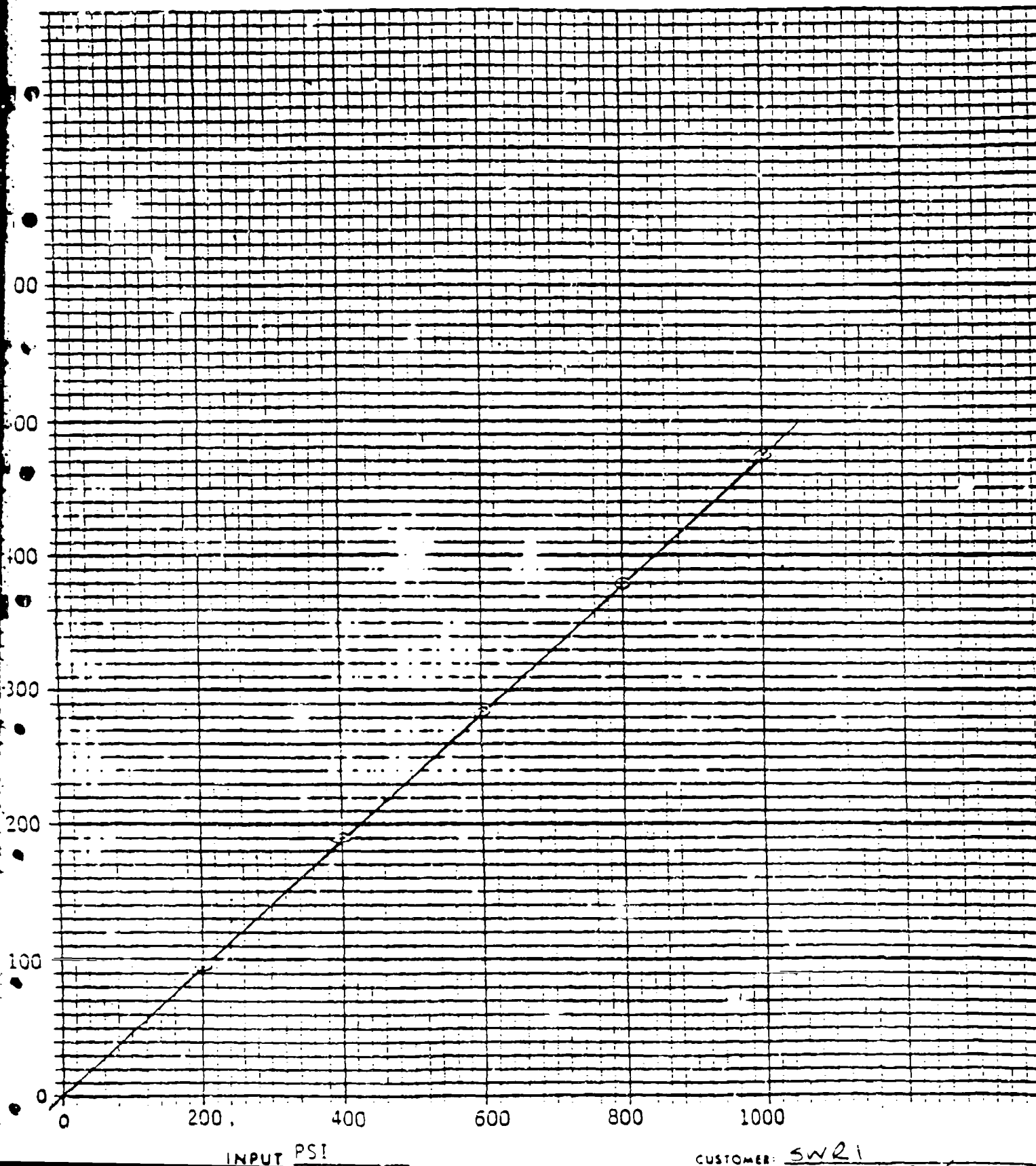
Linearity ±1.0 % F.S.

Output Impedance <100 Ohms

By T. C. P. Smith

Date 11-6-60

*By comparison with reference Standard per ISA S37.10



CUSTOMER: SW21
0715 SW

Model • 102A13
S/N 1901
Average
Sensitivity • 0.537 mv/psi
Linearity ±1.0 %F.S.

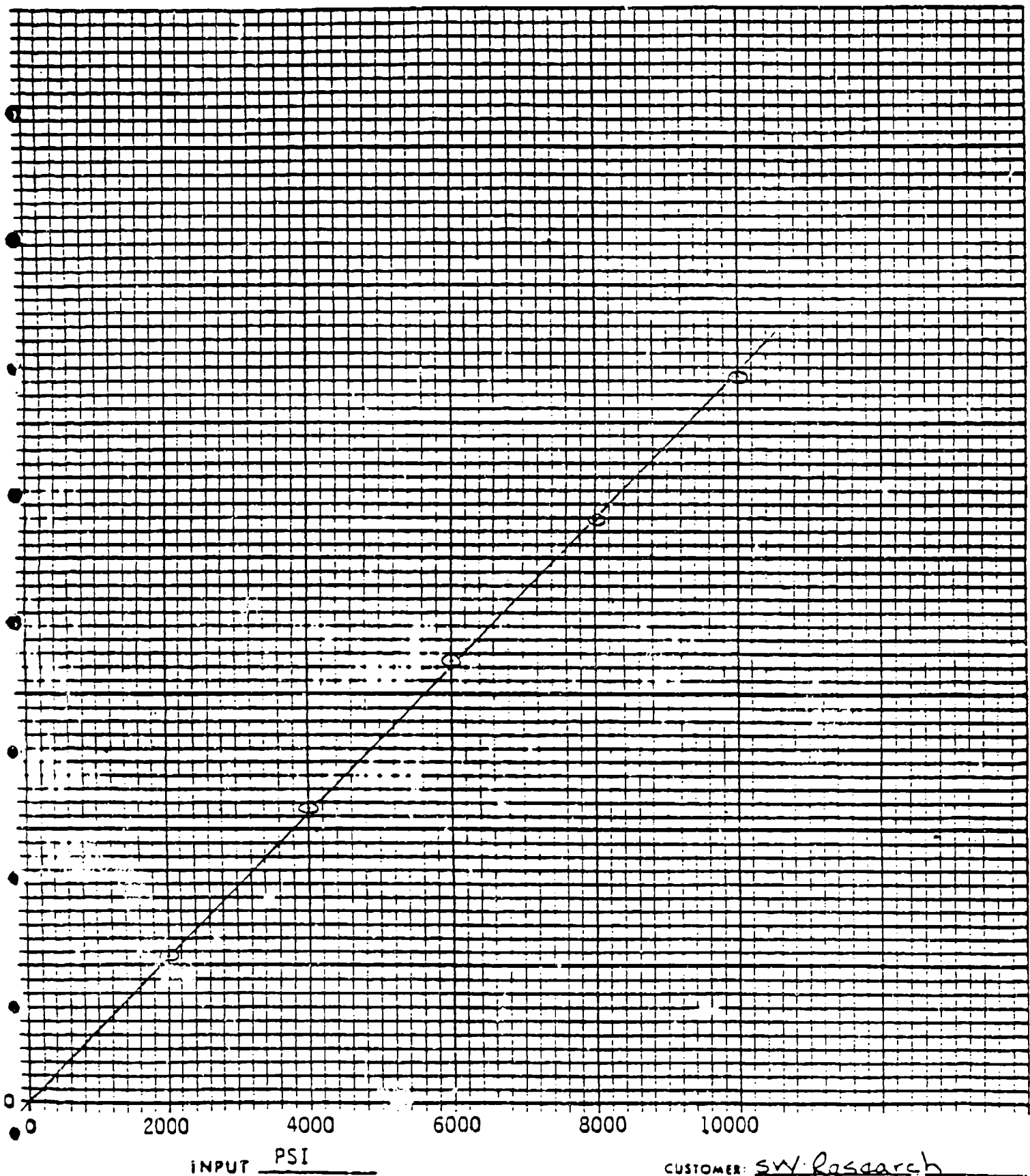
Cal. Range 0-10,000 psi
Input Time Constant 1000 Sec
Rise Time 1 μ Sec
Natural Frequency 550 KHz
Output Impedance <100 Ohms

P.O. BOX 33

BUFFALO, NEW YORK 14225

By T. G. P. L. H.
Date 7-23-80

*By comparison with reference
Standard per ISA S37.10



CUSTOMER: SW Research
P.O. NO. 103302

L.C.P. TRANSDUCER DATA

PIEZOTRONICS INC.

P.O. BOX 33

BUFFALO, NEW YORK 14225

Model 102A03

Cal. Range 0-1000 PSI

Input Time Constant 1200 Sec

S/N 1901

Rise Time 1 μ Sec

Average Sensitivity 0.525 mv/psi

Natural Frequency 55 KHz

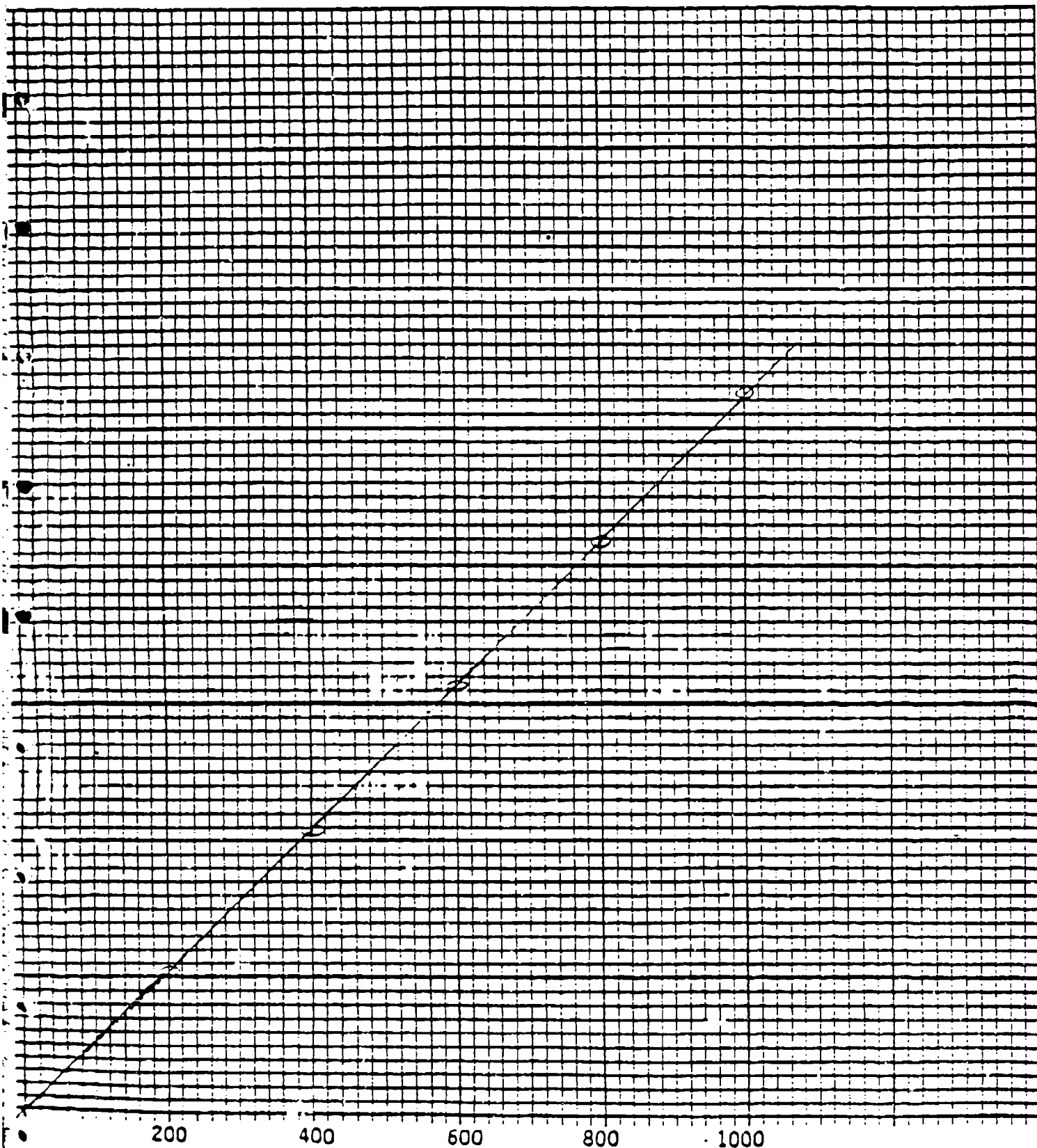
By T. Cipolinski

Date 7-23-80

Linearity ±1.0 % F.S.

Output Impedance <100 Ohms

*By comparison with reference Standard per ISA S37.10



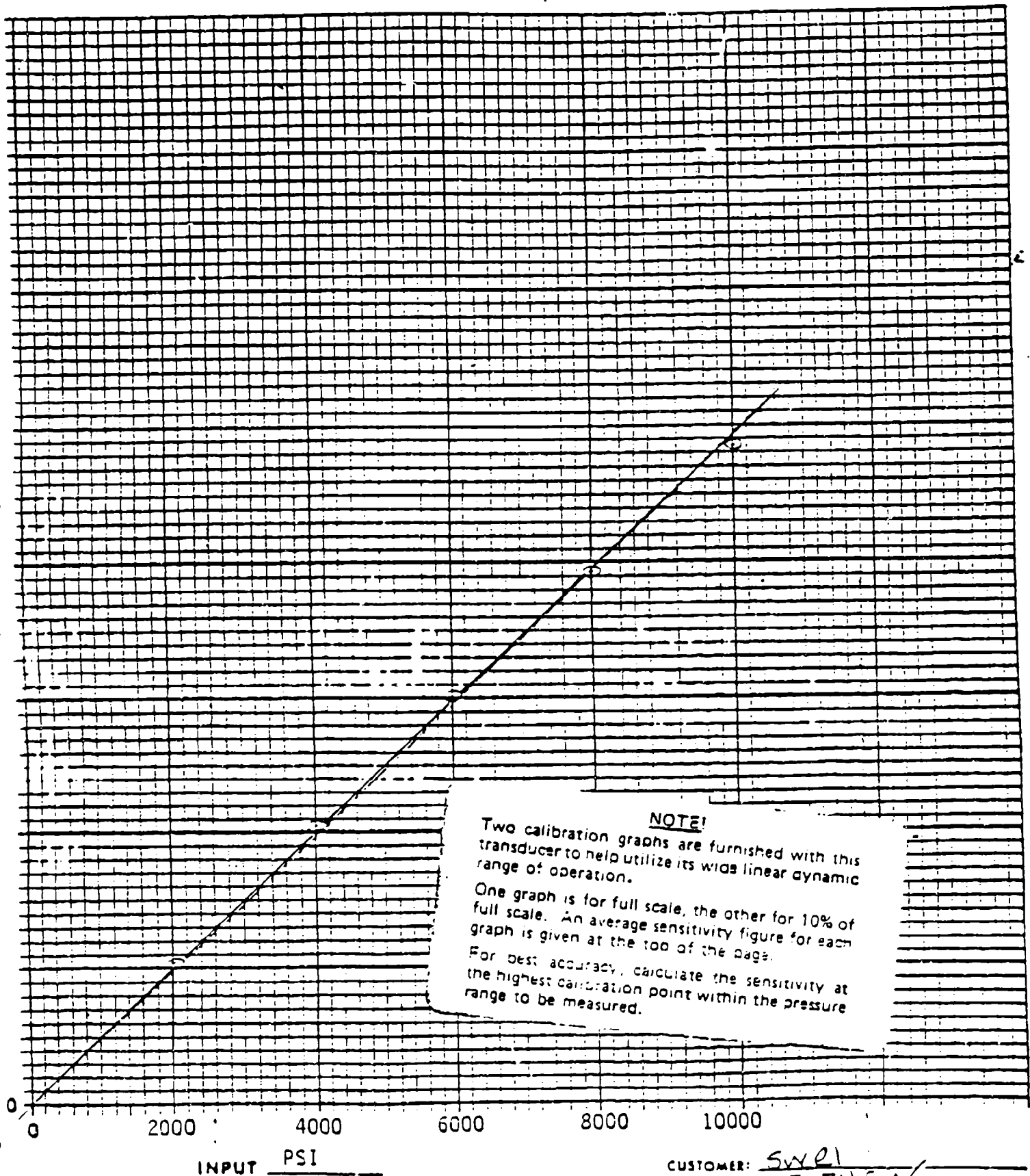
INPUT PSI

CUSTOMER: SW Research

Model • 107A03
S/N 1157
Average Sensitivity • 0.493 mv/psi
Linearity 1.5 - %F.S.

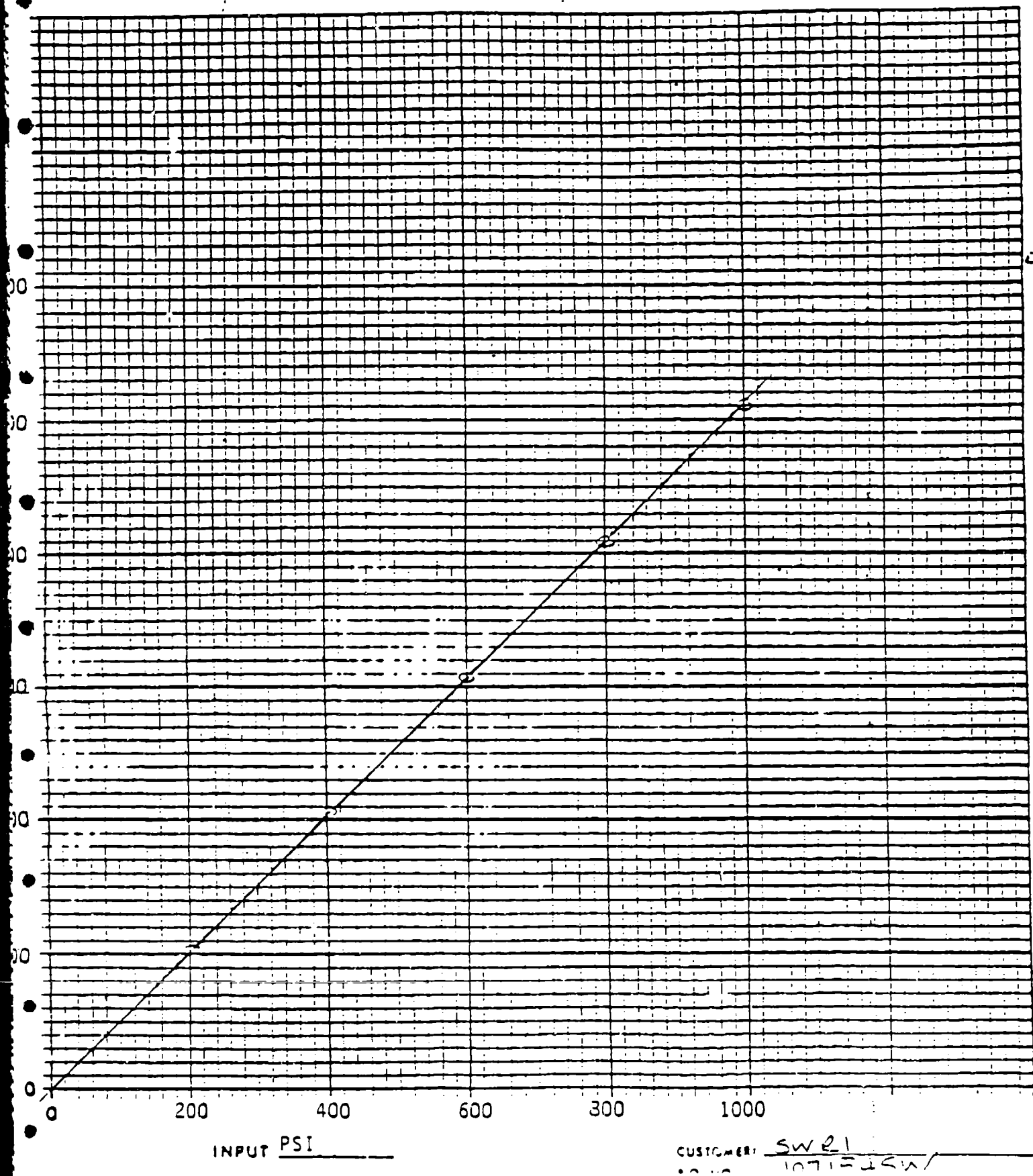
Cal. Range 0-10,000 PSI
Input Time Constant 100 Sec
Rise Time 1 μ Sec
Natural Frequency 50 KHz
Output Impedance <100 Ohms

P.O. BOX 33
BUFFALO, NEW YORK 14225
By T. C. [Signature]
Date 11-6-60
*By comparison with reference
Standard per ISA S37.10



CUSTOMER: SWP
P.O. NO. 107154 SW

Model • <u>102A63</u>	Cal. Range <u>0-1000 PSI</u>	P. O. BOX 33
S/N <u>1157</u>	Input Time Constant <u>1000</u> Sec	BUFFALO, NEW YORK, 14225
Average Sensitivity • <u>0.572</u> mv/psi	Rise Time <u>1</u> μ Sec	By <u>T. G. P. 6-1-6</u>
Linearity <u>±1.0</u> % F.S.	Natural Frequency <u>50</u> KHz	Date <u>11-6-60</u>
	Output Impedance <u><100 Ohms</u>	*By comparison with reference Standard per ISA S37.10



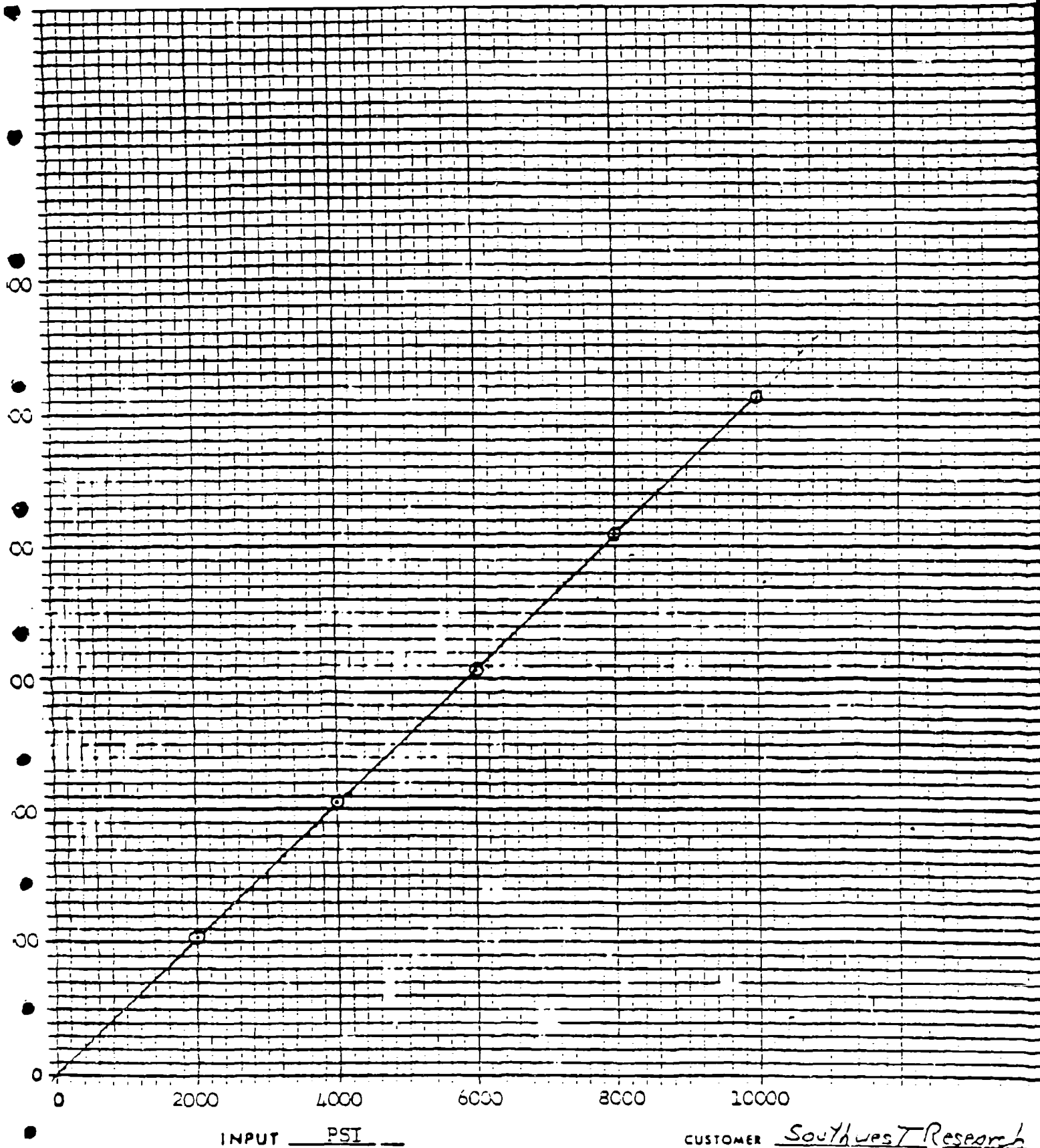
CUSTOMER: SW 21
10715 J SW

Model = 152A-3
S/N 1272
Average Sensitivity * 0.575 mv/psi
Linearity ± 1.0 % F.S.

Cal. Range 0 - 10,000
Input Time Constant 1000 Sec
Rise Time 1 μ Sec
Natural Frequency 450 KHz
Output Impedance <100 Ohms

BUFFALO, NEW YORK 14225

By T. [Signature]
Date 8-18-77
* By comparison with reference
Standard per ISA S37.10



CUSTOMER Southwest Research
P.O. NO. 394045W

Model = 19200
S/N 121
Average Sensitivity = 1.58 mV/psi
Linearity -10 % F.S.

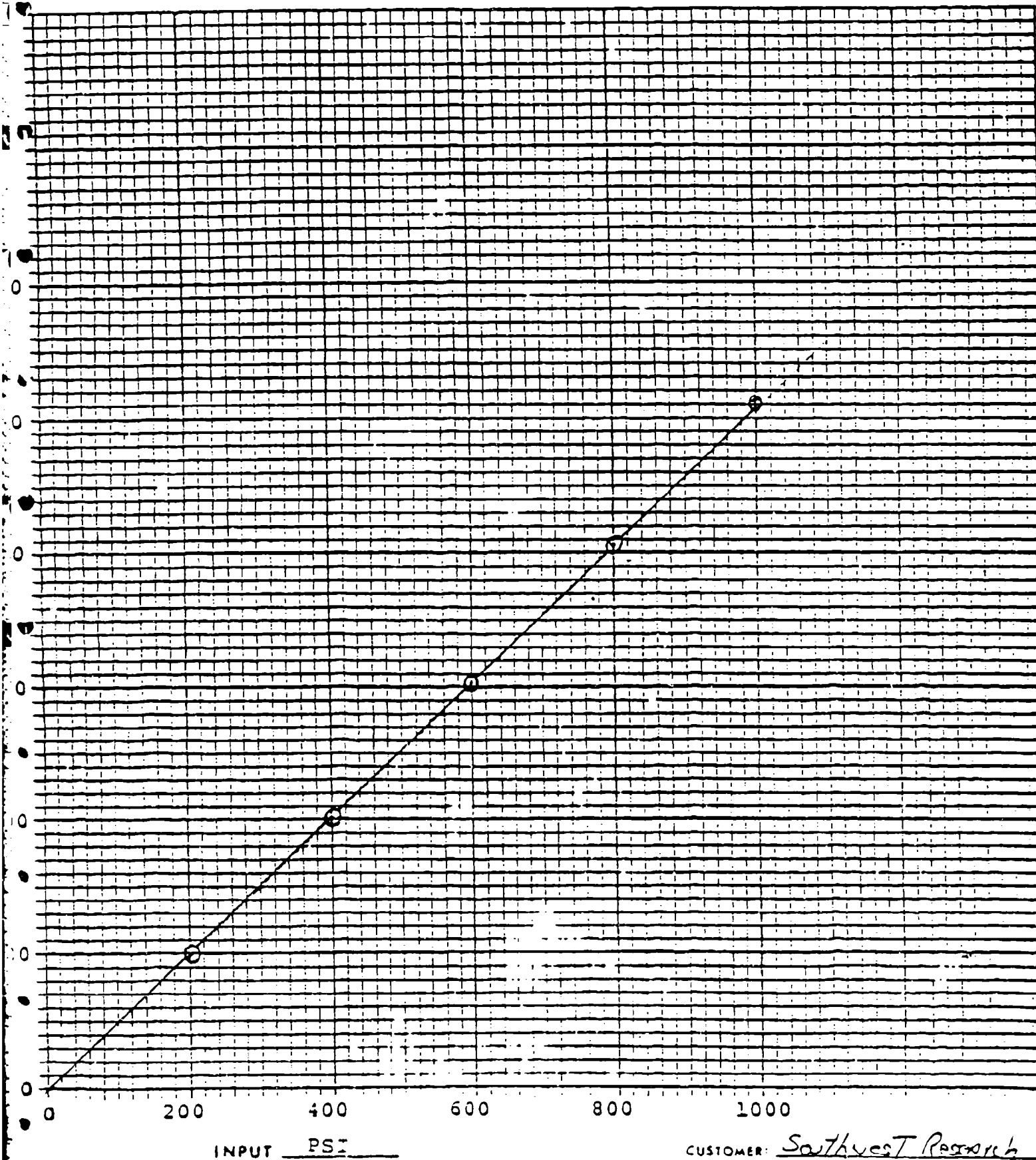
Cal. Range 0 - 1000
Input Time Constant 1000 Sec
Rise Time 1 μ Sec
Natural Frequency 45 KHz
Output Impedance <100 Ohms

BUFFALO, NEW YORK 14225

By T. F. [Signature]

Date 8-17-57

*By comparison with reference
Standard per ISA S37.10



CUSTOMER: Southwest Research
P.O. NO. 7949456

APPENDIX "B"
QUALIFICATION TEST REPORTS
QTR - 2191
SECTION P
FUEL FIRE TEST



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTR-2191-001

DATE: 4-6-82

PAGE

OF

Universal QTR-2191
Report No. Section "P"

Dynamic Science
Report No. 4111-81-075/1899
Revision _____

REPORT OF: Fuel Fire Qualification
Test of Fiber Science 450 Gallon
Filament Wound, Lightweight, Ex-
plosion Proof, External Fuel Tank
for H-53 Helicopter.

TEST PERFORMED BY:

Dynamic Science, Inc.
1850 W. Pinnacle Peak Road
Phoenix, AZ 85027

TEST AUTHORIZED BY:

Fiber Science, Inc.
Salt Lake International Center
506 Billy Mitchell Road
Salt Lake City, UT 84116

Contract No. F09603-79-C-1642

	Date	Signature
Test Initiated	3/26/81	(contract award)
Test Completed	6/26/81	
Report Written By (DSI)	8/20/81	<i>James B. E</i>
Supervisor	8/20/81	
FSI Test Engineer		
Supervisor		
Government Representative		
Final Release		

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 PURPOSE AND BACKGROUND	1
1.2 DESCRIPTION OF TEST SAMPLES	2
1.3 DISPOSITION OF TEST SPECIMEN	2
1.4 CONCLUSIONS AND RECOMMENDATIONS	2
1.5 REFERENCES	3
2.0 FACTUAL DATA	4
2.1 DESCRIPTION OF TEST APPARATUS	4
2.2 TEST PROCEDURE	4
2.3 TEST RESULTS	10
3.0 TEST DATA	13
3.1 TEST CONDITIONS	13
3.2 TEST RESULTS	13
APPENDIX A - FUEL FIRE THERMOCOUPLE DATA	A-1
APPENDIX B - FUEL FIRE PHOTOGRAPHS	B-1
APPENDIX C - FIBER SCIENCE, INC. DOCUMENT NUMBER QTP-2191 SECTION "P" QUALIFICATION TEST PROCEDURE H-53 TANK REQUIREMENTS FOR FUEL FIRE TEST	C-1
APPENDIX D - COMPLETE LISTING OF 35 MM TEST PHOTOGRAPHS	D-1

1.0 INTRODUCTION

1.1 PURPOSE AND BACKGROUND

The test described in this report is a Fuel Fire Qualification Test of the 450 Gallon Filament Wound, Lightweight, Explosion Proof, External Fuel Tank for the H-53 series helicopter.

The Fuel Fire Test is described in Paragraph 3.4.1.7.4 of Technical Exhibit ASD/ENFEA-78, October 1978:

"A tank full of JP-5 shall withstand an open pit fuel fire (JP-4) for ten minutes without rupture. Suspension height above the fuel fire shall be 48 ± 2 inches from tank centerline to fuel surface line."

The fire-proof external tank was originally suggested in Mishap Control No. WR76-022A.

This test was performed for Fiber Science, Inc. by Dynamic Science, Inc., at its test facility in Phoenix, Arizona. This Test Report was prepared by Dynamic Science, Inc., except for Section 1.4.2 and those portions of Data Sheet 2 requiring cross-sectioning of the tank.

1.2 DESCRIPTION OF TEST SAMPLE

The sample used in this test was a prototype of the 450 Gallon, Filament Wound, Lightweight, Explosion Proof, External Fuel Tank for the H-53 series helicopter. This tank was developed and fabricated by:

FIBER SCIENCE, INC.
Salt Lake International Center
506 Billy Mitchell Road
Salt Lake City, UT 84116

under Contract No. F09603-79-C-1642 from USAF Logistics Command, Warner Robins Air Logistics Center. The tank was designated by Fiber Science, Inc., as Part Number 2191-001A, Serial No. 0005, and was manufactured in April 1981. This tank had undergone previous testing.

1.3 DISPOSITION OF TEST SPECIMEN

Following post-test examination by Dynamic Science, Inc., the test specimen was returned to Fiber Science, Inc. for further analysis.

1.4 CONCLUSIONS AND RECOMMENDATIONS

1.4.1 Conclusions

The fuel fire test was conducted with a slight breeze (7 - 12 mph). The reservoir fuel pan was insufficient in width, under this condition, and thus only about 75 percent of the circumference of the tank was engulfed in flames.

After ten minutes of burn, extinguishing of the fire began in accordance with specification requirements. The tank was in test a total of 30 minutes, or 20 minutes beyond the specification requirements before the fire could be extinguished.

1.4.2 Recommendations Concerning Test Procedure

Based on the experience of this test, there are two procedure changes that should be incorporated in future tests:

1. The fuel reservoir should be wider to minimize the effects of wind in order to ensure that the tank is fully engulfed in flame.
2. The fire crew on hand should be allowed to extinguish the fire in the manner they deem best, rather than being restricted by other instructions.

1.5 REFERENCES

1. Technical Exhibit ASD/ENFEA-78, October 1978.
2. Mishap Control No. WR76-022A
3. "Qualification Test Procedure, H-53 Tank, Requirements for Fuel Fire Test," Fiber Science, Inc., Document No. QTP-2191 Section "P," December 1980.

2.0 FACTUAL DATA

2.1 DESCRIPTION OF TEST APPARATUS

Table 2-1 presents a summary of all instruments and equipment used for the collection of data; the equipment manufacturers' names, instrument serial numbers, ranges, accuracy, and dates of latest calibration. All other data (i.e., static measurements) were obtained via standard measurement techniques.

2.2 TEST PROCEDURE

The requirements of the Fuel Fire Test are as previously stated in Section 1.1.

Section 2.2.1 describes the Fuel Fire Test procedure. Section 2.2.2 describes the electronic data acquisition process. Section 2.2.3 describes photography.

2.2.1 Fuel Fire Test Procedure

The test procedure generally followed the outline of Fiber Science, Inc. document QTP-2191 Section "P," "Qualification Test Procedure, H-53 Tank, Requirements for Fuel Fire Test," (Appendix C).

The procurement of military grade fuels JP-4 and JP-5 by a non-military organization presented a major obstacle in the conduct of this test. Therefore, with the approval of Fiber Science, Inc., the commercial fuel Jet-A (described in Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, P. 7-18, as "similar to JP-5") was substituted as both the reservoir and tank fuel.

TABLE 2-1. FUEL FIRE INSTRUMENTATION AND TEST EQUIPMENT SUMMARY						
Item	Model	Manufacturer	Serial No.	Range	Accuracy	Date of Last Calibration
Thermocouples	Type K Chromel-Alumel	Omega Engineering, Inc.	None	-300°-2300°F	±0.75%	None
Remote Signal Conditioning Module	M140	Ectron	3081 3082	*	*	Cal Before Use
Instrumenta- tion Tape Recorder	Sabre III	Sangamo	7153	*	*	1-28-81
Playback Tape Recorder	Sabre III	Sangamo	7628	*	*	1-28-81
FM Demodulators	GFD-15/TU01	Data Control Systems	1073501 thru 1073523	*	*	Cal Before Use
Butterworth Analog Filters	4122	Ithaco	25745 thru 25751	*	*	3-06-81
Brush Recorder	2400	Gould, Inc.	00919		±2.35%	1-10-81
24 PPS Camera	16 Standard	Mitchell	238	24 PPS	From AC Source	None
*The Dynamic Science data acquisition system provides a flat, linear response up to 1 KHz with ±5% error.						

The tail plug of the tank, accessible only for test purposes, was covered over with a graphite/epoxy mixture by Fiber Science, Inc. as it would be for standard units. Internal thermocouples were routed through the various tank access covers and the nose plug. External thermocouples were held in place by the aforementioned graphite/epoxy mixture. The rubber hose portions of the fuel and air valves were painted with Avco's Flamarest 1400-S Fireproofing coating. (Directions for mixing and applying this substance were not supplied until less than 48 hours prior to the test and the manufacturer specifies a 72 hour cure. The degree of protection provided was therefore unknown.) This material would normally be applied by Fiber Science prior to the tank leaving their facility.

The fuel tank with integral pylon assembly was hung from a Fiber Science "Qualification Test Fixture" using the attachment hooks of the pylon assembly. The Qualification Test Fixture was bolted to a steel A-frame fixture such that the tank was in a two degree nose down attitude and the center point of the tank was 48 inches above the top surface of the reservoir fuel, per Figure 1 of Appendix C.

The fuel reservoir consisted of six 4' X 8.5' X 4" steel pans constructed from 18 gauge steel. These pans were laid side by side to form a continuous 24' X 8.5' reservoir. A one-inch-deep layer of sand was placed in the bottom of each pan to provide insulation from the heat of fire to avoid warping the pans.

The steel A-frame with tank attached was placed in the empty fuel reservoir. All thermocouple attachments were completed and the thermocouple connectors were wrapped with asbestos tape. The attachment points of the Qualification Test Fixture to the A-frame were also protected with asbestos tape. Steel cables were attached to the mounting bolts at either end of the pylon and looped over the top of the A-frame to provide redundant support of the tank in the event of a melt-through of the aluminum pylon assembly.

The fuel tank was filled through the aft filler access to the point of overflow from a standard airport fuel tanker truck. Per Fiber Science Qualification Test Procedure QTP 2191, Section "P," Paragraph 4.5, the tank contains 450 to 457 gallons of fuel when filled by this procedure while suspended in a two degree nose down attitude. The reservoir pans were filled to a depth of 3.5 inches.

Ignition of the fuel reservoir was accomplished with a remote electric match ignition system with a manual torch backup. Time zero for the test was established to be that time when one of the external thermocouples registered 1750°F or when the temperature leveled off at an apparent steady maximum.

The fire was allowed to burn unabated for ten minutes after time zero, at which time the test was completed and the fire crew began the extinguishing process.

The thermocouple outputs were recorded on magnetic tape and the event was photographed with both a motion picture camera and a 35 mm slide camera.

2.2.2 Electronic Data Acquisition

The electronic data obtained in this test consisted of temperatures measured by ten internal and nine external thermocouples, as shown in Figure 2-1 and Table 2-2.

The individual transducers and other components of the data acquisition system are previously described in Table 2-1. Each thermocouple was attached to an Electron differential amplifier within one of the Remote Signal Conditioning Module (RSCM) mainframes by an umbilical cable. After amplification, the transducer signals were converted to the frequency domain by the Voltage Controlled Oscillators within the RSCM mainframe. The information

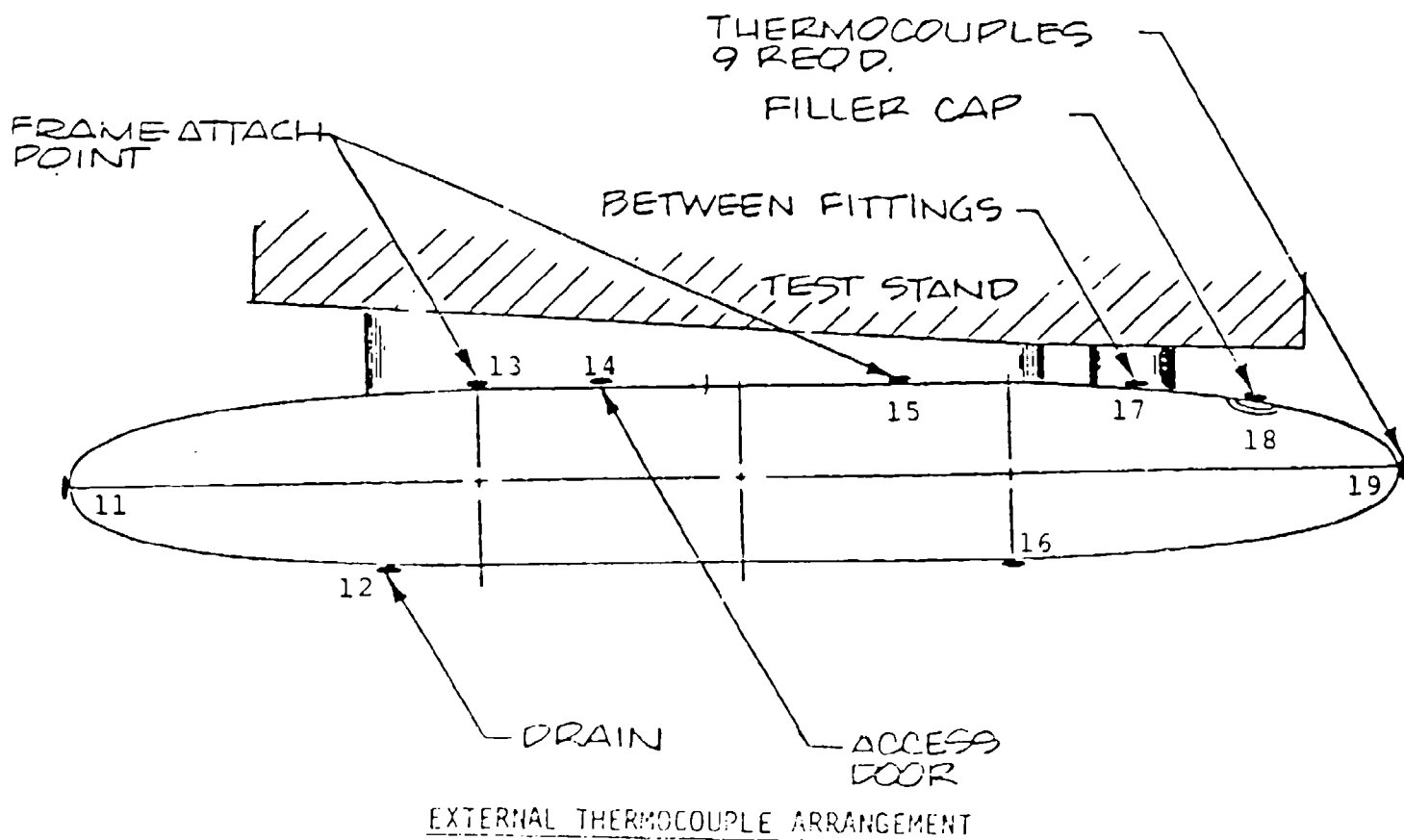
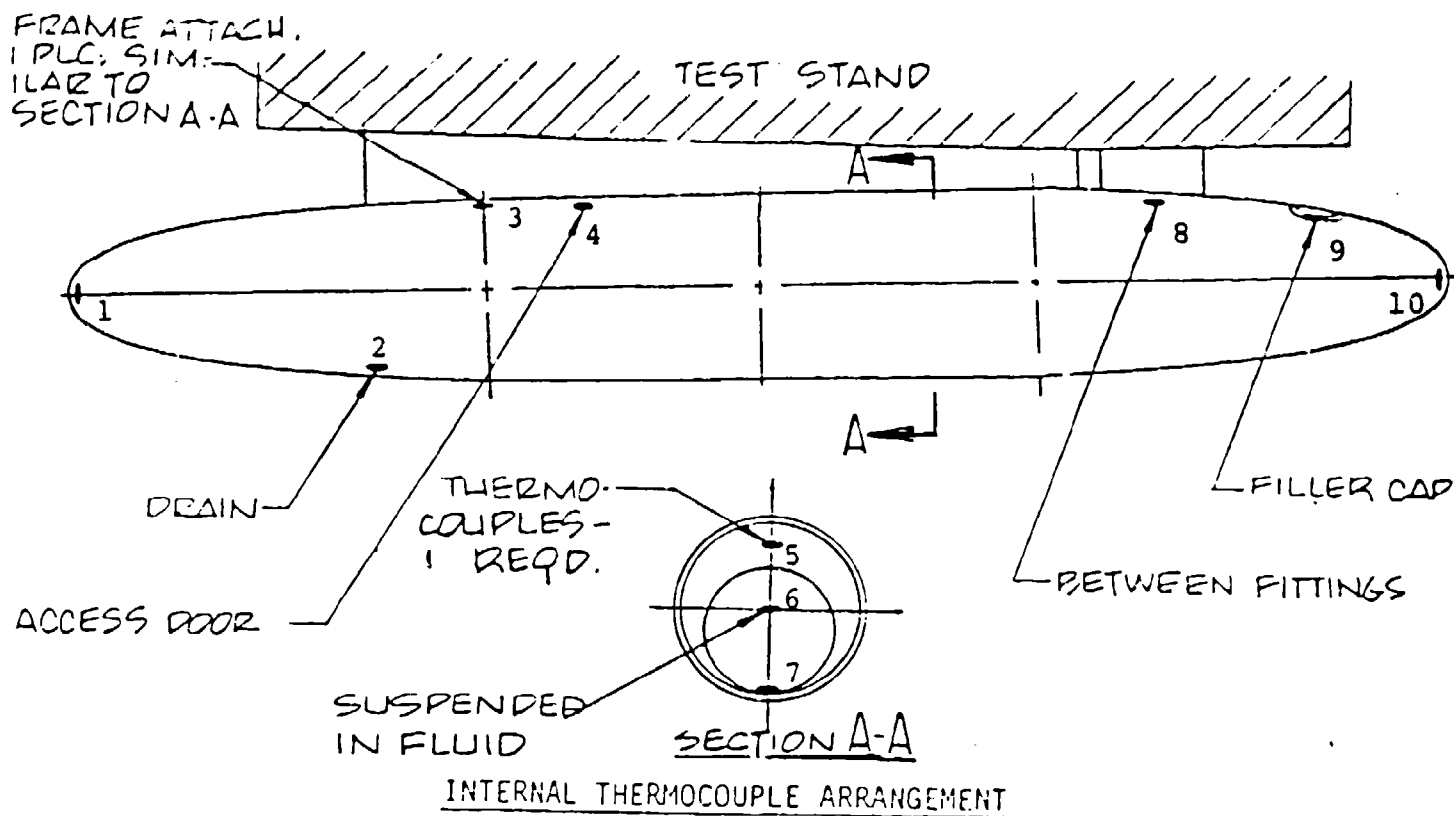


FIGURE 2-1. FUEL FIRE THERMOCOUPLE LOCATIONS.

TABLE 2-2. DESCRIPTION OF FUEL FIRE THERMOCOUPLE LOCATIONS

Thermocouple		Location
T1	Internal	Near Nose Plug
T2	Internal	Near Drain Plug
T3	Internal	Near Top of Forward Frame
T4	Internal	Below Forward Access Cover
T5	Internal	Near Top of Aft Frame
T6	Internal	Tank Centerline Behind Aft Frame
T7	Internal	Near Bottom of Aft Frame
T8	Internal	Between Fuel and Air Valves
T9	Internal	Near Fuel Filler Access
T10	Internal	Near Tail Plug
T11	External	Nose Plug
T12	External	Drain Plug
T13	External	Over Forward Frame
T14	External	Over Forward Access Cover
T15	External	Over Aft Frame
T16	External	Bottom of Tank, Rear of Aft Frame
T17	External	Between Fuel and Air Valves
T18	External	Over Fuel Filler Access
T19	External	Tail Plug

was then multiplexed and transmitted via hardline umbilical to the Sabre III instrumentation tape recorder for recording.

The recorded multiplexed signal was later played back and demodulated by the Data Control Systems demodulator. The demodulated analog signal was then filtered and plotted by the Gould brush recorder.

The data traces presented in Appendix A are the actual thermocouple output voltage levels. Corresponding temperature levels were determined from the manufacturer's calibration table and superimposed on each chart for reference.

2.2.3 Photographic Coverage

The Fuel Fire Test was recorded on 16 mm color film by one studio quality motion picture camera, as shown in Table 2-3. A hand-held 16 mm camera was used as a backup. The film speed was nominally 24 fps; however, due to loading of the AC generator used to power the camera, the actual film speed during the test was observed to be 21 fps.

Additional photographic coverage consisted of 35 mm slides and 16 mm post-test documentary footage.

2.3 TEST RESULTS

The tank did not rupture during the test; however, it was observed to be leaking to some extent along the entire length of the underside after the fire was extinguished.

It should be noted that the fire was not completely extinguished until approximately 30 minutes after test initiation. This resulted in an addition of approximately 20 minutes to the specified burn time. During the extinguishing process, the tank

was sprayed with water while awaiting standby fire units to arrive. This water could have become trapped in the honeycomb cells on the side of the tank, mixed with fuel vapors and some fuel leaking from the tank post-test, and thus judged to be "fuel" leaking. The extent of actual fuel leakage observed is therefore considered questionable in the absence of a chemical analysis.

As the pass/fail criteria for this test is the absence or presence of a rupture, and a rupture is generally defined as a break or breach, the tank appears to meet specification requirement.

Test No: T1-1 Test Date: June 26, 1981

Test Type: Fiber Science Tank Fuel Fire Test

Vehicle A:

Vehicle B:

Comments: Qualification Test for Fiber Science

450 Gallon H-53 Helicopter External Tank

CAMERA	YES
STILLS	
SLIDES	X
MOVIE	X
POLAROID	
VIDEO	
DOCUMENTARY	X

CAMERA SYMBOLS FRAME RATE

PIT
O

1. 1000 fr/sec

GROUND

2. 200 fr/sec

GROUND

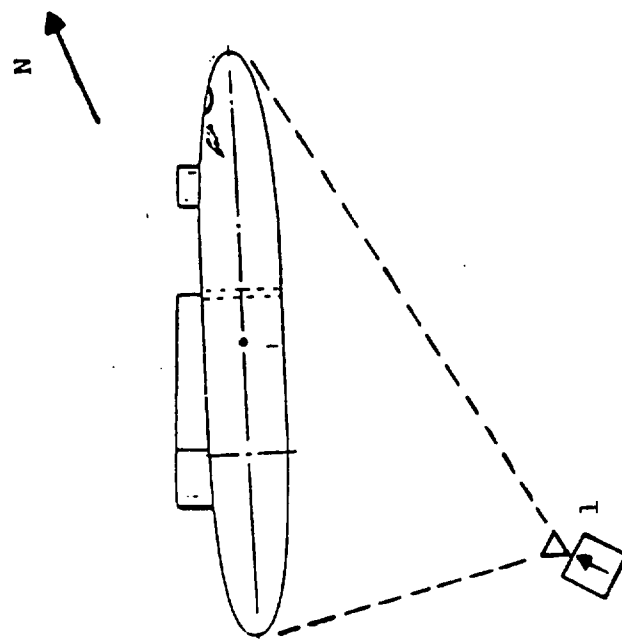
3. Other 24 fr/sec

Δ BARRIER

4. 400 fr/sec

☒ OVERHEAD☒ ON-BOARD

PANNING

[illegible]

DSI FORM NO. TSO 125

3.0 TEST DATA

3.1 TEST CONDITIONS

The test was set up according to the procedures set forth in Section 2.2. Pre-test approval was obtained (Data Sheet 1) and the test proceeded.

A summary of the test conditions is presented in Table 3-1.

3.2 TEST RESULTS

After the tank had been filled and sealed and the reservoir had been filled, instrumentation was initiated, and the ignition system was fired. The remote ignition system failed to ignite all six reservoir pans, and ignition was completed by hand. Time zero was established when exterior thermocouple readings leveled off. Thermocouple readings are presented in Appendix A.

Due to delay caused by instrumentation setup problems earlier in the day, the test was initiated two-and-one-half hours later than originally planned. In the meantime, a 7-12 mph wind came up. Because of the wind and the relatively narrow fuel reservoir, only the bottom and downwind side of the tank were fully engulfed by the flames.

During the course of the test, a significant flame was observed to be burning around the fuel filler and air vent valves. One possible explanation is that the elevated internal temperature caused fuel expansion significant enough to force fuel and/or vapors out through the valves where it was subsequently ignited. Another possible explanation is that the flame observed around the filler and vent valves was actually burning epoxy resin which is present in both these areas. It was not possible to distinguish between these two conditions while the reservoir was burning.

Some fuel leakage from the top of the tank was apparent once the reservoir fire was controlled.

After the specified burn time of ten minutes, the fire crew began to extinguish the fire. Following instructions given earlier, they attempted to minimize the amount of extinguishant sprayed on the test article. Due in part to the magnitude of the fire in the reservoir, and in part to the fire caused by the fuel leaking from the tank above the reservoir, the fire was not extinguished quickly and the crew ran out of the "light water" foam. They were then forced to spray a plain water jet on the tank to keep it cool until more fire units could arrive. This water jet tore away most of the graphite windings that had been exposed on the downwind side of the tank. Extra fire units arrived and the fire was finally extinguished some 33 minutes after time zero.

Prior to final extinguishing, the tape recorder had run out of tape and the camera had run out of film.

Following the conclusion of the test, the fuel remaining in the tank was pumped out into a fuel truck. During the fuel removal operation, it was noted that long, sticky strands of a brown material were clogging the screen of the siphon tube. It is possible that the very high internal temperature had melted the thermoplastic liner inside the tank and that the strands of material were thermoplastic. This explanation would account for the leakage of fuel noted after the test.

The damage to the tank is described in the post-test observations of Data Sheet 2. Table 3-2 presents a summary of the thermocouple readings throughout the first ten minutes of the test. All readings presented from internal thermocouples are considered unreliable. Dynamic Science does not believe that the relatively quick rise times indicated, or the ultimate reading attained, are

realistic for this type test. It is probable that actual temperatures of this magnitude would have melted the tank liner as well as some portion of the internal fiberglass windings. Readings from the external thermocouples are presented with a high degree of confidence and believed to be accurate. Color photographs of the test are presented in Appendix B.

DATA SHEET 1. PRE-FUEL FIRE EXAMINATION

Testing Activity: Dynamic Science, Inc.

Tank Serial No.: 0005

Test Date: June 26, 1981

Activity Test Engineer: Terry Bjork

Fiber Science, Inc. Test Engineer: Richard R. Lyman

Government Representative: Hugh Hilliard

EXAMINATION OF PRODUCTS:

Visual Inspection: Approved

Delaminations (Tap Test): Approved

MOUNTING:

Aircraft Simulated Attachment Deviations If Any:

Fuel and air fittings exposed (fairing in place) -
instrumentation in nose plug on forward end -
secondary support cables attached at pylon support bolts

ARRANGEMENT:

Approved Test Arrangement:

Testing Activity Approval

Approved By Terry Bjork Date 6-26-81

F.S.I. Test Engineer Approval

Approved By Richard R. Lyman Date 26 JUNE 81

Government Approval

Approved By Hugh Hilliard Date 26 Jun 81

Minimum of two signatures required.

TABLE 3-1. FUEL FIRE TEST SUMMARY

Test Description: FSI 450 Gallon Tank Fuel Fire
Qualification Test

Tank Serial Number: 0005 Mfg. Date: April 1981

Test Number: T1-1

Number of Data Channels: 19

Number of Cameras: 1

Date: June 26, 1981 Time: 9:29 AM Temperature: 99°F

PRE-TEST DATA

Tank Fuel: Jet-A - 450 gallons approx.

Reservoir Fuel: Jet-A - 255 gallons approx.

Wind: 7-12 mph E/ESE

POST-TEST DATA

Initial Ignition: 9:28:04

Complete Reservoir Ignition (t_0): 9:29:47

Begin Extinguishing (test complete): 9:39:50

Extinguishing Complete: 10:02:45

Number of Ruptures: None

TO BE COMPLETED BY FIBER SCIENCE

EVALUATION OF DATA

CAMERAS: _____

THERMOCOUPLE RECORDINGS: _____

GENERAL CONDITION: _____



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTP-2191 Section "P"

DATE: 11/20/80 PAGE 19 OF 19

DATA SHEET 2. POST FUEL FIRE EXAMINATION (CONTD)

PYLON CONDITION:

Light sheet aluminum on right side nearly completely melted away. Main pylon support members blackened but intact. Pylon internal mechanisms blackened but intact.

TO BE COMPLETED BY FIBER SCIENCE

DISSECTION OF TANK

Approved By _____ Date _____

GENERAL INTERIOR CONDITION

CONDITION OF INNER WINDING

CONDITION OF LINER

APPENDIX A
FUEL FIRE THERMOCOUPLE DATA
(Analog Filter = 100 Hz)

DEGREES F

T1 INTERNAL
NGSE PLUG

2503
2199
1914
1641
1377
1122
868
611
344
80

DEGREES F

T2 INTERNAL
NEAR DRAIN PLUG

2503
2199
1914
1641
1377
1122
868
611
344
80

DEGREES F

T3 INTERNAL - REAR OF
FORWARD FRAME TOP

2503
2199
1914
1641
1377
1122
868
611
344
80

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T1

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T2

ACCUCHART

Gould Inc.

Cleveland, Ohio

Printed in U.S.A.

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T3

DEGREES F

503
99
914
541
377
122
858
611
344
80

DEGREES F

503
799
914
641
377
122
858
611
344
80

DEGREES F

2503
2199
1914
1641
1377
1122
858
611
344
80

73

9

10

11

DEGREES F

T4 INTERNAL - BELOW
FRONT ACCESS COVER

503
199
914
641
377
122
868
611
344
80

DEGREES F

T5 INTERNAL - REAR
OF AFT FRAME TOP

503
199
914
641
377
122
868
611
344
80

DEGREES F

T6 INTERNAL - REAR OF
AFT FRAME AT TANK C

503
199
914
641
377
122
868
611
344
80

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T4

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T5

DEGREES F

2503
2199
1914
1641
1377
1122
868
611
344
80

T6

ACCUCHART

Gould Inc.

Cleveland, Ohio

Printed in U.S.A.

DEGREES F

2503
2199
1914
1641
1377
1122
858
611
344
80

T4

DEGREES F

2503
2199
1914
1641
1377
1122
858
611
344
80

T5

DEGREES F

2503
2199
1914
1641
1377
1122
858
611
344

T6

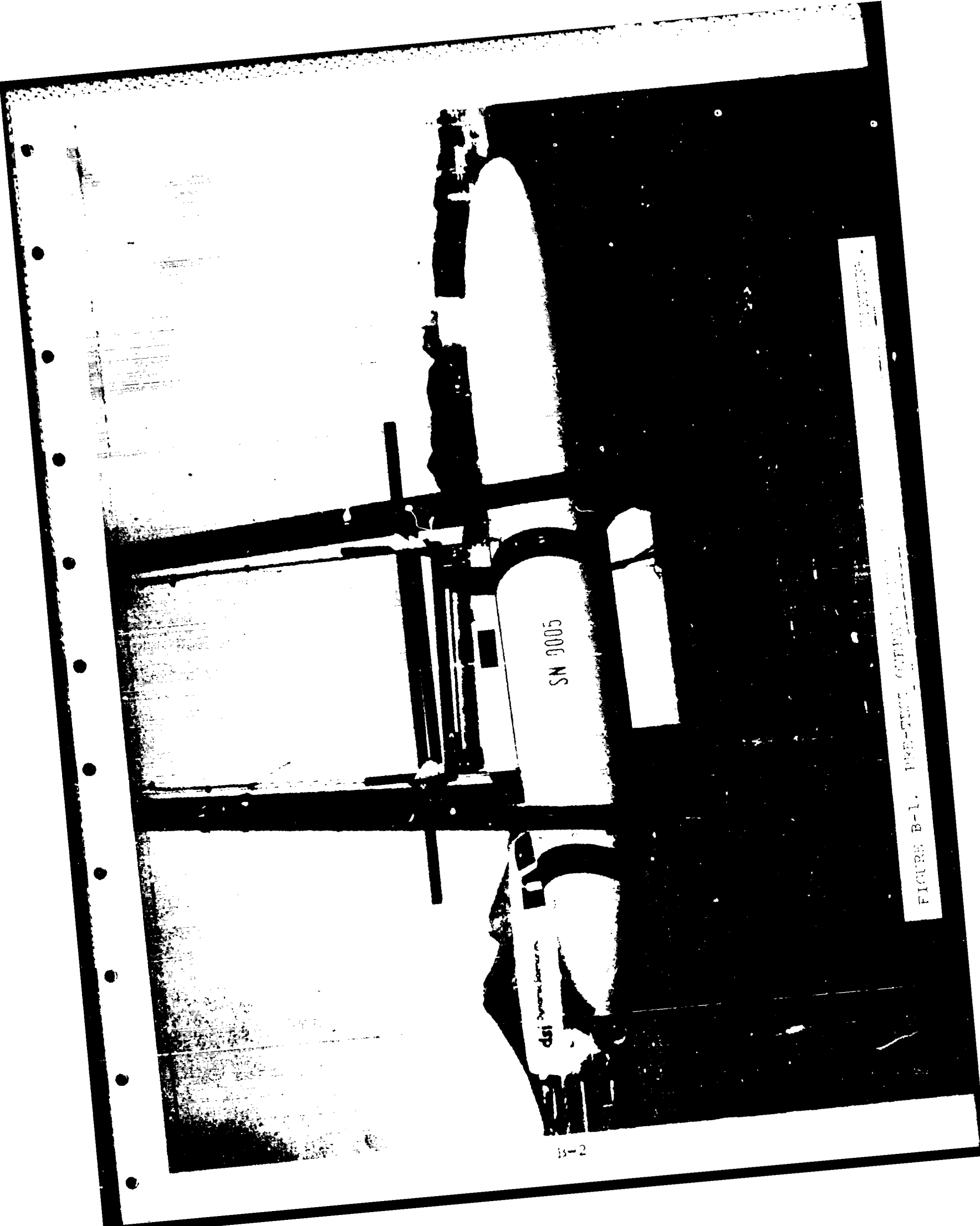


FIGURE B-1. PRE-TEST OUTPUT



FIGURE B-2. PRE-TEST OVERALL REAR VIEW OF TANK ON "TOWER".



FIGURE B-3. PRE-TEST CLOSE-UP VIEW OF NOZZLE FITTING.



FIGURE B-4. PRE-TEST CLOSE-UP VIEW OF FUEL ACCESS.



FIGURE B-5. OVERALL VIEW OF TANK EARLY IN TEST.



FIGURE B-6. CLOSE-UP VIEW OF TANK DURING TEST.

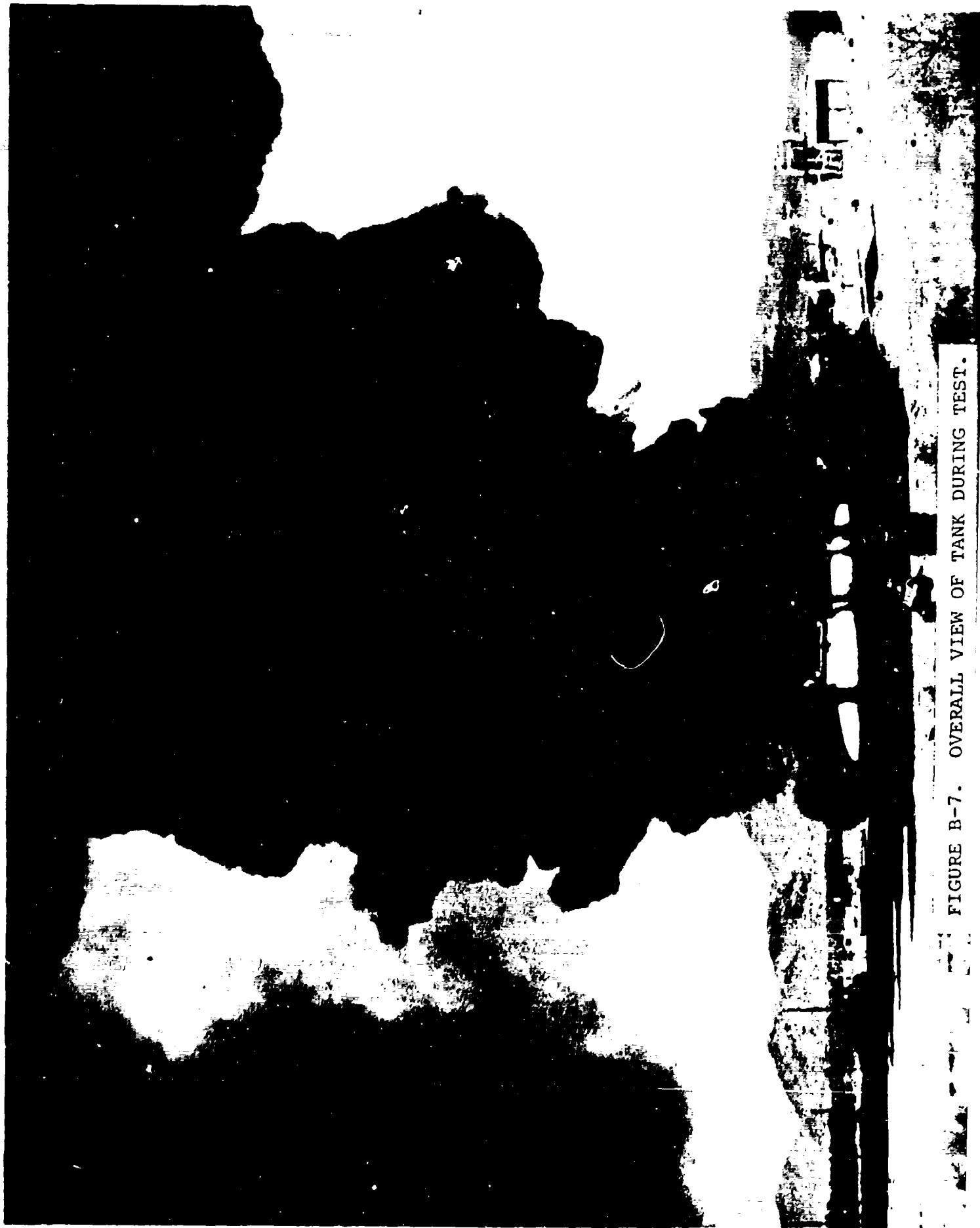


FIGURE B-7. OVERALL VIEW OF TANK DURING TEST.

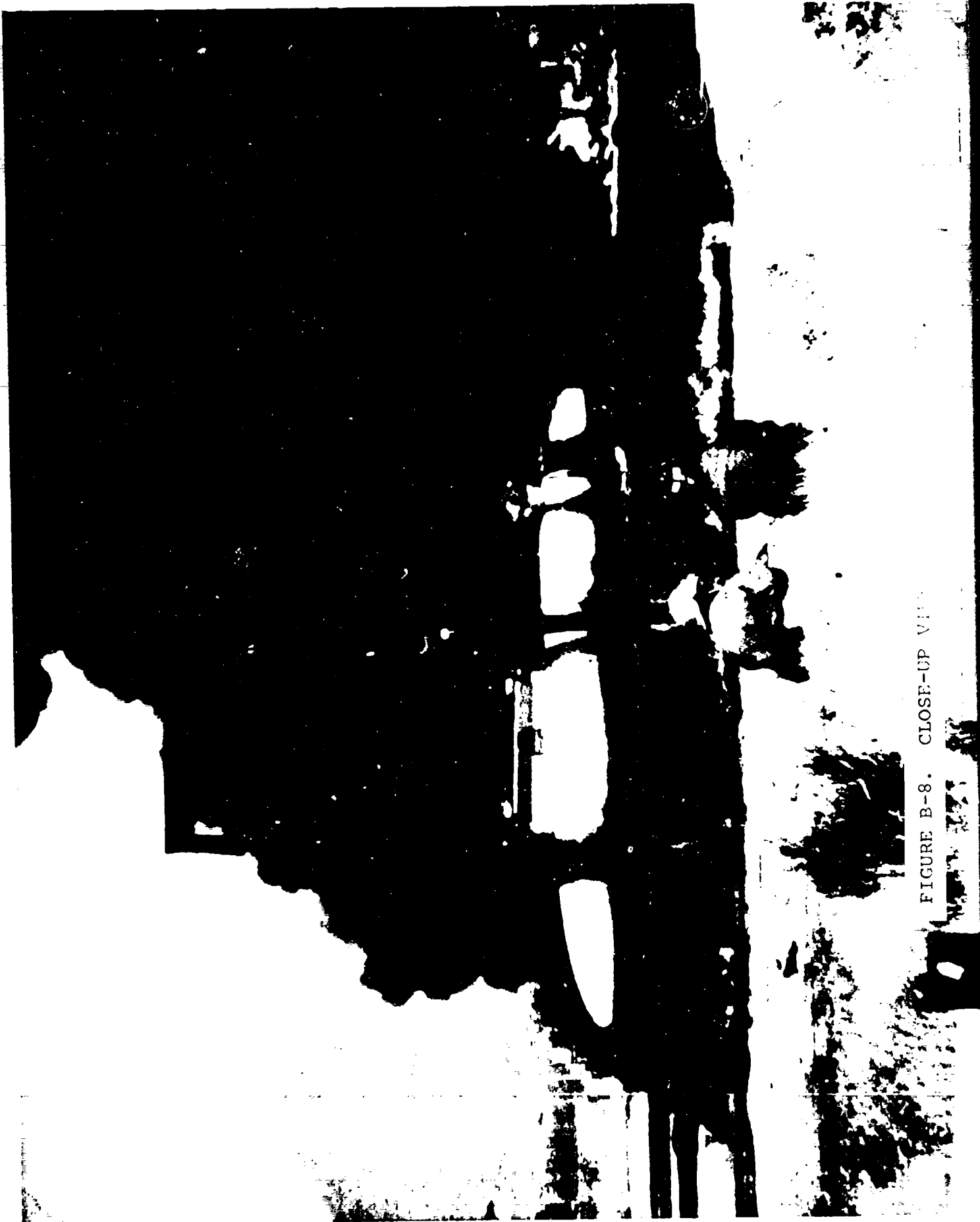


FIGURE B-8. CLOSE-UP VIEW



FIGURE B-9. POST-TEST OVERALL LEFT SIDE VIEW OF TANK.

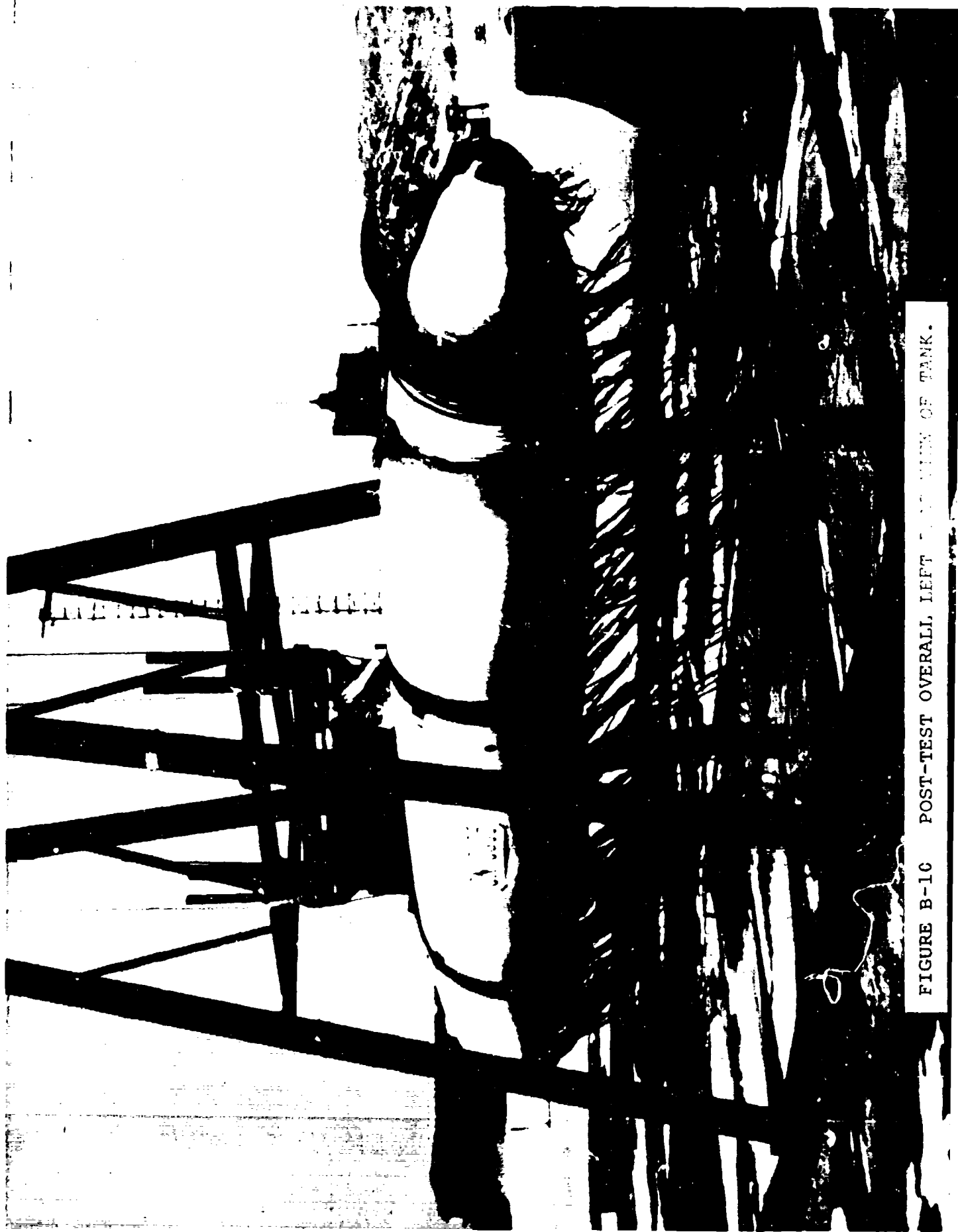


FIGURE B-10 POST-TEST OVERALL LEFT SIDE VIEW OF TANK.

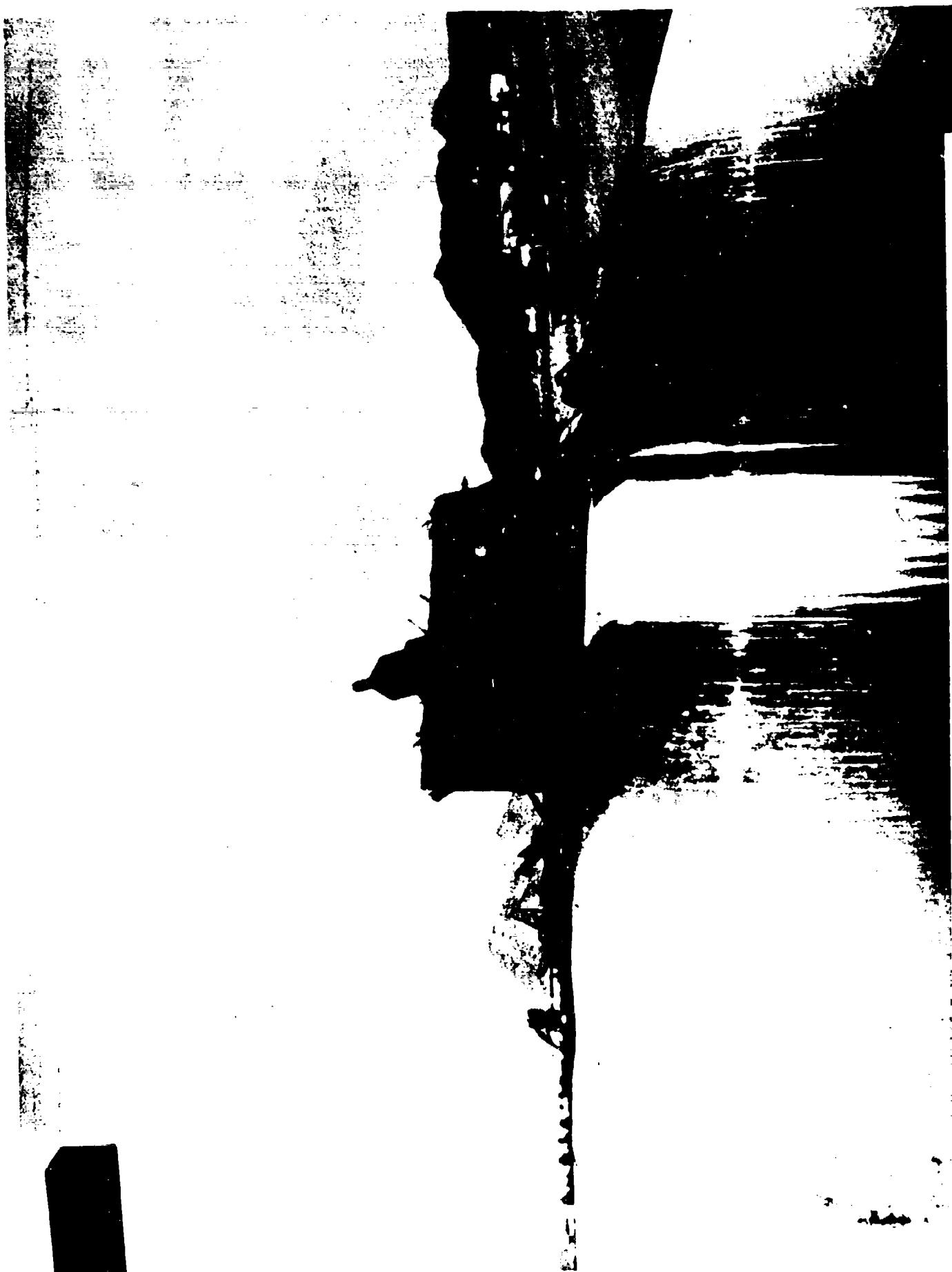


FIGURE B-11. POST-TEST CLOSE-UP LEFT SIDE VIEW OF FUEL AND AIR VALVE REGION.

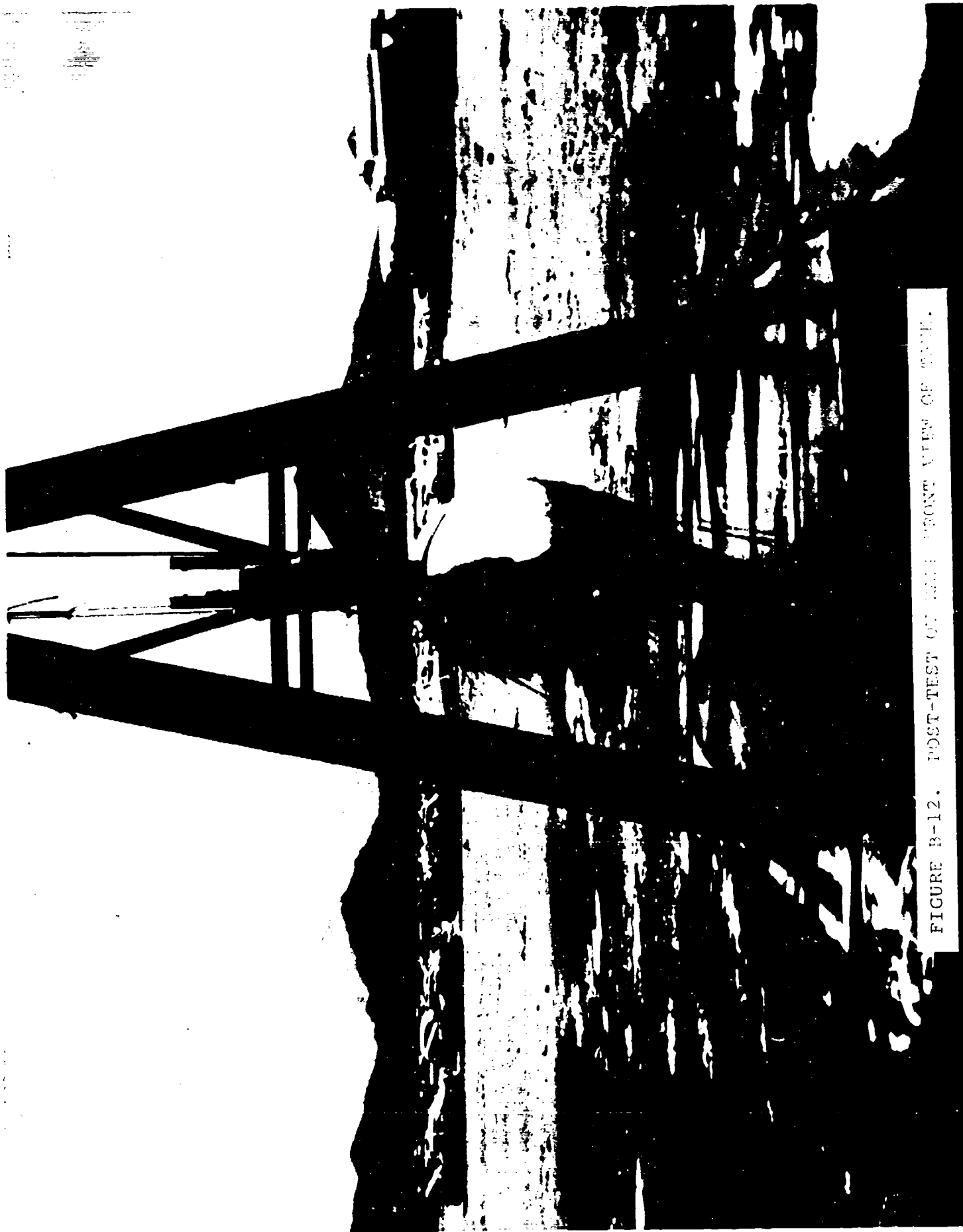


FIGURE B-12. POST-TEST OF LARGE FRONT VIEW OF TOWER.

APPENDIX "B"
QUALIFICATION TEST REPORTS
QTR - 2191
SECTION R
LIGHTNING TEST



FIBER SCIENCE, INC.
SALT LAKE CITY, UTAH

NO. QTR-2191-001

DATE: 4-6-82

PAGE

OF

LIGHTNING QUALIFICATION TESTS
ON A
450 GALLON FILAMENT - WOUND
FUEL TANK

BY
J.E. PRYZBY

FOR
FIBER SCIENCE, INC.
SALT LAKE INTERNATIONAL CENTER
506 BILLY MITCHELL ROAD
SALT LAKE CITY, UT 84116

P.O. A3607
DATA BOOK 16 PP 90-94

JULY 16, 1981

LIGHTNING TECHNOLOGIES, INC.
10 DOWNING PARKWAY
PITTSFIELD, MA 01201

Table of Contents

	Page
1.0 Introduction	1
2.0 Summary of Results	1
3.0 Description of the Test Specimen	2
4.0 Description of Tests	2
4.1 Lightning Strike Attachment Tests	2
4.1.1 High Voltage Test Circuit	3
4.1.2 Test Results	3
4.2 Physical Damage Tests	12
4.2.1 High Current Test Circuit	12
4.2.2 High Current Test Results	13
5.0 Discussion of Results	20
5.1 Physical Damage	20
5.2 Electrical Sparking	22
5.3 Induced Voltages	22

1.0 Introduction

Simulated lightning attachment and physical damage tests were performed on a full scale 450 gallon filament-wound external fuel tank (part no. 2191-001) for the H-53 helicopter. A Sargent Fletcher pylon assembly (part no. 27-450-4400) was attached to the tank. The tests were performed according to Fiber Science Qualification Test Procedure QTP-2191 Section R dated 29 November 1980.

Testing took place at Lightning Technologies, Inc. during the period of 4 - 8 June 1981. The tests were witnessed by R. Lyman of Fiber Science, Inc. and H. Hilliard of the U.S. Air Force. Tests were conducted by J.A. Plumer and J.E. Pryzby of Lightning Technologies, Inc.

2.0 Summary of Results

For the lightning attachment tests, the high voltage probe was placed at various locations along the fuel tank. These included locations opposite the drain valve, lower adapter screw, graphite/epoxy and glass interface, graphite area, nose fuel filler cap, and inside ring.

The tests showed that lightning may be expected to strike the drain valve, fuel probe, lower adapter screw and the composite skin itself, but not the filler cap, which is recessed in the filament wound skin. The general location of most lightning strikes to the tank is determined by the location of the tank on the helicopter. In the application planned, the lower and outboard surfaces of the tank may be expected to receive most of the strikes. None of the high voltage tests conducted on this tank resulted in puncture of the composite skin.

The high current physical damage tests were conducted with the electrode positioned over the fuel cap, glass and composite skins in the nose area and over the forward central rib. The resistance of the composite skins limited the test current to currents of 135 kA, which, while representing a severe strike, did not fall within the tolerance range of SAE current component A (a very severe stroke). Evidence of internal sparking was noted by evidence of light on Polaroid photographs of the inside of the tank for 6 of the 14 strike current tests. The location of this sparking could not be determined positively, but was thought to be at the pylon attachment bolts. Minor damage and local delamination occurred to the composite skin from these tests but no evidence of puncture through the tank wall was noted.

During some of the high current tests, voltages induced in the fuel quantity probe wiring inside the tank were made. Voltage transients of up to 1600 volts were measured between the Hi Z and Lo Z probe conductors at the probe connector on the top of

the tank. Since most fuel quantity probes are capable of withstanding a surge of 10 kV without sparking between capacitive elements, the voltages measured here are not likely to cause a hazard. It must be remembered, however, that additional voltages may be induced in the portion of the electrical circuits that run between the tank and the gauging system within the helicopter. These voltages could not be evaluated during these tests, and can only be evaluated by tests of the tank installed on the complete helicopter.

Induced voltages were not measured in the pylon ejection circuitry because the circuits leading to the ejection cartridges are located primarily in the helicopter, and were not available for these tests.

3.0 Description of the Test Specimen

The test specimen was a full scale, pre-production, 450 gallon filament-wound external fuel tank (P/N 2191-001, SN006) for the H-53 helicopter. A Sargent Fletcher pylon assembly (P/N 27-450-4400) was attached to the tank.

4.0 Description of Tests

4.1 Lightning Strike Attachment Tests

Simulated lightning strike attachment tests (also called high voltage tests) were performed first to determine detailed lightning strike attachment points, and especially, to determine if metallic objects on the tank, such as the drain valve, would attract strikes. The tank was initially positioned with the high voltage electrode adjacent to the drain valve at a distance of 12". The pylon was connected to the generator ground circuit. A 475:1 resistive voltage divider in conjunction with a Tektronix 544 oscilloscope was used to measure the voltage applied between the test electrode and the fuel tank. A Polaroid-type camera was positioned so that its lens entered the interior of the tank through the filler cap opening near the pylon. Any light detected by the camera during testing would be indicative of interior sparking. Figure 1 shows the tank in position for the lightning strike attachment tests.

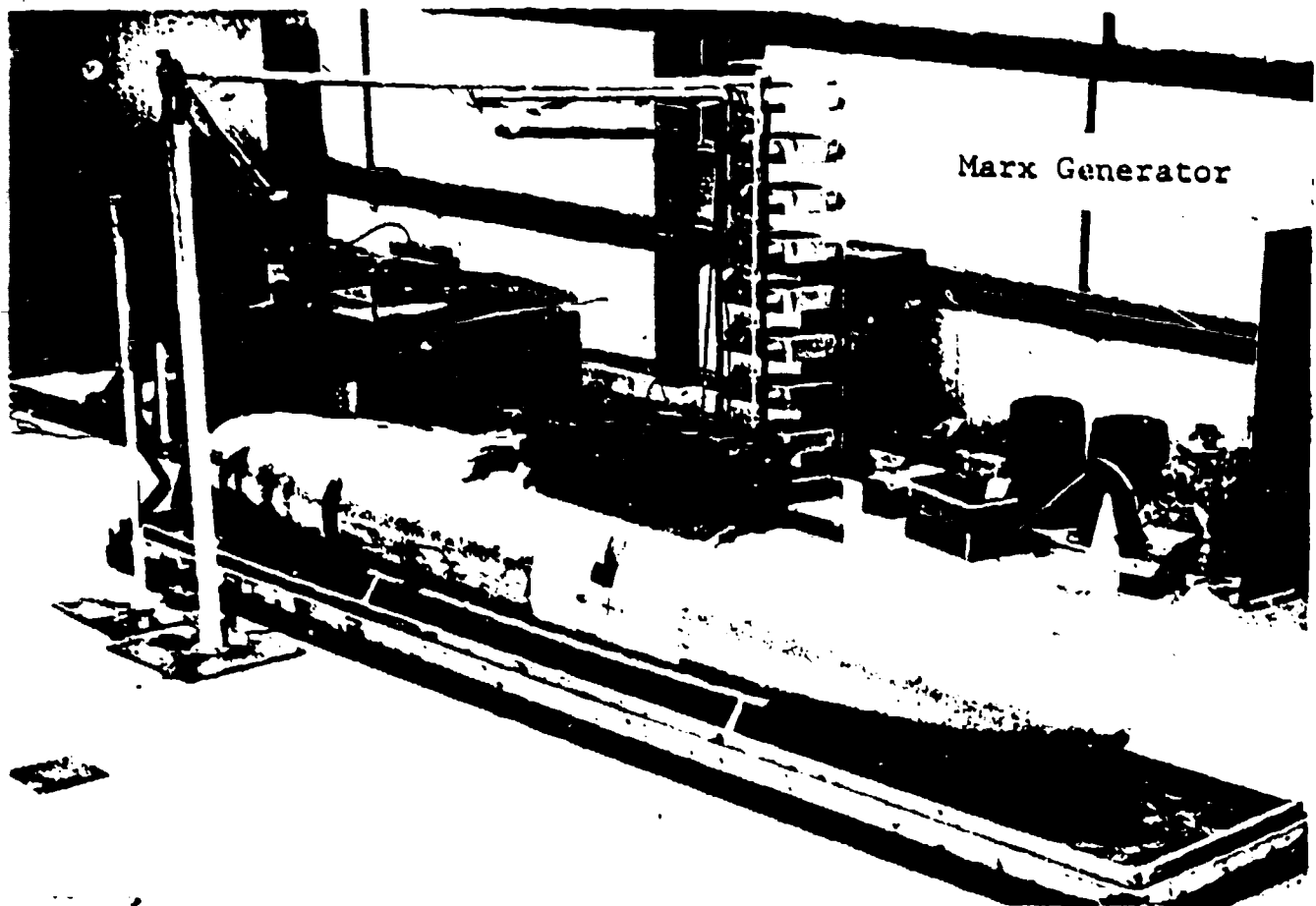


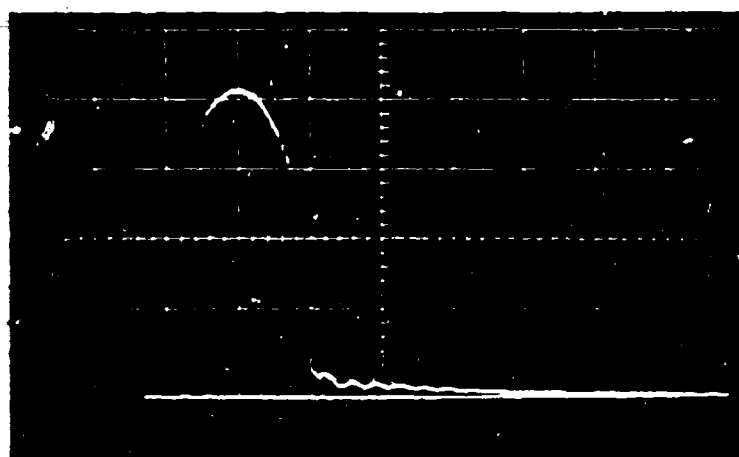
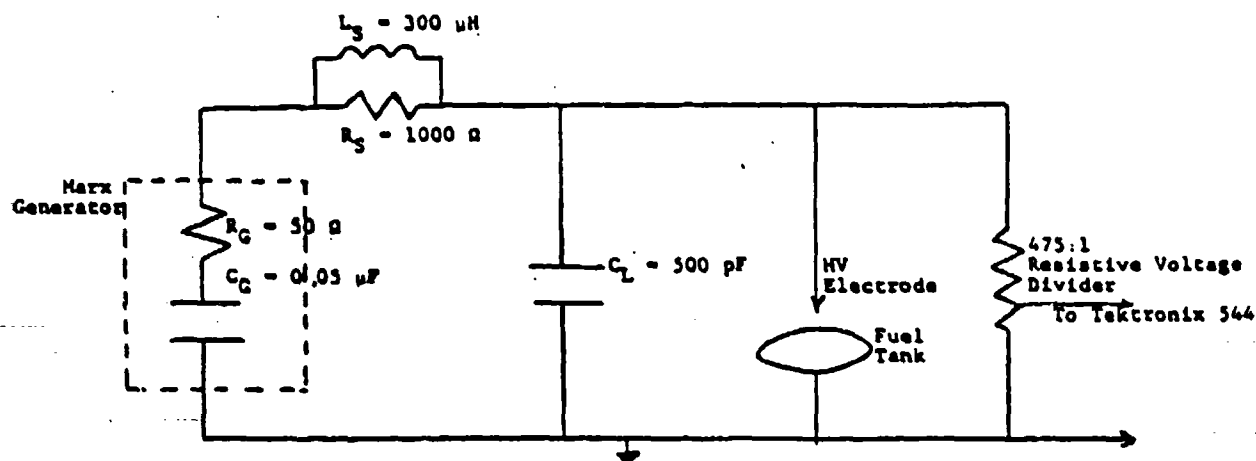
Figure 1 - Test Setup for Lightning Strike Attachment Tests.

4.1.1 High Voltage Test Circuit

A 500,000 volt Marx-type impulse generator was utilized to produce the voltage for these tests. The test circuit schematic is shown in Figure 2.

4.1.2 Test Results

An initial waveform checkout was performed using an aluminum foil covering over the tank. The test verified that the applied voltage waveform met the specification of $1,000 \text{ kV}/\mu\text{s} \pm 50\%$ rate-of-rise as specified in Paragraph 4.1.1 of SAE Committee AE4L "Lightning Tests Waveforms and Techniques for Aerospace Vehicles and Hardware", June 20, 1978. A typical applied voltage waveform is shown in Figure 2.



95 kV/div

0.5 μs/div

418 kV Peak

dv/dt = 909 kV/μs

Figure 2 - Test Circuit and Typical Applied Voltage for Simulated Lightning Strike Attachment Tests.

Testing began with the electrode placed adjacent to the drain valve at a distance of 12". The Polaroid film showed that light had appeared inside the tank during Test 3 indicating interior sparking. No further evidence of interior sparking occurred during the remainder of the lightning strike attachment tests. In addition, there was no evidence of puncture of the tank wall during these tests. The test results are tabulated in Table 1 and photographs of most of lightning strike attachments are shown in Figures 3 - 11.



Figure 3 - Lightning Strike Attachment Test No. 3. Flashover to Edge of Composite at Drain Valve Screw.



Sparking at
Drain Valve Screw

Figure 4 - Lightning Strike Attachment Test No. 4. Flashover to Composite Skin.

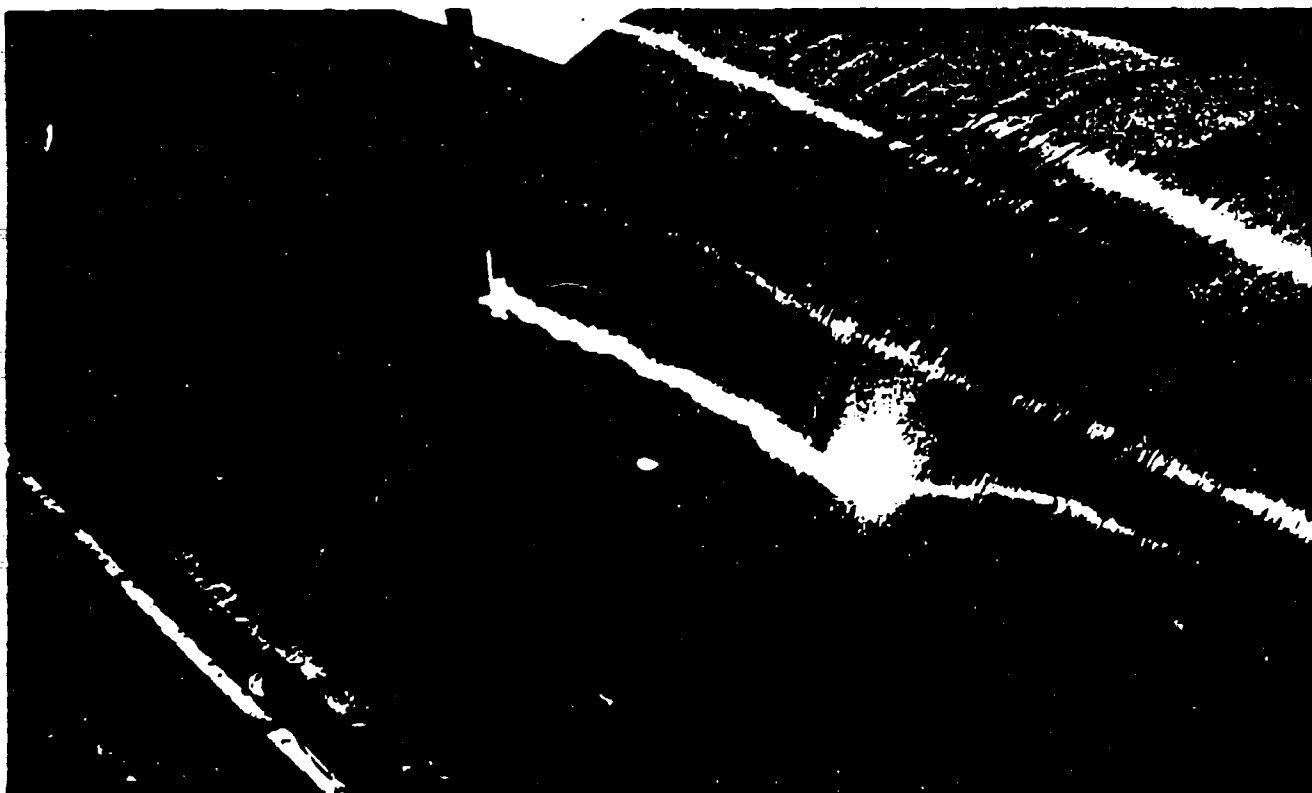


Figure 5 - Lightning Strike Attachment Test No. 9. Flashover to Plain Area of Lower Skin.



Figure 6 - Lightning Strike Attachment Test No. 10. Flashover to Edge of Glass.

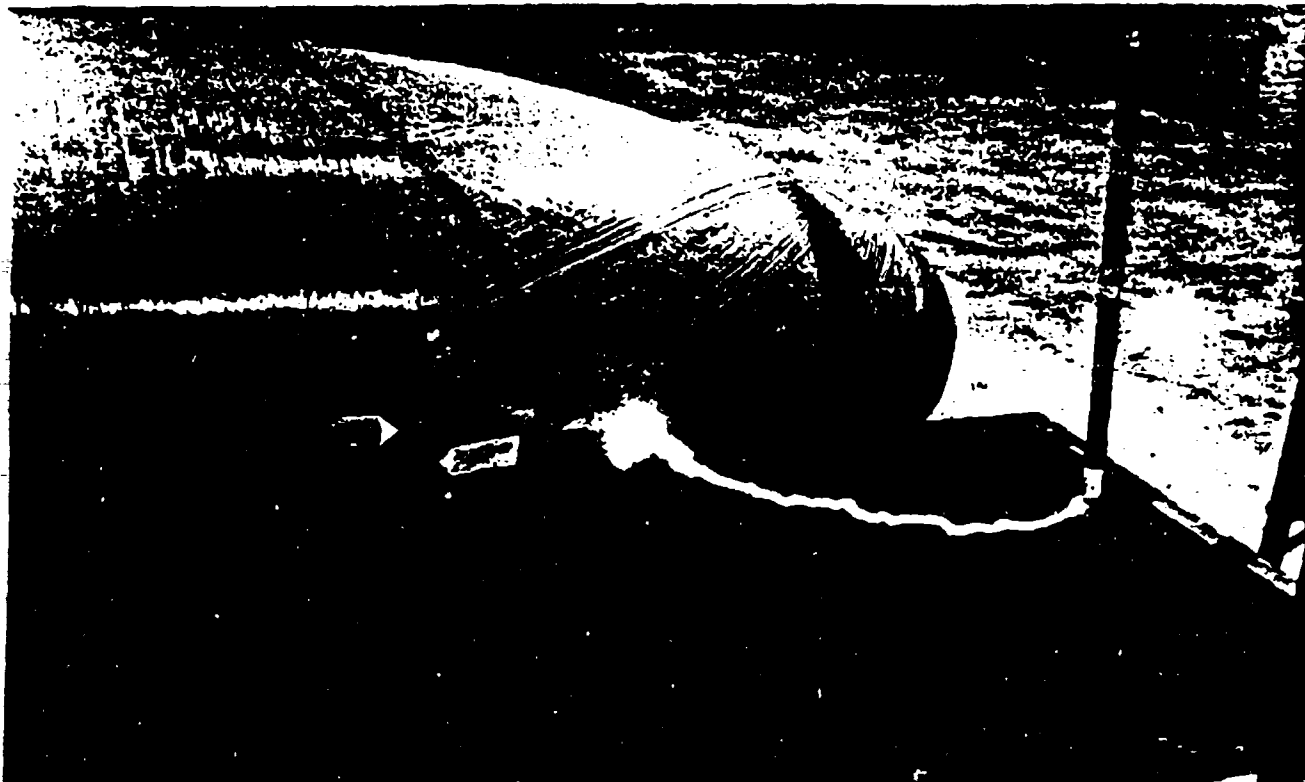


Figure 7 - Lightning Strike Attachment Test No. 12. Flashover to Edge of Graphite Wrap.

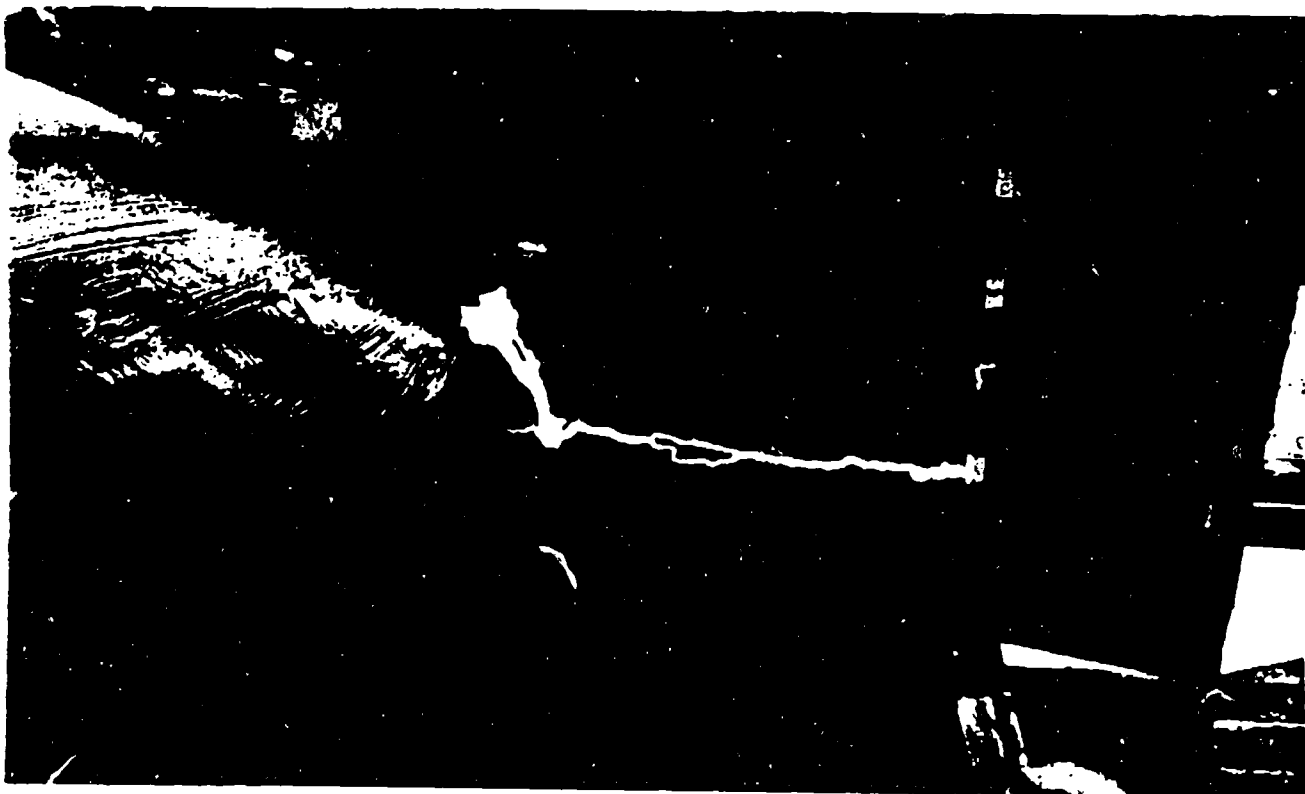


Figure 8 - Lightning Strike Attachment Test No. 13. Flashover to Several Spots on Edge of Graphite.

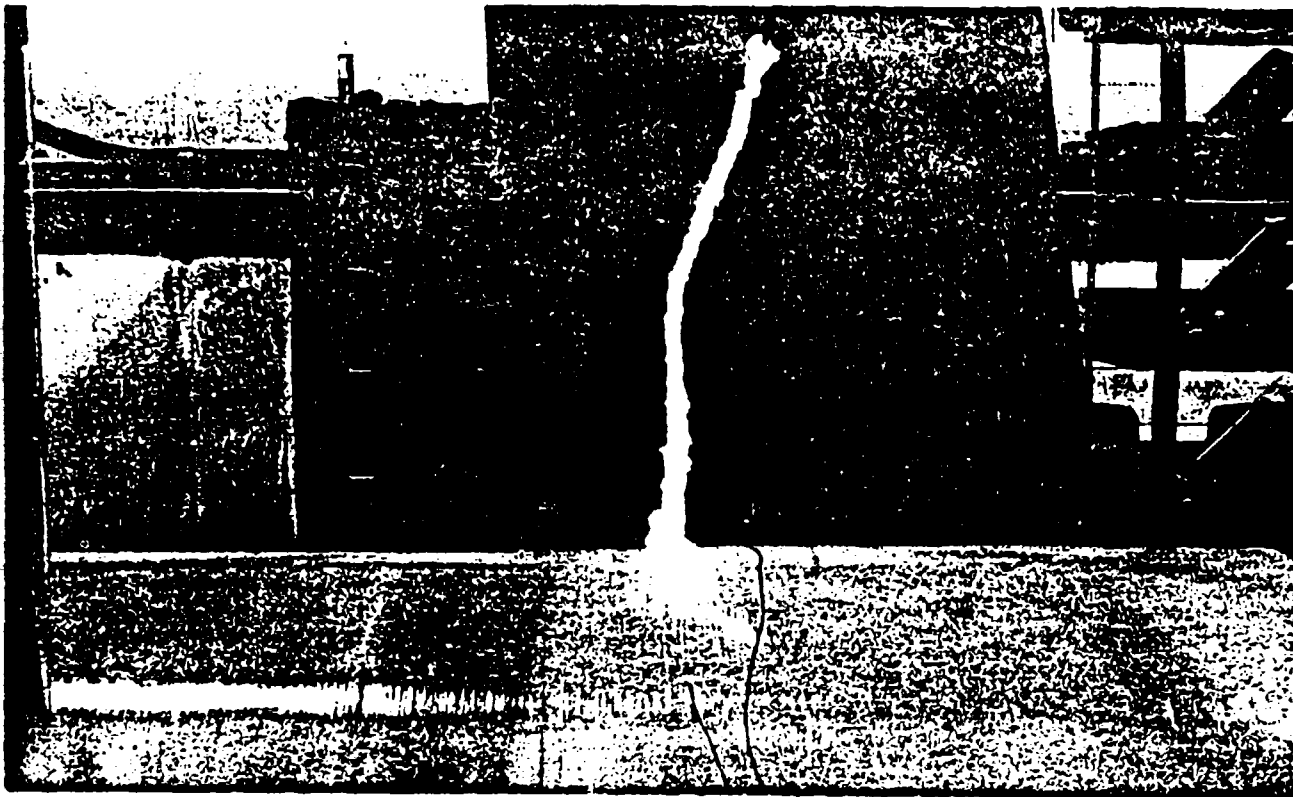


Figure 9 - Lightning Strike Attachment Test No. 16. Flashover to Area Several Inches Forward of Ring.



Figure 10 - Lightning Strike Attachment Test No. 18. Flashover to Label.



Figure 11 - Lightning Strike Attachment Test No. 19.
Flashover to Edge of Graphite Around Cap.

Table 1 - Lightning Attachment Tests on
Fiber Science Fuel Tank (PN 2191-001, SN 006)

Test No.	Electrode Position	Results	Photograph Figure No.
1	12" from aluminum foil	Waveform checkout 1,000kV/ μ s $\pm$ 50%	
2	12" from drain valve	F/O to edge of composite at drain valve screw.	
3	12" from drain valve	F/O to edge of composite at drain valve screw. Light in interior of tank	3
4	12" from fuel probe lower adapter screw	F/O to composite skin	4
5	12" from drain valve	F/O to edge of drain valve	
6	12" from drain valve	" "	
7	" " " "	" "	
8	" " " "	" "	
9	12" from plain area of lower skin	F/O to plain area of lower skin	5
10	18" from edge of glass & adjacent to transi- tion between graphite/ epoxy and glass	F/O to edge of glass	6
11	" " "	F/O to glass 1" aft of edge of glass	
12	18" from side of graphite area	F/O to edge of graphite wrap	7
13	18" from nose fuel filler cap	F/O to several spots on edge of graphite	8
14	" " " "	" " " "	
15	" " " "	" " " "	

Table 1 - continued

Test No.	Electrode Position	Results	Photograph Figure No.
16	15" from spot over inside ring	F/O to area several inches forward of ring	9
17	" " " "	F/O to area of ring	
18	20" from aft fuel filler cap	F/O to label	10
19	13" from aft fuel filler cap	F/O to edge of graphite around cap	11
20	" " " "	F/O to edge of cap opening	

NOTE: F/O = Flashover

4.2 Physical Damage Tests

Simulated lightning strike physical damage tests (high current tests) were conducted to determine the extent of damage which would occur to the composite skin from a severe lightning stroke current. In addition, a Polaroid-type camera was positioned so that its lens entered the interior of the tank through the filler cap opening near the pylon. This camera was used to detect the presence of sparking in the interior of the tank during the high current tests. Any such sparking would normally be considered a source of ignition.

4.2.1 High Current Test Circuit

A 17 μF , 50 kilojoule capacitor bank was used to generate the test currents. The electrode was placed in contact with the tank at several locations during the test. The test circuit schematic and typical input current are shown in Figure 12.

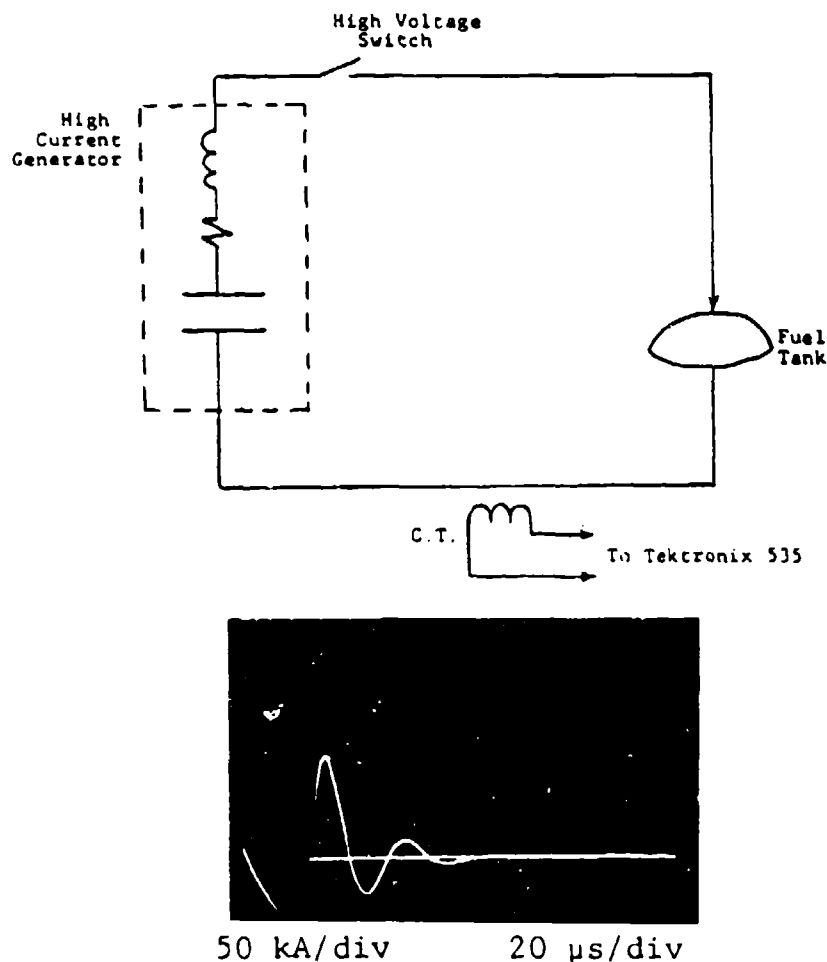


Figure 12 - Test Circuit Schematic and Typical Oscillogram of Applied Current for Simulated Lightning Damage Tests.

4.2.2 High Current Test Results

Table II presents the results of the high current physical damage tests. Peak currents tended to be lower than the 200 kA + 10% peak current specified for zones 1A and 1B in MIL-STD-1757 Method T03. This was due to the high impedance of the fuel tank which limited the peak current. As a result, several strokes of lower amplitude were made to several spots, so that the cumulative damage would represent that produced by a more severe stroke. The Polaroid camera showed that light flashes did occur during several of the tests indicating internal sparking. Preliminary examination of the tank interior did not reveal any evidence of puncture and it was not possible to determine the location of the sparking that was seen on the Polaroid photographs because the interior of the tank could not be inspected from the existing port. Further investigation for the location of the internal sparking will need to be made by dissection of the tank. Photographs of some of the high current tests are shown in Figures 13 - 21.

Table II - High Current Physical Damage Tests on
Fiber Science Fuel Tank (PN 2191-001, SN 006)

Test No.	Peak Current kA	Action Integral A ² .s	Electrode Position	Results	Photograph Figure No.
21	125	0.26x10 ⁶	Over center of nose fuel filler cap	Small amounts of physical damage to composite at edge of filler cap. Light on Polaroid film	13
22	90	0.10x10 ⁶	"	Strike to edge of cap. Small amount of additional damage to composite.	
23	110	0.15x10 ⁶	"	Strike to edge of cap. Induced voltage of 1600 volts in fuel quantity probe wiring.	
24	~110	~0.15x10 ⁶	"	Strike to composite skin at edge of cap. Light on Polaroid film. Induced voltage of 1600 volts in fuel quantity probe wiring.	14
25	73	0.11x10 ⁶	"	" " " "	15
26	45	0.03x10 ⁶	"	" " " "	
27	~ 40	~0.02x10 ⁶	"	" " " "	16
28	80	0.07x10 ⁶	"	" " " "	17
29	60	0.06x10 ⁶	"	" " " "	18
30	135	0.22x10 ⁶	Over composite skin adjacent to filler cap	" " " "	19

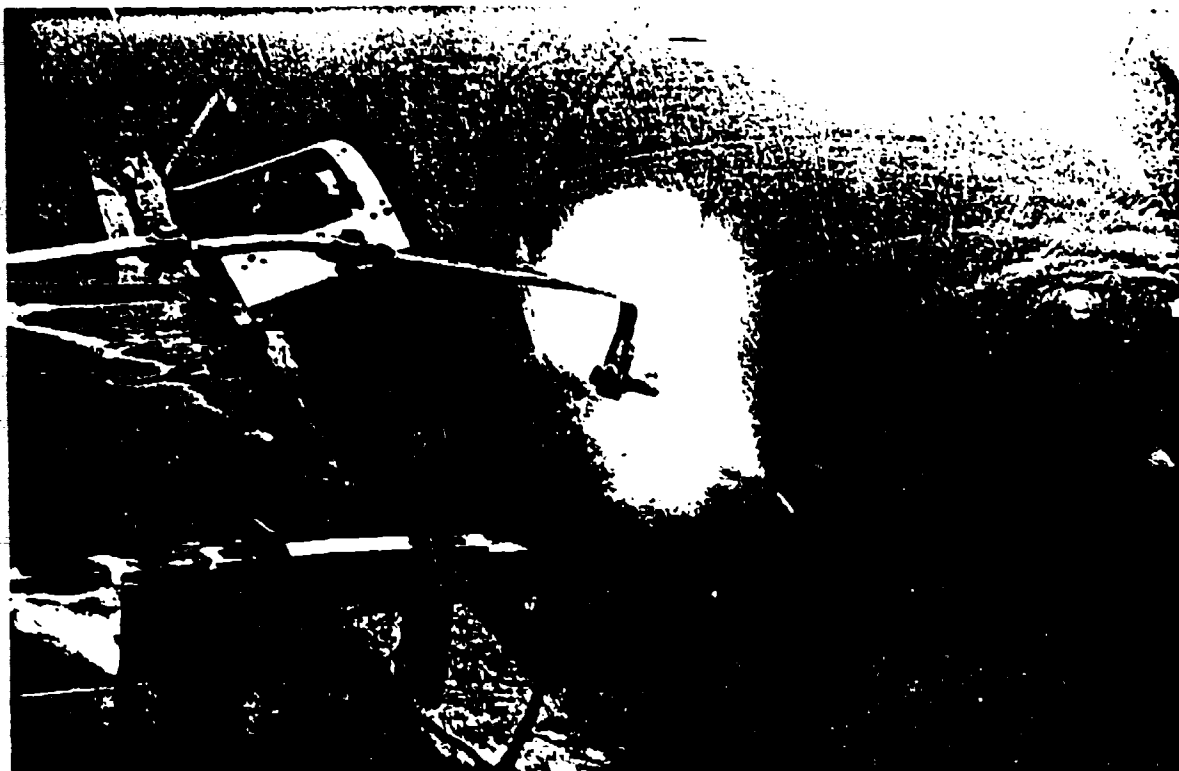


Figure 13 - High Current Test No. 21. Electrode Over Center of Nose Fuel Filler Cap Area.



Figure 14 - High Current Test No. 24. Electrode Over Center of Nose Fuel Filler Cap Area.

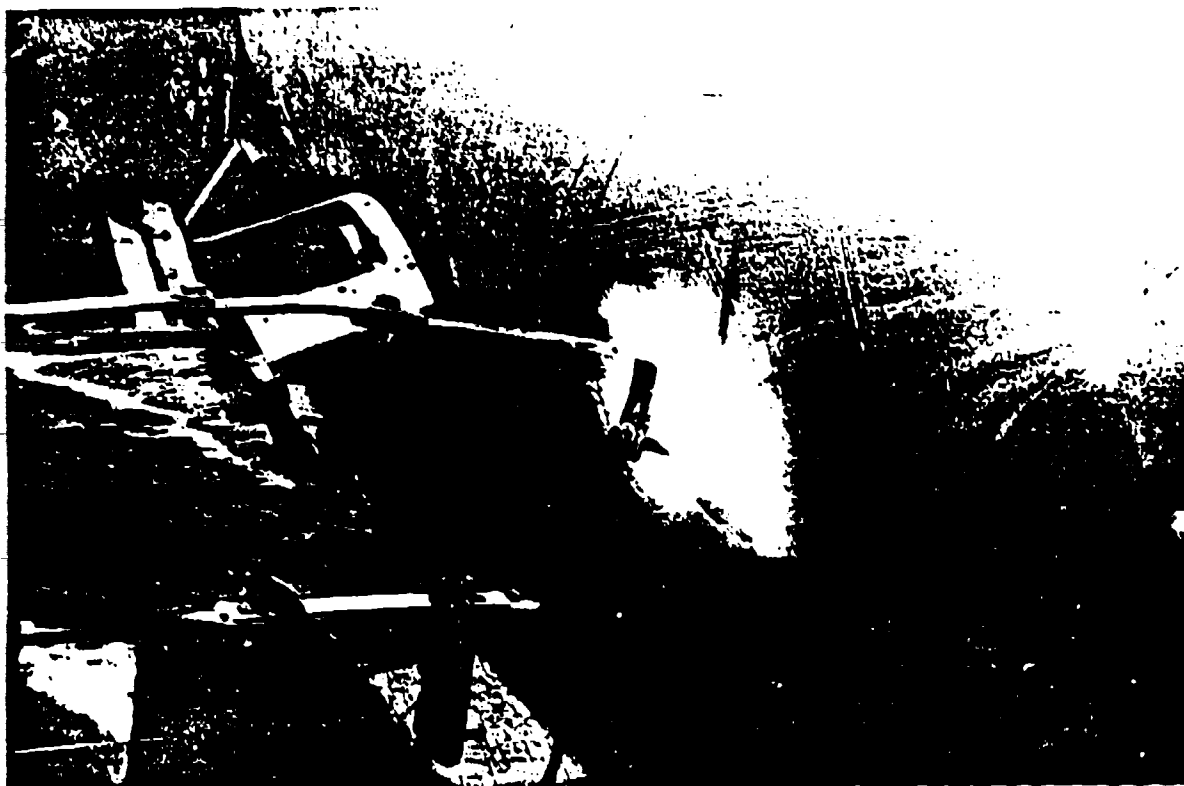


Figure 15 - High Current Test No. 25. Electrode Over Center of Nose Fuel Filler Cap Area.



Figure 16 - High Current Test No. 27. Electrode Over Center of Nose Fuel Filler Cap Area.



Figure 17 - High Current Test No. 28. Electrode Over Center of Nose Fuel Filler Cap Area.



Figure 18 - High Current Test No. 29. Electrode Over Center of Nose Fuel Filler Cap Area.



Figure 19 - High Current Test No. 30. Electrode Over Center of Nose Fuel Fill Cap Area.

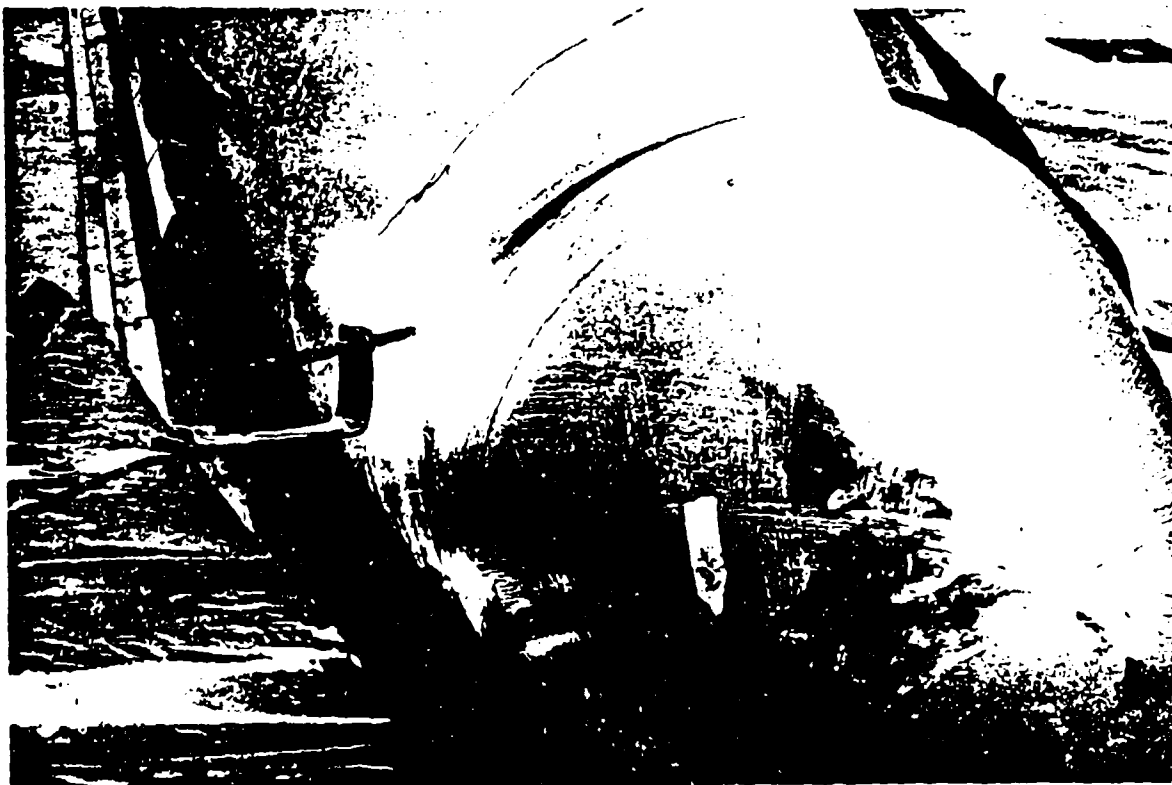


Figure 20 - High Current Test No. 31. Electrode Adjacent to Glass and Composite Skins in the Nose.

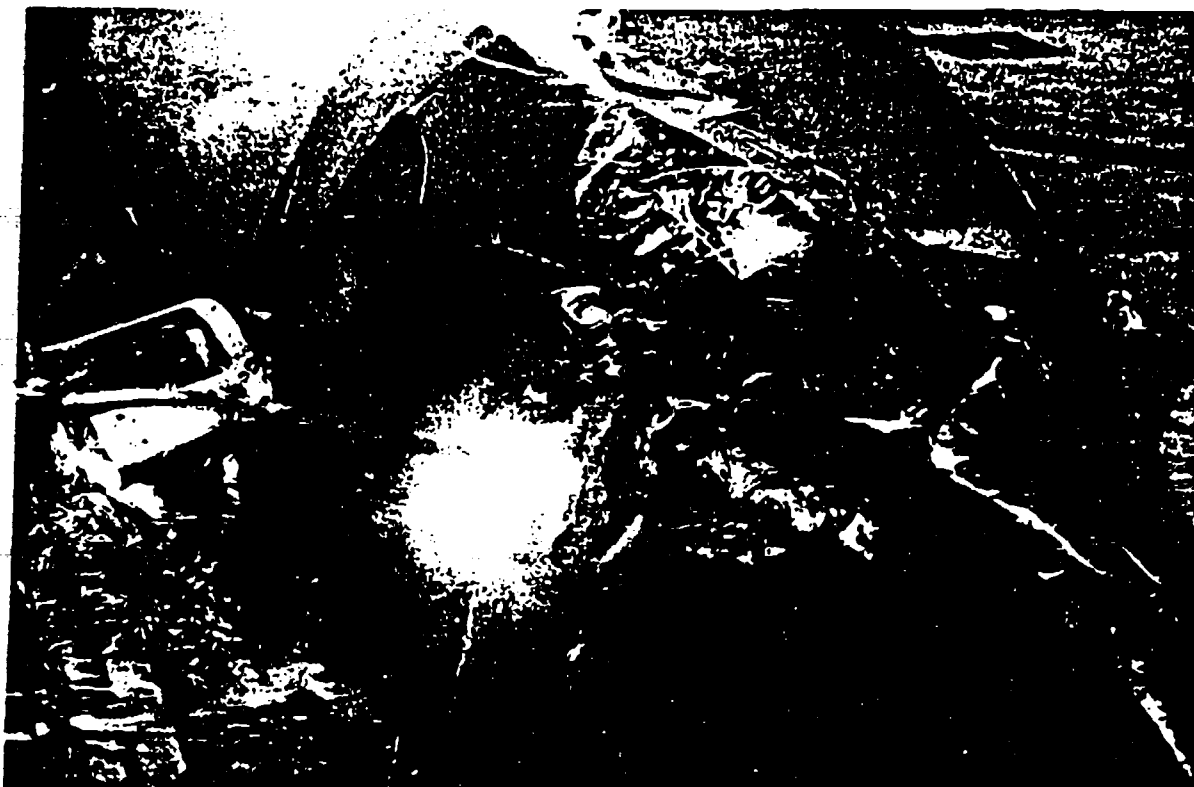


Figure 21 - High Current Test No. 33. Electrode Over Forward Central Rib.

5.0 Discussion of Results

5.1 Physical Damage

In all cases the amount of physical damage to the composite skin was limited to puncture of the outer layers of tape and delamination of a short length of tape in either direction. None of the strikes resulted in puncture of the inner liner of the tank, but light was detected by a Polaroid camera viewing the inside. See Figures 22 - 24. The light indicated sparking within the tank, but the source of the sparking could not be identified due to inability of the camera to view the entire inside of the tank.

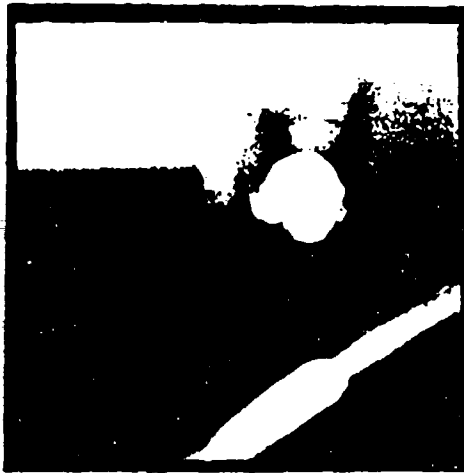


Figure 22 - Light in Tank Interior During High Current Test 32.



Figure 23 - Light in Tank Interior During High Current Test 33.



Figure 24 - Background View of Tank Interior As Seen By Polaroid Camera.

5.2 Electrical Sparking

The electrical sparking noted in Paragraph 5.1 must be considered a source of ignition of flammable fuel vapors. Whereas the location of this sparking could not be determined from the tests, the fact that the sparking occurred during all of the tests, no matter where the electrode was positioned, indicates that it probably occurred where the current exited from the tank, possibly at the fasteners that attach the composite tank to the pylon assembly, because the current necessarily passes through these attachments during all tests. This same path would also be taken by lightning currents striking the tank when mounted on the helicopter.

Determination of the sparking locations can probably be made by dissection and inspection of the interior of the tank. Once the locations of sparking are known, it should be possible to design effective protection against sparking, or to isolate the sparking from flammable vapors.

5.3 Induced Voltages

The induced voltages measured in the fuel quantity probes are beneath the levels necessary to cause sparks in most fuel quantity probes, but it must be remembered that most of the electrical length of these circuits is outside of the tank, between the tank and the quantity measuring electronics located in the helicopter. For this reason, the measurements recorded here can not be considered conclusive. The tank must be tested on the helicopter to determine the total induced voltage that may be present at the quantity probes as a result of lightning strikes to the tank in flight.

For this same reason no measurements were made on the pylon actuator circuits. No portion of these circuits enters the tank. Here again, the induced voltages that may reach the actuators are induced in the circuitry between the actuators and the helicopter electrical system, and a full-vehicle test is necessary for their evaluation.

**LIGHTNING TEST WAVEFORMS AND TECHNIQUES
FOR
AEROSPACE VEHICLES AND HARDWARE**

**Report of
SAE Committee AE4L**

June 20, 1978

Users of this document should ascertain that they are in possession of the latest version.

This version supersedes SAE Special Task F Report "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware" dated May 5, 1976.

Information concerning the status of this document, and additional copies of it, may be obtained from the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, Pa. 15096.

LIGHTNING TEST WAVEFORMS AND TECHNIQUES FOR AEROSPACE VEHICLES AND HARDWARE

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	1
2.0 LIGHTNING STRIKE PHENOMENA	2
2.1 Natural Lightning Strike Electrical Characteristics	
2.1.1 Prestrike Phase.	2
2.1.2 High Peak Current Phase.	2
2.1.3 Continuing Current	2
2.1.4 Restrike Phase	4
2.2 Aerospace Vehicle Lightning Strike Phenomena. . . .	4
2.2.1 Initial Attachment	4
2.2.2 Swept Stroke Phenomenon.	4
2.2.3 Lightning Attachment Zones	4
2.3 Aerospace Vehicle Lightning Effects Phenomena . . .	5
2.3.1 Direct Effects	5
2.3.2 Indirect Effects	6
2.3.3 Effects on Personnel	6
3.0 STANDARD LIGHTNING PARAMETER SIMULATION.	7
3.1 Purpose	7
3.2 Waveform Descriptions for Qualification Testing . .	7
3.2.1 Voltage Waveforms.	7
3.2.2 Current Waveforms.	8
3.3 Waveform Descriptions for Engineering Tests	9
3.3.1 Purpose.	9
3.3.2 Voltage Waveforms.	9
3.3.3 Current Waveforms.	9
4.0 TEST TECHNIQUES	13
4.1 Qualification Tests	
4.1.1 Full Size Hardware Attachment Point	
Tests - Zone 1	13
4.1.2 Direct Effects - Structural	13
4.1.3 Direct Effects - Combustible Vapor Ignition	
Via Skin or Component Puncture, Hot Spots	
or Arcing	15
4.1.4 Direct Effects - Streamers.	16
4.1.5 Direct Effects - External Electrical	
Hardware	16
4.1.6 Indirect Effects - External Electrical	
Hardware	17

4.2	Engineering Tests	18
4.2.1	Model Aircraft Lightning Attachment Point Test	18
4.2.2	Full-Size Hardware Attachment Point Test - Zone 2.	18
4.2.3	Indirect Effects - Complete Vehicle	20

1.0 INTRODUCTION

This document presents test waveforms and techniques for simulated lightning testing of aerospace vehicles and hardware. The waveforms presented are based on the best available knowledge of the natural lightning environment coupled with a practical consideration of state-of-the-art laboratory techniques. This document does not include design criteria nor does it specify which items should or should not be tested.

Tests and associated procedures described herein are divided into two general categories:

- o Qualification tests
- o Engineering tests

Acceptable levels of damage and/or pass-fail criteria for the qualification tests must be provided by the cognizant regulatory authority for each particular case.

The engineering tests provide important data that may be necessary to achieve a qualifiable design.

The term Aerospace Vehicle covers a wide variety of systems, including fixed wing aircraft, helicopters, missiles, and spacecraft. In addition, natural lightning is a complex and variable phenomenon and its interaction with different types of vehicles may

be manifested in many different ways. It is therefore difficult to address every possible situation in detail. However, the test waveforms described herein represent the significant aspects of the natural environment and are therefore independent of vehicle type or configuration. The recommended test techniques have also been kept general to cover as many test situations as possible. Some unique situations may not fit into the general guidelines; in such instances, application of the waveform components must be tailored to the specific situation.

The test waveforms and techniques described herein for qualification tests simulate the effects of a severe lightning strike to an aerospace vehicle. Where it has been shown that test conditions can affect results of the test, a specific approach is recommended as a guideline to new laboratories and for consistency of results between laboratories.

It is not intended that every waveform and test described herein be applied to every system requiring lightning verification tests. The document is written so that specific aspects of the environment can be called out for each specific program as dictated by the vehicle design, performance, and mission constraints.

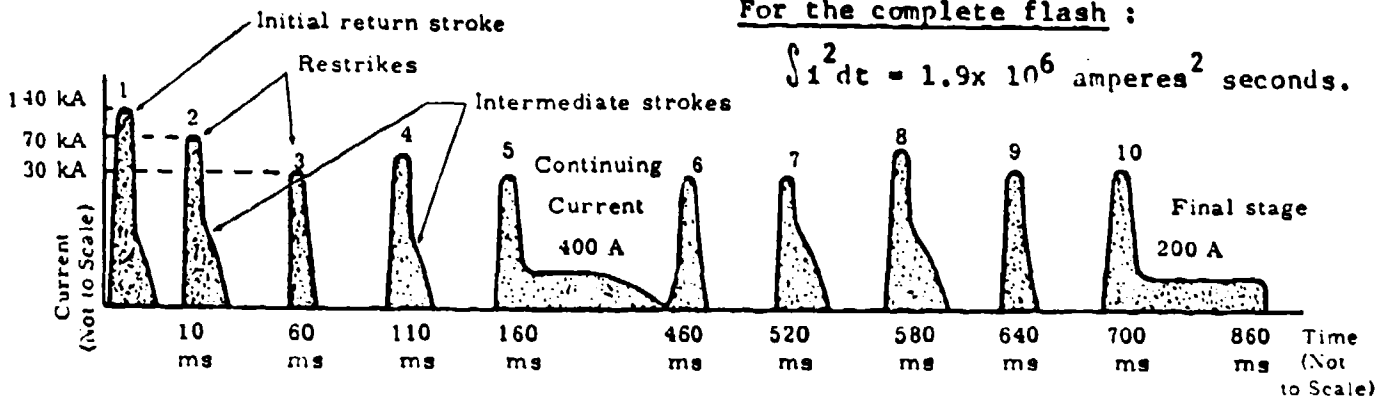
For each stroke:

Time to peak current = $1.5 \mu\text{s}$

Time to Half Value = $40 \mu\text{s}$

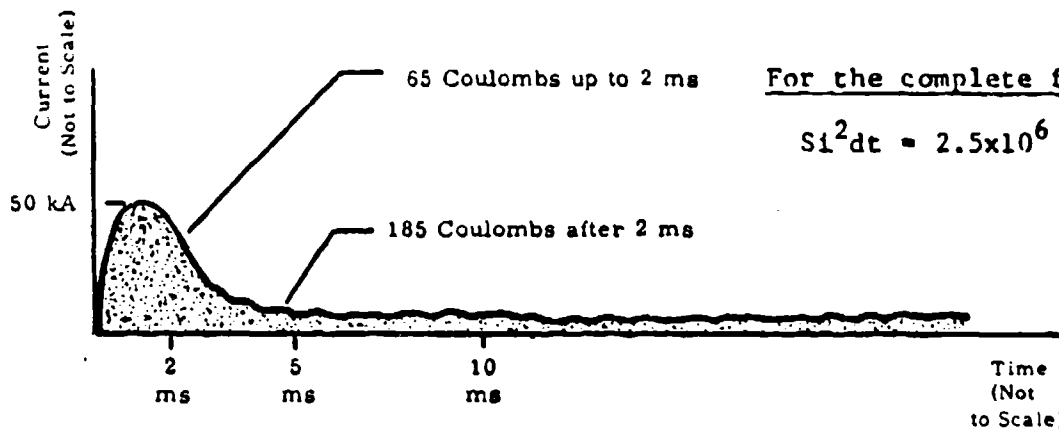
For the complete flash :

$$\int i^2 dt = 1.9 \times 10^6 \text{ amperes}^2 \text{ seconds.}$$



(A) Severe negative lightning flash current waveform.

(Courtesy of Cianos/Pierce)



For the complete flash:

$$\int i^2 dt = 2.5 \times 10^6 \text{ amperes}^2 \text{ seconds}$$

(B) Moderate positive lightning flash current waveform.

Figure 2-2 Lightning flash current waveforms.

2.1.4 Restrike Phase

In a typical lightning flash there will be several high current strokes following the first return stroke. These occur at intervals of several tens of milliseconds as different charge pockets in the cloud are tapped and their charge fed into the lightning channel. Typically the peak amplitude of the restrikes is about one half that of the initial high current peak, but the rate of current rise is often greater than that of the first return stroke. The continuing current often links these various successive return strokes, or restrikes.

2.2 Aerospace Vehicle Lightning Strike Phenomena

2.2.1 Initial Attachment

Initially the lightning flash will enter and exit the aircraft at two or more attachment points. There will always be at least one entrance point and one exit point. It is not possible for the vehicle to store the electrical energy of the lightning flash in the capacitive field of the vehicle and so avoid an exit point. Typically these initial attachment points are at the extremities of the vehicle. These include the nose, wing tips, elevator and stabilizer tips, protruding antennas, and engine pods or propeller blades. Lightning can also attach to the leading edge of swept wings and some control surfaces.

2.2.2 Swept Stroke Phenomenon

The lightning channel is somewhat stationary in space while it is transferring electrical charge. When a vehicle is involved it becomes part of the channel. However, due to the speed of the vehicle and the length of time that the lightning channel exists, the vehicle can move relative to the lightning channel. When a forward extremity, such as a nose or wing mounted engine pods are involved, the surface

moves through the lightning channel. When the lightning channel appears to sweep back over the surface as illustrated in Figure 2-3. This is known as the swept stroke phenomenon. As the sweeping action occurs, the type of surface can cause the lightning channel attachment point to dwell at various surface locations for different periods of time, resulting in a skipping action which produces a series of discrete attachment points along the sweeping path.

The amount of damage produced at any point on the aircraft by a swept-stroke depends upon the type of material, the arc dwell time at that point, and the lightning currents which flow during the attachment. Both high peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce reattachment of the arc at a new point.

When the lightning arc has been swept back to one of the trailing edges it may remain attached at that point for the remaining duration of the lightning flash. An initial exit point, if it occurs at a trailing edge, of course, would not be subjected to any swept stroke action.

The significance of the swept stroke phenomenon is that portions of the vehicle that would not be targets for the initial entry and exit point of a lightning flash may also be involved in the lightning flash process as the flash is swept backwards across the vehicle.

2.2.3 Lightning Attachment Zones

Aircraft surfaces can then be divided into three zones, with each zone having different lightning attachment and/or transfer characteristics. These are defined as follows:

Zone 1: Surfaces of the vehicle for which there is a high probability of initial lightning flash attachment (entry or exit).

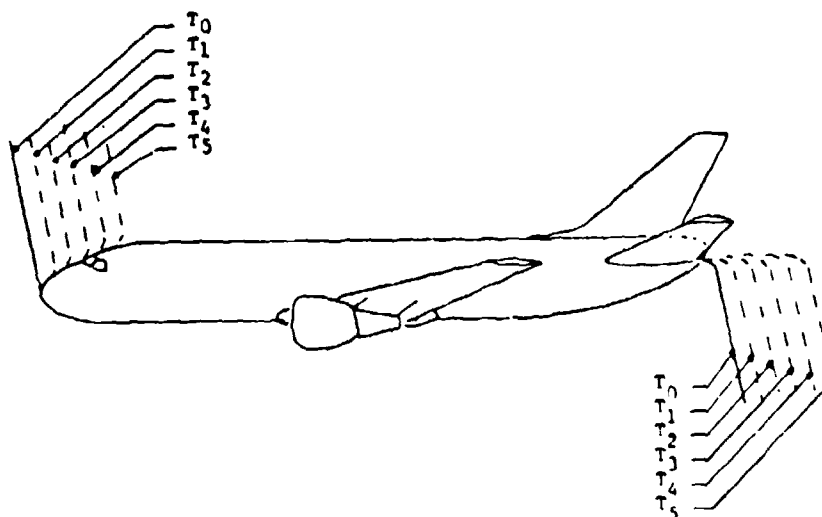


Figure 2-3 Swept stroke phenomenon.

Zone 2: Surfaces of the vehicle across which there is a high probability of a lightning flash being swept by the airflow from a Zone 1 point of initial flash attachment.

Zone 3: Zone 3 includes all of the vehicle areas other than those covered by Zone 1 and Zone 2 regions. In Zone 3 there is a low probability of any attachment of the direct lightning flash arc. Zone 3 areas may carry substantial amounts of electrical current but only by direct conduction between some pair of direct or swept stroke attachment points.

Zones 1 and 2 may be further divided into A and B regions depending on the probability that the flash will hang on for any protracted period of time. An A type region is one in which there is low probability that the arc will remain attached and a B type region is one in which there is a high probability that the arc will remain attached. Some examples of zones are as follows:

Zone 1A: Initial attachment point with low probability of flash hang-on, such as a leading edge.

Zone 1B: Initial attachment point with high probability of flash hang-on, such as a trailing edge.

Zone 2A: A swept stroke zone with low probability of flash hang-on, such as a wing mid-span.

Zone 2B: A swept stroke zone with high probability of flash hang-on, such as a wing inboard trailing edge.

2.3 Aerospace Vehicle Lightning Effects Phenomena

The lightning effects to which aerospace vehicles are exposed and the effects which should be reproduced through laboratory testing with simulated lightning waveforms can be divided into DIRECT EFFECTS and INDIRECT EFFECTS. The direct effects of lightning are the burning, eroding, blasting, and structural deformation caused by lightning arc attachment, as well as the high-pressure shock waves and magnetic forces produced by the associated high currents. The indirect effects are predominantly those resulting from the interaction of the electromagnetic fields accompanying lightning with electrical apparatus in the aircraft. Hazardous indirect effects could in principle be produced by a lightning flash that did not directly contact the aircraft and hence was not capable of producing the direct effects of burning and blasting. However, it is currently believed that most indirect effects of importance will be associated with a direct lightning flash. In some cases both direct and indirect effects may occur to the same component of the aircraft. An example would be a lightning flash to an antenna which physically damages the antenna and also sends damaging voltages into the transmitter or receiver connected to that antenna. In this document the physical damage to the antenna will be discussed as a direct effect and the voltages or currents coupled from the antenna into the communications equipment will be treated as an indirect effect.

2.3.1 Direct Effects

The nature of the particular direct effects associated with any lightning flash depends upon the structural component involved and the particular phase of the lightning current transfer discussed earlier.

2.3.1.1 Burning and Eroding

The continuing current phase of a lightning stroke can cause severe burning and eroding damage to vehicle structures. The most severe damage occurs when the lightning channel dwells or hangs on at one point on the vehicle for the entire period of the lightning flash, such as in Zone 1B. This can result in holes of up to a few centimeters in diameter on the aircraft skin.

2.3.1.2 Vaporization Pressure

The high peak current phase of the lightning flash transfers a large amount of energy in a short period of time, a few tens of microseconds. This energy transfer can result in a fast thermal vaporization of material. If this occurs in a confined area such as a radome, a high pressure may be created which may be of sufficient magnitude to cause structural damage. The vaporization of metal and other materials and the heating of the air inside the radome, create the high internal pressure that leads to structural failure. In some instances entire radomes have been blown from the aircraft.

2.3.1.3 Magnetic Force

During the high peak current phase of the lightning flash the flow of current through sharp bends or corners of the aircraft structure can cause extensive magnetic flux interaction. In certain cases, the resultant magnetic forces can twist, rip, distort, and tear structures away from rivets, screws, and other fasteners. These magnetic forces are proportional to the square of the magnetic field intensity and thus are proportional to the square of the lightning current. The damage produced is related both to the magnetic force and to the response time of the system.

2.3.1.4 Fire and Explosion

Fuel vapors and other combustibles may be ignited in several ways by a lightning flash. During the prestrike phase high electrical stresses around the vehicle produce streamers from the aircraft extremities. The design and location of fuel vents determine their susceptibility to streamer conditions. If streamers occur from a fuel vent in which flammable fuel-air mixtures are present, ignition may occur. If this ignition is not arrested, flames can propagate into the fuel tank area and cause a major fuel explosion.

The flow of lightning current through vehicle structures can cause sparking at poorly bonded structure interfaces or joints. If such sparking occurs where combustibles such as fuel vapors are located, ignition may occur.

Lightning attaching to an integral tank skin may puncture, burn holes in the tank, or heat the inside surface sufficiently to ignite any flammable vapors present.

2.3.1.5 Acoustic Shock

The air channel through which the lightning flash propagates is nearly instantaneously heated to a very high temperature. When the resulting shock wave impinges upon a surface it may produce a destructive overpressure and cause mechanical damage.

2.3.2 Indirect Effects

Damage or upset of electrical equipment by currents or voltages is defined as an indirect effect. In this document such damage or upset is defined as an indirect effect even though such currents or voltages may arise as a result of a direct lightning flash attachment to a piece of external electrical hardware. An example would be a wing-tip navigation light. If lightning shatters the protective glass covering or burns through the metallic housing and contacts the filament of the bulb, current can be injected into the electrical wires running from the bulb to the power supply bus. This current may burn or vaporize the wires. The associated voltage surge may cause breakdown of insulation or damage to other electrical equipment.

Even if the lightning flash does not contact wiring directly, it will set up changing electromagnetic fields around the vehicle. The metallic structure of the vehicle does not provide a perfect Faraday cage electromagnetic shield and therefore some electromagnetic fields can enter the vehicle, either by

diffusion through metallic skins or direct penetration through apertures such as skin joints and windows or other nonmetallic sections. If the fields are changing with respect to time and link electrical circuits inside the vehicle, they will induce transient voltages and currents into these circuits. These voltages may be hazardous to avionic and electrical equipment, as well as a source of fuel ignition.

Voltages and currents may also be produced by the flow of lightning current through the resistance of the aircraft structure.

2.3.3 Effects on Personnel

One of the most troublesome effects on personnel is flash blindness. This often occurs to flight crew member(s) who may be looking out of the vehicle in the direction of the lightning flash. The resulting flash blindness may persist for periods of 30 seconds or more, rendering the crew member temporarily unable to use his eyes for flight or instrument-reading purposes.

Personnel inside vehicles may also be subjected to hazardous effects from lightning strikes. Serious electrical shock may be caused by currents and voltages, conducted via control cables or wiring leading to the cockpit from control surfaces or other hardware struck by lightning. Shock can also be induced by the intense thunderstorm electromagnetic fields.

The shock varies from mild to serious; sufficient to cause numbness of hands or feet and some disorientation or confusion. This can be quite hazardous in high-performance aircraft, particularly under the thunderstorm conditions during which lightning strikes generally occur.

Tests to evaluate these personnel effects are not included in this document.

3.0 STANDARD LIGHTNING PARAMETER SIMULATION

3.1 Purpose

Complete natural lightning flashes cannot be duplicated in the laboratory. Most of the voltage and current characteristics of lightning, however, can be duplicated separately by laboratory generators. These characteristics are of two broad categories: The VOLTAGES produced during the lightning flash and the CURRENTS that flow in the completed lightning channel. With a few exceptions, it is not necessary to simulate high-voltage and high-current characteristics together.

The high-voltage characteristics of lightning determine attachment points, breakdown paths, and streamer effects, whereas the current characteristics determine direct and indirect effects.

In most cases, lightning voltages are simulated by high-impedance voltage generators operating into high-impedance loads, while lightning currents are simulated by low-impedance current generators operating into low-impedance loads.

The waveforms described in this section are idealized. Definitions relating to actual waveshapes are covered in ANSI and IEEE Standard Techniques for Dielectric Tests, ANSI C68.1 (1968) and IEEE No. 4. These specifications are equivalent and are in turn equivalent to High Voltage Test Techniques, IEC 60-2 (1973). The definitions in these documents should be used to determine the front time, duration and rate of rise of actual waveforms.

Severe lightning flash voltage and current waveforms, as described in Paragraph 3.2 have been developed for purposes of qualification testing: waveforms in Paragraph 3.3 are for R&D or screening test purposes and are designated engineering tests.

3.2 Waveform Descriptions for Qualification Tests

3.2.1 Voltage Waveforms

The basic voltage waveform to which vehicles are subjected is one that rises until breakdown occurs either by puncture of solid insulation or flashover through the air or across an insulating surface. The path that the flashover takes, either puncture or surface flashover, depends on the rate of rise of the voltage as shown in Figure 3-1.

During some types of testing it is necessary to determine the critical voltage amplitude at which breakdown occurs. This critical voltage level depends upon both the rate of rise of voltage and the rate of voltage decay. Two examples are (1) determining the strength of the insulation used on electrical wiring and (2) determining the points from which electrical streamers occur on a vehicle as a lightning flash approaches.

Although the exact voltage waveform produced by natural lightning is not known, flight service data and conservative test philosophy justify the definition of fast rising voltage waveforms for the tests just described. Voltage testing for qualification purposes thus calls for two different standard voltage waveforms. These are shown in Figure 3-2 and are described in the following sections. The qualification tests in which these waveforms are applied are presented in the test matrix of Table 1. The objectives of each test, the test setup, measurement and data requirements are described in Section 4.0.

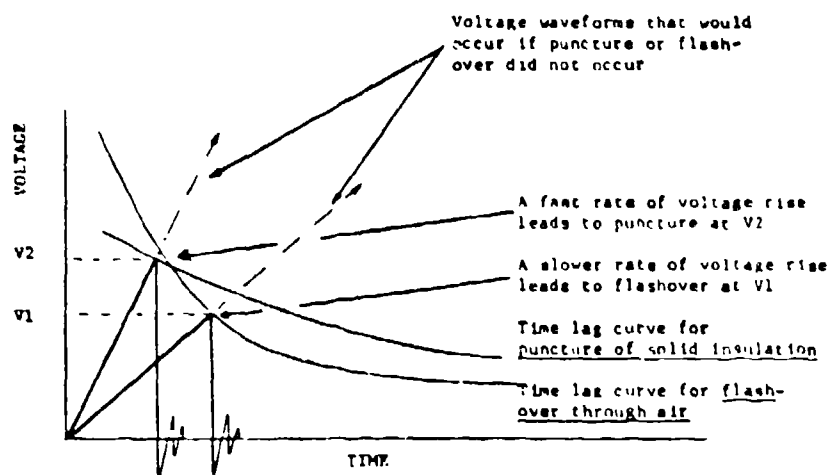


Figure 3-1 Influence of rate of rise on flashover path

3.2.1.1 Voltage Waveform A - Basic Lightning Waveform

This waveform rises at a rate of 1000 kV per microsecond ($\pm 50\%$) until its increase is interrupted by puncture of, or flashover across, the object under test. At that time the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of the lightning voltage generator) is not specified. Voltage waveform A is shown in Figure 3-2.

3.2.1.2 Voltage Waveform B - Full Wave

Waveform B is a 1.2 x 50 microsecond waveform which is the electrical industry standard for impulse dielectric tests. It rises to crest in 1.2 ($\pm 20\%$) microseconds and decays to half of crest amplitude in 50 ($\pm 20\%$) microseconds. Time to crest and decay time refer to the open circuit voltage of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown on Figure 3-2.

3.2.2 Current Waveforms

It is difficult to reproduce a severe lightning flash by laboratory simulation because of inherent facility limitations. Accordingly, for determining the effects of lightning currents and for laboratory qualification testing of vehicle hardware, an idealized representation of the components of a severe lightning flash incorporating the important aspects of both positive and negative flashes has been defined and is shown on Figure 3-3.

For qualification testing, there are four components, A, B, C, and D, used for determination of direct effects and test waveform E used for determination of indirect effects. Components A, B, C, and D each simulate a different characteristic of the current in a natural lightning flash and are shown on Figure 3-3. They are applied individually or as a composite of two or more components together in one test. There are very few cases in which all four components must be applied in one test on the same test object. Rise time or rate of change of current has little effect on physical damage, and accordingly has not been specified in these components. Current waveform E, also shown on Figure 3-3, is intended to determine indirect effects. When evaluating indirect effects, rate of change of current is important and is specified.

The tests in which these waveforms are applied are presented in Table 1. The objectives of each test along with setup, measurement, and data requirements are described in Section 4.0.

3.2.2.1 Component A - Initial High Peak Current

This component simulates the first return stroke and is characterized by a peak amplitude of 200 kA ($\pm 10\%$) and an action integral ($\int i^2 dt$) of 2×10^6 amp²-seconds ($\pm 20\%$) with a total time duration not exceeding 500 microseconds.

The actual waveshape of this component is purposely left undefined, because in laboratory simulation the waveshape is strongly influenced by the type of surge generator used and the characteristics of the device under test. Natural lightning currents are unidirectional, but for laboratory simulation this component may be either unidirectional or oscillatory.

3.2.2.2 Component B - Intermediate Current

This component simulates the intermediate phase of a lightning flash in which currents of several thousand amperes flow for times on the order of several milliseconds. It is characterized by a current surge with an average current of 2 kA ($\pm 10\%$) flowing for a maximum duration of 5 milliseconds and a maximum charge transfer of 10 coulombs. The waveform should be unidirectional, e.g. rectangular, exponential or linearly decaying.

3.2.2.3 Component C - Continuing Current

Component C simulates the continuing current that flows during the lightning flash and transfers most of the electrical charge. This component must transfer a charge of 200 coulombs ($\pm 20\%$) in a time of between 0.25 and 1 second. This implies current amplitudes of between 200 and 800 amperes. The waveform should be unidirectional, e.g. rectangular, exponential or linearly decaying.

3.2.2.4 Component D - Restrike Current

Component D simulates a subsequent high peak current. It is characterized by a peak amplitude of 100 kA ($\pm 10\%$) and an action integral of 0.25×10^6 ampere²-second ($\pm 20\%$).

3.2.2.5 Current Waveform E - Fast Rate of Rise Stroke Test for Full-Size Hardware

Current waveform E simulates a full-scale fast rate of rise stroke for testing vehicle hardware which at full scale would be 200 kA at 100 kA/ps. The peak amplitude of the derivative of this waveform must be at least 25 kA per microsecond for at least 0.5 microsecond, as shown in Figure 3-3. Current waveform E has a minimum amplitude of 50 kA. An amplitude of 50 kA is used to enable testing of typical aircraft components with conventional laboratory lighting current generators. The action integral, fall time, and the rate of fall are not specified. If desired and feasible, components A or D may be applied with a 25 kA per microsecond rate of rise for at least 0.5 microsecond and the direct and indirect effects evaluation conducted simultaneously.

3.3 Waveform Descriptions for Engineering Tests

3.3.1 Purpose

Lightning voltage and current waveforms described in the following paragraphs have been developed for engineering design and analysis.

The tests in which these waveforms are applied are presented in Table 2. The objectives of each test, along with setup, measurement and data requirements are described in Section 4.0.

3.3.2 Voltage Waveforms

During tests on model vehicles to determine possible attachment points the length of gap used between the electrode simulating the approaching leader and the vehicle depends upon the model scale factor. During such tests it is desirable to allow the streamers from the model sufficient time to develop. Accordingly, for model tests it is necessary to standardize the time at which breakdown occurs, even though the rate of rise of voltage is different for different tests.

It has been determined in laboratory testing that the results of attachment point testing are influenced by the voltage waveform. Fast rising waveforms (on the order of a few microseconds) produce a relatively few number of attach points, usually to the apparent high field regions on the model and all such attach points are classified as Zone 1. Fast rising waveforms have been used for practically all aircraft

model attach points tests in the U.S. Slow front waveforms (on the order of hundreds of microseconds) produce a greater spread of attach points, possibly including attachments to low field regions. Therefore the test data must be analyzed by appropriate statistical methods in defining Zone 1 regions.

Two high voltage waveforms are described in the following paragraphs and shown on Figure 3-4. The first is a fast waveform which is to be used for what will be termed "fast front model tests." The second waveform is a slow rising waveform which will be employed for "slow front model tests."

3.3.2.1 Voltage Waveform C - Fast Front Model Tests

This is a chopped voltage waveform in which flashover of the gap between the model under test and the test electrodes occurs at 2 microseconds ($\pm 50\%$). The amplitude of the voltage at time of flashover and the rate of rise of voltage prior to breakdown are not specified. The waveform is shown on Figure 3-4.

3.3.2.2 Voltage Waveform D - Slow Front Model Tests

The slow fronted waveform has a rise time between 50 and 250 microseconds so as to allow time for streamers from the model to develop. It should give a higher strike rate to the low probability regions than otherwise might have been expected.

3.3.3 Current Waveforms

Current waveform components F and G, shown on Figure 3-5, are intended to determine indirect effects on very large hardware and full size vehicles. These waveforms are specified at reduced amplitudes to overcome inherent full vehicle test circuit limitations and also to allow testing at non-destructive levels to be made on operational vehicles at non-destructive levels. Scaling will depend on the nature of the coupling process as detailed in the following paragraphs.

3.3.3.1 Test Waveform F - Reduced Amplitude Unidirectional Waveform

Component F simulates, at a low current level, both the rise time and decay time of the return stroke current peak of the lightning flash. It has a rise time of 2 microseconds ($\pm 20\%$), a decay time to half amplitude of 50 microseconds ($\pm 20\%$) and a minimum amplitude of 250 amperes. Indirect effects measurements made with this component must be extrapolated to the full lightning current amplitude of 200 kA.

1.3.3.2 Test Waveforms G_1 and G_2 - Damped Oscillatory Waveforms

Fast rate of rise current waveforms and higher amplitude waveforms may often be usefully employed for indirect effects testing. For indirect effects dependent upon resistive or diffusion flux effects (i.e. not aperture coupling) a low frequency oscillatory current - waveform G_1 , in which the period ($1/f$) is long compared with the diffusion time, should be used. This requires a frequency, f , of 2.5 kilohertz or lower (i.e. the duration of each half-cycle is equal to or greater than 200 μ s). Where resistive or diffusion effects are measured, the scaling should be in terms of the peak current, with full scale being 200 kA.

For indirect effects dependent upon aperture coupling the high frequency current, waveform G_2 , should be used. The maximum frequency of waveform G_2 should be no higher than approximately 300 KHz or $1/10$ of the lowest natural resonant frequency of the aircraft/return circuit, whichever is lower. Where aperture-coupled effects are measured the scaling should be in terms of rate-of-rise (di/dt), with full scale being 100 kA/ μ s.

When testing composite structures with waveform G_2 , resistive and diffusion flux induced voltages may occur as well as aperture coupled voltages, and results should be scaled both to 200 kA and to 100 kA/ μ s.

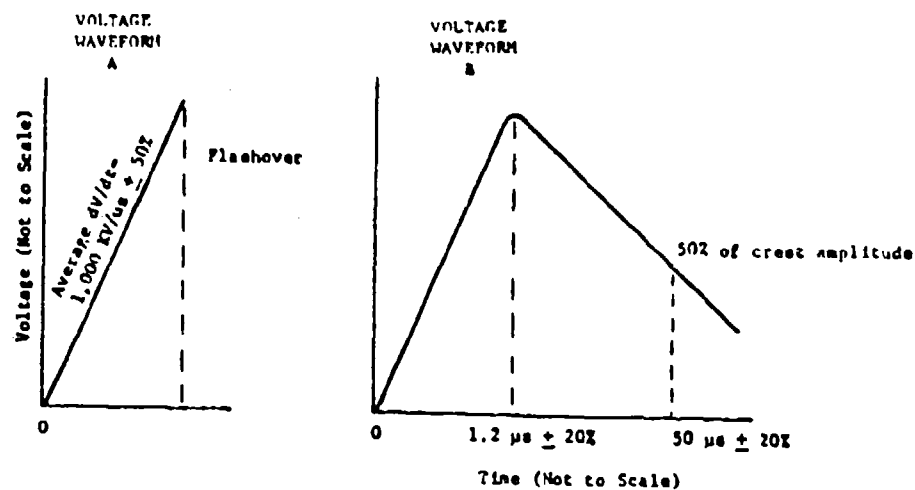


Figure 3-2 Idealized High-voltage test waveforms for qualification testing.

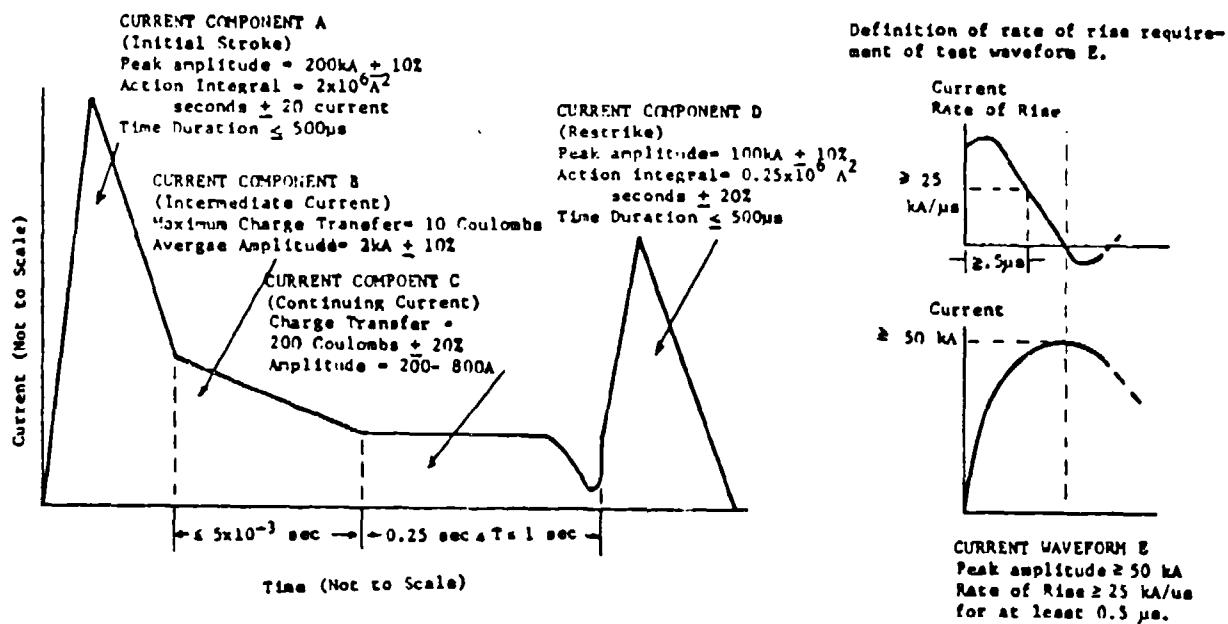


Figure 3-3 Idealized current test waveform components for qualification testing.

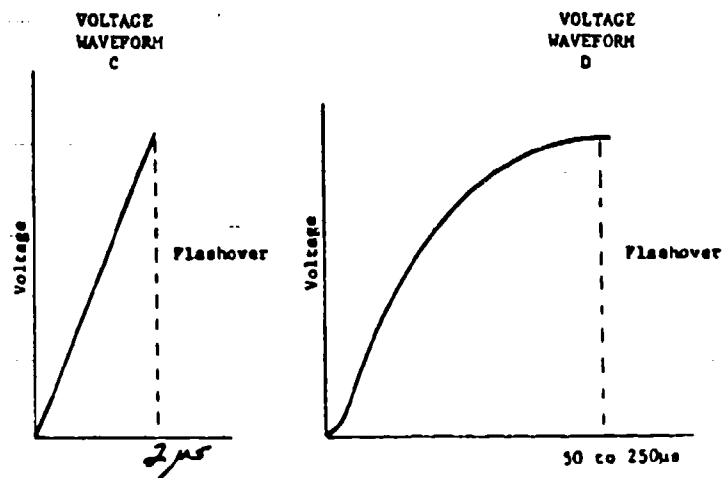


Figure 3-4 Idealized high voltage waveforms for engineering tests.

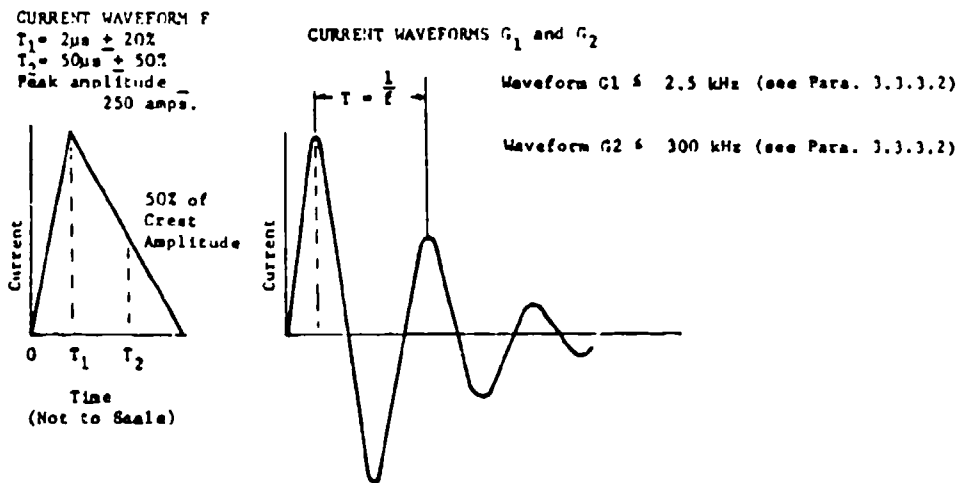


Figure 3-5 Idealized current waveforms for engineering tests. (Note: Peak amplitudes are not the same.)

Table 1

Application of Waveforms for Qualification Tests

Test	Zone	Voltage Waveforms			Current Waveforms/Components					Test Technique Para. No.
		A	B	D	A	B	C	D	E	
Full size hardware attachment point	1A,B	X		X						4.1.1
Direct effects - structural	1A				X	X				4.1.2, 4.1.2.2.1
"	1B				X	X	X	X		4.1.2, 4.1.2.2.2
"	2A					X	X	X		4.1.2, 4.1.2.2.3
"	2B					X	X	X		4.1.2, 4.1.2.2.4
"	3				X		X			4.1.2, 4.1.2.2.5
Direct effects - combustible vapor ignition	Same current components as for structural tests									4.1.3
Direct effects - streamers			X							4.1.4
Indirect effects - external electrical hardware									X ³	4.1.5

Note 1. Use average current of $2 \text{ kA} \pm 10\%$ for a dwell time less than 5 milliseconds measured in Test 4.2.2 up to a maximum of 5 milliseconds

Note 2. Use average current of 400 amp for dwell time in excess of 5 msec as determined by engineering tests.

Note 3. Indirect effects should also be measured with current components A, B, C, D as appropriate to the test zone

Note 4. The appropriate fraction of component "C" expected for the location and surface finish.

Table 2

Application of Waveforms for Engineering Tests

Test	Zone	Voltage Waveforms		Current Waveforms/Components					Test Technique Para. No.
		C	D	C	E	F	G ₁	G ₂	
Model aircraft lightning attachment point test									
Fast front		X							4.2.1
Slow front			X						4.2.1
Full size hardware attachment test	2A			X	X				4.2.2
Indirect effects - complete						X or X + X			4.2.3

4.0 TEST TECHNIQUES

The simulated lightning waveforms and components to be used for qualification testing are presented in Table 1. This table gives the current components that will flow through an aircraft structure or specimen in each zone. In some cases, however, not all of the current components specified in the table will contribute significantly to the failure mechanism. Therefore, in principle, the non-contributing component(s) can be omitted from the test. If components are to be omitted from a test for this reason, the proposed test plan should be agreed upon with the cognizant regulatory authority.

Table 2 presents waveforms suggested for engineering tests. The objective of each qualification or engineering test, setup and measurement details and data requirements are described in the following paragraphs.

4.1 Qualification Tests

4.1.1 Full Size Hardware Attachment Point Tests - Zone 1

4.1.1.1 Objective

This attachment point test will be conducted on full size structures that include dielectric surfaces to determine the detailed attachment points on the external surface, and if the surface is nonmetallic, the path taken by the lightning arc in reaching a metallic structure.

4.1.1.2 Waveforms

Test voltage waveform A should be applied between the electrode and the grounded test object. In the case of test objects having particularly vulnerable or flight-critical components it may be advisable to repeat the tests using waveform D as a confirmatory test.

4.1.1.3 Test Setup

The test object should be a full-scale production line hardware component or a representative prototype, since minor changes from design samples or prototypes may change the lightning test results. All conducting objects within or on nonmetallic hardware that are normally connected to the vehicle when installed in the aircraft should be electrically connected to ground (the return side of the lightning generator). Surrounding external metallic vehicle structure should be simulated and attached to the test object to make the entire test object look as much like the actual vehicle region under test as possible.

The test electrode to which test voltage is applied should be positioned so that its tip is 1 meter away from the nearest surface of the test object. Dimensions of the test electrode are not critical. Generally, model tests or field experience will have indicated that lightning flashes can approach the object under test from several different directions. If not, the tests should be repeated with the high voltage electrode oriented to create strokes to the object from several different directions.

If the test object is so small that a 1-meter gap permits strokes to miss the test object, or if a 1-meter gap is inappropriate for other reasons, shorter or longer gaps may be used. Multiple flashovers should be applied from each electrode position. Tests may be commenced with either positive or negative polarity. If test electrode positions are found from which the simulated lightning flashovers do not contact the test piece, or do not puncture it if it is nonmetallic, the tests from these same electrode positions should be repeated using the opposite polarity.

4.1.1.4 Measurements and Data Requirements

Measurements that should be taken during these tests include the following:

a. Test Voltage and Amplitude Waveform. The voltage applied to the gap should be measured. Photographs of the voltage waveform should be taken to establish that waveform A is in fact being applied. Voltage measurements should be made of each test voltage waveform applied since breakdown paths, and hence the test voltage, may change. Particular attention should be given to assuring that the gap flashes over on the wavefront. If a flashover occurs on the wave tail, the test should be repeated with the generator set to provide a higher voltage or the test electrode positioned closer to the test object so as to produce flashover on the wavefront.

b. Attachment Points and/or Breakdown Paths The voltage generators used for these tests are high impedance devices. The test current may be much less than natural lightning currents. Consequently, they will produce much less damage to the test object than a natural lightning flash, even though the breakdown will follow the path a full-scale lightning stroke current would follow. Occasionally a diligent search will be required to find the attachment point on metals or the breakdown path through nonmetallic surface. These attachment points or breakdown paths should be looked for after each test and marked, when found, with masking tape or crayon markings to prevent confusion with further test results.

4.1.2 Direct Effects - Structural

4.1.2.1 Objective

These tests determine the direct effects which lightning currents may produce in structures.

4.1.2.2 Waveforms

Simulated lightning current waveform components should be applied, depending on the vehicle zone of the test object, as follows:

4.1.2.2.1 Zone 1A

Waveform components A and B should be applied.

4.1.2.2.2 Zone 1B

Waveform components A, B, C, and D should be applied in that order, but not necessarily as one continuous discharge.

4.1.2.2.3 Zone 2A

Although Zone 2A is a swept stroke zone, static tests can be conducted once the attachment points and dwell times have been determined. Current components D, B, and C should be applied in that order as appropriate to the following discussion.

High peak current restrikes typically produce re-attachment of the arc at a new point. Therefore, current component D is applied first. The dwell time for components B and C in Zone 2A may be determined from swept stroke tests as described in Paragraph 4.2.2 or, alternatively, a worst case dwell time of 50 milliseconds may be assumed without conducting swept stroke tests. The timing mechanism of the generator producing component B should be set to allow current to flow into the test object (at any single point) for the maximum dwell time at that point as determined from the dwell point tests. If the measured dwell time is greater than 5 milliseconds or if a 50 millisecond dwell time has been assumed, the component B current should be reduced to 400 amperes (component C) for the dwell time in excess of 5 milliseconds. If the measured dwell time is less than 5 milliseconds, component B should be applied for the length of time measured, down to a minimum of 1 millisecond.

4.1.2.2.4 Zone 2B

Current components B, C and D should be applied in that order.

4.1.2.2.5 Zone 3

Current components A and C should be applied in that order to test objects in Zone 3. The test currents should be conducted into and out of the test object in a manner similar to the way lightning currents would be conducted through the aircraft.

4.1.2.3 Test Setup

4.1.2.3.1 Test Electrode and Gap

The test currents are delivered from a test electrode positioned adjacent to the test object. The test object is connected to the return side of the generator(s) so that test current can flow through the object in a realistic manner.

CAUTION: There may be interactions between the arc and current carrying conductors. Care must be taken to assure that these interactions do not influence the test results.

The electrode material should be a good electrical conductor with ability to resist the erosion produced by the test currents involved. Yellow brass, steel, tungsten and carbon are suitable electrode materials. The shape of the electrode is usually a rounded rod firmly affixed to the generator output terminal and spaced at a fixed distance above the surface of the test object.

The polarity of components A and D can be either positive or negative. The polarity of the generators used to produce components B and C should be set so that the electrode is negative with respect to the test object, because greater damage is generally produced when the test object is at positive polarity with respect to the test electrode.

4.1.2.4 Measurements and Data Requirements

Measurements for these tests include test current amplitude(s) and waveform(s). Initial stroke, restrike and intermediate current components may be measured with noninductive resistive shunts, current transformers, or Rogowski coils. Continuing currents may be measured with resistive shunts. The output of each of these devices should be measured and recorded.

NOTE: Indirect effects measurements are frequently required for external electrical hardware, as specified in Paragraph 4.1.6. If desired, some of these measurements can be made during the direct effects tests.

Since the condition of the test object or other parts of the test circuit may affect the test current(s) applied, measurements of these parameters should be made during each test applied, and the details of the test setup recorded for each test.

4.1.3 Direct Effects - Combustible Vapor Ignition Via Skin or Component Puncture, Hot Spot or Arcing

4.1.3.1 Objective

The objective of these tests is to ascertain the possibility of combustible vapor ignition as a result of skin or component puncture, hot spot formation, or arcing in or near fuel systems or other regions where combustible vapors may exist.

CAUTION: These tests simulate the possible direct effects which may cause ignition. Ignition of combustible vapors may also be caused by lightning indirect effects such as induced voltages in fuel probe wiring, etc.

If a blunt electrode is used with a very small gap, the gas pressure and shock wave effects in the confined area may cause more physical damage than would otherwise be produced. The electrode should be rounded to allow relief of the pressure formed by the discharge.

For multiple component tests, the test electrode should be placed as far from the test object surface as the driving voltage of the intermediate component B or continuing current component C will allow. A gap spacing of at least 50 mm is desirable but a lesser gap of at least 10 mm is required which will result in more conservative data. When components B or C are preceded by the high peak current component A, the high driving voltage of this generator initiates the arc and subsequent components B and/or C follow the established arc even though driven by a much lower voltage.

4.1.3.2 Waveforms

The same test current waveforms should be applied as are specified for structural damage tests in Paragraph 4.1.2.2.

4.1.3.3 Test Setup

Test setup requirements are the same as those described in Paragraph 4.1.2.3 for structural damage tests, with the following additional considerations:

If a complete fuel tank is not available or impractical for test, a sample of the tank skin or other specimen representative of the actual structural configuration (including joints, fasteners and substructures, attachment hardware, as well as internal fuel tank fixtures) should be installed on a light-tight opening or chamber. Photography is the preferred technique for detecting sparking. If photography can be employed, the chamber should be fitted with an array of mirrors to make any sparks visible to the camera. However, for regions where possible sparking activity cannot be made visible to the camera, ignition tests may be used by placing an ignitable fuel-air mixture inside the tank. This can be a mixture of propane and air (e.g., for propane: a 1.2 stoichiometric mixture) or vaporized samples of the appropriate fuel mixed with air. Verification of the combustibility of the mixture should be obtained by ignition with a spark or corona ignition source introduced into the test chamber immediately after each lightning test in which no ignition occurred. If the combustible mixture was not ignitable by this artificial source, the lightning test must be considered invalid and repeated with a new mixture until either the lightning test or artificial ignition source ignites the fuel.

4.1.3.4 Measurements and Data Requirements

The same test current measurements should be made as are specified for structural damage tests in Paragraph 4.1.2.4.

The presence of an ignition source should be determined by photography of possible sparking. For this purpose a camera is placed in the test chamber and the shutter left open during the test. Experience indicates that ASA 3000 speed film exposed at f4.7 is satisfactory. All light to the chamber interior must be excluded. Any light indications on the film due to internal sparking after test should be taken as an indication of sparking sufficient to ignite a combustible mixture.

CAUTION: This method of determining the possibility of sparking should be utilized only if certainty exists that all locations where sparking might exist are visible to the camera.

More specialized instrumentation may be added if additional information such as skin surface temperatures, pressure rises, or flame front propagation velocities are desired.

4.1.4 Direct Effects - Streamers

4.1.4.1 Objective

Electrical streamers initiated by a high voltage field represent a possible ignition source for combustible vapors. The objective of this test is to determine if such streamers may be produced in regions where such vapors exist.

4.1.4.2 Waveforms

Test voltage waveform B should be applied for this test. The crest voltage should be sufficient to produce streamering, but not sufficient to cause flash-over in the high-voltage gap. Generally, this will require that the average electric field gradient between the electrodes be at least 5 kV/cm.

4.1.4.3 Test Setup

The test object should be mounted in a fixture representative of the surrounding region of the airframe and be subjected to the high-voltage waveform. The voltage may be applied either by (1) grounding the test object and arranging the high-voltage test electrode sufficiently close to the test object to create the required field at the test voltage level applied or (2) connecting the test object to the high-voltage output of the generator and arranging the test object in proximity to a ground plane or other ground electrode that is connected to the ground or low side of the generator. In either case the low voltage side of the generator should be grounded. Either arrangement can provide the necessary electric field at the test object aperture. The test object should be at positive polarity with respect to ground, since this polarity usually provides the most profuse streamering.

4.1.4.4 Measurements and Data Requirements

Measurements should include test voltage waveform and amplitude, and degree and location of streamering. The presence of streamering at locations where combustible vapors are known to exist is considered an ignition source. The presence of streamering can best be determined with photography of the test object while in a darkened area. If the presence of streamers is questionable, the test should be run with a combustible mixture actually present in the test object to determine if ignition occurs, but care should be taken to ensure that the test arrangement simulates relevant operational (i.e., in-flight) characteristics.

4.1.5 Direct Effects - External Electrical Hardware

4.1.5.1 Objective

The object of this test is to determine the amount of physical damage which may be experienced by externally mounted electrical components, such as pitot tubes, antennas, navigation lights, etc. when directly struck by lightning.

4.1.5.2 Waveforms, Test Setup, and Measurements and Data Requirements

Same as for structures test as described in Paragraph 4.1.2.

4.1.6 Indirect Effects - External Electrical Hardware

4.1.6.1 Objective

The objective of this test is to determine the magnitude of indirect effects that occur when lightning strikes externally mounted electrical hardware, such as antennas, electrically heated pitot tubes, or navigation lights. For such hardware the indirect effects include conducted currents and surge voltages, and induced voltages. These currents and voltages may then be conducted via electrical circuits to other systems in the vehicle. Therefore, during the direct effects tests of electrical hardware mounted within Zones 1 or 2, measurements should be made of the voltage appearing at all electrical circuit terminals of the component. In addition, a fast rate of rise test should be conducted for evaluation of magnetically induced effects.

4.1.6.2 Waveforms

Current components A through D used for evaluation of direct effects are also used for evaluation of indirect effects, particularly those relating to the diffusion or flow of current through resistance. The specific waveforms to be used are the same as those specified in Paragraph 4.1.2. In addition, the fast rate of change current waveform E should be applied for evaluation of magnetically induced effects.

Indirect effects measured as a result of this waveform must be extrapolated as follows. Induced voltages dependent upon resistive or diffusion flux should be extrapolated linearly to a peak current of 200 kA.

Induced voltages dependent upon aperture coupling should be extrapolated linearly to a peak rate-of-rise of 100 kA/ μ s.

4.1.6.3 Test Setup

The test object should be mounted on a shielded test chamber so that access to its electrical connector(s) can be obtained in an area relatively free from extraneous electromagnetic fields. This is necessary to prevent electromagnetic interference originating in the lightning test circuit from interfering with measurement of voltages induced in the test object itself. The test object should be fastened to the test chamber in a manner similar to the way it is mounted on the aircraft, since normal bonding impedances may contribute to the voltages induced in circuits. If the shielded enclosure is large enough, the measurement/recording equipment may be contained within it. If not, a suitable shielded instrument cable may be used to transfer the induced voltage signal from the shielded enclosure to the equipment. In this case, the equipment should be located so as not to experience interference.

The test electrode should be positioned so as to inject simulated lightning current into the test object at the probable attachment point(s) expected from natural lightning. For tests run concurrently with direct effects tests on the same test object, this should be an arc-entry (flashover from test electrode to test object); but for tests made only to determine the indirect effects, hard-wired connections can be made between the generator output and test object. This is appropriate especially if it is desired to minimize physical damage to the test object. The test object should be grounded via the shielded enclosure so that simulated lightning current flows from the test object to the shielded enclosure in a manner representative of the actual installation.

4.1.6.4 Measurements and Data Requirements

Measurements should include test current amplitude(s) and waveform(s) as specified for the direct effects tests utilizing the same waveforms in Paragraph 4.1.2. In addition, measurements should be made of conducted and induced voltages at the terminals of electrical circuits in the test object.

Measurement of the voltages appearing at the electrical terminals of the test object should be made with a suitable recording instrument having a bandwidth of at least 30 megahertz.

In some cases it is appropriate to make measurements of the voltage between two terminals, as well as of the voltage between either terminal and ground. Since the amount of induced voltage originating in the test object which can enter systems such as a power bus or an antenna coupler depends partly on the impedances of these items, these impedances should be simulated and connected across the electrical terminals of the test object where the induced voltage is being measured.

The resistance, inductance and capacitance of the load impedance should be included. A typical test and measurement circuit is shown in Figure 4.1.

CAUTION: Interference-free operation of the voltage measurement system should be verified.

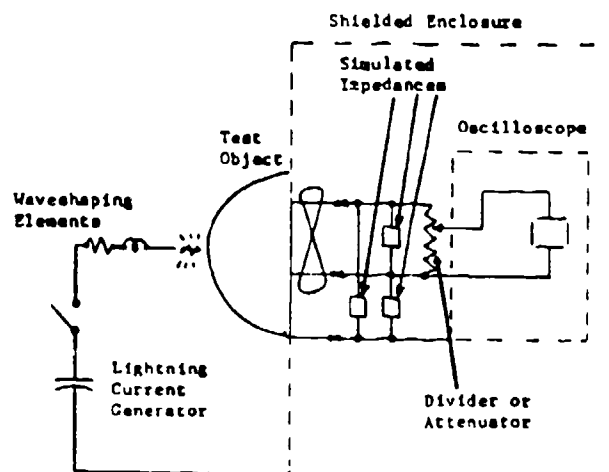


Figure 4-1 Potential elements of electrical hardware indirect effects, test and measurement circuit.

4.2 Engineering Tests

4.2.1 Model Aircraft Lightning Attachment Point Test

4.2.1.1 Objective

The objective of the model test is to determine the places on the vehicle where direct lightning strikes are likely to attach.

4.2.1.2 Waveforms

If it is desired to determine the places on the aircraft where lightning strikes are most probable, then voltage waveform C may be utilized. If it is desired, in addition, to identify other surfaces where strikes may also occur on rare occasion, voltage waveform D may be utilized. The longer rise-time of waveform D allows development of streamers and attachment points in regions of lower field intensity (in addition to those of high intensity at surfaces of high strike probability).

4.2.1.3 Test Setup

Tests on small-scale models are helpful for determining attachment zones. In some cases, tests on models must be supplemented by other means to determine exact attachment zones or points. This is particularly true of aircraft involving large amounts of nonmetallic structural materials.

An accurate model of the vehicle exterior from 1/30 to 1/10 full scale should be constructed. The various possible vehicle configurations should also be modeled. Conducting surfaces on the aircraft should be represented by conductive surfaces on the model, and vice versa.

The model is then positioned on insulators between the electrodes of a rod-rod gap or the electrode and a ground plane of a rod-plane gap. The length of the upper gap should be at least 1.5 times the longest dimension of the model. The direction of approach becomes less controllable at much higher ratios and the stroke may even miss the model. The lower gap, may be as much as 2.5 times the longest dimension of the model and should be at least equal to the model dimension.

Commonly the electrodes are fixed and the model is rotated. The orientations of the electrodes with respect to the model should be such as to define all likely attachment points. Typically, the electrodes, relative to the model, are placed at 30° steps in latitude around the 0° and 90° longitudes, as shown in Figure 4-2. Smaller steps in latitude or longitude may be required to identify all attachment points.

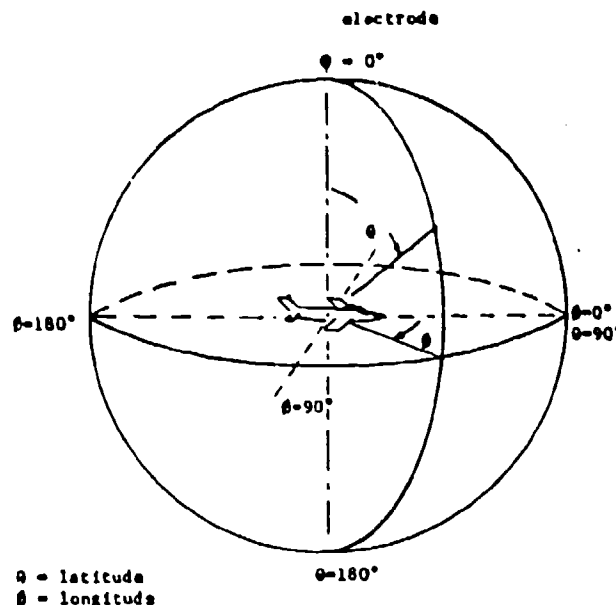


Figure 4-2 Aircraft coordinate system.

If rotation of the model significantly changes the gap length, it may be necessary to reposition the electrode. Typically three to ten shots are taken with the aircraft in each orientation to simulate lightning flashes approaching from different directions. Photographs, preferably with two cameras at right angles to each other, should be taken of each shot in order to determine the attachment points. The upper electrode should be positive with respect to ground and/or the lower electrode.

4.2.2 Full-Size Hardware Attachment Point Test - Zone 2

4.2.2.1 Objective

The mechanism of arc attachment in Zone 2 regions is fundamentally different from that in Zone 1. The basic mechanism of attachment is shown on Figure 4-3. The arc first attaches to point 1 and then, viewing the test object as stationary, is swept back along the surface to point 2. When the heel of the arc is above point 2 the voltage drop at the arc-metal interface is sufficiently high to cause flashover of the air gap and puncture of the surface finish at point 2 causing it to re-attach there.

The arc will again be blown back along the surface until the voltage along the arc channel and arc-metal interface is sufficient to cause flashover and attachment to another point. The voltage at which each new attachment will occur depends strongly upon the surface finish of the object under test. The voltage available to cause puncture depends upon the current flowing in the arc and the degree of ionization in its channel. There is an inductive voltage rise along the arc as rapidly changing currents flow through it. There will also be a resistive voltage rise produced by the flow of current. The inductive voltage rise as well as the resistive rise can be quite significant when a lightning restrike occurs at some point in the flash.

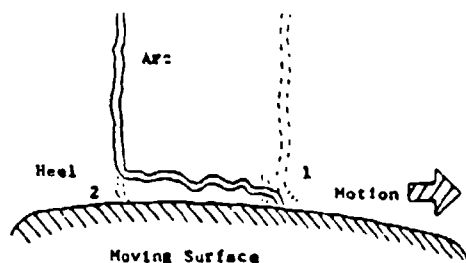


Figure 4-3 Basic mechanism of swept stroke attachment.

In addition, if the flash is discontinuous for a brief period a very high voltage is available prior to flow of the next current component. Because the channel remains hot and may contain residual ionized particles, this voltage stress is greatest along it and subsequent current components are likely to flow along the same channel. Such a voltage may well be higher than voltages created by currents flowing in the channel and may cause re-attachment to metallic surfaces or puncture of nonmetallic surfaces or dielectric coatings.

The time during which an arc may remain attached to any single point (dwell time) is a function of the lightning flash and surface characteristics which govern reattachment to the next point. The dwell time is also a function of aircraft speed.

Swept stroke attachment point and dwell time phenomena are therefore of interest for two main reasons. First, if there is an intervening nonmetallic surface along the path over which the arc may be swept, the swept stroke phenomena may determine whether the nonmetallic surface will be punctured or whether the arc will pass harmlessly across it to the next metallic surface.

Second, the dwell time of an arc on a metallic surface is a factor in determining if sufficient heating may occur at a dwell point to burn a hole or form a hot spot capable of igniting combustible mixtures or causing other damage. Thus, over a fuel tank it is particularly important that the arc move freely, in order that the metal skin of the tank not be heated or burned to a point that fuel vapors are ignited.

The objectives of attachment studies in Zone 2 are then:

For metallic surfaces

(including conventional painted or treated surfaces):

To determine possible attachment points and associated dwell times.

For nonmetallic surfaces

(including metallic surfaces with high dielectric strength coatings):

To determine if punctures may occur.

4.2.2.2 Waveforms

4.2.2.2.1 Metallic Surfaces

To determine arc dwell times on metallic surfaces, including conventional painted or treated surfaces, it is necessary to simulate the continuing current component of the lightning flash. Thus the simulated continuing current should be in accordance with current component C.

The current generator driving voltage must be sufficient to maintain an arc length that moves freely along the surface of the test object. The test electrode should be far enough above the surface so as not to influence the arc attachment to the test surface. If the technique of Figure 4-3 is used, the electrode should be a rod parallel to the air stream and approximately parallel to the test object.

A restrike may be added to the continuing current after initiation to determine whether a restrike with its associated high current amplitude would cause re-attachment to points other than those to which the continuing current arc would re-attach. If a restrike is used it is most appropriate that it be the fast rate of change of current waveform shown as current waveform Z on Figure 3-3.

4.2.2.2.2 Nonmetallic Surfaces

To determine whether it is possible for dielectric punctures or reattachments to occur on nonmetallic surfaces or coating materials, including metallic surfaces with high dielectric strength coatings, it is necessary to simulate the high-voltage characteristics of the arc. High voltages are caused by (1) current restrikes in an ionized channel, or (2) voltage buildup along a deionized channel. These characteristics are simulated by a test in which a restrike is applied along a channel previously established by a continuing current. The restrike must be initiated by a voltage rate of rise of 1000 kV/ μ s or faster and must discharge a high rate of rise current stroke in accordance with current waveform Z. This restrike must not be applied until the continuing current has decayed to near zero (a nearly deionized state) as shown in Figure 4-4.

Several tests should be applied with the continuing current duration and restrikes applied according to different times, T, in order to produce worst-case exposures of the surface and underlying elements to voltage stress.

The amplitude of the continuing current is not critical and may be lower or higher than that of current component C. Other aspects of this test are as described in Paragraph 4.2.2.3.1.

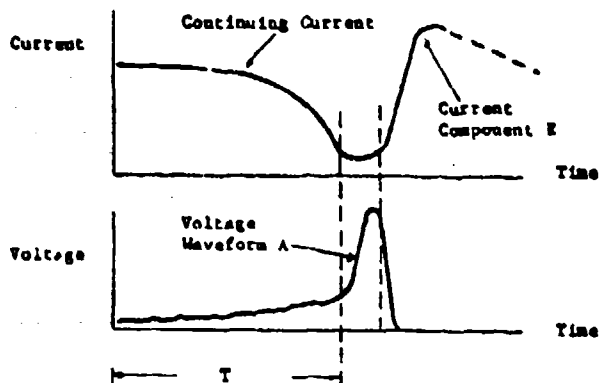


Figure 4-4 Swept stroke waveforms for tests of nonmetallic surfaces.

4.2.2.3 Test Setup

Two basic methods have been used to simulate the swept stroke mechanism. One of these involves use of a wind stream to move the arc relative to a stationary test surface as shown in Figure 4-5. The other method involves movement of the test surface relative to a stationary arc as shown in Figure 4-6. Other methods may also be satisfactory if they adequately represent the in-flight interaction between the arc and the aircraft surface. Relative velocity should include but not be limited to the minimum in-flight velocity of the vehical, which is when the dwell time condition is most critical.

The test electrode should be far enough above the surface so as not to influence the arc attachment to the test surface. If the technique of Figure 4-5 is used, the electrode should be a rod parallel to the air stream and approximately parallel to the test object.

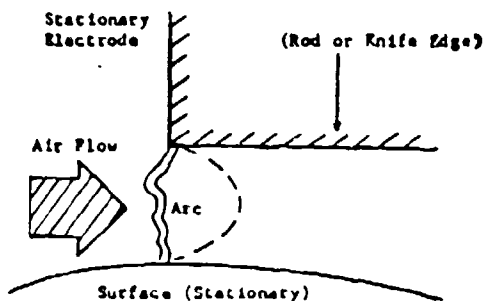


Figure 4-5 Arc moved relative to stationary test surface.

4.2.2.4 Measurements and Data Requirements

The most important measurements are those giving the attachment points, arc dwell times, breakdown paths followed, and the separation between attachment points. These are most easily determined from high speed motion picture photographs of the arc. Measurements should be made of the air flow or test object velocity and the amplitude and waveform of the current passing through the test object.

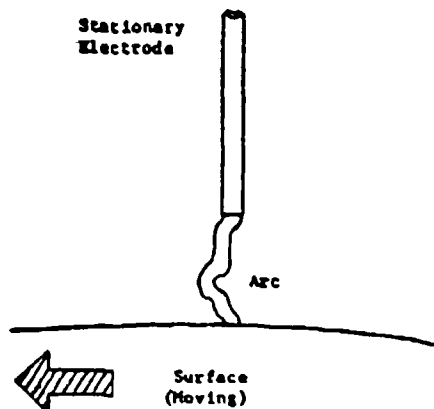


Figure 4-6 Test surface moved relative to stationary arc.

4.2.3 Indirect Effects - Complete Vehicle

4.2.3.1 Objective

The objective of this test is to measure induced voltages and currents in electrical wiring within a complete vehicle. Complete vehicle tests are intended primarily to identify circuits which may be susceptible to lightning induced effects.

4.2.3.2 Waveforms

Two techniques, utilizing different waveforms, may be utilized to perform this test. One involves application of a scaled down unidirectional waveform representative of a natural lightning stroke.

The second technique involves performance of the test with two or more damped oscillatory current waveforms, one of which (component C₂) provides the fast rate of rise characteristic of a natural lightning stroke wavefront, and the other (component C₁) provides a long duration period characteristic of natural lightning stroke duration. Induced voltages should be measured in the aircraft circuits when exposed to both waveforms and the highest induced voltages taken as the test results.

Each test is carried out by passing test currents through to the complete vehicle and measuring the induced voltages and currents. Checks are also made of aircraft systems and equipment operations where possible.

Prepared By
SAE Committee AE4-L

Committee Members:

N.P. Amason
Douglas Aircraft Company

Dong Kim
USAF Flight Dynamics Laboratory

R.O. Brick
The Boeing Company

H. Knoller
Lockheed-California Company

D.W. Clifford
McDonnell Aircraft Company

C.P. Mudd
U.S. Army Aviation Systems Command

G.A. DuBro
USAF Flight Dynamics Laboratory

S.D. Schneider
The Boeing Company

Lovell Earl
USAF Inspection & Safety Center

J.R. Stahmann
PRC Systems Services Company

F.A. Fisher
General Electric Company

W.T. Walker
U.S. Naval Air Test Center

R.H. Hess
Sperry Flight Systems

Ex Officio:

B.J.C. Burrows
UK/AEA Culham Laboratory

A.W. Hanson
UK/AEA Culham Laboratory

P.F. Little
UK/AEA Culham Laboratory

J.A. Plumer, Co-chairman
Lightning Technologies, Inc.

J.D. Robb, Co-chairman
Lightning & Transients Research Institute