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AMRC-R-196

FINAL SUPPLEMENT TO

SUPPORT OF LIGHTNING ANALYSIS AND TESTING ON THE SOLID ROCKET BOOSTER (SRB) VEHICLE

John Schmelzer

September 1979

Prepared for: National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Alabama 35812

Under Contract: NAS8-31168

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CONTENTS

SECTION 1
INTRODUCTION

This report is a supplement to the previously published report[1] of March 1978 and summarizes the work which took place after that date. The lightning analysis and testing are now complete and this work will conclude the contract.

The subject matter herein concerns:

a. computation of the aft strut cable voltages;
b. thrust vector control actuator test results;
c. thermal protection system test results;
d. circuit damage analysis of the range safety system.

In each case the analyses and/or tests were done using the NASA "worst case" lightning waveform[2], i.e., 200kA peak return stroke current and 100kA/μs rate of current rise.

The labor was supported by contract NAS8-31168, Marshall Space Flight Center. The contracting officer's representative was Mr. B. E. Gallaher. Mission Research Corporation was supported by Lightning and Transients Research Institute (LTRI) under the leadership of Mr. J. D. Robb, with subcontract SC-31168-75-0006.

1. Perala, R. A. and R. B. Cook (MRC) and J. D. Robb (LTRI), Final Report: Support of Lightning Analysis and Testing on the Solid Rocket Booster (SRB) Vehicle, AMRC-R-122, Mission Research Corporation, March 1978.
2. Space Shuttle Program Lightning Protection Criteria Document, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, JSC-07636, Revision A, November 4, 1975.

SECTION 2
SUMMARY OF WORK

COMPUTATION OF AFT STRUT CABLE VOLTAGES

In this part, the potential appearing in cables running from the orbiter to the external tank across the aft struts is computed. This potential had been calculated by Johnson Space Center as 180V (see Section 3.3 of reference 1). The potential induced in signal cables crossing a strut from the external tank to one of the solid rocket boosters has been previously computed[1] to be 23V. The total voltage is then the sum of these two values.

In this study, the potential induced in the orbiter-external tank cables is computed to be 121V. The total voltage is then 121+23 = 144V. The computations involve two steps, (1) a current division between the struts and other metallic parts and the cable shields, and (2) a calculation of the induced voltage using the transfer impedance of the cable. A "worst case" lightning current path is used, i.e., the 200kA peak current flows in at the leading edge of an orbiter wing and across the aft struts on one side to a solid rocket booster and out the exhaust. The computations were previously published as an addendum to reference 1 and are reproduced here as Appendix A.

THRUST VECTOR CONTROL ACTUATOR TEST RESULTS

The conductive exhaust is one of the likely lightning paths during launch; lightning current would therefore travel through a rocket nozzle. The solid rocket booster nozzle is steered by two actuators (hydraulic cylinders) mounted at 90° to each other. The cylinder pistons are electrically insulated from the rest of the cylinder by "O" rings and the hydraulic oil. Arcs to the piston will therefore occur and pits will be formed, which may abrade the "O" rings during operation and cause loss of oil and thus steering. An experiment at Lightning and Transients Research Institute and measurement of the leakage at Marshall Space Flight Center (MSFC) were chosen over analysis as leading to the quickest and most accurate results. The experiments are described in Appendices B and C:

Appendix B, LTRI Simulated Lightning Strikes
Appendix C, MSFC Oil Leakage Test Report

The measured oil leakage during a rigorous exercise of the damaged cylinder was only 2% of that allowable.

THERMAL PROTECTION SYSTEM TEST RESULTS

The thermal protection system consists of cork or ablative material applied to the areas of the solid rocket booster which will receive the greatest aerodynamic and/or exhaust heating. The function is to thermally insulate cables and electronic components and to prevent overheating of metal sections which might fatigue.

A lightning strike to the insulating material would be expected to blast away portions of it; increased aerodynamic or exhaust heating would then occur below the damaged area. Simulated lightning strikes on test panels were performed at LTRI (both swept strokes and stationary arcs) and the panels were exposed in the Hot Gas Facility at MSFC. Thermocouples behind the damaged areas recorded the temperature. These experiments are described in Appendices D and E:

Appendix D, LTRI Simulated Lightning Strikes
Appendix E, MSFC Temperature Measurements

Blast damaged areas up to four inches in diameter were found after the simulated lightning strikes. In two out of the eight thermal tests, the temperatures exceeded slightly the design maxima, but no excessive additional removal of insulating material was found in the Hot Gas Facility test. MSFC considers the results to be marginally acceptable, as indicated in their letter of October 2, 1978, reproduced as Appendix F.

CIRCUIT DAMAGE ANALYSIS OF RANGE SAFETY SYSTEMS

A damage analysis of the circuitry of the external tank range safety system and the solid rocket booster range safety system was undertaken. This circuitry had not been analyzed at the time that the final report[1] was written. The methodology used was identical to that in Section 5.3 of the final report. It should be noted that a value of 180V for the potential appearing in cables running from the orbiter to the external tank across the aft struts was assumed in all of the circuit damage analyses, although a lower value was computed in the later stages of this study. The analyses and recommendations have been distributed for inclusion with those done before March 1978.

APPENDIX A

INDUCED CABLE VOLTAGES DUE TO LIGHTNING CURRENT ON ORBITER-EXTERNAL TANK AFT STRUTS

AMRC-R-122

ADDENDUM TO FINAL REPORT

SUPPORT OF LIGHTNING ANALYSIS AND TESTING
ON THE SOLID ROCKET BOOSTER (SRB) VEHICLE

"INDUCED CABLE VOLTAGES DUE TO LIGHTNING
CURRENT ON ORBITER-EXTERNAL TANK AFT STRUTS"

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October 1978

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INDUCED CABLE VOLTAGES DUE TO LIGHTNING CURRENT ON ORBITER-EXTERNAL TANK AFT STRUTS

INTRODUCTION

The worst case is a strike to the orbiter wing, in at 3 and out at A. The entire 200kA strike will then flow through the aft struts (see Figures 1 and 2). Figure 3 shows the cable runs to be analyzed. The right hand side is taken as the worst case since the hydrogen feed line bypasses current from the cable run on the left side.

There are two cables running in a tunnel, a section of which is shown in Figure 4. Each cable has been scaled from Figure 5 to be 1.4 inches in diameter.

This analysis will break the conduction path into two parts, A and B (Figure 3), solve the current division problem for each path in order to find the cable shield currents, find the voltage induced in the cables for each path using a transfer impedance measured for a similar cable, and add those voltages. This sum will then be added to the 23V previously computed[1] for cables running from the external tank to the solid rocket booster across the aft strut.

[1]Perala, R. A. and R. B. Cook (MRC) and J. D. Robb (LTRI), Final Report: Support of Lightning Analysis and Testing on the Solid Rocket Booster (SRB) Vehicle, AMRC-R-122, Mission Research Corporation, March 1978, p. 18.

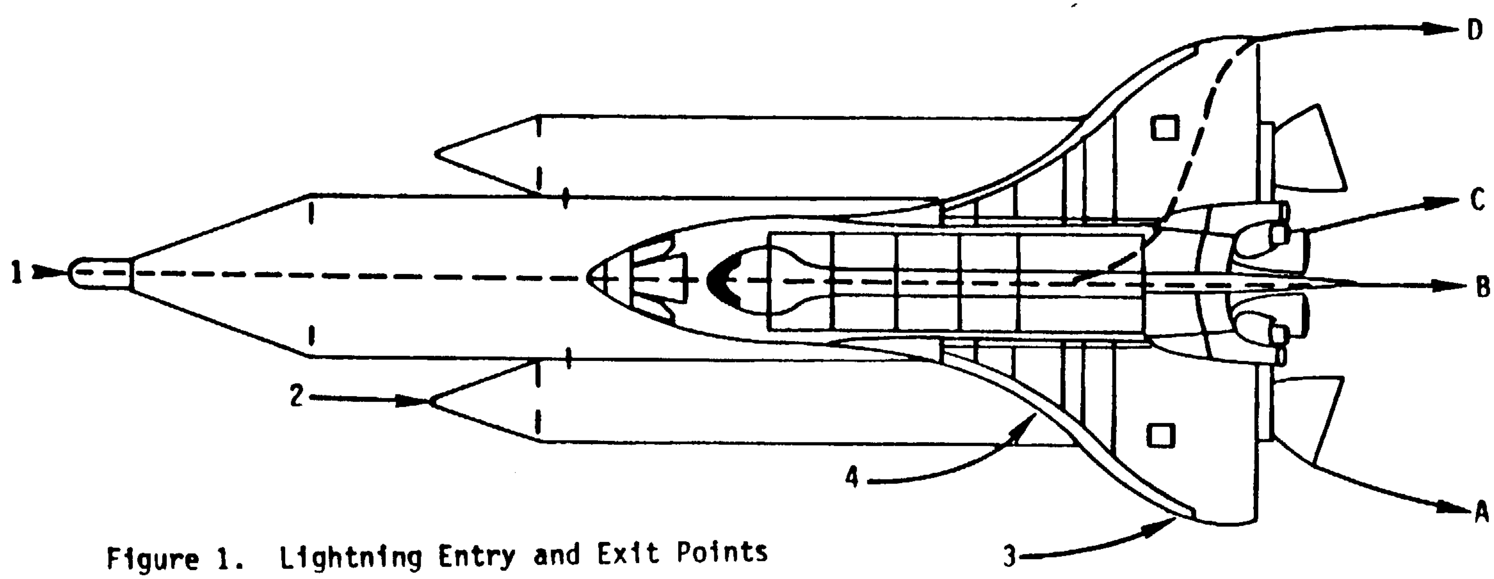

Figure 1. Lightning Entry and Exit Points

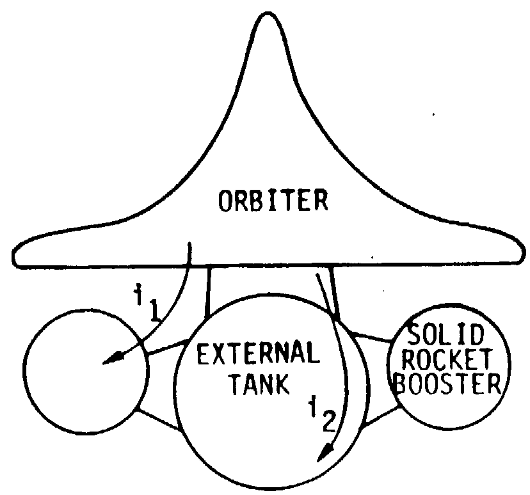

Figure 2. Current Division Through Aft Struts. (For a worst case, let i_1 = 200kA, i_2 = 0.)

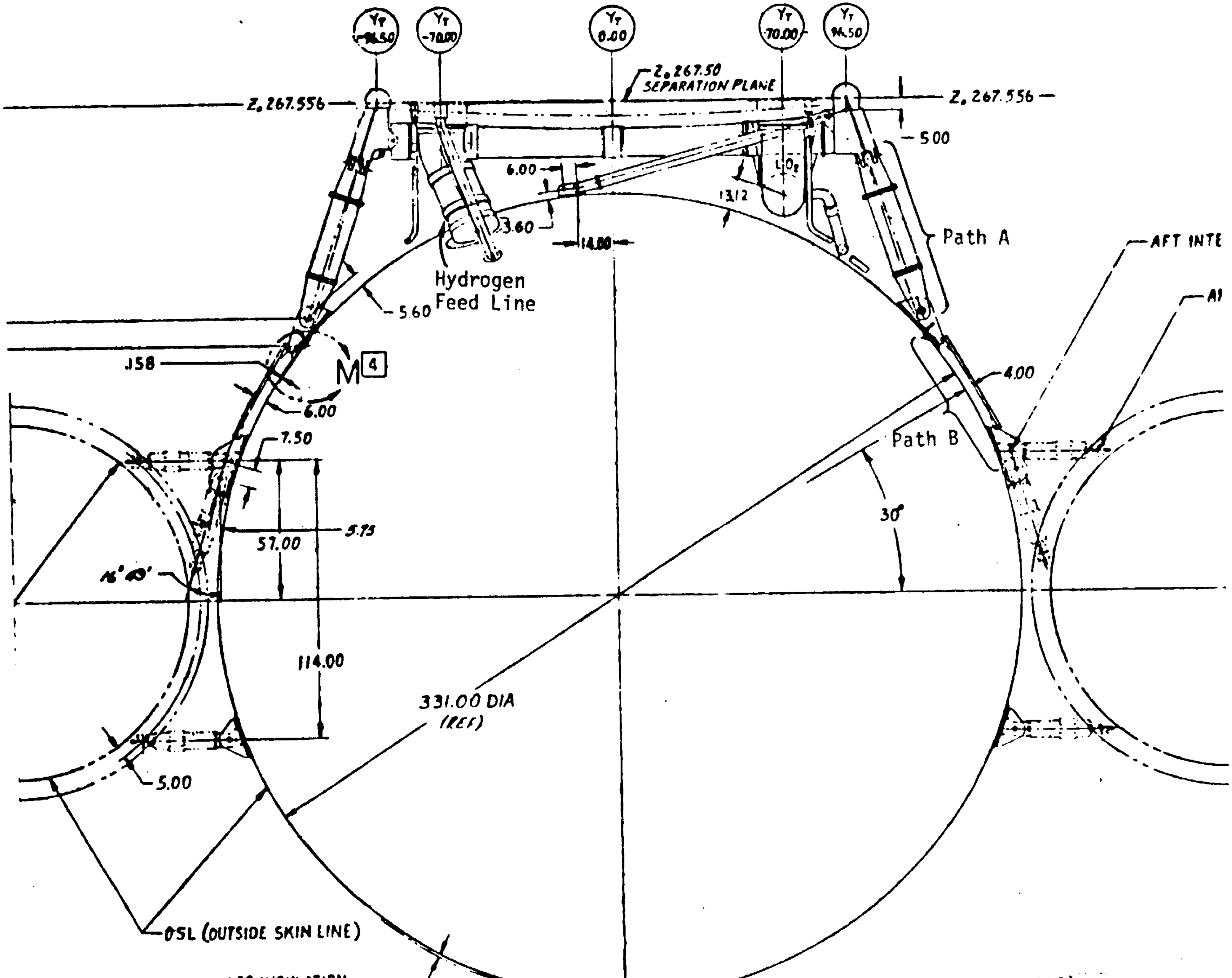

Figure 3. View Looking Forward Showing Cable Runs (NASA Drawing VC 78-000002)

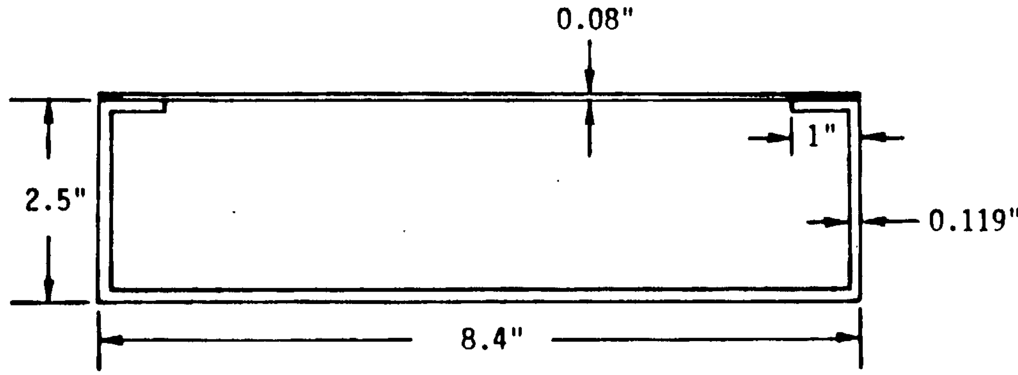

Figure 4. Cable Tunnel Cross Section

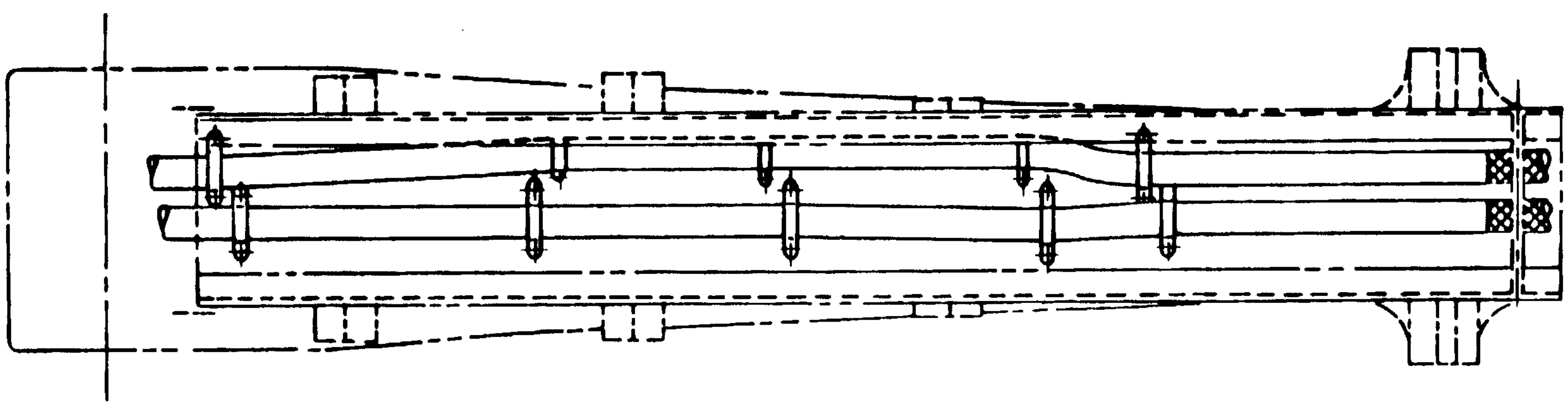

Figure 5. Cable Tunnel with Cables (from NASA Drawing 82631003109)

PATH A

The cable tunnel on the 11.9-inch diameter strut is shown in Figure 6. From this scale drawing, the cross-section model of Figure 7 is derived.

The inductance of the strut is given by[2]

$$L_{strut} = 0.00508\ell \left(\ell n \frac{4\ell}{d} - 0.75\right)\mu H \tag{1}$$

where ℓ is the strut length (inches) and d is the strut diameter (inches). Path A is seventy inches long so

$$L_{strut} = 0.00508\ (70)\ \left(\ell n \frac{4 \cdot 70}{11.9} - 0.75\right)$$

$$= 0.856\mu H\ .$$

Similarly, the inductance of the tunnel is found to be[2]

$$L_{tunnel} = 0.00508\ell \left(\ell n \frac{2\ell}{B+C} + 0.5 - 0.0024\right)$$

where B and C are the cross-section dimensions

$$= 0.00508\ (70)\ \left(\ell n \frac{2 \cdot 70}{2.6 + 8.4} + 0.5 - 0.0024\right)$$

$$= 1.08\mu H\ .$$

The mutual inductance is difficult to compute but is found with the use of the model in Figure 8, which is the model of Figure 7 with the rectangular tunnel replaced by a round tunnel of equal perimeter. The mutual inductance is found to be[3] 0.477μH.

[2]Grover, F. W., Inductance Calculations: Working Formulas and Tables, Dover: New York, 1962, p. 35.

[3]*Ibid.*, p. 31.

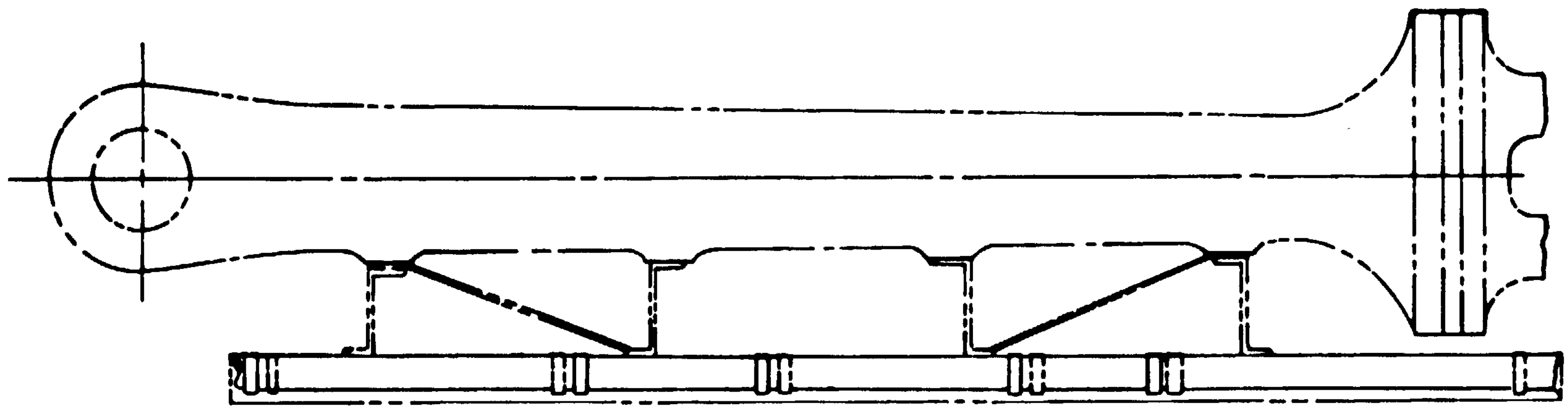

Figure 6. Cable Tunnel on Strut, Path A, from NASA Drawing 82631003109

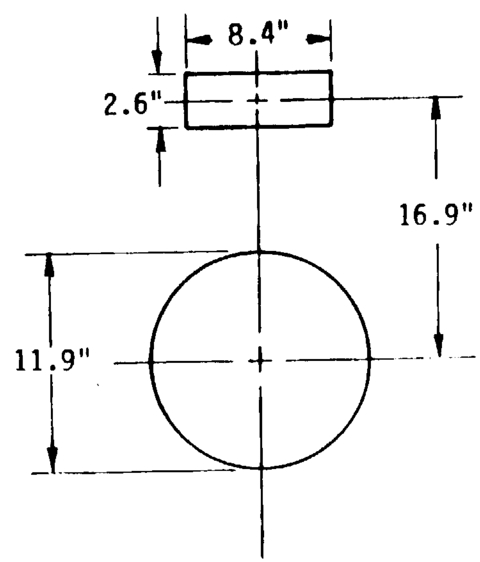

Figure 7. Cross-Sectional Model of the Cable Tunnel on Strut

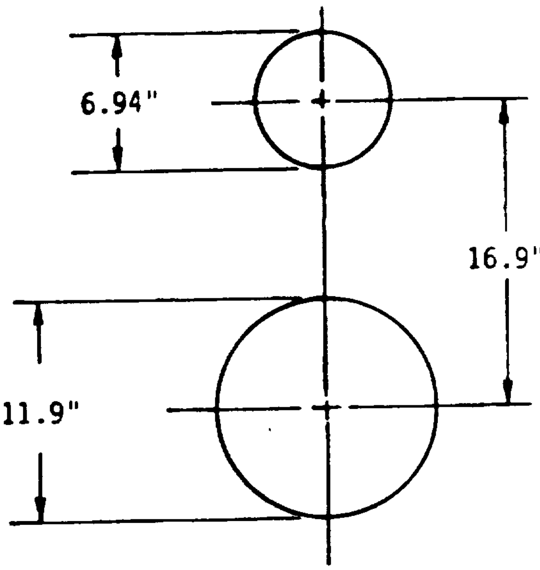

Figure 8. Cross-sectional model of the cable tunnel on strut used for computing their mutual inductance.

The equivalent circuit of Figure 9 can now be drawn, neglecting strut and tunnel resistances, which are inconsequential.

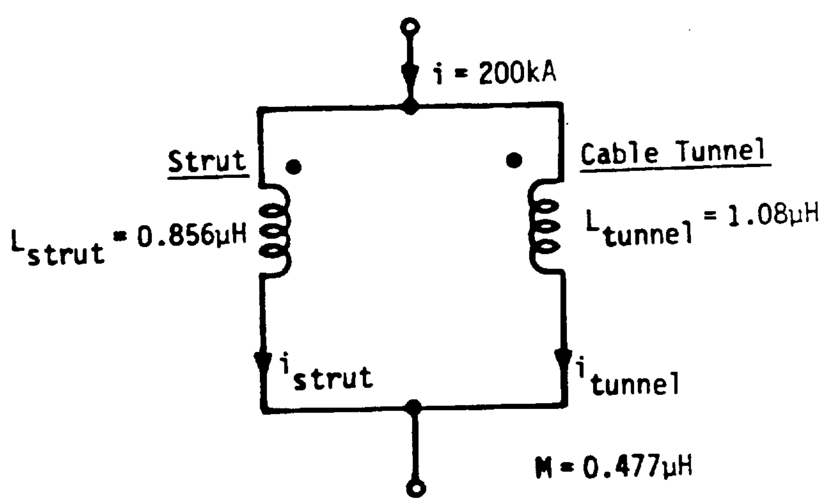

Figure 9. Equivalent circuit of Path A, with cables lumped into the cable tunnel.

The current division is now

$$\frac{i_{strut}}{i_{tunnel}} = \frac{L_{tunnel} - M}{L_{strut} - M}$$

$$= \frac{1.08 - 0.477}{0.856 - 0.477}$$

$$= 1.59$$

or

$$i_{tunnel} = 0.386i = 0.386(200kA) = 77.2kA.$$

The tunnel and cables are now placed in parallel in a similar manner. The inductances and resistances of the cables and tunnel are first computed.

NASA has measured the resistance (at unknown frequency) of a similar 0.52-inch OD cable[4] to be 0.7mΩ/ft = 0.06mΩ/in. The resistance of the tunnel cables in scaled from this value assuming equal shield thicknesses:

$$R_{cable} = 0.06 \frac{m\Omega}{in.} \left(\frac{0.52in.}{1.4in.}\right) 70in$$

$$= 1.52m\Omega$$

The conductivity of the steel tunnel is assumed to be[5] $1.5 \cdot 10^6$℧/m = $3.8 \cdot 10^4$℧/in. Some frequency-domain computations are now done for convenience. The frequency of choice has a period of four times the rise time, or 125kHz. The skin depth at this frequency is

[4]Perala, *et al.*, *op. cit.*, p. B3-11.

[5]Attwood, S. S., Electric and Magnetic Fields, Dover: New York, 1967, p. 127.

$$\delta_{steel} = (\pi f \mu \sigma)^{-\frac{1}{2}}$$
$$= \{\pi(125 \cdot 10^3) 4\pi \cdot 10^{-7} (1.5 \cdot 10^6)\}^{-\frac{1}{2}}$$
$$= 1.16 \cdot 10^{-3} \text{m}$$
$$= 4.57 \cdot 10^{-2} \text{in.}$$

where $\mu = \mu_0$ since the steel is expected to be saturated at these currents. Reference to Figure 4 shows that the current carrying area of the tunnel is then 1.0 inch^2. The tunnel resistance is then

$$R_{tunnel} = \frac{\ell}{\sigma A}$$
$$= \frac{70}{3.8 \cdot 10^4 (1.0)}$$
$$= 1.84 \text{m}\Omega \ .$$

The inductance of the two cables in parallel (including the mutual inductance) is[6]

$$L_{cables} = 0.00508\ell \left(\ell n \frac{2\ell}{\sqrt{\rho d}} - \frac{7}{8} \right) \mu\text{H}$$

where $\rho = 0.70$ inch is the radius of one cable and $d = 2.8$ inches (scaled from Figure 5) is the distance between centers. Making the substitutions,

$$L_{cables} = 1.33 \mu\text{H}.$$

The equivalent circuit of the tunnel and cables in path A is now shown by Figure 10, in which there is no magnetic coupling between the cables and the tunnel since the tunnel current is assumed to flow on its outside.

[6] Grover, *op. cit.*, p. 37.

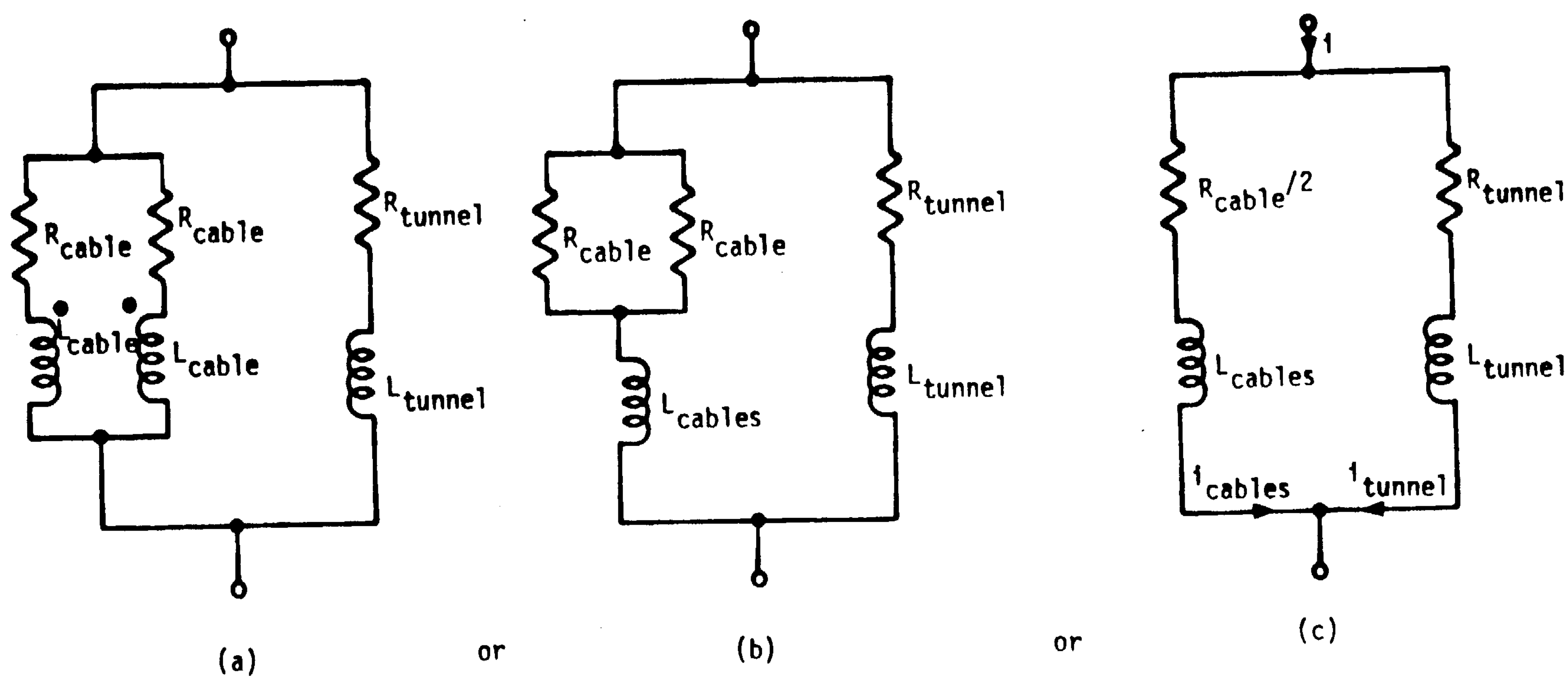

Figure 10. Evolving Equivalent Circuits for the Tunnel and Cables in Path A

A current division is now done at 125kHz in the circuit of Figure 10(c).

$$Z_{cables} = \frac{R_{cable}}{2} + j\ 2\pi\ f\ L_{cables}$$

$$= \frac{1.52 \cdot 10^{-3}}{2} + j\ 2\pi\ (125 \cdot 10^{3})\ 1.33 \cdot 10^{-6}$$

$$= 0.76 \cdot 10^{-3} + j\ 1.04$$

$$= j\ 1.04 \quad \Omega$$

$$Z_{tunnel} = R_{tunnel} + j\ 2\pi\ f\ L_{tunnel}$$

$$= 1.84 \cdot 10^{-3} + j\ 2\pi\ (125 \cdot 10^{3})\ 1.08 \cdot 10^{-6}$$

$$= 1.84 \cdot 10^{-3} + j\ 0.848$$

$$= j\ 0.848 \quad \Omega$$

The current division is now

$$\frac{i_{cables}}{i_{tunnel}} = \frac{Z_{tunnel}}{Z_{cables}}$$

$$= \frac{j\ 0.848}{j\ 1.04}$$

$$= 0.815$$

or

$$i_{cables} = 0.449\ i \qquad (2)$$

$$= 0.449\ (77.2kA)$$

$$= 34.7kA$$

and

$$i_{cable} = \frac{i_{cables}}{2} \qquad (3)$$

$$= \frac{34.7kA}{2}$$

$$= 17.3kA\ .$$

The transfer resistance and inductance of the previously mentioned 0.52-inch OD cable has been measured[7] as $R_T = 3.53m\Omega/m$ and $L_T = 1.40nH/m$. The peak voltage induced in a cable in path A is then expected to be

$$v_a = \ell\left[R_T\ i_{cable} + L_T \frac{d}{dt}\ i_{cable}\right] \qquad (4)$$

$$= 1.78\left[3.53 \cdot 10^{-3}(17.3 \cdot 10^{3}) + 1.40 \cdot 10^{-9}\ \frac{17.3 \cdot 10^{3}}{2 \cdot 10^{-6}}\right]$$

$$= 109 + 12.1$$

$$= 121V$$

PATH B

Reference to Figure 3 shows that the cable tunnel in path B is electrically in parallel with the external tank. The length of path B is the same as that of path A, so the tunnel resistance and inductance are not changed. But one would expect the external tank to form a low resistance, inductance-free path in parallel with the cable tunnel. The model

[7] Perala, *et al*, *op. cit.*, p. 13.

for path B will then place the cable tunnel above an infinite conducting plane of thickness δ_{steel} and connected to the plane at each end as shown in Figure 11. The exact form of the contacts at the ends of the tunnel is not obvious from Figure 3, so they are taken as 15-inch resistanceless disks for simplicity.

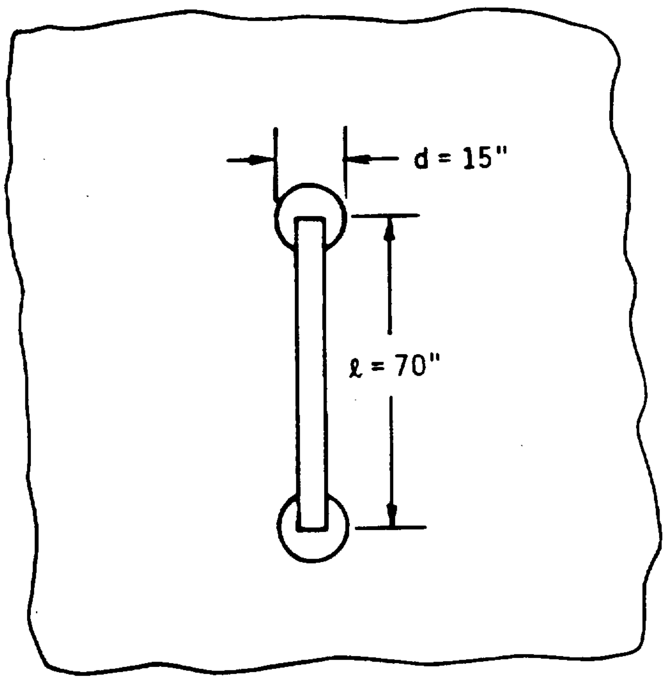

Figure 11. Model of Path B

The resistance of the plane between the disks is computed using the analogy between their capacitance and the conductance between them, i.e., if

$$C = \varepsilon \; f(\text{geometry})$$

then

$$G = \sigma \; f(\text{geometry}).$$

The capacitance is well known and given by

$$C = \frac{\varepsilon \pi \delta}{\ell n \frac{2\ell}{d}} \quad F$$

so

$$G = \frac{\sigma \pi \delta}{\ell n \frac{2\ell}{d}} \quad \mho$$

or

$$R_{plane} = \frac{\ell n \frac{2\ell}{d}}{\sigma_{steel}\ \pi\ \delta_{steel}}$$

$$= \frac{\ell n \frac{2(70)}{15}}{3.8 \cdot 10^{4} (\pi) 4.57 \cdot 10^{-2}}$$

$$= 0.409 m\Omega.$$

An equivalent circuit of path B can now be drawn as Figure 12, neglecting the inconsequential tunnel resistance.

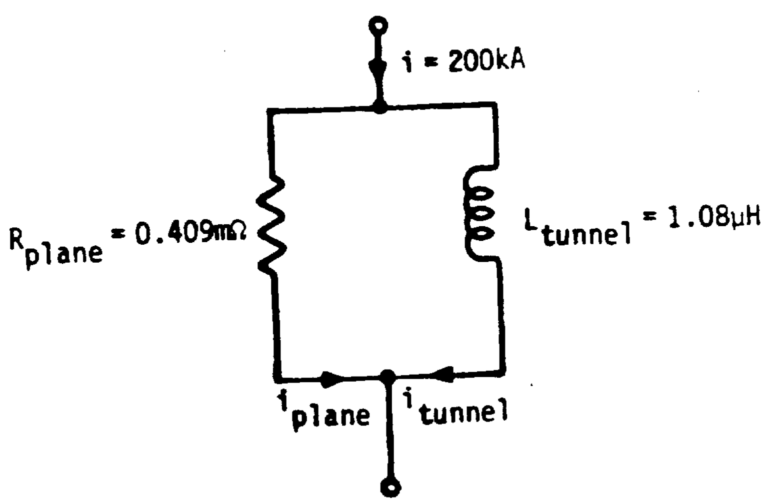

Figure 12. Equivalent circuit of Path B, with cables lumped into the cable tunnel.

The current division is

$$\frac{i_{plane}}{i_{tunnel}} = \frac{|Z_{tunnel}|}{|Z_{plane}|}$$

$$= \frac{2\pi \ f \ L_{tunnel}}{R_{plane}}$$

$$= \frac{2\pi(125 \cdot 10^{3})1.08 \cdot 10^{-6}}{0.409 \cdot 10^{-3}}$$

$$= 2070$$

or

$$i_{tunnel} = 4.82 \cdot 10^{-4} i$$

$$= 4.82 \cdot 10^{-4} (200\text{kA})$$

$$= 96.4\text{A}.$$

A cable current can be found with Equation (2) and (3),

$$i_{cable} = \frac{0.449}{2} i_{tunnel}$$

$$= \frac{0.449}{2} 96.4$$

$$= 21.7\text{A} .$$

The peak voltage induced in a cable in path B is then found with Equation (4),

$$v_b = \ell\left[R_T\, i_{cable} + L_T \frac{d}{dt}\, i_{cable}\right]$$

$$= 1.78\left[3.53\cdot 10^{-3}(21.7) + 1.40\cdot 10^{-9}\ \frac{21.7}{2\cdot 10^{-6}}\right]$$

$$= 0.16V\ .$$

CONCLUSION

The voltage induced in a cable running from the orbiter to a solid rocket booster is then given by

$$v = v_a + v_b + 23V$$

$$= 121 + 0.16 + 23$$

$$= 144V$$

where 23V is the value previously computed for cables running from the external tank to the solid rocket booster across the aft strut.

APPENDIX B

LTRI TEST REPORT
SIMULATED SIGHTNING STRIKES TO THE
THRUST VECTOR CONTROL ACTUATOR

DIRECT LIGHTNING EFFECTS TESTS
SRB TVC ACTUATOR
(Solid Rocket Booster Thrust Vector Control Actuator)

L&T Report No. 672

By

J.D. Robb
T. Chen

September 1978

Prepared For

Mission Research Corporation
Albuquerque, N.M. 87118

Subcontract SC-31168-75-0006

Under Contract to
Marshall Space Flight Center
Huntsville, Alabama

Prepared By

Lightning & Transients Research Institute
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St. Paul, Mn. 55113

FOREWORD

This report, L&T No. 672, covers lightning tests of the Space Shuttle SRB Thrust Vector Control Actuator. LTRI scientific personnel participating in the tests included J.D. Robb and Dr. T. Chen.

Mr. John Schmelzer representing Mission Research Corporation witnessed the tests.

The technical representative on the contract for NASA was Mr. B.E. Gallaher.

1.0 INTRODUCTION AND SUMMARY

Lightning tests have been carried out to determine the degree of pitting expected from lightning strike currents passing from the Solid Rocket Booster (SRB) case through the Thrust Vector Control (TVC) actuator to the SRB exhaust plume. Calculations have been made by MRC staff at Mission Research Corporation to determine the lightning current component magnitudes which would pass through the TVC actuator if a 200,000 ampere lightning strike passed through the entire shuttle vehicle and these were applied in these tests. The problem of primary concern was lightning current pitting of the hydraulic cylinder surface which could tear the "O" ring seals during activation and cause hydraulic fluid leakage. No evaluation was made of the Flight Center and the actuator was therefore returned.

2.0 TEST OBJECT IDENTIFICATION

The hydraulic cylinder tested was a cylinder for Saturn IC which was essentially the same as the Shuttle SRB actuator in the critical areas of the hydraulic seal and cylinder surface.

3.0 TEST PROCEDURE

The test procedure is attached in Appendix I. The test arrangement is illustrated in Figure 1.

4.0 TESTS AND TEST RESULTS

The desired current components defined by MRC calculations consisted of a high current impulse of 21,000 amperes, followed immediately by a DC continuing current of 20 amperes DC for 300 milliseconds. The actual test currents were 21 kiloamperes with a continuing current of about 22 amperes. The DC component could have been adjusted to a closer current value but only at the expense of additional test time and it was felt that the easily obtained value of current was sufficient in view of the wide variation to be expected in natural lightning continuing currents.

The tests were carried out according to the test procedure as shown in Table I by firing two current levels, the level specified and twice this current level with various configurations of bonding jumpers as specified in the attached data sheet.

The test current oscillograms and photographs of the test arrangements for the tests are shown in the attached figures.

5.0 CONCLUDING DISCUSSION

Lightning test currents corresponding to the calculated values of current through the actuator for a 200,000 ampere strike to the Shuttle were passed through the actuator and it has been returned to Marshall Space Flight Center for assessment of the damage.

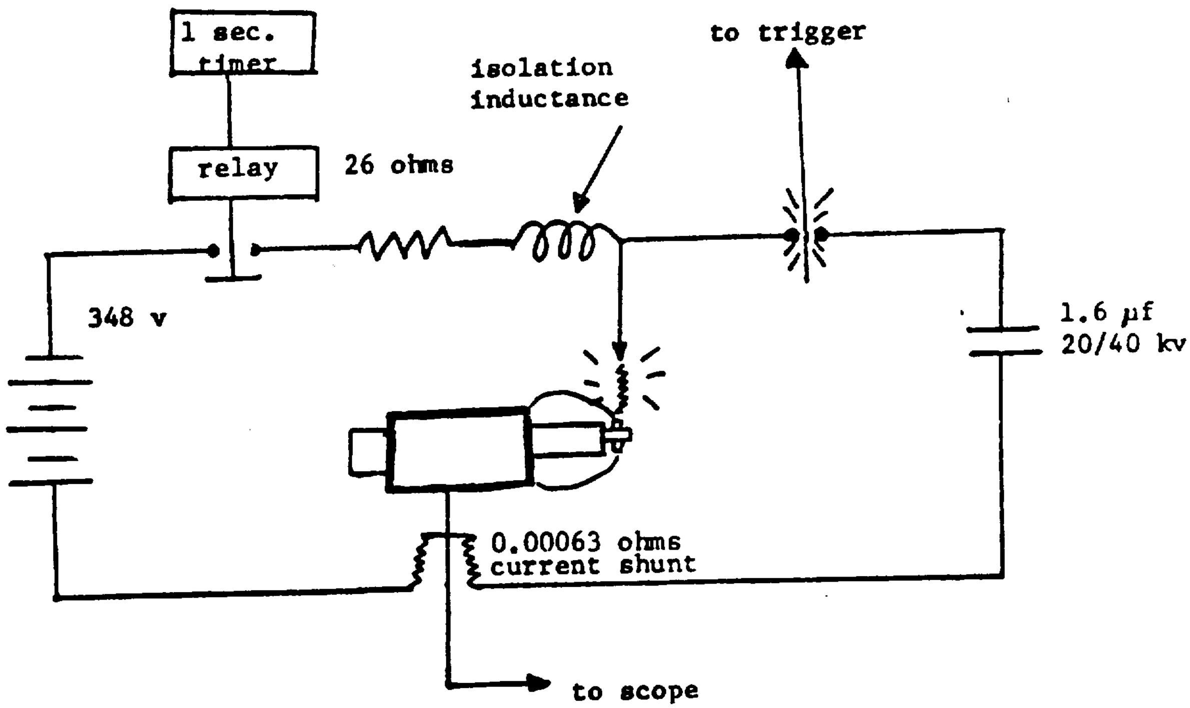
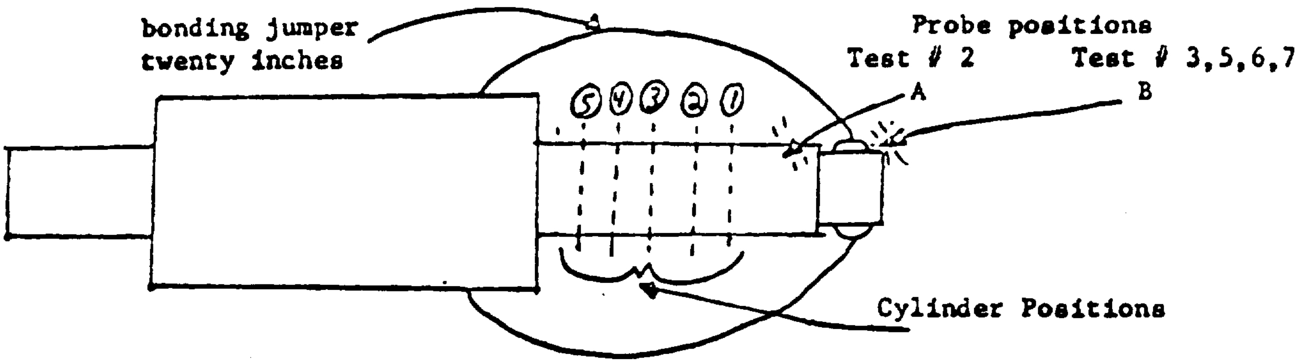


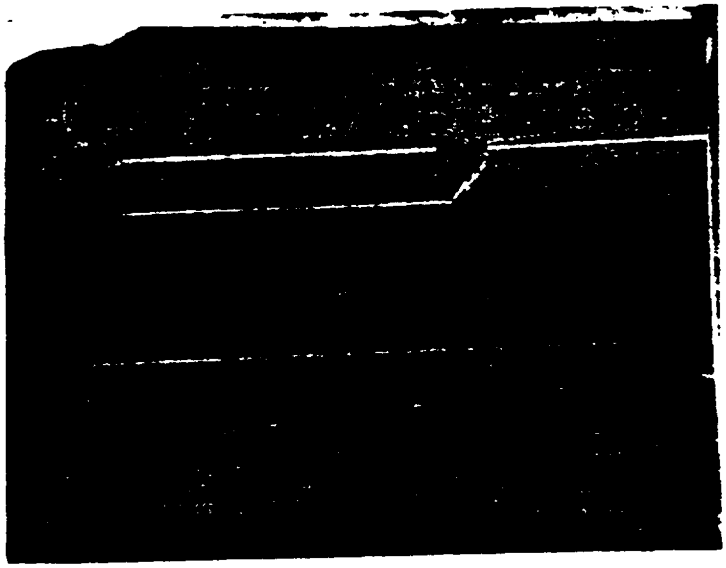
Figure 1. Test arrangement for the SRBTVC actuator lightning tests.

TABLE I
Data Sheet

Lightning Tests SRB TVC Actuator



Test No.	Probe Position	Cylinder Position	Charge KV	High Current KA	DC Current A	DC Duration	No. of Bond Straps	Remarks
1			20	20	22	1 sec		Calibration
2	A	2	20	20	22	1 sec	0	
3	B	1	20	20	22	1 sec	2	
4	B	3	40				2	Prefired, current sparked over to ground. No current thru test object
5	B	3	40	40	22	1 sec	2	Repeating #4
6	B	4	40	40	22	1 sec	4	
7	B	5	20	20	22	1 sec	4	

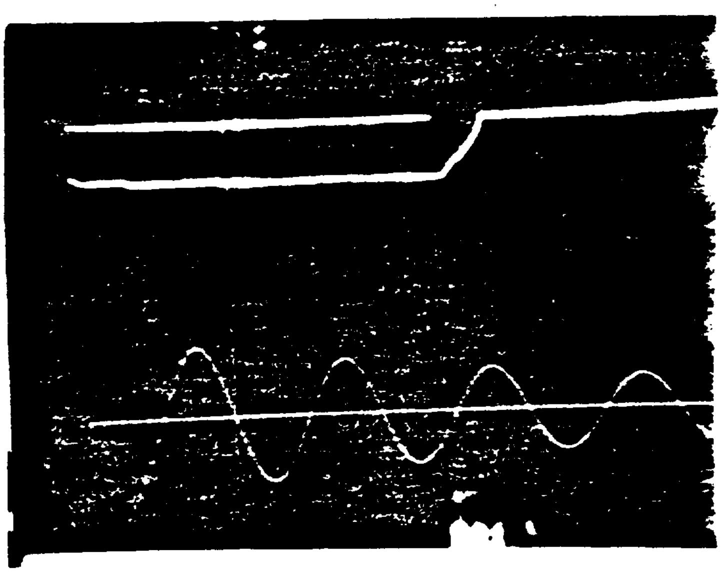


For all oscillograms:

Slow sweep (upper sweep)
o.2 sec./div.
32 Amp./div.

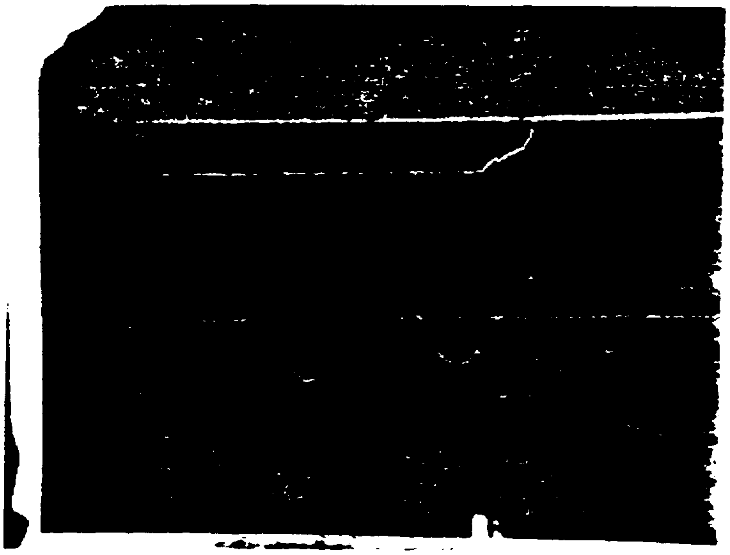
Fast sweep (lower sweep)
5 μs/div.
18 KA / div.

TEST # 1



TEST # 2

TEST # 2



For all oscillograms:

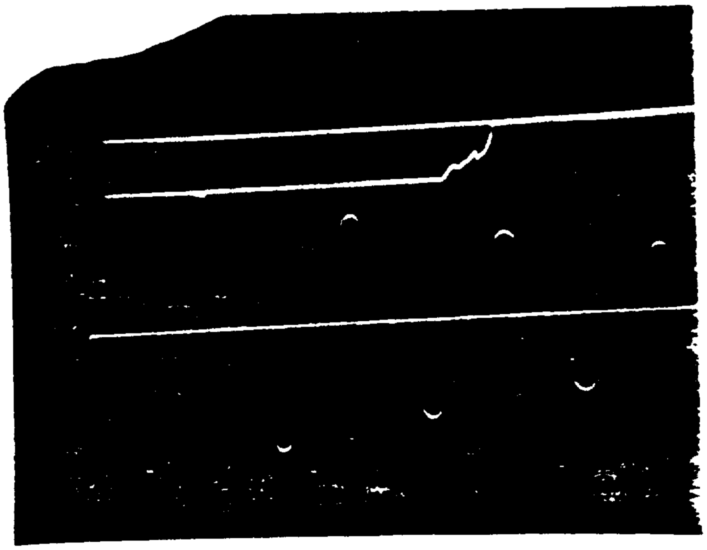
Slow sweep (upper sweep)

0.2 sec./div.
32 Amp./div.

Fast sweep (lower sweep)
5 μs/div.
18 KA/div.

TEST # 3

TEST # 3



TEST # 5

Slow sweep

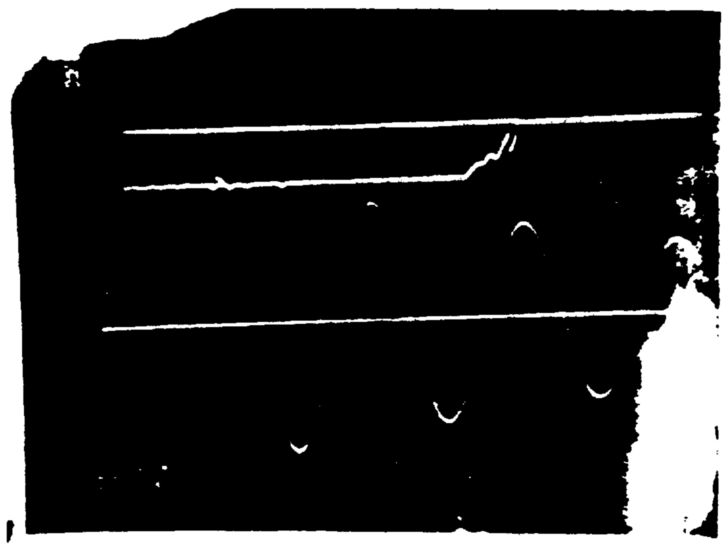
0.2 sec./div.
32 Amp./div.

Fast sweep

5 μs/div.
18 KA/div.

TEST # 5

TEST # 6



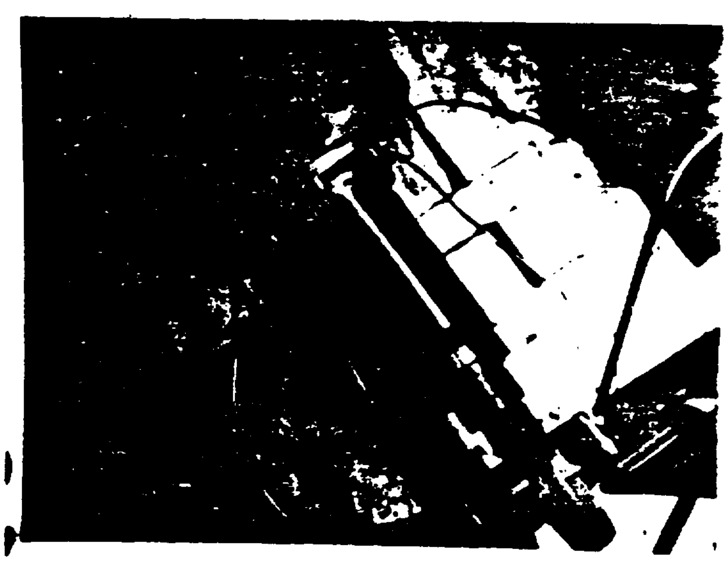
Slow Sweep

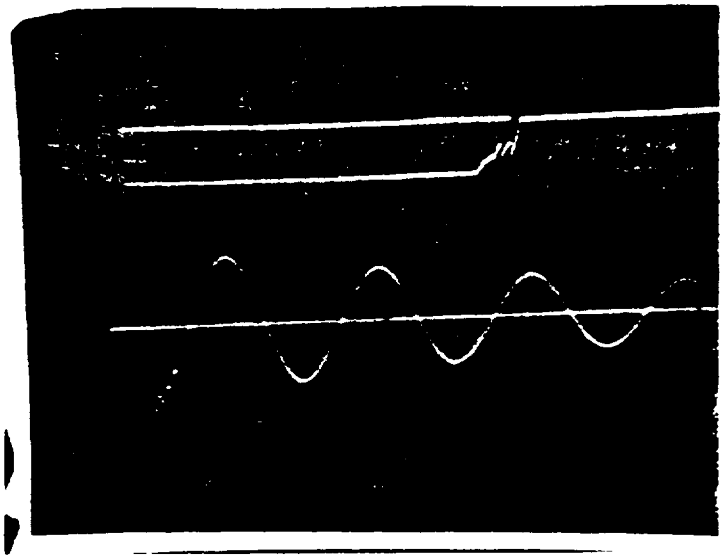
0.2 sec./div.
32 Amp./div.

Fast Sweep

5 μs/div.
18 KA/div.

TEST # 6





TEST # 7

Slow sweep

0.2 sec./div.
32 Amp./div.

Fast sweep

5 μs/div.
18 KA/div.

TEST # 7

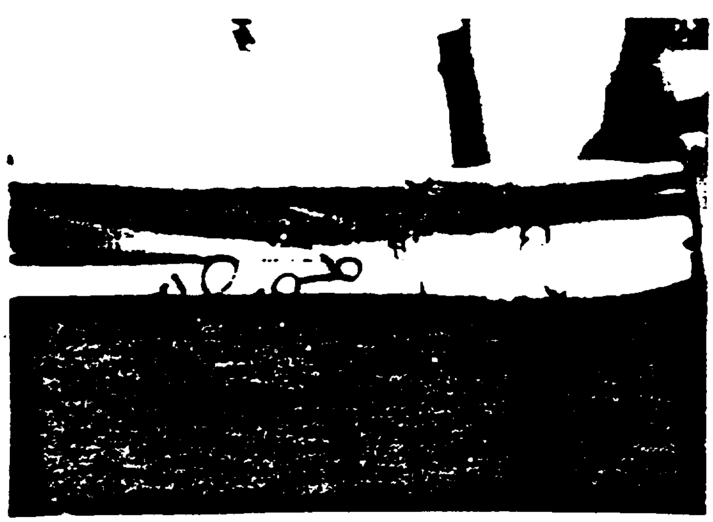


Photo of test object
after all of the tests

PRELIMINARY TEST PLAN FOR DETERMINING THE
DIRECT EFFECTS OF LIGHTNING STROKES TO THE
SRB TVC ACTUATOR

1. INTRODUCTION AND BACKGROUND

One of the most likely lightning entry/exit points for the Space Shuttle cluster during the launch phase is the SRB conductive plume. This means that the lightning current would travel up the plume into the SRB Nozzle. Each SRB has two actuator arms which connect between the aft skirt and the nozzle compliance ring. It is therefore possible that a substantial lightning current can flow in these actuator arms.

The actuator arms are continuous metal with one exception: the piston and the piston rod are dielectrically separated from the actuator body. The piston is separated by means of the actuator hydraulic fluid, and the piston rod is separated from the actuator body by rubber "O" rings. To mitigate lightning effects in the present configuration, there are two bond straps, each twenty inches long, connected from the compliance ring to the actuator body.

Because these bonding jumpers still represent a significant impedance, a substantial voltage may appear across the "O" ring gap. If arcing occurrs, pitting of the rod may occur, which could result in subsequent loss of fluid and thrust vector control.

It is therefore important that the significance of this effect be determined.

2. OBJECTIVE

The objective of this test is to determine the effects of lightning currents on the TVC actuator.

3. RATIONALE

These tests are required because the SRB is required to survive a direct lightning stroke as defined in Reference 1.[1] This effect can best be determined experimentally.

4. TEST OBJECT

The test object is a Saturn 1C actuator. This has the same actuator body and piston dimensions and clearances as the SRB TVC actuator and therefore no extrapolation of the test data is required.

5. TEST DESCRIPTION

The test set up is indicated schematically in Figure 1. The lightning generator is connected to the actuator in a low inductance coaxial geometry, i.e., the plus side of the generator feeds the piston via the center conductor of a coaxial geometry, and the return is via the outer conductor, which is really a cage of parallel wires.

The lightning generator provides a threat level (x) waveshape having a 2 μsec rise time and is a damped sinusoid having a Q os 6, and a peak amplitude of 21 KA. The continuous current is 300 ms long and has an

1. Space Shuttle Lightning Protection Criteria Document, JSC07636, NASA, Lyndon B. Johnson Space Center, Houston, Texas, September 1973.

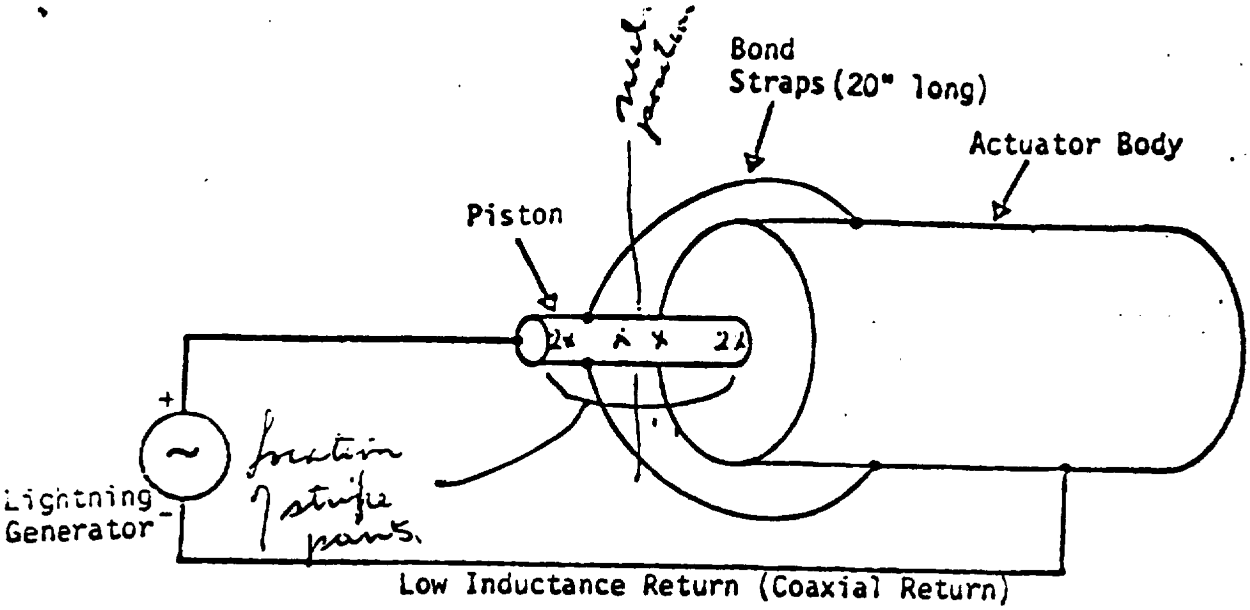


Figure 1. Schematic Diagram of Test Set Up

amplitude of 24 A. This is based on measurements of bond strap and actuator arms resistances made at MSFC, and computations of inductances, and solving an equivalent circuit model.

Because the piston has a twelve inch stroke, it is estimated that a total of four shots can be made, each one with the piston displaced three inches from the previous shot. The four shots will consist of a permutation of threat level (x) and the number of bond straps as follows:

Shot No.	Amplitude	No. Bond Straps
1	x	2
2	2x	2
3	x	4
4	2x	4

This information will be carefully recorded in the data log and correlated with the piston position.

After the test, the test object will be shipped back to MSFC for evaluation.

APPENDIX C

MSFC TEST REPORT
THRUST VECTOR CONTROL ACTUATOR OIL LEAKAGE

DIRECT LIGHTNING EFFECTS DEVELOPMENT TEST - SRB TVC ACTUATOR

1.0 INTRODUCTION AND SUMMARY

Hydraulic actuator development testing has been carried out to determine the degree of damage to the actuator O-ring seals caused by the pitting surfaces due to simulated lightning strokes. Calculations had previously been made by the staff of Mission Research Corporation to determine the lightning current magnitudes that would pass through the TVC actuator if a 200,000 ampere lightning strike passed through the Shuttle vehicle. These currents were passed through the actuator in a test performed by Lightning & Transients Research Institute causing pitting and roughness of the piston due to arcing of the lightning current across the cylinder/piston interface (ref. L&T Report No. 676, Enclosure I). The actuator was then returned to MSFC and this test reports on the leakage caused by the lightning damage while the actuator was being exercised under full pressure and flight profiles.

2.0 TEST OBJECT IDENTIFICATION

The hydraulic actuator tested was a Saturn 1-C actuator which was essentially the same as the Shuttle SRB actuator in the critical areas of the hydraulic O-ring seals and piston surface.

3.0 TEST PROCEDURE

The test procedure is attached in Enclosure II. The test arrangement is illustrated in Figure I.

4.0 TESTS AND TEST RESULTS

The tests were performed in accordance with the procedure in Enclosure II with the exception of test #4 as discussed below. Hydraulic fluid temperature at beginning of test was 78°F and at end of test was 84°F. Total pressurized time was 47 minutes. There was essentially no leakage at the beginning of the test.

Test #1 consisted of moving the damaged area, caused by the expected lightning current passed through the actuator with four bond straps, across the cylinder/piston interface. The test lasted for 125 seconds (SRB flight time) with the piston moving at 0.12 hertz. At the end of the test the leakage rate had increased from essentially 0 to 1 drop per 10 seconds. Allowable leakage was 2½ gallons. This test was considered successful.

Test #2 consisted of moving the damaged area, caused by the expected lightning current passed through the actuator with two bond straps, across the cylinder/piston interface. This is the present design configuration. The test lasted 125 seconds with the piston moving at 0.12 hertz. At the end of the test the leakage rate had increased from 1 drop per 10 seconds to 1 drop per 5 seconds. This test was considered successful and confirmed that the design configuration is adequate.

Test #3 consisted of moving the damaged area, caused by 2 times the expected lightning current with two bond straps, across the cylinder/piston interface. The test lasted 125 seconds with the piston moving at 0.12 hertz. At the end of the test the leakage rate had increased from 1 drop per 5 seconds to 1 drop per second. This test was considered successful and demonstrated that the design configuration was adequate for a lightning strike twice the expected amplitude.

Test #4 deviated from the test plan in order to make it a more severe test. The stroke was increased to full extension and retraction of the piston. This allowed the damaged area of all five test lightning strikes to wipe all O-rings. Two of the damage areas were from double the expected lightning current. In addition the piston was left free to rotate so that a greater surface area of the O-rings would be damaged. Total rotation during the test was about 45 degrees. The test was allowed to run for 10 minutes. At this time the leakage rate had become a thin stream. The test was terminated because the leakage was still minimal and the test time and severity far exceeded any flight conditions.

5.0 CONCLUDING DISCUSSION

Total leakage for all the tests was 200 milli liters. Allowable leakage for one SRB flight is approximately 9.8 liters. In addition to the test runs, the actuator was cycled approximately 75 additonal times during test set-ups while adjusting bias for null position and to adjust stroke length.

The success criteria was to pass test #2. The severity of test #4 plus the additional cycling time indicates that a large margin of safety exists over and above this. We can conclude,therefore,that the SRB actuator can survive a lightning strike in flight without degrading the mission performance.

Testing was performed at MSFC, building 4656,by EC25 and EL55.

Buford E Gallaher

B. E. Gallaher, EL55

W.A. Swords

W. A. Swords, EC25

APPENDIX D

LTRI TEST REPORT
SIMULATED LIGHTNING STRIKES TO THE THERMAL PROTECTION SYSTEM

Attachment I

DIRECT LIGHTNING EFFECTS TESTS
SPACE SHUTTLE SRB
THERMAL PROTECTION SYSTEM (TPS)

L&T Report No. 652

By

J.D. Robb
T. Chen

December 1977

Prepared For

Mission Research Corporation
Albuquerque, N.M. 87118

Subcontract SC-31168-75-0006

Prepared By

Lightning & Transients Research Institute
2531 West Summer Street
St. Paul, Mn. 55113

1.0 INTRODUCTION AND SUMMARY

Lightning tests have been conducted on the thermal protection system for the Space Shuttle Solid Rocket Booster (SRB) to determine the effects of direct lightning strikes. The tests consisted of swept high current lightning strokes, stationary high current lightning strokes and dielectric strength tests of the materials. The tests showed areas of cracks and delamination up to about 4 inches in diameter and dielectric strengths of about 200,000 volts maximum.

2.0 RATIONALE

The tests are required because the TPS material is required to survive a direct lightning strike as defined in Reference 1.* The effect of lightning can best be determined experimentally.

3.0 TEST OBJECTS

The test objects consisted of samples of TPS material as listed in Table I consisting of cork and foam materials of several thicknesses.

4.0 TEST PLAN

The test plan is attached in Appendix I and describes the test arrangements and the experimental test waveforms.

5.0 TEST PROGRAM

5.1 Swept Stroke Tests

The swept stroke tests were carried out using the test arrangement illustrated in Figures 1a and 1b. The test waveforms for the high current discharges are shown in Figure 2. The arc was initiated by an 0.008 inch diameter stainless wire off the left side of the test panel. The arc was blown over the test panel by the windstream and a high rate of rise current 5×10^{10} A/S (using a 600 KV Marx impulse generator) was initiated as the arc reached the approximate center of the panel. The component was followed immediately by a high current component (100,000 amperes), an intermediate component, 15 coulombs at 3000 amperes decaying to the residual of the 400 ampere continuing component. With this rate of rise arc sweeping about three feet maximum was required to puncture the TPS material.

The damage as illustrated in Figure 3 consisted of punctures of the TPS of quarter inch diameter pit marks on the aluminum base metal and cracking of the TPS for a distance of about two inches from the contact point for about a four inch diameter area of indicated damage. Further hot gas testing will be carried out on the test sample by Marshall Space Flight Center to determine the implications of the lightning test damage.

5.2 Stationary Arc High Current Testing

The object of these tests was to determine the effects of a 200,000 ampere stationary discharge on the TPS material. The test discharges were fired into the TPS material and the damage which was similar to the swept stroke test is illustrated in Figure 4. As with the swept strokes, the test samples are being returned to Marshall Space Flight Center for hot gas testing.

5.3 DC Dielectric Strength Tests

The DC dielectric tests were carried out by placing a standard ASTM dielectric strength test electrode on the material and charging it to a potential at which the TPS material punctured beneath it. The voltage was raised in 25 KV increments and left at each level for 30 seconds until puncture occurred. The test results are shown in Table II. On the thickest cork test sample puncture could not be obtained conveniently with the DC facilities available because of the large DC leakage currents. The currents indicated a DC resistance value of about 140 megohms. This test result indicates that the precipitation static charging of the material should be rapidly bled off because of the relatively low resistivity of the cork. This value of 140 megohms while slightly beyond the maximum allowable value of 100 megohms used by LTRI for anti-static coatings for aircraft flying in dense snow should be more than adequate for the limited short duration charging anticipated for the TPS.

To complete the dielectric tests, impulse tests were carried out on the material. A small Marx generator was used and a voltage of about 200,000 volts was required to puncture the thickest TPS material. The impulse dielectric strengths of the test samples are also presented in Table II.

6.0 CONCLUDING DISCUSSION

Lightning tests have been carried out on the TPS samples supplied by MSFC and the tests showed cracking of the TPS about 4 inches in diameter, a puncture crater about 3/4 inch in diameter and dielectric strengths varying from 100 to 300,000 volts. With the high rate of rise discharge used in the swept stroke tests, a maximum arc length of about three feet was required to puncture the TPS by inductive drop potentials. The pitting of the metal base material was only about one-quarter inch in diameter and an estimated 0.010 inch in depth. Thus the damage produced by these severe test waveforms would be described by LTRI as only moderate.

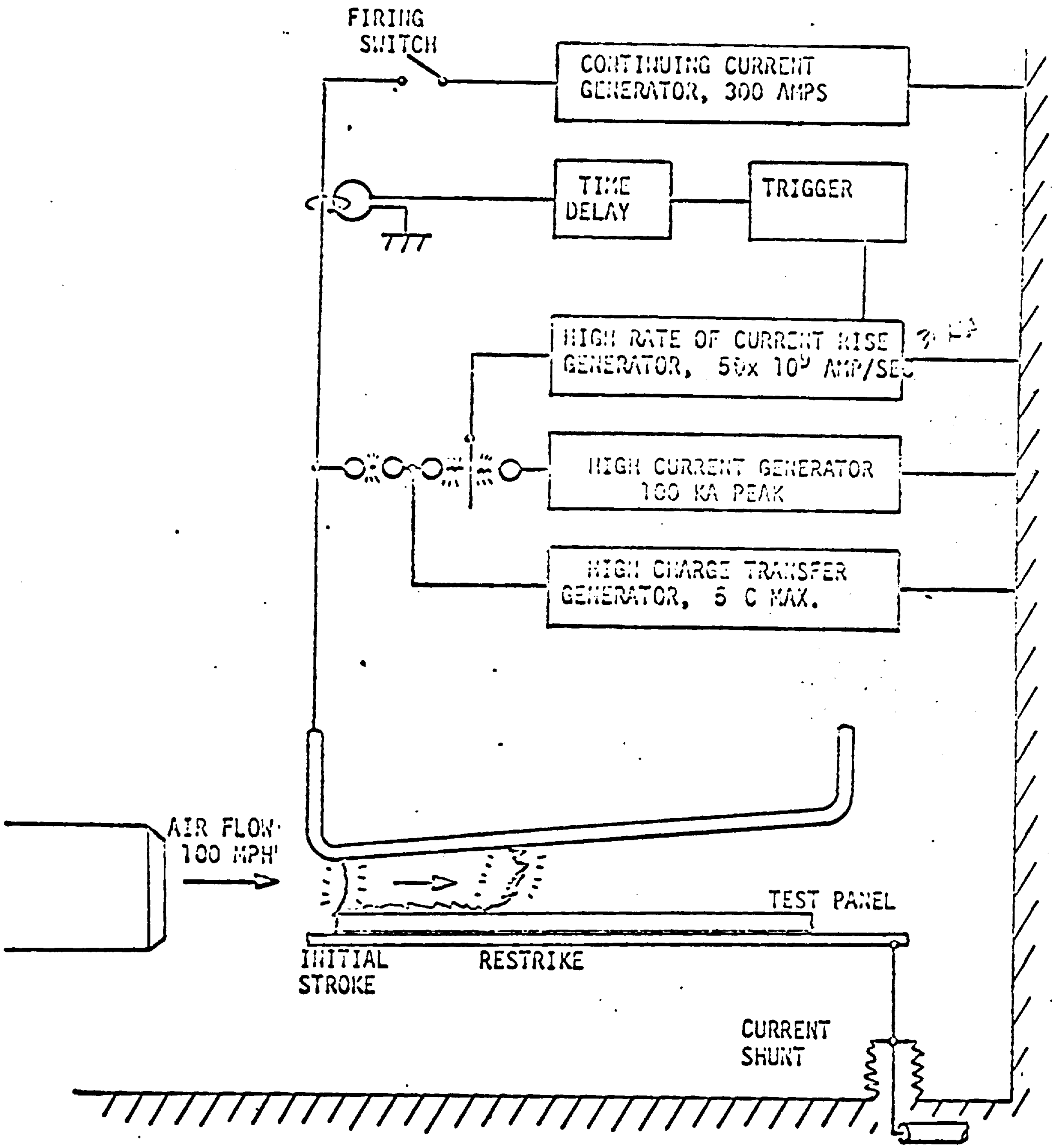


Figure 1a. Test Arrangement for the TPS Tests.

APPENDIX E

THERMAL TESTS OF LIGHTNING-DAMAGED THERMAL PROTECTION SYSTEM PANELS

RESULTS OF AERO-THERMAL VERIFICATION TESTS OF SIMULATED LIGHTNING STRUCK SRB TPS SPECIMENS

1. BACKGROUND: The nose cone and aft skirt are the most likely areas of the SRB to be struck by lightning during the on-pad and low altitude ascent conditions. Simulated lightning strikes were imposed on some representative TPS test panels. Reference letters EL51(173-177), "Performance of a Simulated Lightning Test on the SRB Thermal Protection System"; EE11(77-273), "Simulated Lightning Tests on SRB Thermal Protection System (TPS)".

Four of these lightning struck panels were tested in the MSFC Hot Gas Facility (HGF) to determine any additional damage to the TPS by simulated flight aeroheating. Also, the tests were to determine if the TPS, after a lightning strike, can maintain the structural temperature within the design limit of 300°F.

2. TEST DESCRIPTIONS: Four lightning struck TPS test panels were tested in the HGF as per the SRB TPS verification test criteria (Appendix I), reference EP44(78-77). The total heat (BTU/ft^2-sec) for each specimen tested, in table 1 of the criteria, is a typical maximum value for its areas of application on the flight vehicle. The indicated q_{cw} (BTU/ft^2-sec) values are the maximum cold wall heating rates for the indicated test position. These maximum values were used to determine the test durations (time = total heat/q_{cw}) to assure that some TPS remained on the general specimen area to the end of the test.

3. TEST RESULTS: Figures 1, 2, 3, and 4 are temperature - time plots of thermocouples mounted to the backside of the substrate. These measurements were located at the approximate geometric center of the damaged area (T1 and T3) and at the interface of the damaged and undamaged area (T2 and T4). The approximate local test heating rate at each lightning struck area is also indicated.

The samples were tested at the specified durations except C6. This test was manually terminated at 42.75 seconds instead of the planned 45.4 seconds due to the substrate temperature exceeding 300°F at the center of the forward damaged area.

It appears that thermocouples T1 and T2 of panel C6 became unbonded at approximately 48 seconds, producing erroneous data beyond this time. A computer projection of the temperatures was made to determine the resulting values if the test had proceeded to the planned 45.75 seconds and had the debonding of the thermocouples not occurred. The resulting values for T1, T2, and T4 as indicated in the test results matrix are acceptable and T3 is marginal at 312°F.

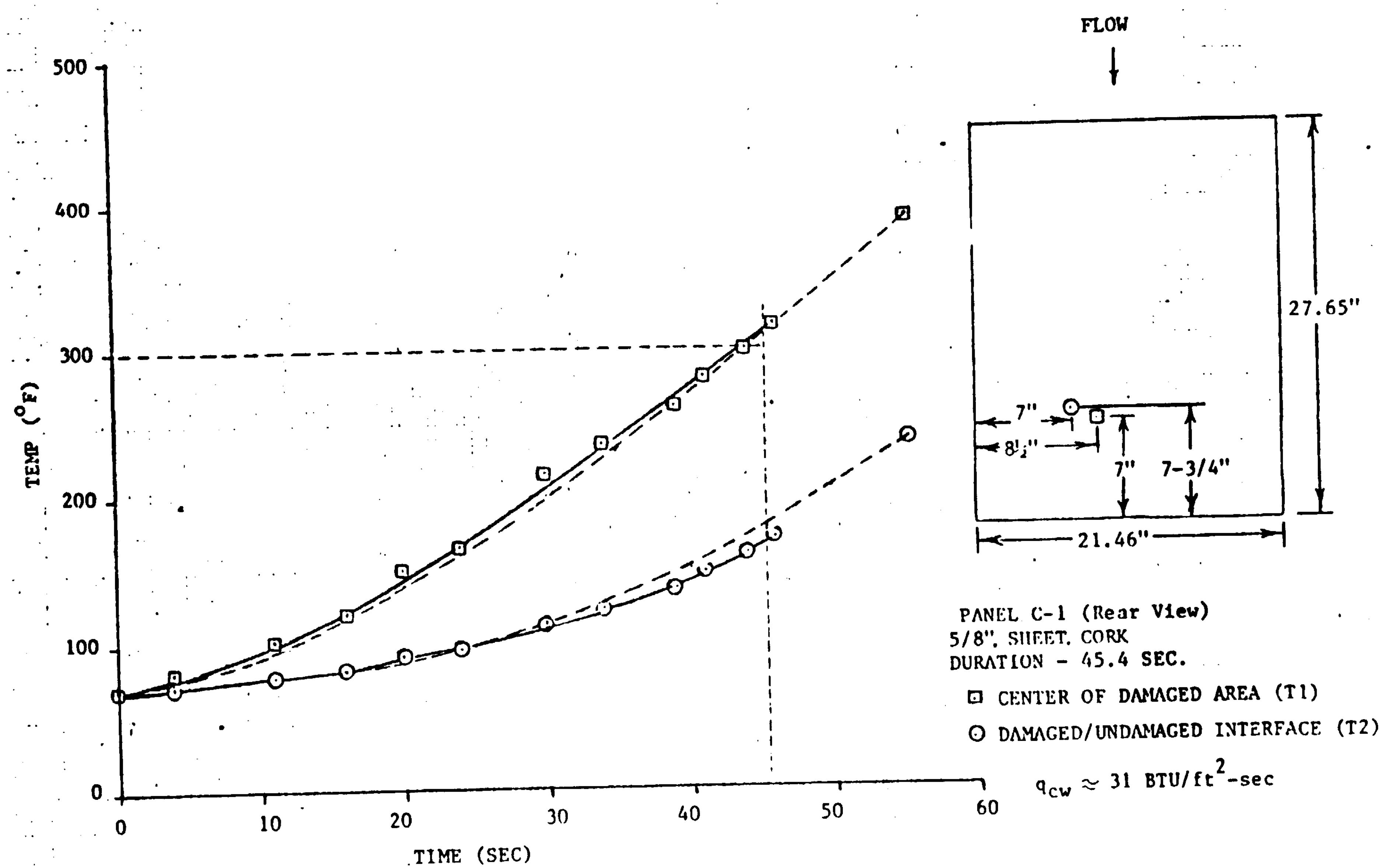
Temperature projections were also made for panel C1. The projected values vs. the measured values were 312°F and 312°F for T1 and 177°F and 168°F for T2, respectively. The differences were within 5% of reading, validating the technique. Valid data was not obtained for panel C10.

Figures 5, 6, 7, and 8 are overlay sketches of the before test and after test photographs of the test panels. They indicate the expanded damaged areas due to the aero-thermal heating of the tests.

The test results matrix indicates the local heating rate at the damaged area, test duration, resultant total heat, the temperature changes at the damaged area, a representative vehicular area where the TPS is applied, and comments as to the structure (substrate) temperature remaining within design limit (300°F.

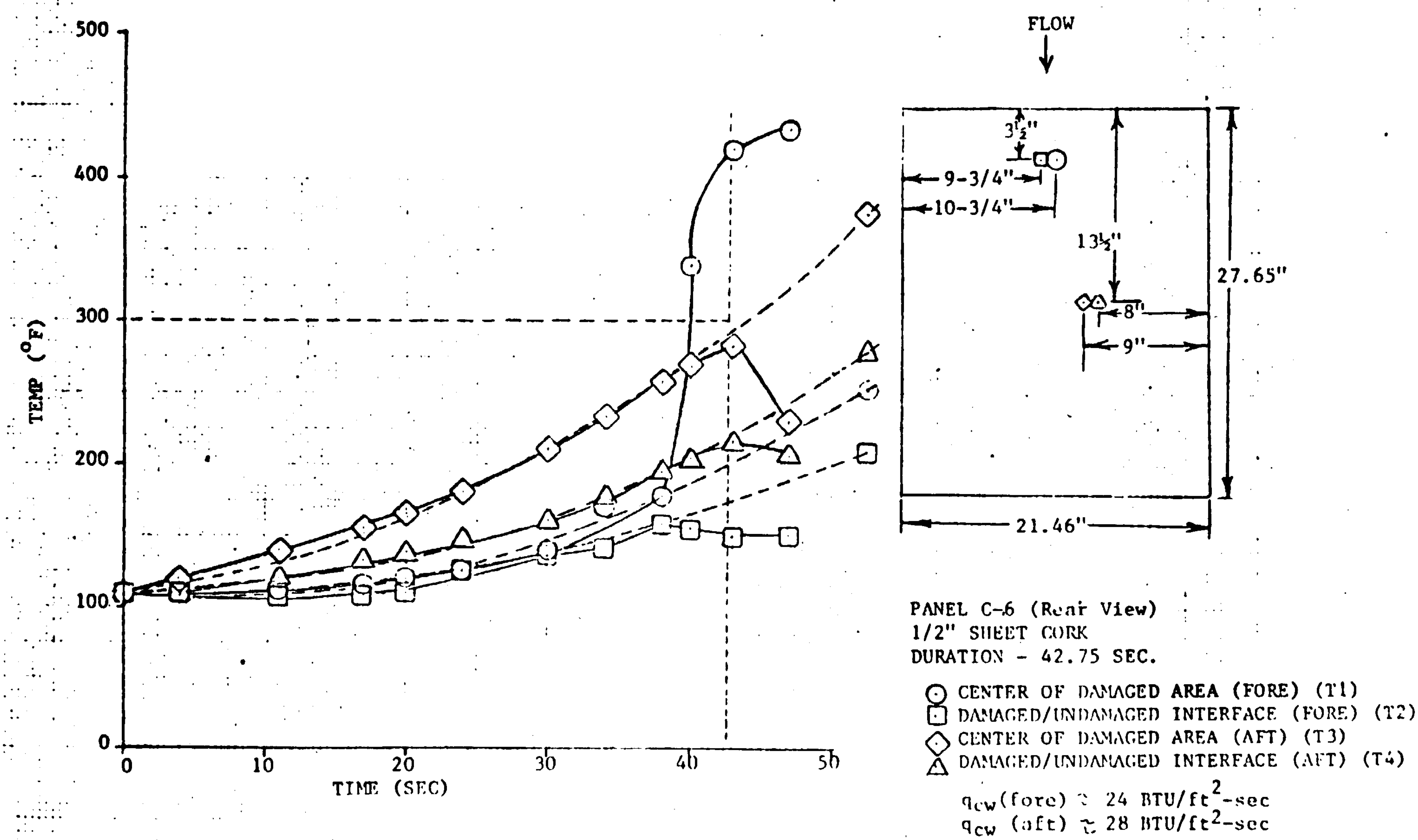
TEST RESULTS MATRIX

TEST NO.	PANEL NO.	TPS (IN)	LOCAL q_{cw} (BTU/FT2-SEC)	DURATION (SEC)	TOTAL HEAT (BTU/FT^2-SEC)	INITIAL TEMP (°F)	END TEMP (°F)	Δ TEMP (°F)	APPLICABLE SRB AREA	COMMENTS
419	C1	5/8 cork	31	45.4	1407	T1-71 T2-71	(312) T1-312 T2-168 (177)	241 96	Aft Skirt	Marginal Acceptable
420	C6	1/2 cork	24 28	42.75 42.75	1026 1197	T1-107 T2-106 T3-107 T4-107	T1-(215) T2-(182) T3-(312) T4-(235)	(108) (76) (205) (128)	Aft Skirt	Acceptable Acceptable Marginal Acceptable
421	C10	1/4 cork	27	22.68	612	T1 T2	NOT VALID DATA		Aft Skirt	
422	M13	1/8 MSA-1	7	58.5	410	T1-90 T2-90	T1-180 T2-153	90 63	Nose Cone	Acceptable Acceptable



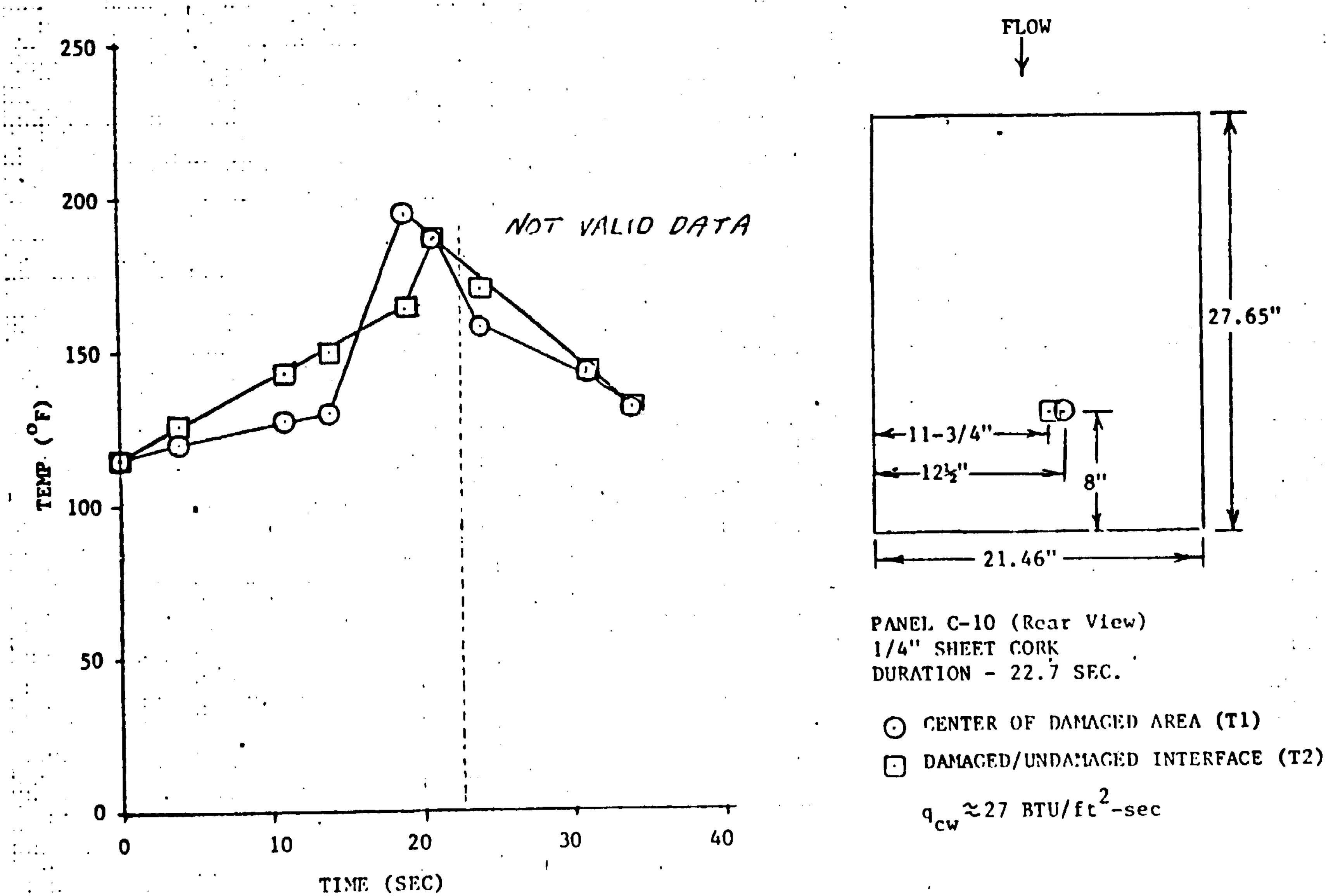
FLOW
500
400
300
200
100
0
TEMP (^{o}F)
0
10
20
30
40
50
60
TIME (SEC)
27.65"
7"
8½"
7"
7-3/4"
21.46"
PANEL C-1 (Rear View)
5/8", SHEET, CORK
DURATION - 45.4 SEC.
CENTER OF DAMAGED AREA (T1)
DAMAGED/UNDAMAGED INTERFACE (T2)
$q_{cw} \approx 31$ BTU/ft^2-sec

FIG. 1



500
400
300
200
100
0
TEMP (°F)
0
10
20
30
40
50
TIME (SEC)
FLOW
3½"
9-3/4"
10-3/4"
13½"
8"
9"
27.65"
21.46"
PANEL C-6 (Rear View)
1/2" SHEET CORK
DURATION - 42.75 SEC.
CENTER OF DAMAGED AREA (FORE) (T1)
DAMAGED/UNDAMAGED INTERFACE (FORE) (T2)
CENTER OF DAMAGED AREA (AFT) (T3)
DAMAGED/UNDAMAGED INTERFACE (AFT) (T4)
q_{cw}(fore) ≈ 24 BTU/ft^2-sec
q_{cw} (aft) ≈ 28 BTU/ft^2-sec

FIG. 2



PANEL C-10 (Rear View)
1/4" SHEET CORK
DURATION - 22.7 SEC.

⊙ CENTER OF DAMAGED AREA (T1)
⊡ DAMAGED/UNDAMAGED INTERFACE (T2)

$q_{cw} \approx 27$ BTU/ft^2-sec

FIG.3

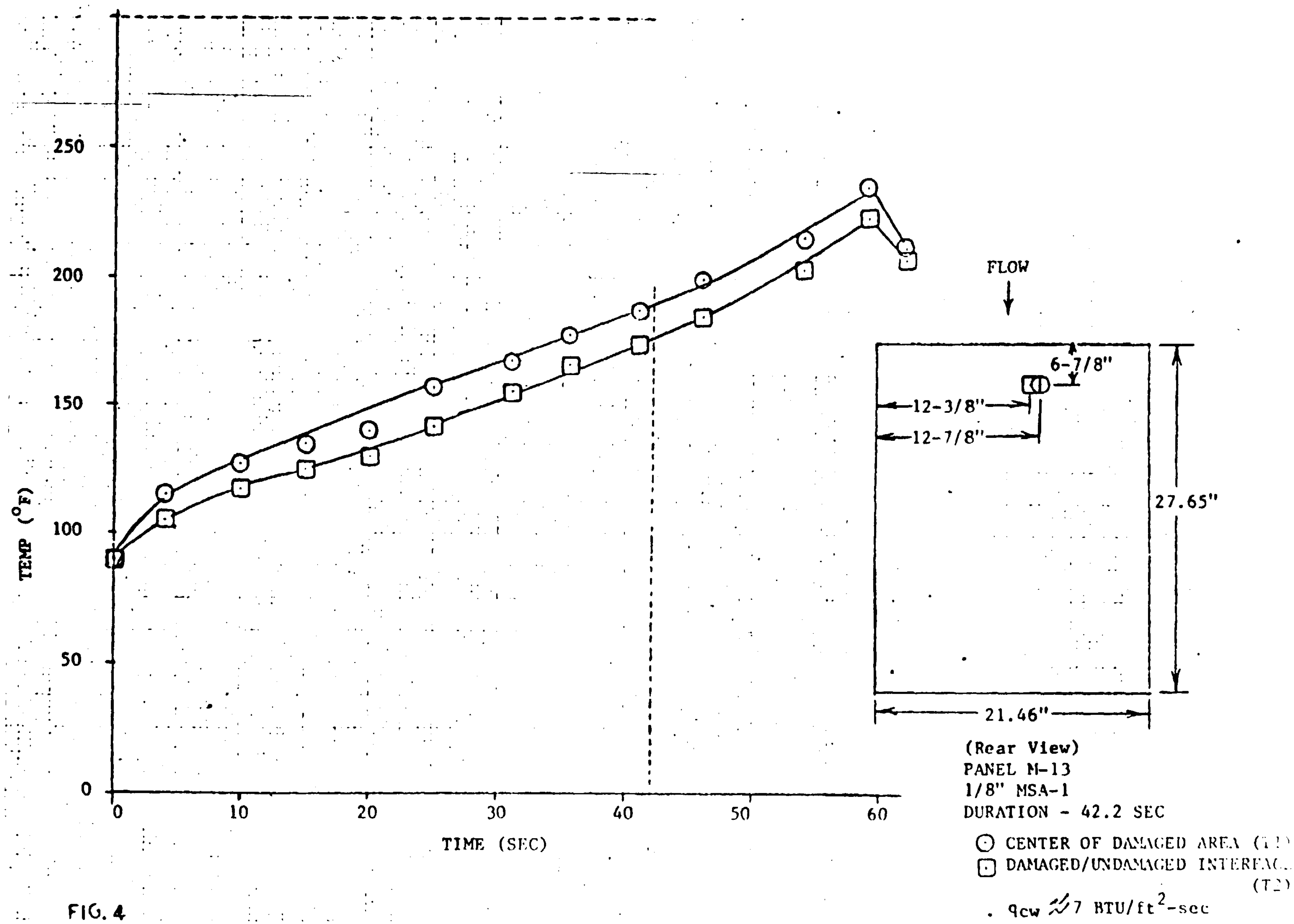

TEMP (°F)
250
200
150
100
50
0
10
20
30
40
50
60
TIME (SEC)
FLOW
6-7/8"
12-3/8"
12-7/8"
27.65"
21.46"
(Rear View)
PANEL M-13
1/8" MSA-1
DURATION - 42.2 SEC
CENTER OF DAMAGED AREA
DAMAGED/UNDAMAGED INTERFACE
(T2)
qcw ≈ 7 BTU/ft²-sec

FIG. 4

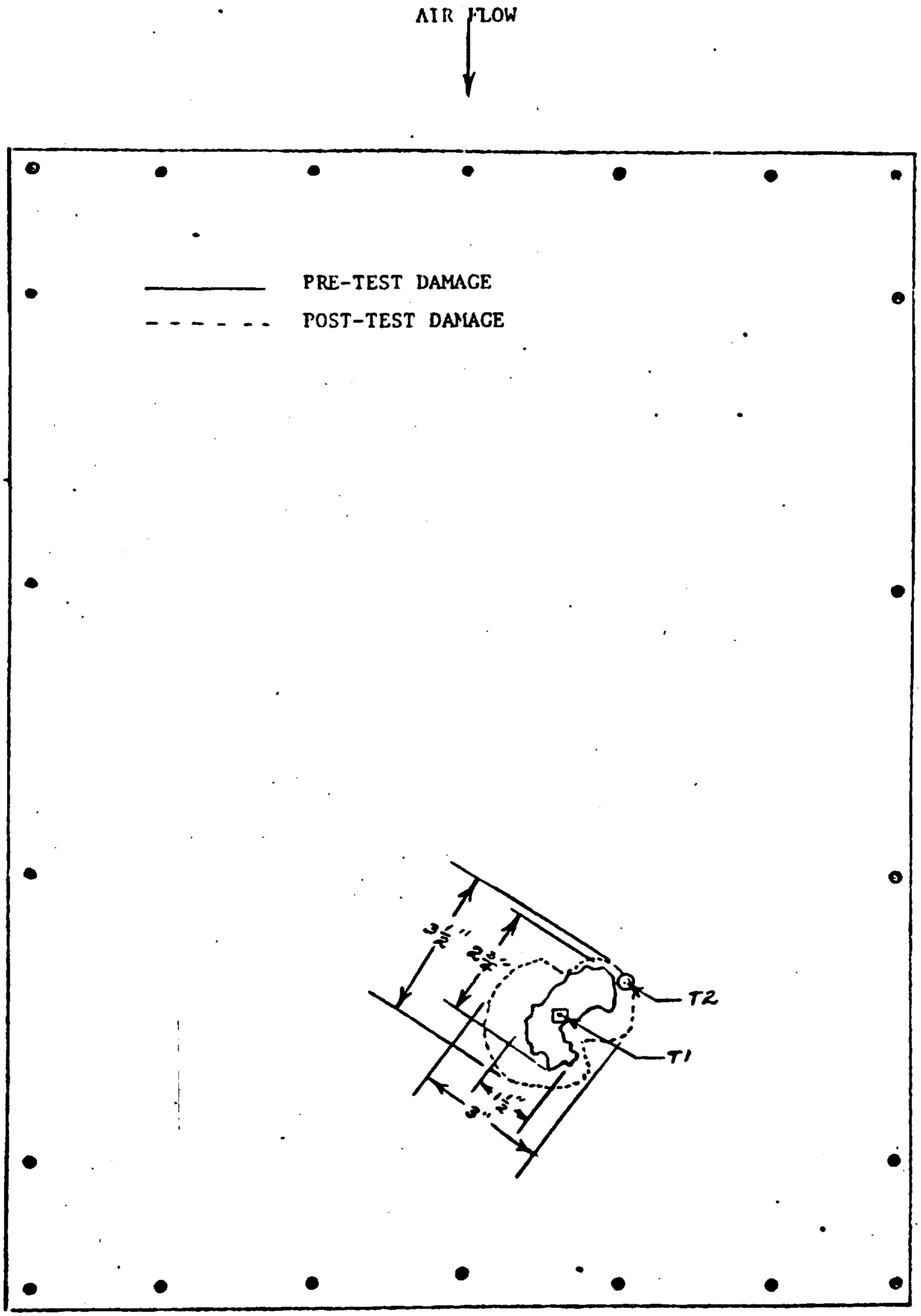


FIGURE 5. PANEL C1 - 5/8" CORK

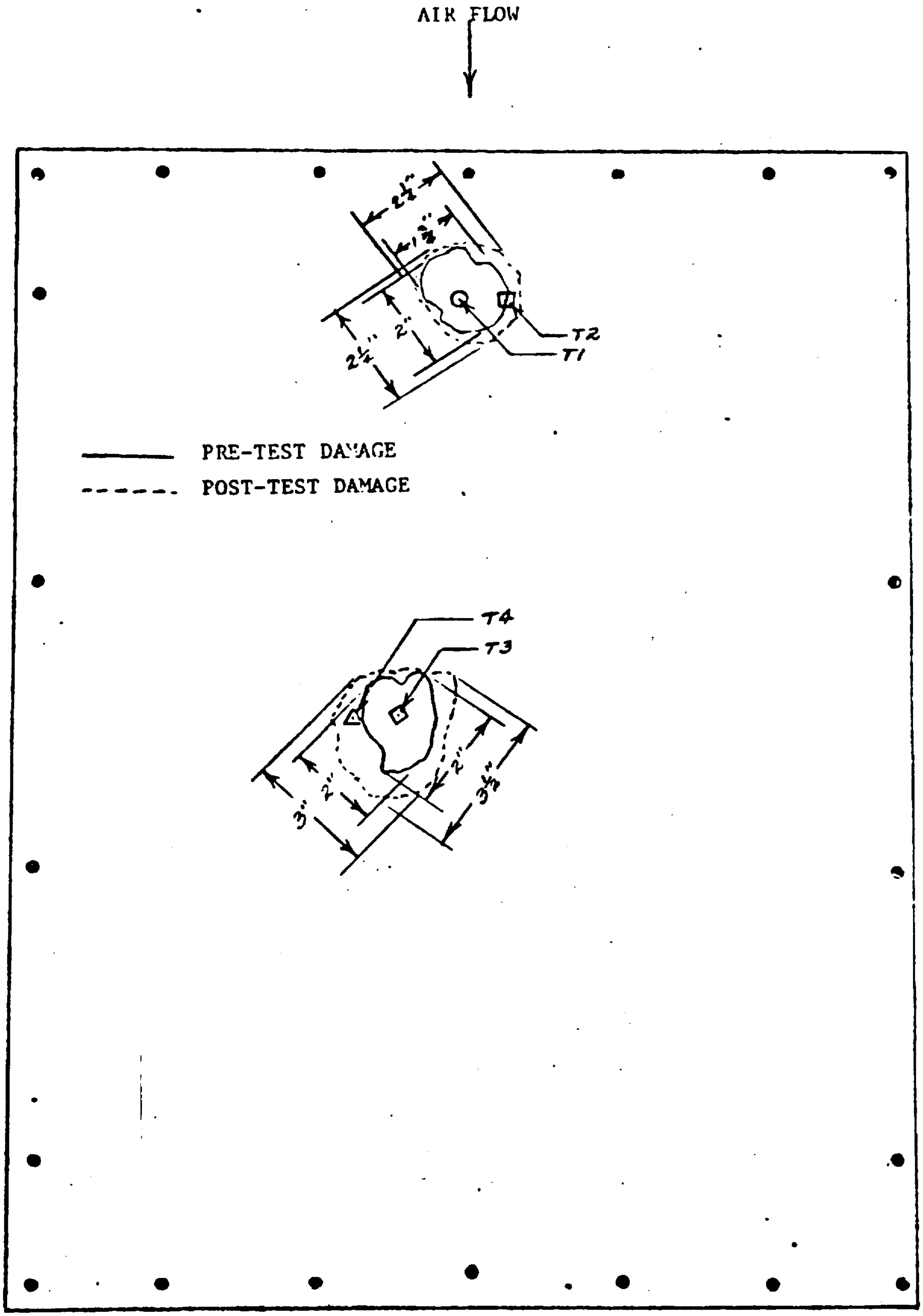


FIGURE 6. PANEL C6 - 1/4" CORK

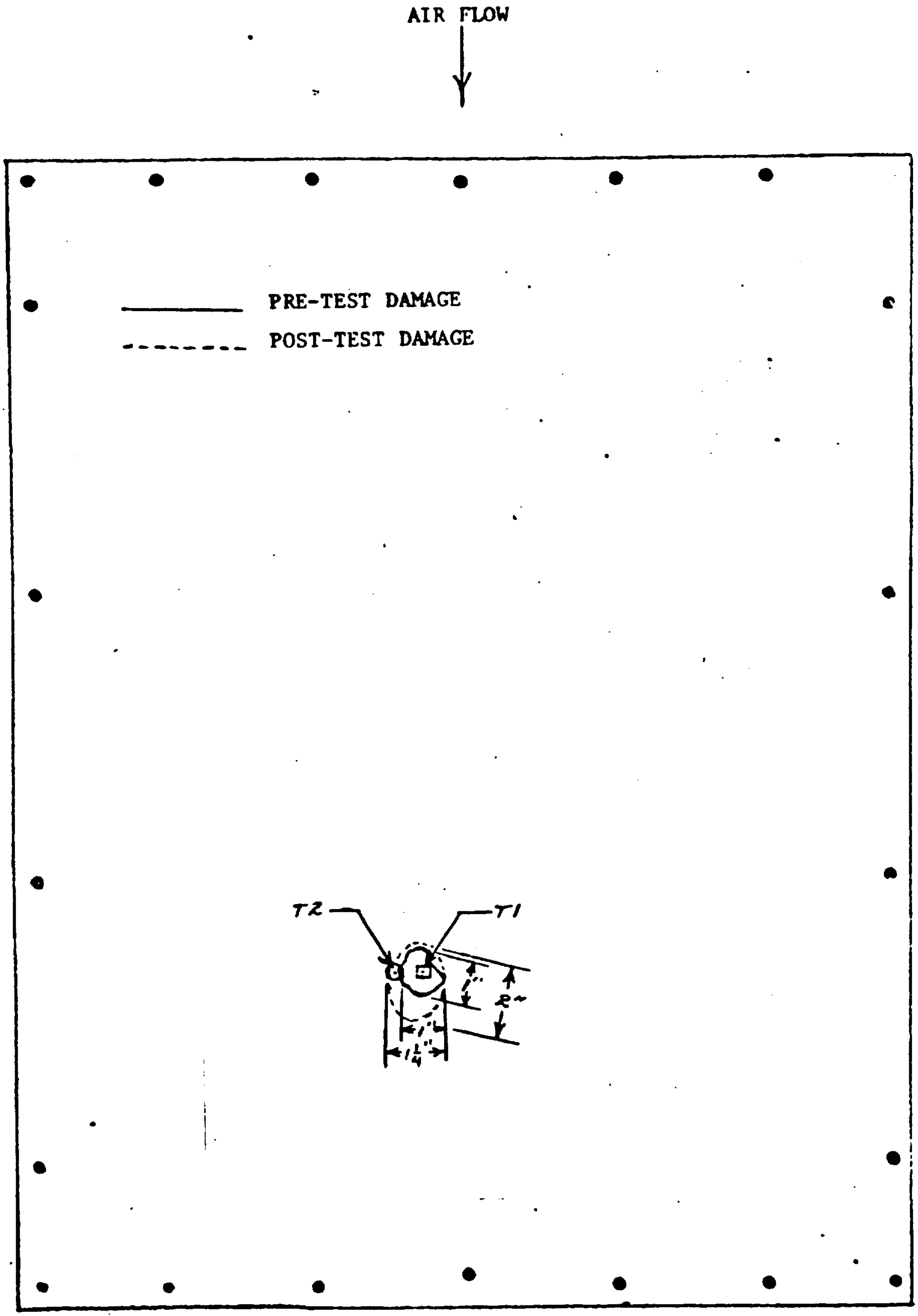


FIGURE 7. PANEL C10 - 1/2" CORK

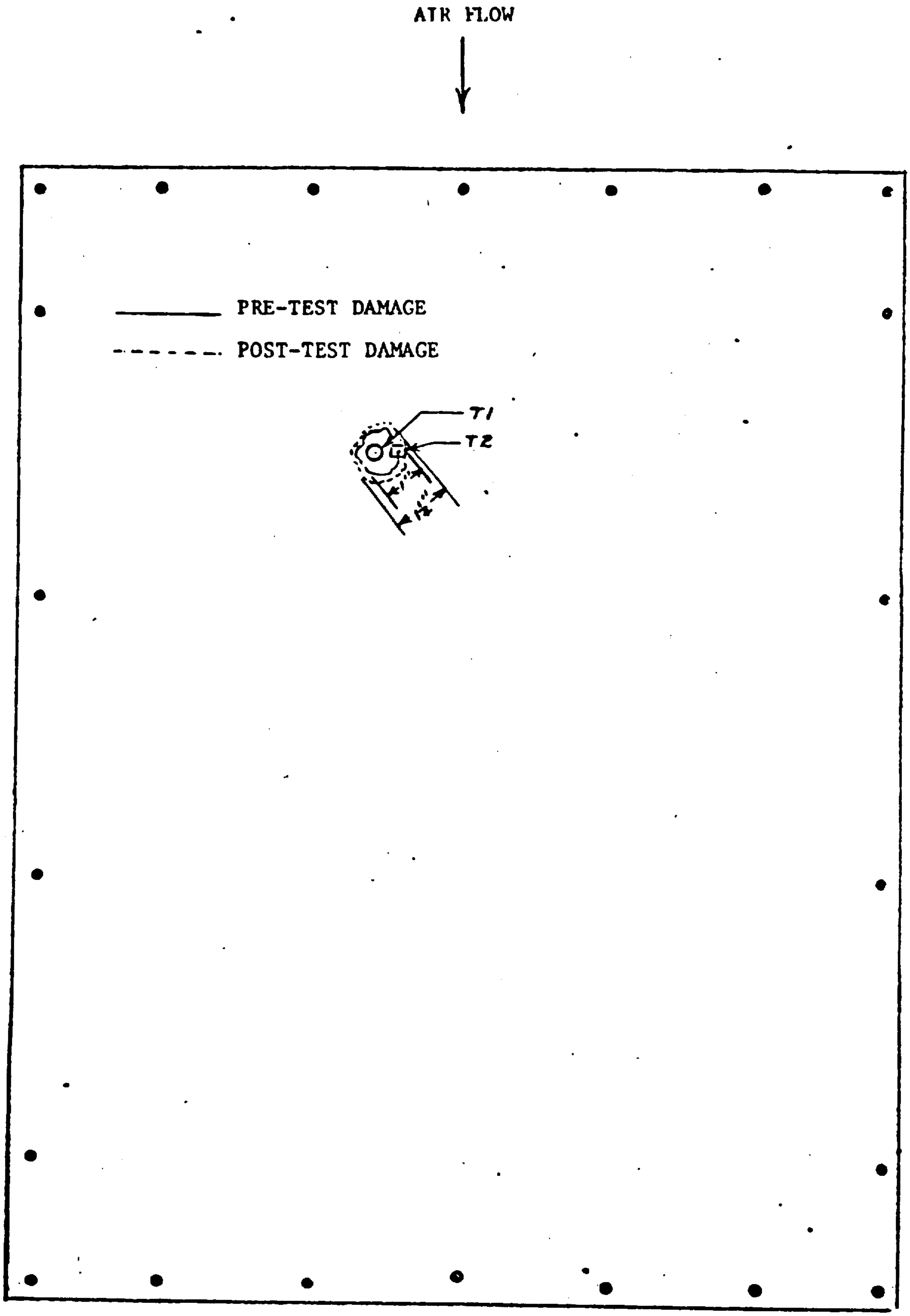


FIGURE 8. PANEL M13 - 1/8" MSA-1

APPENDIX F

MSFC ASSESSMENT OF DAMAGE TO THE THERMAL PROTECTION SYSTEM

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

Reply to Attn of: EL51 (151-78) OCT 2 1978

TO: EE11/W. P. Horton
THRU: EL41/W. A. Huff

FROM: EL51/R. D. Collins, Jr.

SUBJECT: Assessment of Lightning Damage to the SRB Thermal Protection System (TPS)

Enclosed are the reports concerning the tests performed on the SRB TPS specimens. Six specimens each of MSA and Cork TPS coated panels were sent to Lightning and Transients Research Institute (LTRI) where they were struck with simulated lightning as required by JSC-07636, Shuttle Lightning Protection Criteria Document. Results of this test are reported in Enclosure 1 and show that damage and cracking up to 4 inches in diameter could occur.

Four of these specimens with the worst damage were then tested in the MSFC Hot Gas Facility for aero-thermal degradation. Results of this test are reported in Enclosure 2. Removal of additional TPS material due to aerodynamic forces was not significant and consisted primarily of rounding and beveling of the ragged surfaces. Temperatures on the bare metal surfaces were monitored during the test and did not exceed 5% of design values.

As a result of these tests we can conclude that although some TPS material will be removed if struck by lightning, no significant additional degradation will occur, and temperature excursions are acceptable.

Rufus D. Collins, Jr.

Rufus D. Collins, Jr.
Chief, Systems Engineering Division

2 Enclosures

cc:
(See page 2)