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Paper No. 27

HIGH CURRENT LIGHTNING TEST OF SPACE SHUTTLE EXTERNAL TANK LIGHTNING PROTECTION SYSTEM*

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ABSTRACT

During lift-off, the Shuttle launch vehicle (External Tank, Solid Rocket Boosters and Orbiter) may be subjected to a lightning strike. This paper describes tests of Martin Marietta's proposed lightning protection method for the External Tank and development materials which were subjected to simulated lightning strikes. Results showed that certain of the high resistance paint strips performed remarkably well in diverting the 50 kA lightning strikes over the CPR 421 Thermal Protection System.

INTRODUCTION

It has long been recognized that lightning is a real threat to aircraft, and although one normally thinks of spacecraft as operating outside of the earth's atmosphere, they must, however, traverse the lightning environment which may extend to 15,000 meters (50,000 feet).

Kennedy Space Center, one of the launch sites for Shuttle, is equipped with extensive and sophisticated arrays of lightning detection and monitoring equipment, but even so, they cannot predict or prevent all possible lightning strikes to launched vehicles. Although assurances can be given that a lightning strike probably will not occur during launch, based upon "blue sky" atmospheric conditions, other circumstances may not always permit the delays imposed by the "blue sky" restriction. Therefore, some protective measures must be incorporated in the complete Space Shuttle system to insure survivability. Because of the complicated outer surfaces of the Shuttle System, tests must be performed to demonstrate the adequacy of the protective measures.

The Space Shuttle in the launch configuration consists of three major systems: the Orbiter, the External Fuel Tank (ET), and the Solid Rocket Boosters (SRB's). In this configuration, if a lightning strike should occur, it is most likely to strike the nose of the ET as shown in Figure 1. To complicate matters, The Shuttle ET contains cryogenics (liquid hydrogen and liquid oxygen) and must therefore be thermally insulated to prevent excessive loss of cryogens due to heat input from the external environment. Good thermal insulators generally do not possess much mechanical strength and because they are extremely poor electrical conductors, they cannot be expected to conduct lightning current safely. As a result, a lightning strike to an area protected by one of these types of materials may cause severe damage to the insulation system. Therefore, the design of such a system is complicated by the lightning threat and the materials and installation costs for protective measures.

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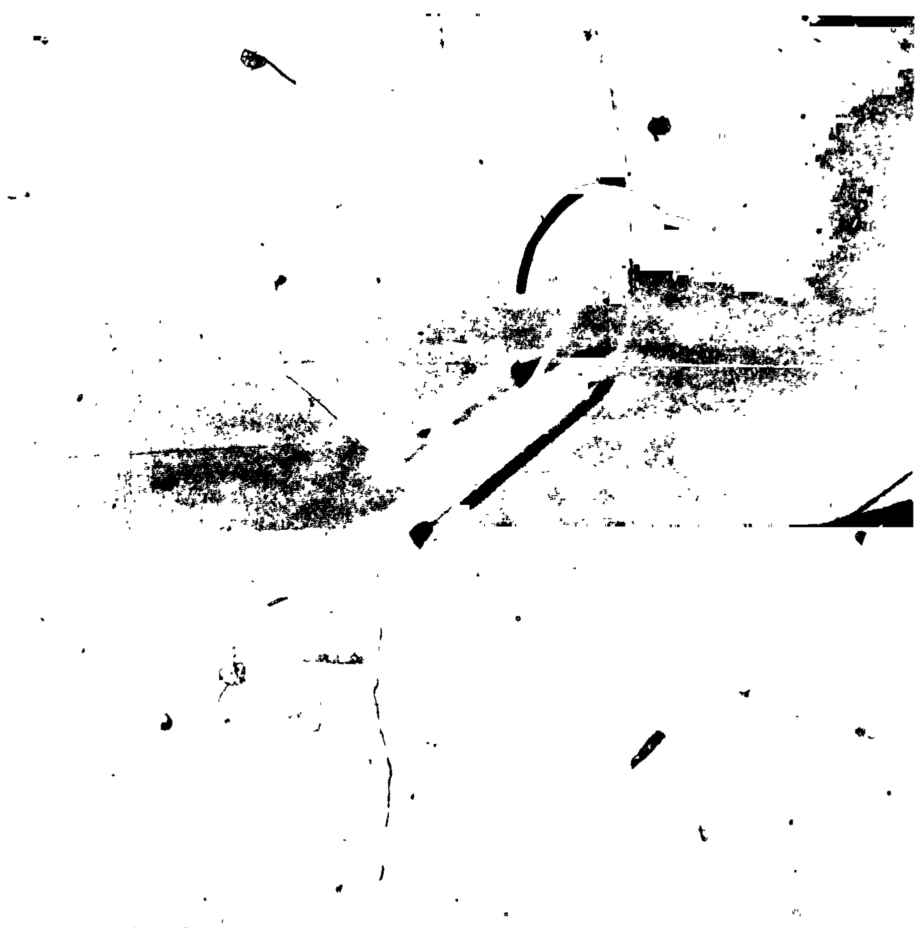

FIGURE 1 – LIGHTNING ATTACHMENT TEST OF SHUTTLE MODEL[1]

This paper describes the design approach taken by Martin Marietta Corporation for lightning protection of the Shuttle External Tank. The paper also describes the test panels manufactured by Martin Marietta for lightning tests to verify the design concept and adequacy of conductive materials. The actual lightning tests were conducted at the McDonnell Aircraft Company's Lightning Simulation Laboratory located in St. Louis, Missouri. The test set-up and test results are detailed herein. The lightning tests were conducted in accordance with Reference 2.

<u>Lightning Threat</u>

Natural lightning is a complicated phenomena and has been extensively studied and statistically summarized by noted authorities such as Uman[3] and Cianos and Pierce[4]. For testing purposes, the lightning environment is generally simplified, based upon the various statistical studies plus the combined knowledge and engineering judgment of many experts in the field of lightning theory and simulation. The effects of lightning are considered as being either direct or indirect effects. The direct effects are those which are normally associated with observable physical damage and the indirect effects are those normally associated with the more subtle aspects of lightning effects such as the induced electrical transients on wiring. For this presentation, we are concerned with the direct effects of lightning.

For direct effects testing, the NASA idealized lightning model waveform shown in Figure 2 was used. The magnitudes of the various components of this waveform are considered to be those found in a severe lightning strike and not often found in nature. However, each component has relevance toward producing the various damage mechanisms found in a real lightning strike. For additional information, the reader is referred to the References listed.

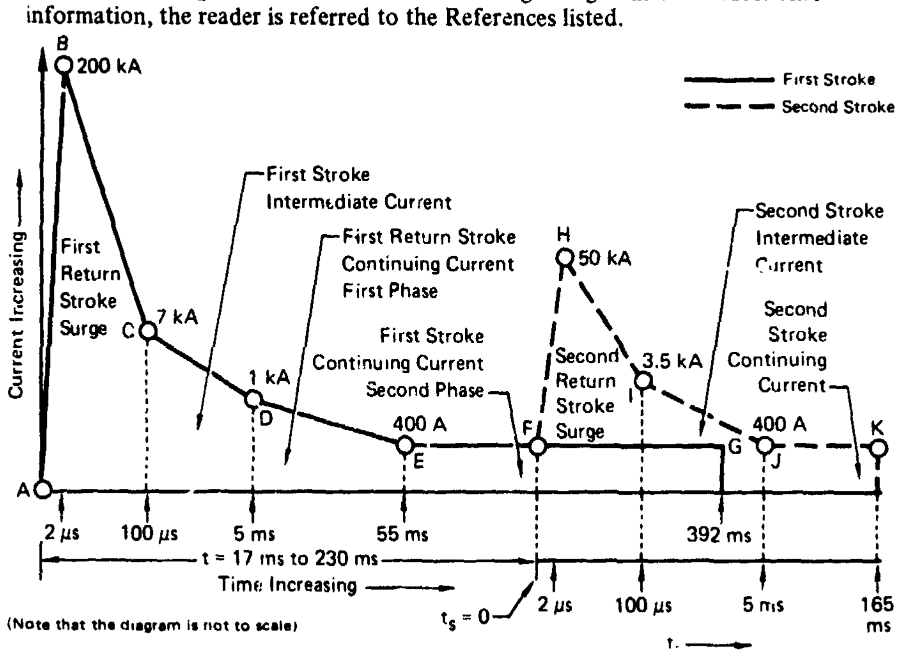

FIGURE 2 – NASA (JSC) LIGHTNING MODEL

In the launch configuration for the Space Shuttle, the lightning rod on the nose of the ET is the most likely attachment point for lightning and any portions aft of this area are considered to be in a lightning swept stroke region and are therefore subject to a lightning restrike. The lightning test conditions for a primary (most likely) attach point are those of the first stroke shown in Figure 2 and the restrike test conditions are those of the second stroke shown in this figure. Either of the test conditions can inflict severe damage to a spacecraft system or to a conventional aircraft if it is not adequately protected. In particular, the thermal protection system (TPS) used on the Shuttle ET (see Figure 3) is vulnerable to lightning. If the lightning should puncture the TPS, a hole several inches in diameter may be blown in the TPS, thus exposing the cold bare metal of the tank. A small hole in the TPS itself may be tolerable but aerodynamic forces during ascent may cause larger portions to be torn away. In addition, the direct lightning arc attachment to the metal skin may cause a hole to be burned thru the tank wall.

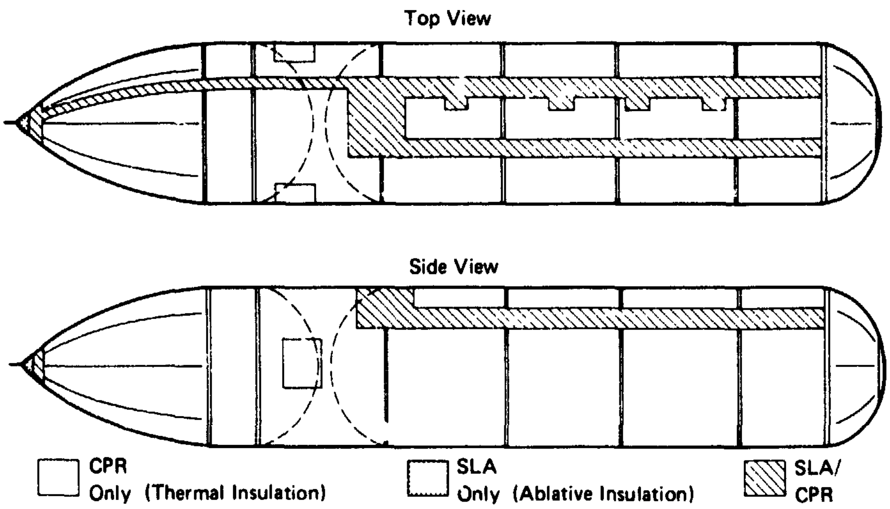

FIGURE 3 – SHUTTLE EXTERNAL TANK THERMAL PROTECTION SYSTEM CONFIGURATION

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As mentioned above, the lightning rod on the ET is the most likely lightning attach point and the areas aft of the nose may also become lightning attach points as shown in Figure 4 because of the "swept stroke" behavior of lightning. Lightning may approach and initially attach to the nose of the ET from a wide range of angles. Once the main arc channel is established, it will not deviate appreciably from this path unless a more desirable lower resistance path is available. Thus, the spacecraft could fly thru a lightning arc channel with the result that it will sweep rearward on the tank with probably several reattachments to the side of the tank. The velocity of the vehicle, the external surface of the vehicle and the air flow boundary layer conditions all influence the reattachment behavior. In addition, the second fast rising high peak return stroke surge of the lightning current will probably force a new reattachment of the arc. Because all of these factors can influence test results, it is desirable to test under the most realistic conditions possible. Therefore, for this test series, the complete second stroke current waveform shown in Figure 2 was used and the arc was blown by a 10 feet/second airstream to conservatively simulate the early movement of the launch vehicle. When the nose clears the protection system of the launch pad, the vehicle will actually be moving at 19.5 meters per second (64 feet/second). At this low velocity, the lightning arc would not be blown very far and thus the simulation would impose a "worst case" test condition regarding the possibility of burn-thru of the metal tank wall if the arc would attach directly to the skin.

Protection System Theory

When lightning strikes a conductive surface on a moving vehicle, the strike may sweep across the surface. The resulting surface damage will be distributed over the path length and should be relatively minor in a given spot However, if lightning strikes an insulated surface overlaying a conductive substrate, the strike

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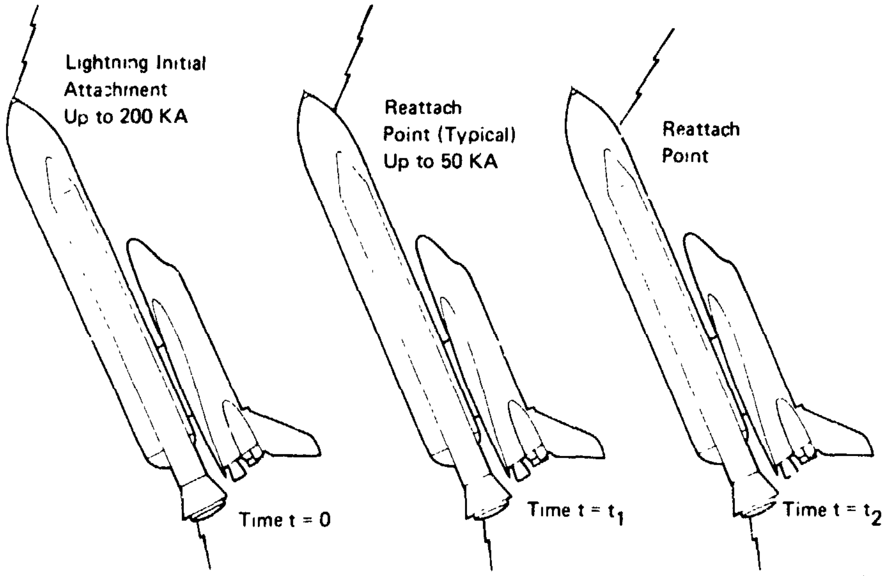

FIGURE 4 – ILLUSTRATION OF LIGHTNING ARC BEHAVIOR (SWEPT STROKE) ON MOVING VEHICLE

may penetrate the insulation and attach to the underlying metal. The lightning strike cannot readily sweep over the surface, and thus confined, can cause more extensive damage.

On the External Tank, the thermal protection system (TPS) insulator is used to maintain a low temperature on structural members. The strain characteristic of metal is greater at low temperatures and falls off quite rapidly at elevated temperatures. Consequently, from both thermal and structural considerations, the integrity of the TPS has to be preserved.

Considering the direct lightning effects of lightning confined by TPS and the thermal/structural effects when TPS is removed in divots by lightning, it becomes paramount that the TPS be protected from lightning! Theoretically, it should be possible to protect an insulated surface from lightning by covering it with a conductive layer. If the conductive layer is in the form of a narrow strip, it would have to be grounded to structure at intervals so that neither the resistive voltage drop nor the inductive drop (the inductance of the layer L times the restrike rise time, di/dt) would not exceed the voltage breakdown of the insulating material at any point along the strip.

The TPS system on the External Tank is extensive (see Figure 3) and from inception, the design has included conductive strips over the forward nose (ogive) area of TPS. Aluminum foil of an undefined thickness was originally proposed. This concept was soon abandoned when consideration was given to the possible impingement of the aluminum upon the underbelly TPS tiles of the Orbiter, thus damaging the tiles and possibly jeopardizing reentry.

With weight, manufacturing cost, and other considerations in mind, the overall lightning protection concept on the ET was re-examined.

First, except for the lightning rod, the ET is not required to be designed to take the full return stroke (200 kA), see Figures 2 and 4, but only the restrike (50 kA).

Second, the ET will not be struck while on the launch pad since it is within the cone of protection of the lightning protection system of the launch tower. It will only be struck when it clears the tower and is moving at 64 feet/second. The strike would be to a moving, not a static vehicle!

With these more realistic requirements (50 KA restrike and a moving vehicle) efforts were directed toward a more practical approach to the area of TPS needing protection. The general protection scheme now recommended is four conductive strips (paint) extending from the base of the lightning rod aft. One of these four strips would be connected to the oxygen pressurization line where the line enters the nose cap (see Figure 5). The width, frequency, and method of strip attachment to structure, thickness, etc. has still to be resolved.

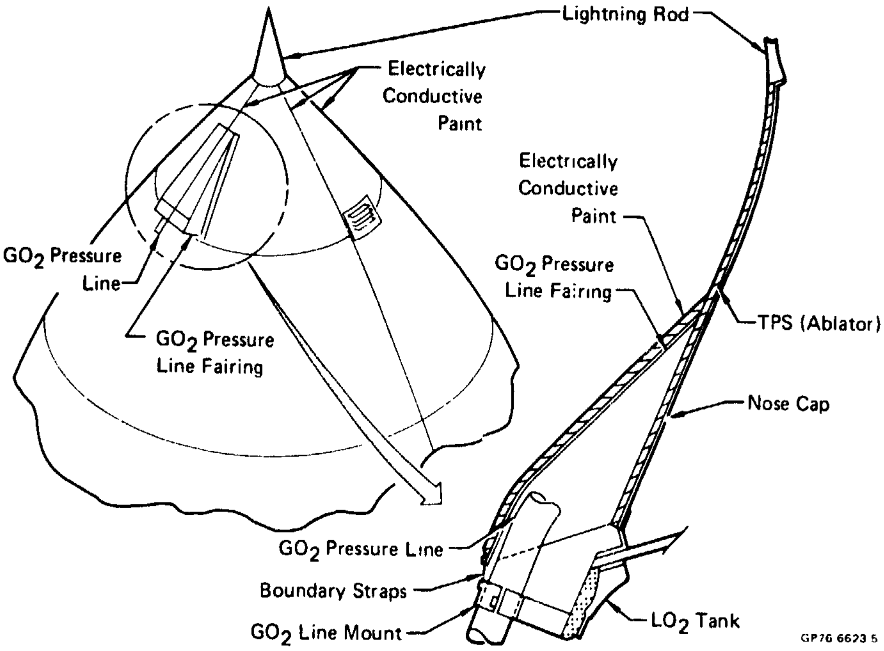

FIGURE 5 – LIGHTNING PROTECTION SYSTEM FOR SHUTTLE EXTERNAL TANKS

Test Panel Design and Construction

Resistivity, adhesion, and TPS compatibility tests were conducted by Martin Marietta Corporation on a number of materials. These tests resulted in narrowing the field to four candidate coatings: one low-resistance silver-filled (Electrodag 504), two intermediate-resistance carbon or graphite-filled (Electrodag 501 and Eccocoat SEC), and one high-resistance carbon-filled (Dynalog 305). Both Electrodag 504 and 501 use a MEK solvent while Eccocoat SEC and Dynalog 305 use water as a solvent.

Fourteen panels were supplied by Martin Marietta Corporation for lightning tests at McDonnell Aircraft Lightning Laboratory and are described in Table 1. Each panel consisted of an .20 cm thick (.080 inch) slightly curved aluminum plate 83 x 111 cm (36 inches by 44 inches) covered with approximately 2.5 to 3.7 cm (1 to 1.5 inches) of Thermal Protection System (TPS) sprayed-on foam (CPR 421) covered in its entirety with FRL seal coat. A strip of electrically conductive paint approximately 10 cm (4 inches) wide was sprayed the length of the panel over the centerline of the foam and contacted the metal substrate at both ends.

TABLE 1 – LIGHTNING TEST PANELS

Martin Marietta Part Number	Conductive Strip Thickness	Conductive Strip Color	Conductive Strip Type
-079#1	0.025 cm (10 mil)	Black	Eccocoat SEC
-079#2	0.025 cm	Black	Eccocoat SEC
-080#1	0.025 cm	Black	Dynaloy 305
-080#2	0.025 cm	Black	Dynaloy 305
-089#1	0.025 cm	Black	Electrodag 501
-089#2	0.025 cm	Black	Electrodag 501
-090#1	0 0051 cm (2 mil)	Silver	Electrodag 504
-090#2	0.0051 cm	Silver	Electrodag 504
-099#1	0.051 cm (20 mil)	Black	Eccocoat SEC
-099#2	0.051 cm	Black	Eccocoat SEC
-100#1	0.051 cm	Black	Dynaloy 305
-100#2	0.051 cm	Black	Dynaloy 305
-109#1	0.051 cm	Black	Electrodag 501
-109#2	0.051 cm	Black	Electrodag 501

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Lightning Test Setup

The lightning test setup provided a means of generating the pertinent test conditions which were discussed in the lightning threat section, as well as the necessary instrumentation for verifying compliance of the various parameters. The test setup provided for a high-current arc to be struck to the test panel and for the arc to be blown by a 3 meter per second (10 feet/second) windstream. A simplified block diagram of the test setup is shown in Figure 6 and a view of the test setup is shown in Figure 7. The various portions of the test setup are further described in the following paragraphs.

The 3 meters per second wind velocity was provided by a motor driven centrifugal blower. The high velocity flow normally produced by this type blower was greatly attenuated and smoothed by a stilling chamber equipped with high density screens. The output from the stilling chamber was then ducted over the strike region on the panel. The duct was constructed of non-metallic materials (plexiglas and fiberglass with nylon screws) so as not to influence arc behavior. The test panel itself acted as the floor of the wind tunnel. The air velocity was measured at many points throughout the duct and beyond and found to be very uniform.

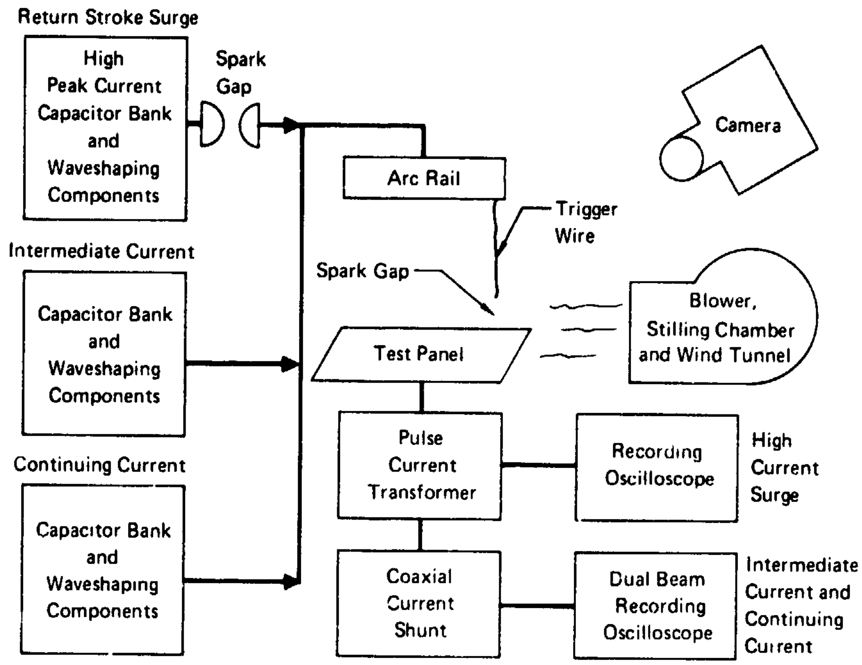

FIGURE 6 – TEST SETUP – SIMPLIFIED BLOCK DIAGRAM

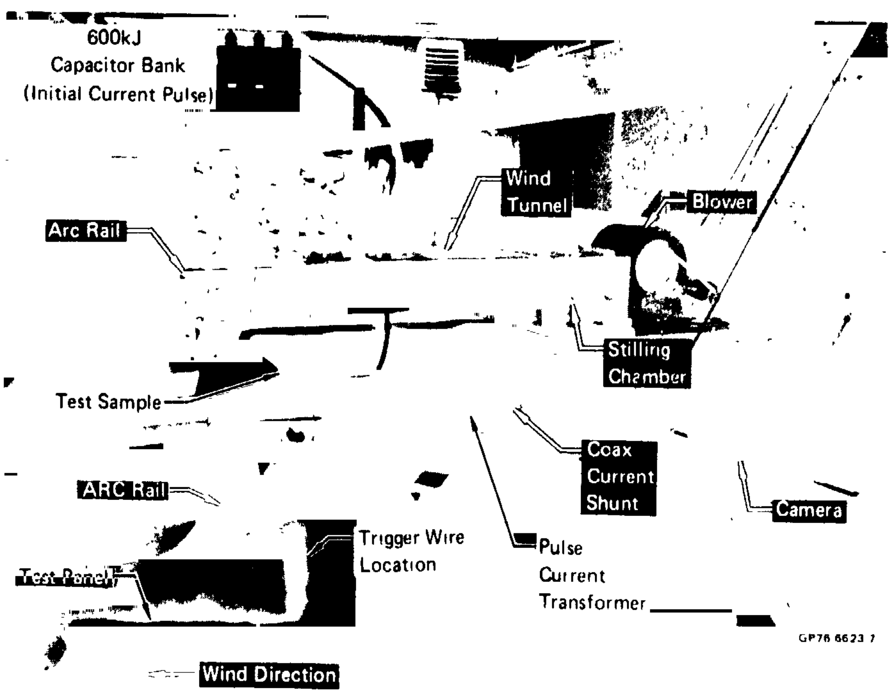

FIGURE 7 – LIGHTNING TEST SETUP

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The test panel was placed at the exit of the stilling chamber but isolated from it by a 10 cm wide piece of fiberglass so as to keep the metal of the test panel isolated from the stilling chamber. The lower edges of the plexiglas on the sides of the tunnel were allowed to rest directly on the TPS of the test panel. The test panel was electrically grounded at the metal tab at the end of the panel. The overhead rail electrode which allowed the arc channel to move with the air stream was mounted 8 inches above the test panel as shown in Figure 7.

Referring to the second return stroke portion of the waveform shown in Figure 2, it is difficult to realize the large differences in both time and amplitude of the various portions of the waveform because neither axis is drawn to scale. To provide the complete second return stroke current requires either one large versatile lightning generator or multiple generators connected together to provide a continuous waveform. This test requirement had never been imposed prior to this test. In fact, the original MCAIR 600 kJ lightning generator was upgraded to a 1 MJ capacity to meet this test requirement. The return stroke surge was provided by the 600 kJ capacitor bank and waveshaping components and the output voltage for this portion was approximately 75 kV. The return stroke intermediate current and return stroke continuing current were supplied by 90 kJ and 390 kJ capacitor banks respectively, along with their associated isolation and waveshaping components. The 90 kJ and 390 kJ banks were operated at approximately 11 kV so that a 25 cm (10 inch) arc length could readily be maintained. An overall view showing the relationship of the test setup to the various capacitor banks is shown in Figure 8.

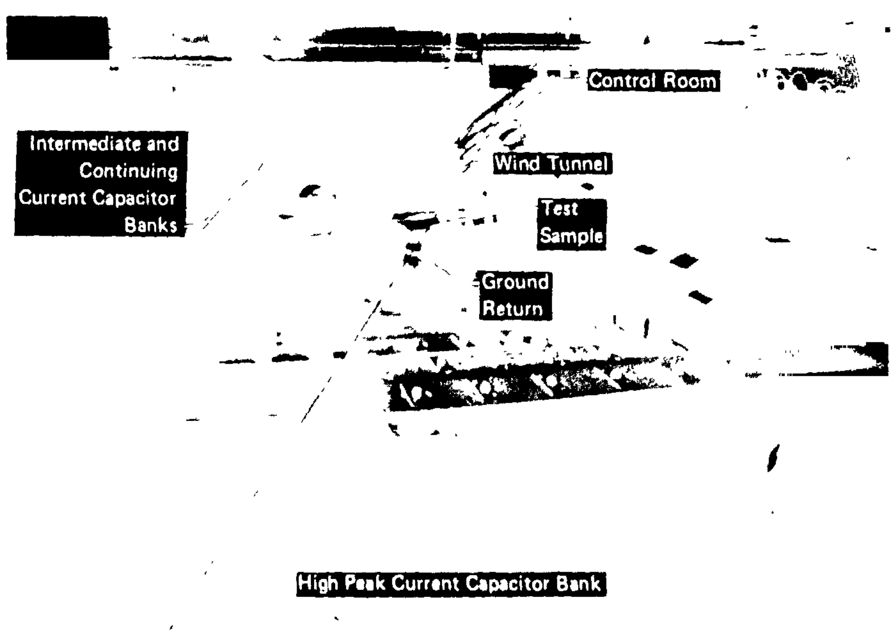

FIGURE 8 – OVERALL VIEW OF TEST SETUP

The output from the 1 MJ lightning generator was connected to the arc rail above the test panel as shown in Figure 7. A 0.32 gage copper wire was attached to the arc rail at the wind tunnel exit and extended to within 2.5 cm (1 inch) of the paint strip on the test panel as shown in Figure 9. A nylon cord was used to maintain the position of the lower portion of the wire when the blower was on and prior to the initiation of the lightning strike. The arc initiator wire was used to insure arc attachment to the paint near the central portion of the panel. When the arc is initiated, the wire immediately vaporizes to form the continuation of the arc from the overhead rail to the test panel. The arc is then blown by the windstream away from the tunnel exit as the various capacitor banks continue to dump thru the arc path to the test panel. By terminating the trigger wire above the panel, the arc channel at the surface of the panel is less likely to be affected by metal vapor ions, leading to a more realistic swept strike behavior. Initially the panels were positioned under the trigger wire so that the shortest electrical path thru the paint to the substrate was upstream (inside the wind tunnel). But because of damage occurring inside the wind tunnel which may affect test results, succeeding tests were conducted with the shortest electrical distance outside the wind tunnel.

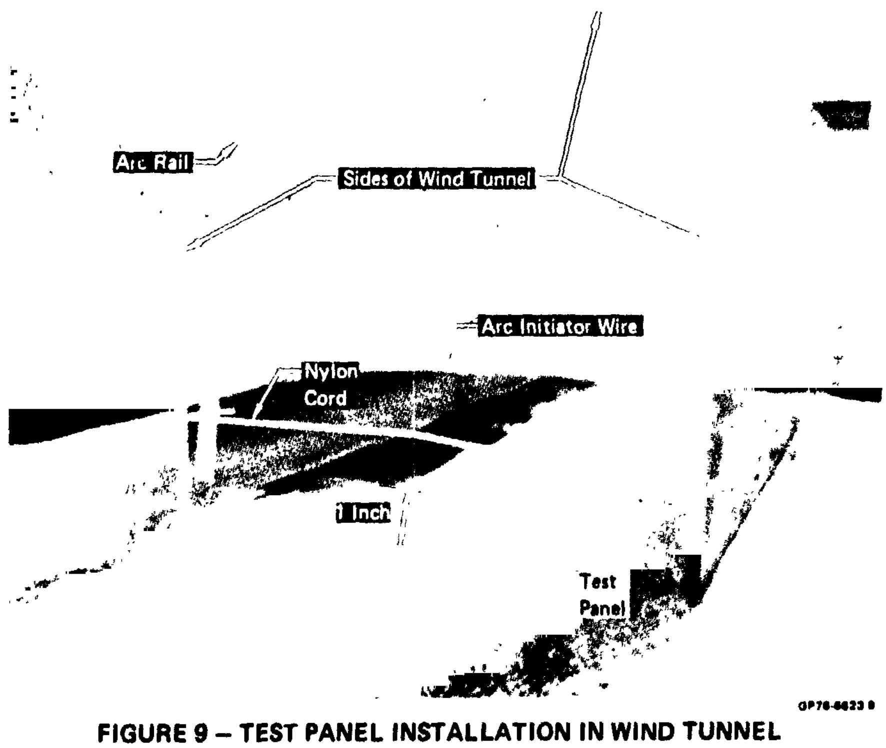

FIGURE 9 – TEST PANEL INSTALLATION IN WIND TUNNEL
(Prior to Test)

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Because the various portions of the complete lightning current waveform vary widely in both magnitude and time, several different instruments were required to accurately record all phases. In addition, all instrumentation was electrically isolated to prevent erroneous readings because of ground loops. The return stroke surge current was measured using a Pearson wide band pulse current transformer and monitored on a Tektronix 485 oscilliscope. The intermediate current and continuing current portions of the lightning waveform were measured using a T&M Research Company coaxial current shunt. These two portions were recorded on the two different sweeps of a dual beam Tektronix 555 Oscilloscope. Each beam was separately driven with different vertical amplitudes and time bases. All three time bases were triggered simulataneously. A comparison of the NASA simplified idealized 2nd return stroke waveform and the various portions of the actual typical test waveform are shown in Figure 10. It should be noted that the idealized model waveform is not to scale either vertically or horizontally whereas the oscilloscope waveforms are linear on both axes. Close examination of the intermediate current and continuing current oscilloscope waveforms reveals the corresponding points on the two traces.

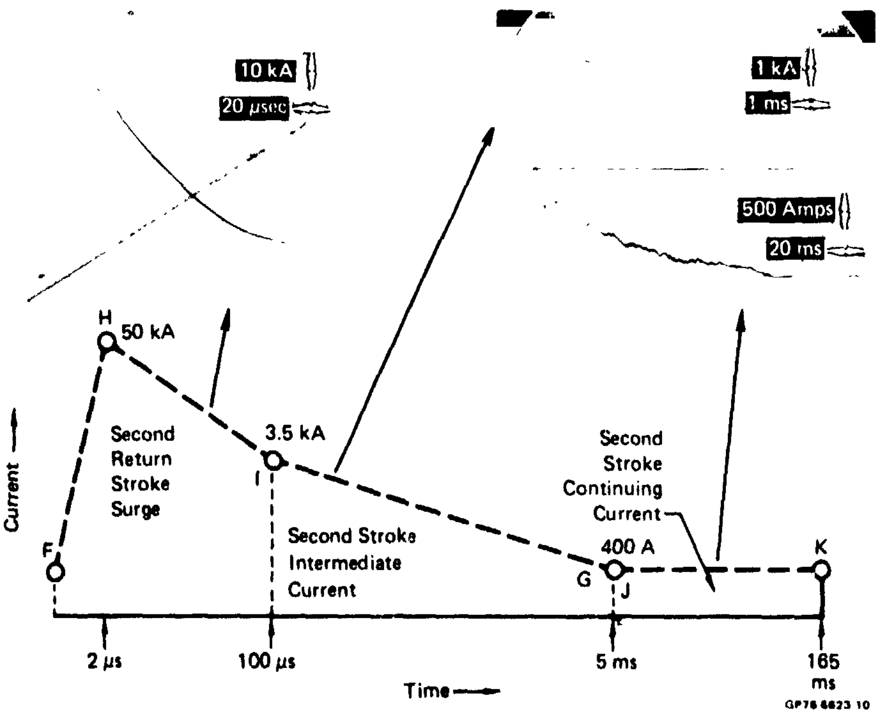

FIGURE 10 – COMPARISON OF NASA WAVEFORM AND ACTUAL TEST WAVEFORM

Still cameras equipped with filters were used to photograph the arc on Polaroid film. The optical filters greatly attenuated the arc brillance, allowing good optical definition of the main arc movement, but it masked out lower luminance activity. The cameras were opened prior to the test and remained open during the entire test. The tests were also visually monitored.

Test Procedure

In general, each test panel was mounted in the test setup and subjected to the lightning current shown in Figure 10 unless noted otherwise in the Test Results. Photos and current waveforms were taken during the strikes. Some panels were struck more than once to note damage progression.

Test Results and Discussion

Each of the panels was subjected to the lightning current waveform shown in Figure 10. Note that both amplitude and time scales are non-linear in this figure. The results of these simulated lightning strikes are tabulated in Table 2 and photos of all tests panels were taken. A typical tested panel is shown in Figure 11. Damage to this panel after several repeated strikes is shown in Figure 12. In general, the panels having relatively low electrical resistance paint were tested sucessfully, whereas those having a high resistance received only a portion or none of the intended lightning current. The elctrical resistance of the conductive strips typically increased as a result of the lightning strike; some panels only showed slight increases in resistance whereas the very low resistance paints increased more than three orders of magnitude. On some panels, the reasons for the increase was obviously erosion or cracking in the conductive paint, but on other panels, the reasons were not readily apparent.

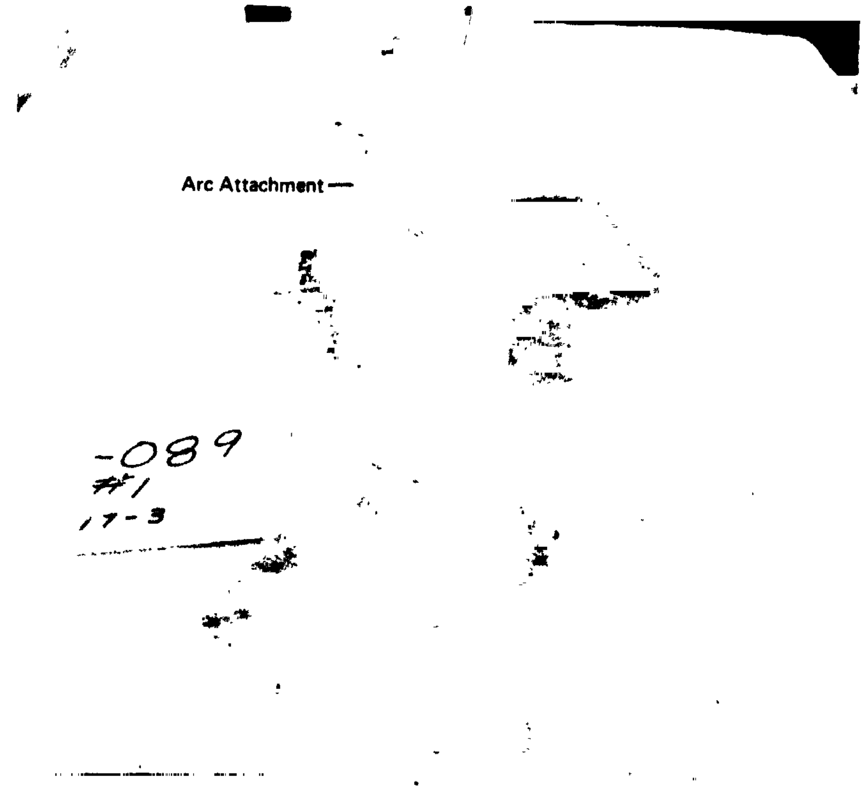

FIGURE 11 – PANEL 089 AFTER FIRST LIGHTNING TEST

TABLE 2 – TEST RESULTS

Panel #	Res Before	Res After	Notes:
090 #2	0.32Ω	33kΩ	Discolored paint, removed quarter size hole of paint and CPR 421 at strike point; removed paint and CPR 421 at edge of panel inside wind tunnel; conductive path severed at opposite end of panel. (Shortest electrical path inside wind tunnel).
079 #1	135Ω	19Ω	No damage at strike point; track visible in paint. Removed paint and CPR 421 at edge of panel inside wind tunnel. Conductive path severed at opposite end of panel (cracked at CPR 421 seam). (Shortest electrical path inside wind tunnel.)
099 #1	60Ω	178Ω	No damage at strike point; some cracking in paint at CPR 421 seams at downwind end of panel; some aluminum burned away at paint attachment to aluminum.
080 #1	25.2kΩ	35.4kΩ	Small amount of current into panel; burned 2.5 cm (1") off end of trigger wire. Slight burn marks at end of panel; no other visible damage.
080 #1	35.4kΩ	35.4kΩ	No current to panel; trigger wire 1.3 cm off panel – no damage. Camera lens opening increased
089 #1	204Ω	220Ω	Prefired while charging capacitor banks. Trigger wire 1.3 cm off panel. No visible damage; visible arc path in paint.
089 #2	194Ω	210Ω	No damage to conductive paint or CPR 421. Some aluminum burned at downwind end at paint/aluminum interface.
109 #1	82Ω	85.6Ω	No damage to conductive paint or CPR 421 Aluminum panel edge burned.
109 #2	91.4Ω	95.3Ω	No damage to conductive paint or CPR 421. Aluminum burned at edge of paint/aluminum interface.
079 #2	140Ω	174Ω	No damage at initiation point. Dime size chips of paint removed 25 cm aft of strike at edge of paint. Cracking in paint at edge of panel. Aluminum panel burned in several places at or near paint/aluminum interface.
090 #1	0.26Ω	Open	Quarter sized divot of paint and CPR 421 removed at strike point. Paint discolor in both directions from strike. Aluminum burned at downwind end at paint/aluminum interface.

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TABLE 2 – TEST RESULTS (Cont)

Panel #	Res. Before	Res. After	Notes:
080 #2	22kΩ	28.4kΩ	Only small amount of current into panel no visible damage to panel. Burned 2.5 cm off end of trigger wire.
100 #1	5.7kΩ	5.7kΩ	Would not fire to test panel. Trigger wire intact.
100 #1	5.7kΩ	8.55kΩ	Decreased trigger wire gap to 1.3 cm off panel. Two explosive sounds approx. 1/2 second apart. Flame burned briefly at trailing edge of panel. No damage to panel at strike; cracks and burned paint at edge of panel. Several burned aluminum spots at end of panel.
100 #2	6.2kΩ	11kΩ	Some current into panel but not enough to melt trigger wire. No damage at strike Arc tracks and some charring at end of panel.
079 #2	171Ω	251Ω	Second test of this panel. Paint and CPR 421 coming loose at strike point. Several square inches of paint and CRP 421 removed aft of strike; cracking and peeling of paint at trailing edge.
089 #1	220Ω	232Ω	Second test on this panel. Dime size divot removed few inches from strike point, additional cracking halfway to trailing edge; paint chipping and cracking at trailing edge of CPR 421. Panel generally still good.
089 #1	232Ω	256Ω	Third test on this panel. Additional cracking and material removal at same locations as observed on previous shot. Panel still appears in reasonable shape.
089 #1	256Ω	457Ω	Fourth test on this panel. 7.6 cm (3") diameter hole blown in CPR 421 and 0.48 cm (3/16") diameter hole melted thru aluminum. This hole is approximately 10 cm aft of strike point. See Figure 12.
099 #2	55.4Ω	2.8kΩ	No damage at strike point or along top of panel. Crack in paint at top forward edge of panel upwind end. Crack in paint at trailing edge at junction of two layers of CPR 421.

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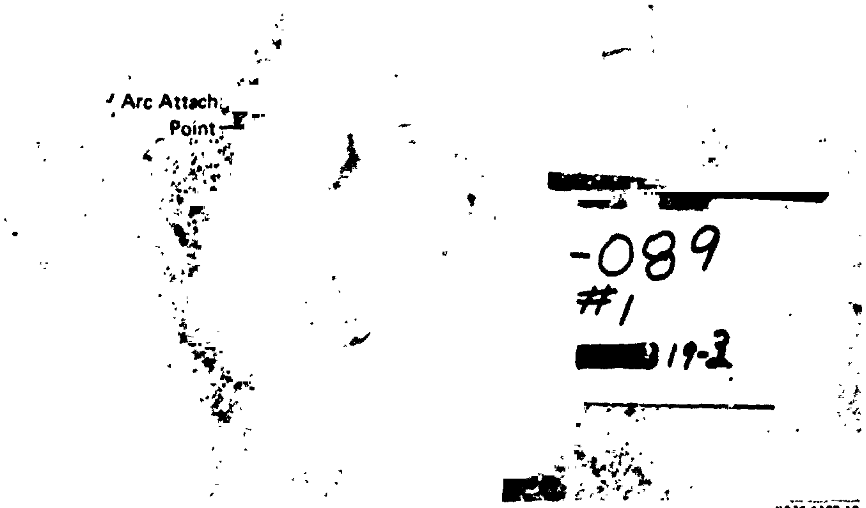

FIGURE 12 – PANEL 089 AFTER FOURTH LIGHTNING TEST

In general, it appears that the Electrodag 501 and Eccocoat SEC painted panels survived the lightning strikes the best. The low resistance silver-filled paint (Electrodag 504) performed less effectively than the moderate resistance paints because more of the current was carried by the paint rather than the ionized air channel above the paint. Consequently, the paint strip essentially exploded causing some damage to the surface of the TPS.

As a result of these tests, it appears that the initial current into the various paint strips locally heats a conductive path in the paint to the vaporization point and then the majority of the lightning current is conducted in the ionized gases above the paint. This condition is verified because the magnitude of the lightning current was relatively independent of the electrical resistance of the paint up to a certain value. The lightning current would not establish an ionized path in the panels utilizing the high resistance paints, i.e., the initial current into the test panel was limited by the high resistance of the paint and the available output voltage. For example, Panel 080 No. 1 had an initial resistance of 25KΩ, thus the maximum initial current into the paint would be limited to approximately $75\ kV/25K\Omega = 3$ amperes. Apparently three amperes were not sufficient to vaporize the paint. However, it should be noted that the high resistance paints appear to be more easily degraded by current flow as evidenced on some tests; the current into the paint strip, although not sufficient to vaporize very thin (32 ga) copper wire, caused a large resistance change. The conclusion that most of the lightning current is conducted in the ionized gases above the paint is also indicated by the fact that Panels 090 No. 2 and 079 No. 1 suffered severe damage only in the confined areas at the end of the panel inside of and butted to the wind tunnel. The explosive pressures in the gases probably caused the damage to occur to the TPS.

On most of the panels which appeared to test properly, a burning or eroding of the aluminum substrate occurred at the trailing edge (down wind) of the panel. In some cases, the burning occurred some distance to the side of the conductive paint strip attachment to the aluminum substrate. Inspection of the still photos appears to indicate the arc on the upper rail probably was not moving at the wind tunnel velocity 3 meters per second as is commonly seen in similar tests at higher wind velocities. Photographs similar to that shown in Figure 7 indicate that in addition to the many secondary attachments along the path length that a final arc appears to be established from the arc rail to the trailing edge of the panel thru the ionized plasma produced by the exploding paints rather than the original arc moving slowly with the air stream. This cannot be verified at this time because high-speed movies of the actual arc travel were not taken.

The tests reveal that certain of the tested paints would survive several lightning strikes provided that the attachment to the aluminum substrate is improved so that explosive pressures are not allowed to occur in these areas. In addition, it is obvious that the most severe test of the paint system is the high peak current pulse and not the later continuing current. Therefore, if a portion of the continuing current were diverted, the difference in the results of the test would probably be negligible.

Conclusions and Recommendations

Based upon the results of these tests, it is concluded tnat 10 cm (4 inch) wide, 0.25 or 0.51 cm (10 or 20 mil) thick coatings of Eccocoat SEC or Electrodag 501 could be used as lightning diverters over CPR 421 Thermal Protection System (TPS) material providing that adequate techniques for the attachment of the paints to a substrate material can be demonstrated.

It is recommended that additional design and testing be accomplished to determine the maximum allowable distance between attachment points (grounding points) and the method of attachment to the substrate. This test essentially demonstrated the capacity of the conductive strip to conduct the high-current pulse without damaging the TPS. Additional tests and/or analyses are needed to evaluate the stress on the TPS resulting from inductive and resistive voltage drops along realistic lengths of diverter strips.

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