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Paper No. 10

LIGHTNING TESTS OF THE ORBITER PYROTECHNIC ESCAPE SYSTEM

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ABSTRACT

An Experimental Test Program was undertaken to demonstrate that the Space Shuttle Orbiter Vehicle pyrotechnics actuated Crew Escape System was not subject to failure resulting from a lightning strike in the vicinity of the cockpit. A test sample representing a full-scale portion of the Orbiter Outer Panel was preheated to 325°F and struck with three different current waveforms to simulate the various effects of lightning: 1) 2μ sec risetime, to 180 kA pulse to evaluate fast current rise shock effects, 2) a 205 kA, 100μ sec wide pulse to evaluate full energy shock effects, and 3) a 490 ampere, 370 msec continuing current to evaluate the thermal effects of a lightning strike.

None of the lightning strikes damaged the pyrotechnics although some damage occurred to the Thermal Protection System.

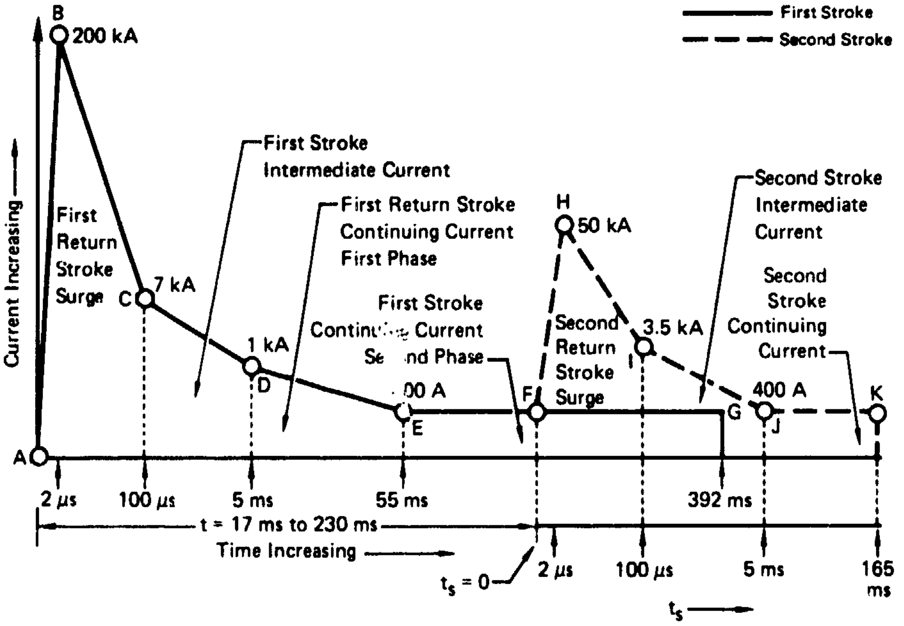
These tests, show that the Orbiter outer panel pyrotechnics are adequately protected against damage resulting from a lightning strike.

INTRODUCTION

The Shuttle Transportation System has been designed to reduce the cost of space operations below prior programs. A major factor in implementing this cost reduction involves the high frequency of launches that can be achieved with one Orbiter. Delays in either launch or entry and return to a landing site due to poor weather conditions would negate part of the cost reduction effort. To help preclude such delays, the Shuttle is designed to tolerate the effects of lightning strikes. One element in assuring the success of the design effort has been a test program to confirm that the explosive components utilized in the Shuttle would not be damaged by the direct thermal and shock effects of a lightning strike. To minimize the extent of the test program, the Shuttle was analyzed to determine the explosive components which would be most susceptible to lightning damage. The analysis was based upon factors such as: areas of the Shuttle surface which contain possible lightning attach points (as determined from a prior test program)[1]; relative distance and structural discontinuities between the attach points and explosive component locations: and chemical composition of explosives. This paper describes the test program that was conducted on the Orbiter device which was determined to be most susceptible to the direct lightning effects. These tests were performed by McDonnell Aircraft Company Laboratories, Lightning Simulation and Armament Systems, St. Louis, Mo. in accordance with Reference 2.

Lightning Threat and Test Philosphy

Natural lightning is a complex phenomenon and is further complicated because no two lightning strikes are identical. Therefore, for purposes of testing, analytical and statistical data have been compiled[3,4] in an effort to devise a model which could be used as the basis for performing suitable lightning simulation tests. The "Space Shuttle Program Lightning Protection Criteria Document", JSC-07636, Revision A[2], was based upon just such data, plus the combined knowledge and engineering judgments of many experts in the field of lightning testing and research. The model lightning flash current waveform listed in the JSC-07636 document is shown in Figure 1. It is basically a "worst case" model, i.e., virtually all naturally occurring lightning strikes will be less severe than that detailed in the lightning model. Thus, if a sample successfully passes the "worst case" lightning strike test conditions, a high degree of confidence will be established in that particular design.



(Note that the diagram is not to scale)

FIGURE 1 – NASA (JSC) LIGHTNING MODEL[2]

The lightning model shown in Figure 1 involves two high-current strokes: the first has a current peak of 200,000 amperes and a current rate of change of 100,000 amperes per microsecond ($100\ \text{kA}/10^{-6}\text{sec}$); the second stroke is one-fourth the magnitude of the first. The model incorporates intermediate currents persisting for a few milliseconds and a continuing current. The second stroke is not always present in a lightning flash; however, if the second stroke exists, it is known to occur during the time interval from 17 to 230 milliseconds following the first return stroke. This model of the second stroke is for use in swept stroke arc reattachment analysis and was not used for this test. The total charge transferred in the two stroke model is 200 coulombs. Two hundred coulombs are contained in the first stroke when a second stroke is not present in the flash.

Although it is desirable to subject a test sample to the complete model flash in one test current waveform, as shown in Figure 1, only rarely can this be done in the laboratory. Therefore, engineering judgments must be made based upon knowledge of the test sample and lightning parameters as to which portions of the model flash are responsible for the types of damage expected, and then these portions of the waveform are used for testing. For example, the brow of the Orbiter vehicle (the region above the cockpit area) is a primary attach point for a lightning strike (Figure 2). The brow contains pyrotechnics which are a part of the pilot's emergency escape system and the brow is covered with a thermal protection system necessary for re-entry protection of the Orbiter. A lightning strike to the brow therefore poses a multiple threat and one which cannot readily be analyzed mathematically because of the unknown interactions of the various materials when subjected to an intense transient electrical current. The pyrotechnics, mild detonating fuse (MDF), can be detonated or "dudded" (rendered inoperative) by a severe mechanical shock or by the rapid application of sufficient heat; both conditions may exist in a lightning stroke. In addition, the thermal protection system consists of lightweight brittle ceramic tiles bonded to a fibrous strain isolation pad (SIP) and this protection system may suffer severe damage because of the explosive vaporization of materials subjected to the high current surge. For the test of a system such as this, the unknown effects of the vaporizing and burning of materials should be assessed. Also, during re-entry of the Orbiter vehicle into the earth's atmosphere, the Orbiter metal skin beneath the TPS tiles on the brow may be heated to 161°C (325°F). Therefore, for this test the "worst case" lightning test condition would be the first stroke shown in Figure 1, applied to a preheated panel.

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FIGURE 2 – LIGHTNING TEST OF SPACE SHUTTLE MODEL

Referring to Figure 1, the first return current surge (kA) has associated with it a very severe shock phenomenon. For this test the results of this shock were to be evaluated in two parts, one to evaluate the effect of the very fast rise time (100 kA/ μsec for 2μsec) and the other to evaluate the effects of the full energy content of the first 100 microseconds of the high-current surge. After the first high-current surge, the principle damage mechanism should be arc heating from the intermediate and continuing currents with the associated burning and eroding of materials. Therefore, for this test, the first stroke intermediate current, the first stroke continuing current first phase, and the continuing current phase were represented by a single constant current level, with the total time (400 milliseconds) consistent with that shown in Figure 1, and the current level selected (500 amperes) so as to deposit the required minimum of 200 coulombs. The possible interaction of effects of the "full energy" return stroke surge and the continuing current was to be obtained by directly coupling the return stroke surge current and the continuing current into one sequentially occurring waveform.

In order to assure "worst case" test conditions, the lightning arc would have to be directed to the area of the test panel directly over the pyro at a point where the metal panel over the pyros was the thinnest. This was accomplished by placing the high-current discharge probe physically close to the test panel, but far enough away to minimize possible interaction with the panel.

Test Specimen

The 45.5 x 61 cm (18 x 24 inch) test sample, designed to simulate a representative full-scale portion of the Orbiter outer panel escape system, is shown in Figures 3 and 4 (topside and underside views). Figure 5 is a sketch of the portion of the panel containing the pyros. For economic reasons a flat plate configuration, rather than the complex curvature of the Orbiter outer panel escape system, was chosen for this test series. The area immediately surrounding the mild detonating fuse (MDF) was the same as the Orbiter configuration, including physical dimensions and material thermal properties. Outlying areas of the panel are first order approximations to the structural configuration of the Orbiter to simulate shock response in the region of the pyro.

The silica Reusable Surface Insulation (RSI) tiles, the Strain Isolation Pad (SIP), the filler bar material between the tiles and the MDF were all supplied by NASA for this test. The tiles had previously been used on another test program and a few micro cracks were noted on a couple of these tiles prior to installation. Upon installation, the cracked areas were located away from the lightning strike locations. The tiles, SIP, and filler bars were installed according to the procedures given in a Rockwell Material Processing Specification for the Orbiter. The Mild Detonating Fuse used for this test was a part of the same lot manufactured by Explosive Technology for Rockwell for installation in the Orbiter flight vehicle. The MDF was bonded in place with Scotchweld 2216 B/A epoxy as installed on the Shuttle vehicle. Two 36-ga iron/constantan thermocouples were installed in the slot with the pyros directly behind the intended strike locations as shown in Figure 5.

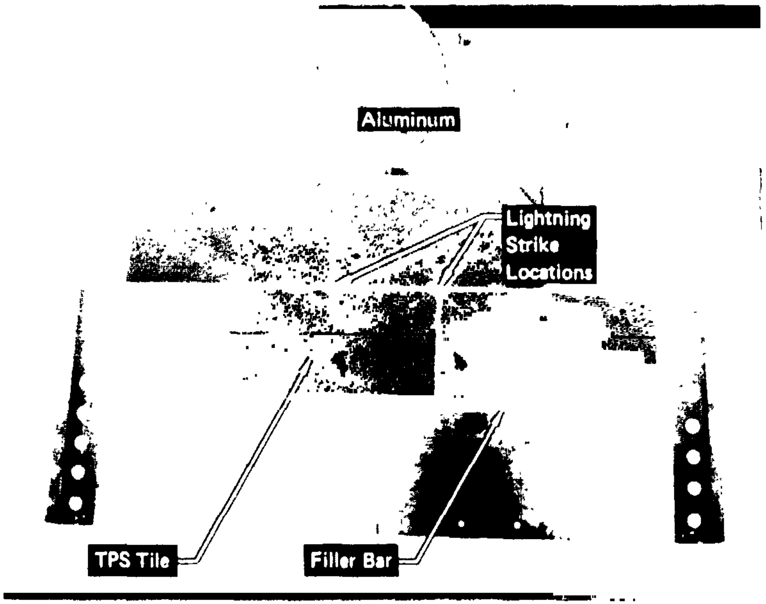

FIGURE 3 – SIMULATED ORBITER OUTER PANEL
Topside View

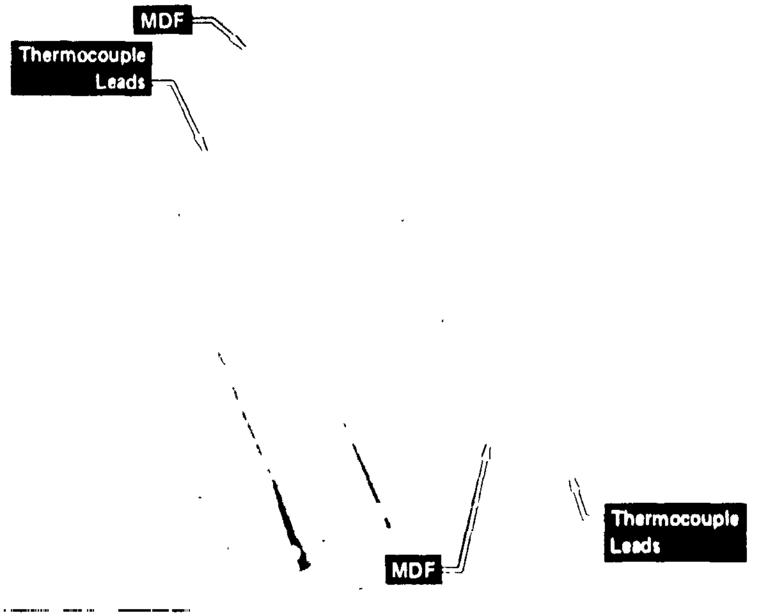

FIGURE 4 – SIMULATED ORBITER OUTER PANEL
Underside View

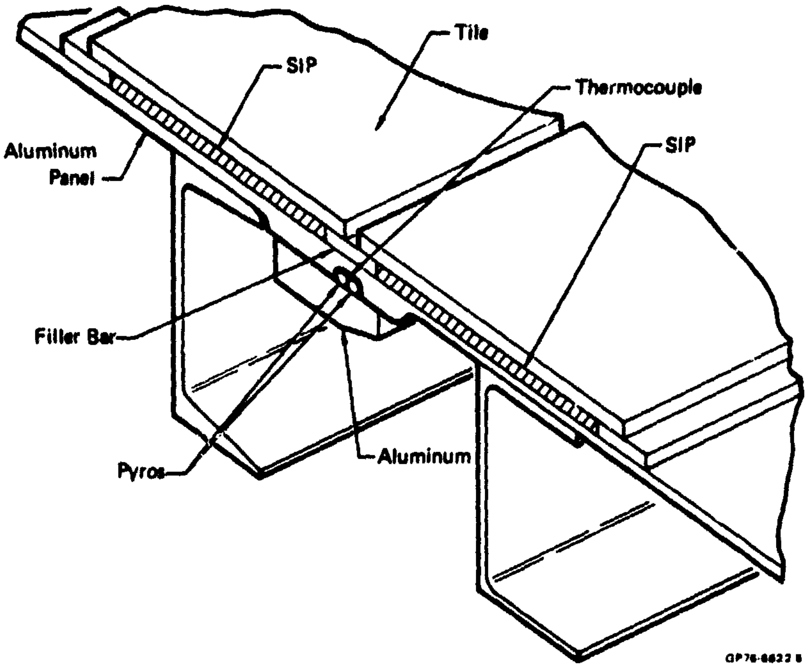

FIGURE 5 – CROSS SECTION OF TEST PANEL PYROTECHNICS INSTALLATION

TEST SETUP

Orbiter Panel

A simplified block diagram of the lightning test setup is given in Figure 6 and an overall view of the test setup is shown in Figure 7. A blast shield enclosed the entire test panel setup, to protect personnel and equipment in the event of detonation occuring during a lightning test. A simplified diagram of the Orbiter panel installation is shown in Figure 8 and the actual installation of the panel for the fast rise-time, high-current test is shown in Figure 9. The high-current output probe was spaced 1/2 inch from the panel immediately above the desired strike point (intersection of the tiles) to insure that the arc would attach at the designated area. The probe was sharpened to a point to minimize the interaction of the probe with the panel. When the fast rise-time, high-current test was conducted, the continuing current supply was disconnected from the circuit shown in Figure 6.

Since it was desired to simulate re-entry heating of the Orbiter panel prior to each lightning strike, a method of heating the test sample was incorporated into the test setup as shown in Figure 9. Several tungsten filament, quartz-iodine linear heat lamps backed by a polished aluminum reflector were used to radiantly heat the test sample. The power to the lamps was manually controlled to obtain an average heating rate of 4.4°C/minute (8°F/minute). Heat losses from the panel were minimized by supporting the panel with fiberglass angles, rather than metal, covering the topside exposed metal surfaces of the panel with blanket thermal insulation, and by using thin stainless foil for electrical contact to the edges of the Orbiter panel.

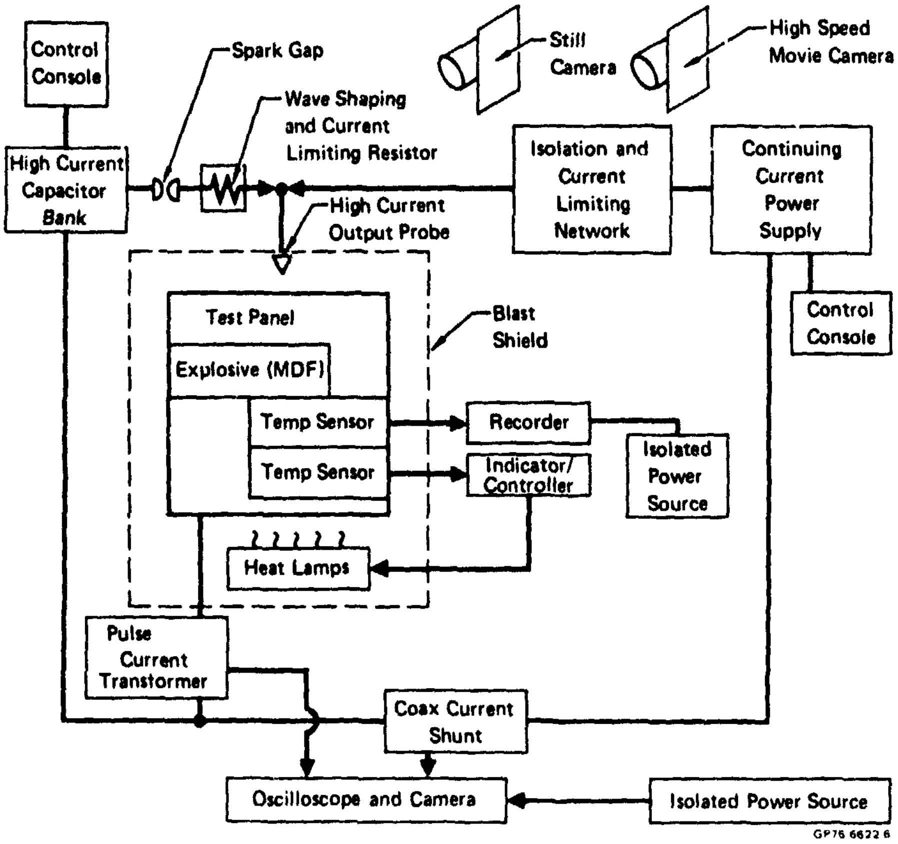

FIGURE 6 – SIMPLIFIED BLOCK DIAGRAM OF LIGHTNING TEST SETUP

For post test evaluation of the pyros, a detonator cap was installed on the ends of the pyros so that both pyros would be detonated simultaneously. Trigger wires at each end of the panel were attached to the MDF and were used to start and stop an electronic counter, thus giving the total elapsed time for the detonation front to propogate between the two fixed points.[5]

Lightning Generators - To provide the fast rise-time, high-current waveform, a 3μf 100 kV capacitor stack capable of attaining 200 kA in 2 μseconds into a low impedance test sample was used. In this configuration the current waveform was a damped sinusoid with the zero cross-over occurring every 4 microseconds.

To provide the 200 kA full-energy current waveform, the MCAIR 600 kilojoule capacitor bank was connected as a 5-stage Marx generator with an output voltage of approximately 110 kV. Waveshaping components were incorporated so that a relatively fast rising, slow decaying waveform was obtained with very little ringing. In this configuration the lightning current was uninterrupted for 100 μseconds.

The continuing current (high coulomb) portion of the lightning waveform was supplied by a 3-phase, 480-volt auto-transformer rectifier power supply adjusted for a current level of slightly less than 500 amps.

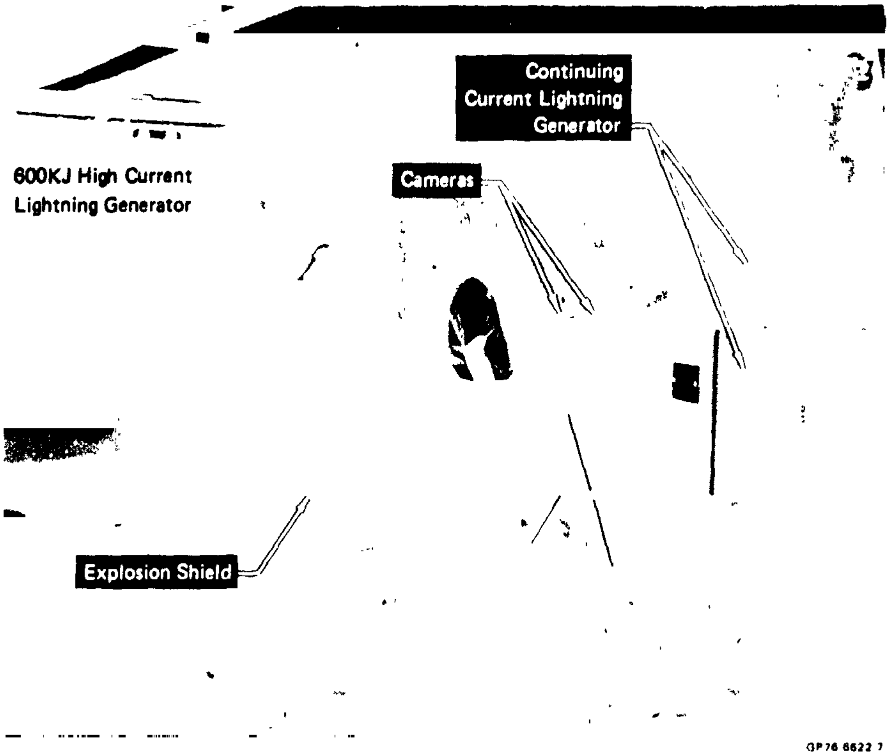

FIGURE 7 – ORBITER OUTER PANEL LIGHTNING TEST SETUP

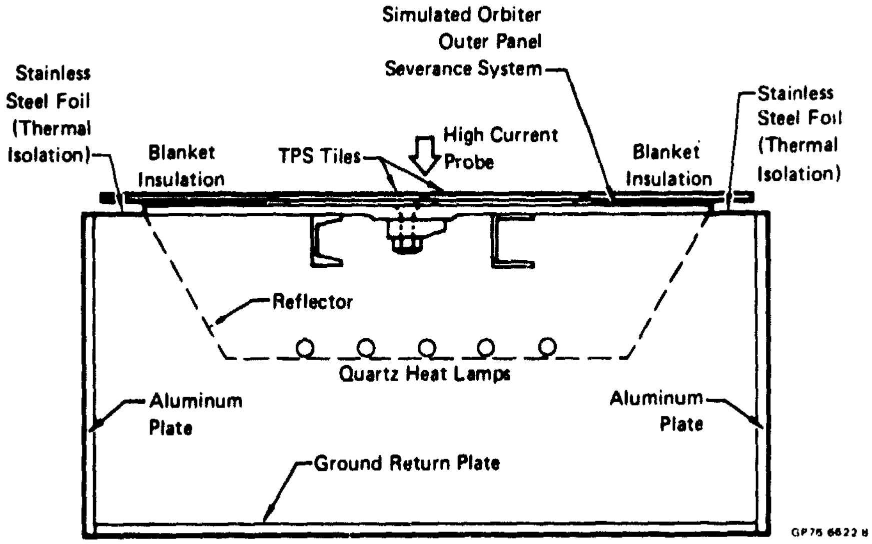

FIGURE 8 – SIMPLIFIED DIAGRAM OF ORBITER PANEL INSTALLATION

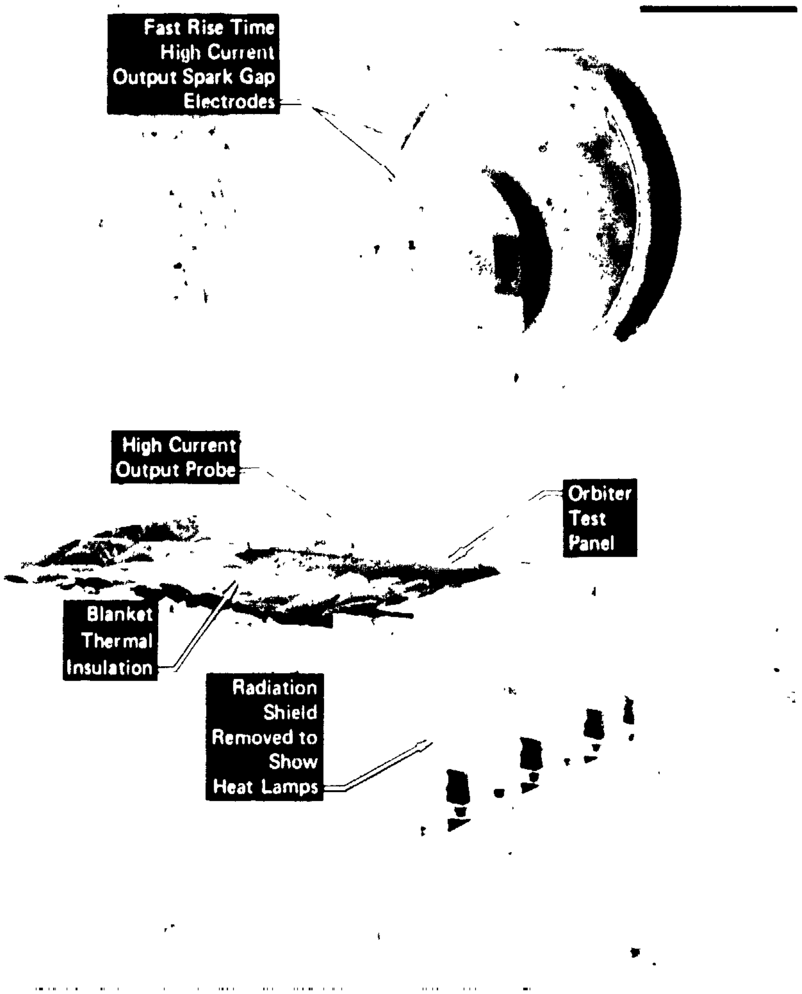

FIGURE 9 – FAST-RISE, HIGH-CURRENT TEST SETUP

Preliminary Test Procedure

(1) Prior to any tests on the simulated Orbiter panel, a piece of filler bar material was subjected to a high-voltage arc to determine its relative dielectric strength and to determine whether a high voltage arc would directly punch thru the filler bar material or flash over the rubber surface to the edge of the material. To determine this, a small high-voltage pulse generator was set up with an output probe to flat plate spacing of 7/16 inch. The voltage output of the generator was then increased in small increments until arc-over occurred. The minimum voltage was 18.2 kV. The filler bar material was then placed on top of the plate and again the voltage pulse was increased until arc-over occurred. The probe-to-plate spacing remained the same.

(2) Prior to the installation of the pyrotechnics in the Orbiter panel, additional preliminary tests were performed to establish final test procedures. The panel was installed in the test fixture and heated to determine the control settings for the heat rate to be used for actual tests. The panel was struck with a fast high-current waveform to verify that accurate and reliable temperature data would be obtained during the actual tests. High-speed movies were also taken to verify camera settings. The Orbiter panel was then removed from the fixture and the pyrotechnics (MDF) were bonded and bolted into the test panel along with the thermocouples.

(3) Before the Orbiter test panel was reinstalled in the test fixture, a dummy plate was installed in the test fixture and struck with the simulated lightning current to verify compliance with the desired waveshape.

TEST RESULTS

Preliminary Tests - The preliminary high-voltage test on the filler bar material showed that the material has a higher dielectric strength than Air because of the RTV coating on the top surface. At a probe to plate spacing of 1.1 cm (7/16 inch), a minimum voltage pulse of 18.2 kV was required to arc the gap. With the filler bar in the gap, the minimum voltage required to arc over was 25 kV. It was also noted that the arc did not directly penetrate the filler bar material but contacted the RTV under the high-voltage probe, tracked across the surface for about 1/2 inch and then punched thru, as seen in Figure 10.

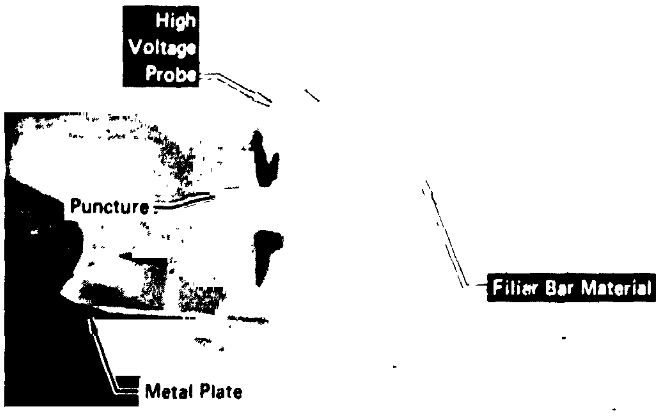

FIGURE 10 – HIGH VOLTAGE FLASH-OVER AND PUNCTURE OF FILLER BAR MATERIAL

<u>Orbiter Panel Lightning Tests</u> - A summary of all the lightning strikes is given in Table I. The panel was struck with the simulated lightning currents while at 325°F. Throughout the lighting tests, the MDF in the panel remained physically undamaged.

TABLE 1 – SUMMARY OF LIGHTNING TESTS ON ORBITER PANEL

Test	Peak Current	Time to Peak Current	I^2t	Charge Transfer	Current Total Time	Max Temp Rise	Notes
Fast Rise Time High Peak Current	180KA	2 μsec	2.3×10^5 A^2 sec.	2.7 Coulomb	≈ 65 μsec	2°F	Arc attachment at edge of filler bar. Damage to SIP and filler bar 3.8 to 4.5 cm (1-1/2 to 1-3/4 in.) dia. Damage to tiles approx 7.6 to 9.5 cm (3 to 3-3/4 in.). Only slight pitting damage to aluminum panel. No visible damage to Pyros.
Full Energy High Peak Current	205KA	25 μsec	1.34×10^6 A^2 sec.	8.2 Coulomb	≈ 260 μsec	14°F	Arc attachment 0.95 cm (3/8 in.) to side of probe in center of filler bar and over to side of intersection of 2 filler bars. Damage to SIP and filler bar 4.5 to 5 cm (1-3/4 to 2 in.) dia. Damage to tiles 9.5 to 10 cm (3-3/4 to 4 in.) dia. No visible damage to Pyros. High speed movie camera failed to function properly.
Continuing Current (High Coulomb)	490 amp Average	≃ 1 msec	9.7×10^4 A^2 sec.	220 Coulomb	470 msec	100°F	Burned 0.63 cm (1/4 in.) dia. hole thru aluminum to epoxy around Pyro. Some RTV continued to burn after cessation of lightning current. No visible damage to Pyros.

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The results of the 2 μsec rise, 180 kA current pulse are shown in Figure 11. Damage to the tiles extends over an area 9.5 cm (1-3/4 inches) in diameter area. The lightning arc did not puncture the RTV used to attach the filler bar to the metal panel as expected; it attached to the metal at the junction of the filler bars and the SIP as shown in Figure 12A. The damage to the metal panel consisted of only slight erosion of the plate over a 0.32 cm (1/8-inch) diameter area. The lightning current waveform is shown in Figure 13. A review of the high-speed movie sequence shows that tile particles are leaving the strike area at an initial velocity approaching the speed of sound. For example, selected frames are shown in Figure 14 and reveal that on the third frame some particles are already 25.4 cm away from the panel. The arc is first seen during frame 1, the exact instant of time of the initiation of the arc during frame 1 is not determinable, therefore the approximate average velocity of the particles during the 2-frame sequence (frame 1 to frame 3) would be 10 inches x 1750 fps ÷ 2 frames = 22.2×10^3 cm/second (8.75×10^3 inches/second).

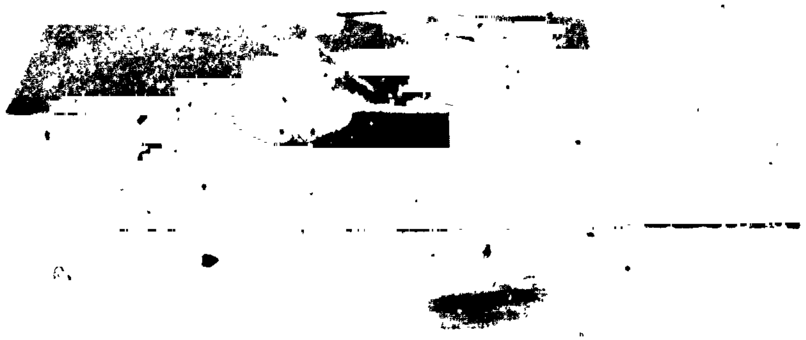

FIGURE 11 – RESULTS OF FAST-RISE, HIGH-CURRENT LIGHTNING TEST

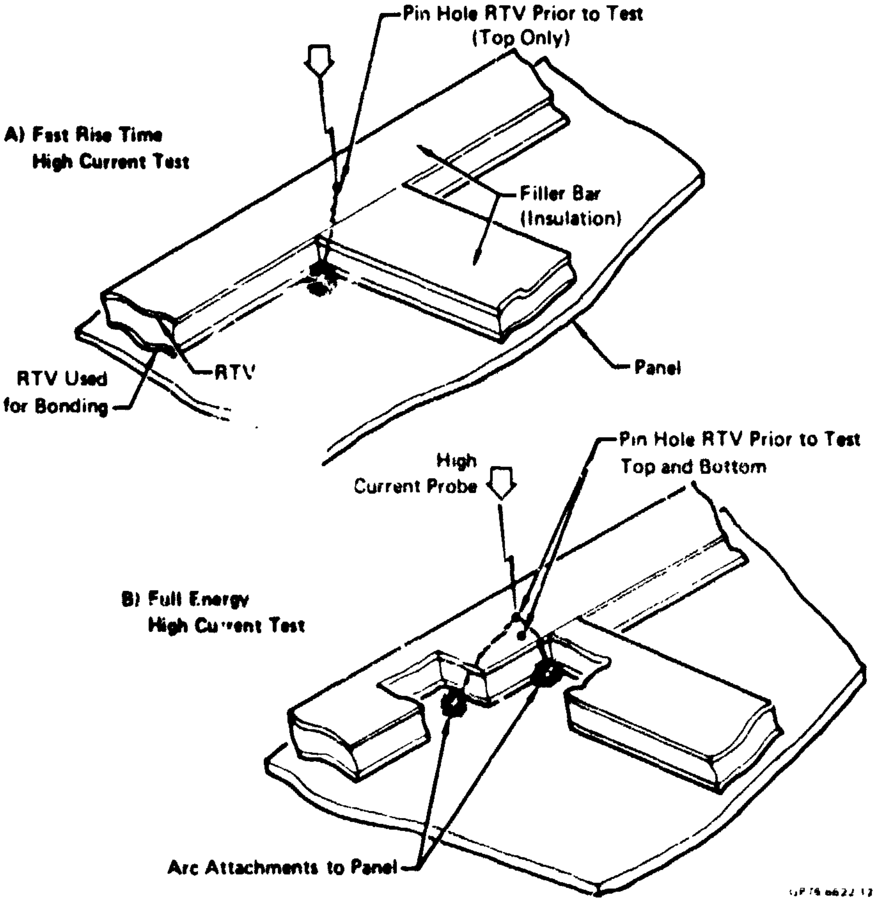

FIGURE 12 – RECONSTRUCTED PROBABLE ARC PATHS TO PANEL DURING HIGH CURRENT SURGE TESTS

ORIGINAL PAGE IS
OF POOR QUALITY

Calibration Illustrating
Fast Rise Time (2 μsec)

Vertical: 100kA/Major Division
Horizon: 2 μsec/Major Division

Note Traces enhanced for clarity.

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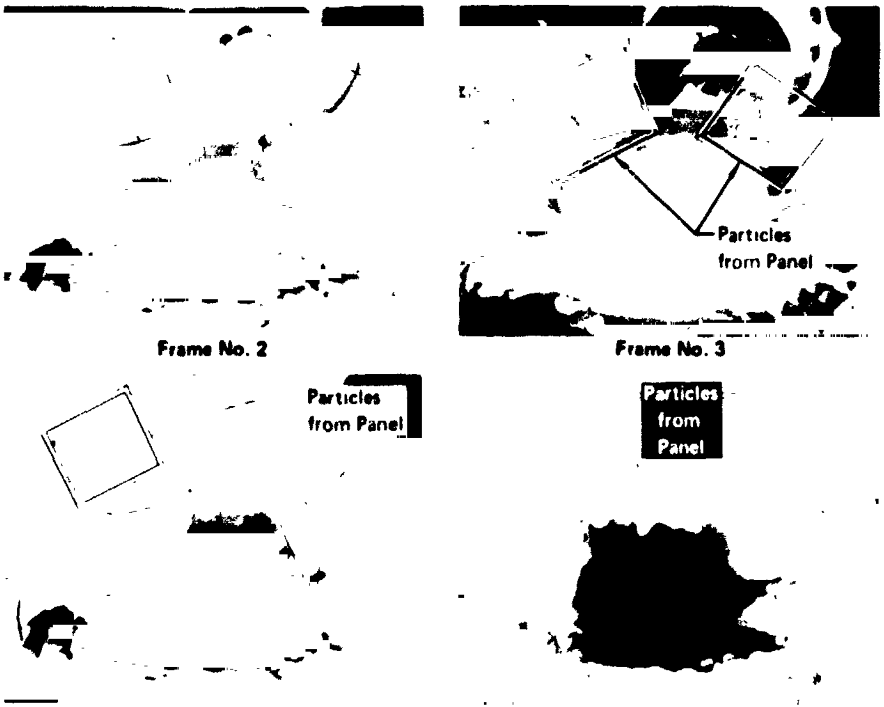
FIGURE 13 – FAST-RISE TIME, HIGH-CURRENT WAVESHAPE



Frame No. 2

Frame No. 3

Frame No. 4

Frame No. 5

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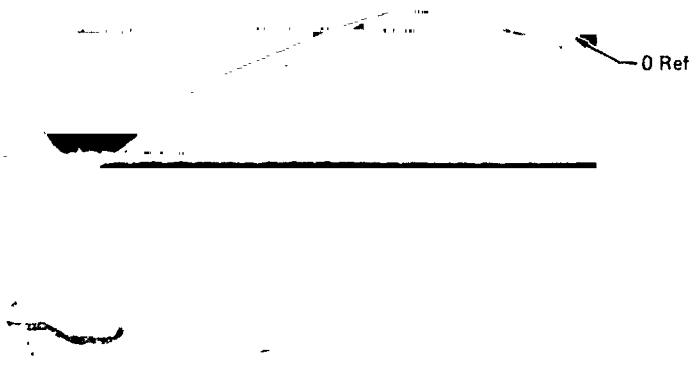
FIGURE 14 – SELECTED FRAMES FROM HIGH-SPEED MOVIE OF FAST HIGH-CURRENT STRIKE

Because of the extensive damage to the tiles resulting from the first lightning test, two tiles and associated SIP were replaced prior to the full-energy, high-current lightning test. It should be noted that the NASA supplied tiles had been previously used on an accoustic test and microcracks were observed on the two replacement tiles prior to their installation on the Orbiter panel.

The results of the full-energy, high-current test were similar to those of the 180 kA test except that the extensive damage to the tiles covered an area 10 cm (4 inches) in diameter plus some additional cracking. Damage to the SIP and filler bar was over an area 5 cm (2 inches) in diameter. Although the RTV on top of and under the filler bar was punctured prior to the test, the arc moved to the side approximately 0.95 cm (3/8 inch) before puncturing the RTV and attaching to the metal plate. Although most of the current went thru the aforementioned hole, another arc attachment point was noted at the edge of the filler bar bond line (Figure 12B). The lightning current waveform is shown in Figure 15. For this test, the continuing current was intended to immediately follow the high-current pulse, but it did not. It was therefore necessary to perform a separate high coulomb test. This later test was performed at the same test location without replacing tiles, SIP or filler bar materials (the reasons for doing this are discussed in the next section).



Vertical: 100 kA/Major Division Horizontal: 20 µsec/Major Division GP76-6622 15

FIGURE 15 – FULL-ENERGY, HIGH-CURRENT WAVESHAPE

The results of the high coulomb (continuing current) test are shown in Figure 16 and the current waveform is shown in Figure 17. For this test the probe was located over the hole previously blown in the RTV used to bond the filler bar to the aluminum panel. After the lightning current ceased, some of the exposed RTV continued to burn for about 20 seconds. Other than this there was no additional damage to the tiles. However, a 0.63 CM (1/4-inch) diameter hole was burned thru the aluminum plate down to the epoxy material surrounding the pyros. The molten aluminum bubbled out of the hole and formed the blister shown in Figure 16 just underneath the output probe. After the aluminum bubble was manually broken and peeled away, the epoxy used to bond the pyros was clearly visible. Some of the epoxy was then scraped away to reveal the exact location of the pyro as shown in Figure 18. Radiographs of the panel at the burn thru area showed that the thermocouple junction was approximately 0.13 - 0.19 CM (0.050 - 0.075 inch) away from the edge of the hole. Temperatures measured during the various lightning tests are shown in Figure 19 and show that the heat energy input to the pyros was small.

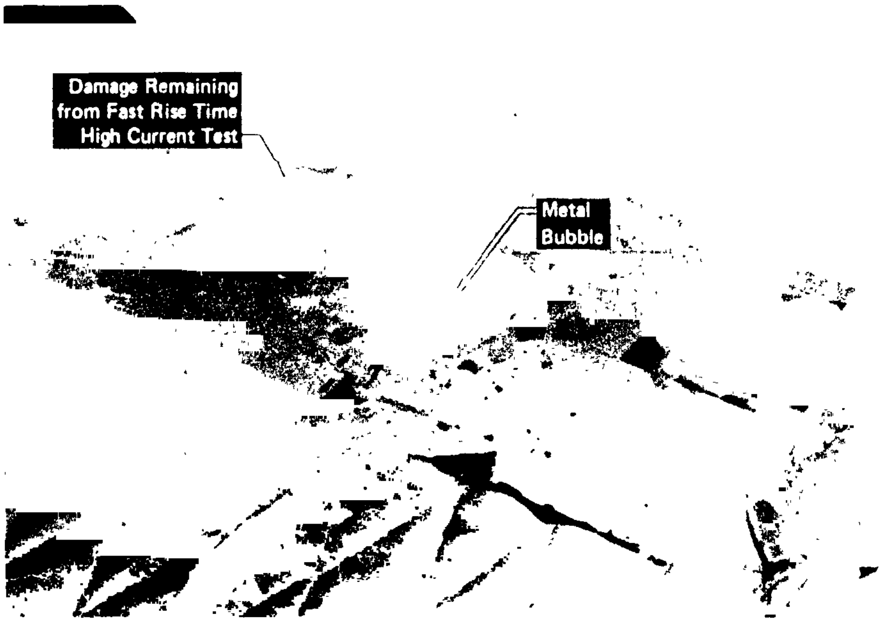
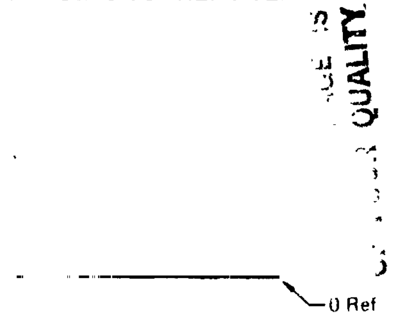


FIGURE 16 – RESULTS OF CONTINUING CURRENT TEST



Vertical: 200A/Major Division Horizon: 100ms/Major Division

FIGURE 17 – CONTINUING CURRENT WAVESHAPE

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FIGURE 18 – CLOSEUP OF DAMAGE AFTER REMOVAL OF EPOXY TO SHOW MDF

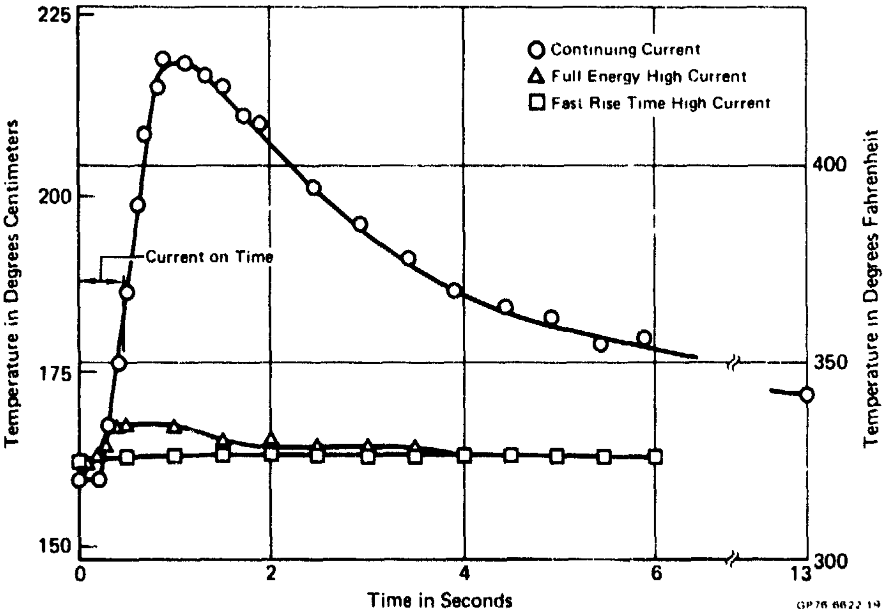

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FIGURE 19 – TEMPERATURES AT PYROS DURING SIMULATED LIGHTNING STRIKES

<u>Pyrotechnics Evaluation</u> – After all lightning tests were completed, the MDF's in the panel were connected to a detonator cap and the cap was initiated. The results of this test is shown in Figure 20. The detonation velocity was measured 6,957 meters per second (22,818 ft/sec) which is approximately midpoint of the acceptable limits of 6500-7100 m/sec indicating that the MDF had not been damaged by any of the lightning strikes to the panel.

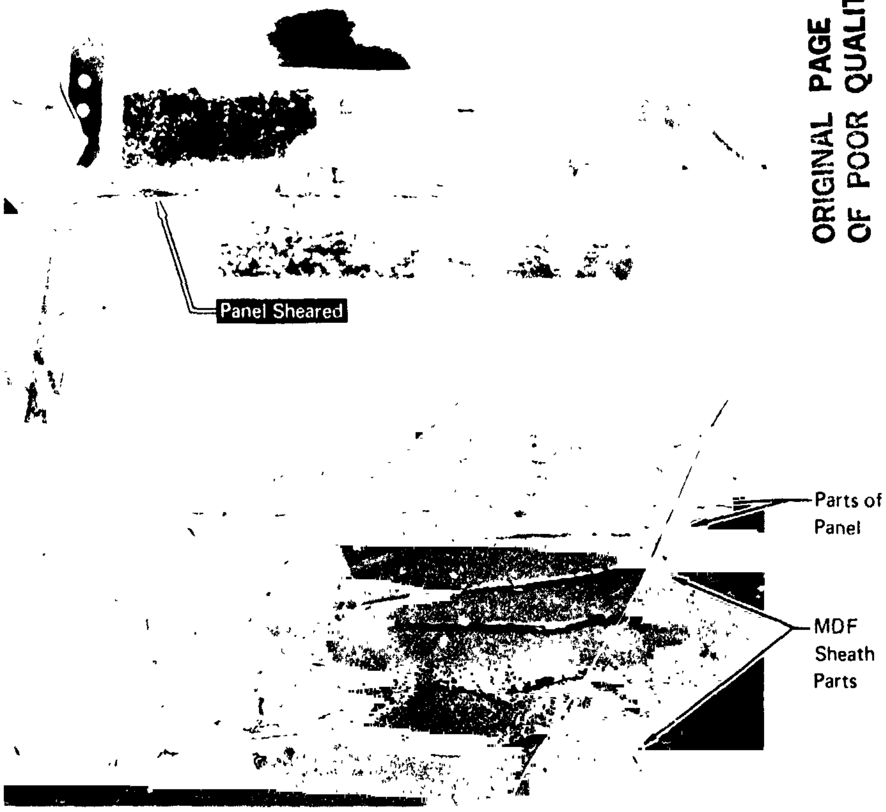

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FIGURE 20 – RESULTS OF DETONATION VELOCITY TEST

DISCUSSION OF TEST RESULTS

The fast rise-time 180-kA current pulse produces the initial fast rising shock effects of a natural lightning strike. However, the actual shock effect on the pyros may have been diminished somewhat because the current attach point to the metal panel was diverted to the side of the filler bar and therefore did not attach directly over the pyros as expected. Although the arc may have penetrated the RTV on top of the filler bar as provided by the pin holes, the arc apparently found a path of less impedance to the side of the RTV used to bond the filler bar to the panel rather than penetrating thru it; a phenomenon similar to that previously noted for the smooth RTV on the top of the filler bar.

The continuing current of the NASA lightning waveform model provides the principle heating effect on the panel, and in our test it was intended to immediately follow the high-current pulse without a time lapse between the two; it did not, and therefore a separate continuing current test was required. It is believed that the two tests present a valid overall test and that the tests do still comprise a "worst case" test. The reasoning and noted anomalies are given in the following paragraphs.

The damage to the tiles resulting from the full-energy, high-current test is greater than, but comparable to, the damage resulting from the fast rise-time 180-kA current pulse. The velocity of the materials leaving the scene of the strike is therefore believed to be comparable for the two high-current tests. Thus, the material from the strike area would be blown away 5.8 cm (2.3 inches) from the strike area at the time that the high-current would have decreased to 500 amperes. Under these conditions there should not be any interaction between the continuing current and the particles from the panel and therefore a separate continuing current test should be valid.

After the full energy high-current test, it was noted that there were not one but two arc attachments to the panel. Although the debris from the panel was out of the arc zone at the time the high-current pulse ceased, ionized gases continued to linger for an extended period of time as noted in the photos in Figure 14 (the arc current lasts for less than the time of 1 frame). Therefore, if the continuing current had followed the high-current pulse at that time, then the continuing current would probably have been divided with a percentage going to each attach point, the one directly thru the RTV used to bond the filler bar to the panel, and the other off to the side (at the intersections of the filler bars) over 1.3 cm (1/2 inch) away (see Figure 12B). If this had occurred then the damage would have been much less than that which occurred during the separate continuing current test where the current was introduced into a single attach point. Since the test conditions for this series of tests were intended to be "worst case," it was decided, after consulting with NASA, that the continuing current would be introduced at the hole punched thru the RTV directly over the pyros. The initial high current lightning pulse would have previously removed the tiles and therefore no attempt was made to replace tiles, SIP, or filler bars before the continuing current test.

The voltage in the continuing current power supply is only about 400 volts, therefore, it is not sufficient to throw a 1.3 cm (1/2 inch) spark to a test panel; however, it is more than sufficient to maintain the arc, once it is established. Therefore, to start the arc, a 0.013 cm (0.005 inch) diameter copper wire was placed between the output probe and the desired arc attach point on the test panel (in this case the hole blown in the RTV residue left from bonding the filler bar to the panel). In a fraction of a second after the current starts flowing, the wire vaporizes and becomes a part of the ionized path between the panel and the probe. The vaporization of the wire is rapid but not so fast as to give a significant explosive shock effect which would damage the tiles. Because the arc was confined by the RTV, the heating and melting of the metal panel was confined to a small volume, and resulted in a hole thru the panel. Apparently the heat from the arc and molten metal at the bottom of the hole in the panel caused some gaseous products to be generated from the epoxy over the pyros because a bubble of metal protruded over the RTV and up to the output probe. It appears that this bubble occurred after the arc had ceased because although the bubble touched the probe it was not mechanically attached in any way. After the metal bubble was manually broken away, the interior of the hole in the plate was observed to be relatively smooth and clean with the mid-depth of the hole being slightly larger in diameter than either the entrance hole near the probe or the exit hole near the epoxy (over the pyros). The epoxy surface was slightly blackened but the damage did not extend any significant depth; estimated to be a couple thousandths of an inch. The epoxy was scraped away to reveal the undamaged sheath of one of the pyros as shown in Figure 18. The epoxy apparently provided a heat barbier between the molten aluminum and the pyros and also provided an electrical barrier keeping the arc from directly attaching to the metal sheath of the MDF. If the epoxy has not been over the MDF, then the pyro may have been "dudded" or possibly even detonated.

The continuing current test produced the heating effects of the continuing portion of the lightning model. The total coulombs transferred to the panel was slightly greater than the 200 specified in the Space Shuttle Lightning Protection Criteria Document, JSC-07636, Revision A, but even under these conditions, the MDF remained undamaged as evidenced by the results of the detonation test.

These tests revealed the significance of a thin layer of RTV in diverting the arc attachment point from one location to another. It, therefore, seems that an extra thick coating of this RTV, applied to the metal plate directly over the pyros (with bare metal to the sides of this rubber strip) could cause the arc to flash to the metal to the side of the pyros. On both sides of the pyros the metal is approximately twice as thick as it is over the MDF; therefore, the only significant damage would be to the tiles.

CONCLUSIONS

From the results of these tests on a simulated Orbiter panel, it is concluded that the Orbiter outer panel escape system is adequate from a lightning point of view so that if a direct lightning strike attached to the Orbiter brow in the vicinity of the MDF pyrotechnics, the pyrotechnics would remain undamaged.

REFERENCES

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[4] *"A Ground-Lightning Environment for Engineering Usage," by N. Cianos and E. T. Pierce, Stanford Research Institute Technical Report 1, SRI Project 1834, August 1972.*

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