Electrostatic Evaluation of the ARES I FTS Antenna Materials

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Written by:
Michael D. Hogue, Ph.D., NASA, NE-S-1
Carlos I. Calle, Ph.D., NASA, NE-S-1

Approved by:
Carlos I. Calle, Ph.D., NASA, NE-S-1

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List of Acronyms

KSC Kennedy Space Center

ESPL Electrostatics and Surface Physics Laboratory, NE-S-1, Kennedy Space Center

FTS Flight Termination System

RF Radio Frequency

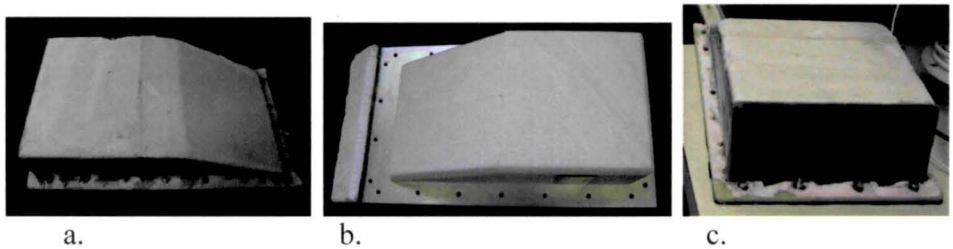
USAF United States Air Force

HV High Voltage

USA United Space Alliance, Corp. Kennedy Space Center

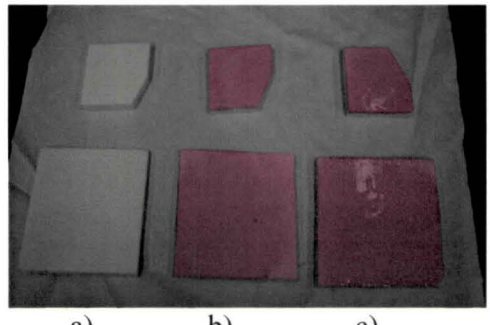
1.0 Background

The Electrostatics and Surface Physics Laboratory was asked by USA and ATK engineering to evaluate whether ice crystal tribocharging on the Ares I FTS antenna housing during launch could cause damage to the antenna. The concern is that electrostatic discharge (ESD) can either make the antenna non-functional or the RF output of an ESD event may interfere with signals to the antenna. An FTS antenna and its housing assembly were provided to the ESPL for evaluation. The housing is shown in Fig. 1. The housing consists of a white foam (SLA-220) outer layer over a fiberglass frame with a phenolic piece on the vertical downstream portion of the antenna. Inside, the four vane FTS antenna is enclosed with a rigid, pink Eccofoam. Also, bare, primed with DC-1200 primer, and primed and coated with Sylgard 186.3 samples of the SLA-220 foam were provided for testing. These foam samples are shown in Fig. 2.



a. b. c.

Figure 1. a) FTS antenna exterior showing the white SLA-220 foam. b) FTS antenna with outter SLA-220/fiberglass cover removed showing the rigid Eccofoam. c) Rear view of FTS antenna outer housing showing the phenolic rear cap.



a) b) c)

Figure 2. Samples of the SLA-220 foam. a) Bare, b) With DC-1200 primer, c) With DC-1200 primer and Sylgard 186.3 overcoat.

Testing on these materials consisted of surface and volume resistivity measurements, charge decay measurements, dielectric breakdown tests, and testing with a simulated triboelectric surface charge on the housing. To determine the magnitude of charge that could develop on the housing exterior, data from a U.S. Air Force study were used [3].

2.0 Air Force Ice Crystal Triboelectric Charging Data

In 1973, the Stanford Research Institute, under contract with the Air Force Avionics Laboratory, conducted an extensive study on the evaluation of induced noise mechanisms on high speed aircraft [3]. The study found that the primary source of vehicle-induced interference noise was caused by triboelectrically generated discharges. Since, due to its limited funding, the performance of actual experiments to determine the level of triboelectric charge generation on Ares I component materials with ice particle impact was beyond the scope of this project, we decided to use the Air Force data as the basis for our experiments.

For the Air Force study, sensors and electronic instrumentation to measure and record electrostatics charging due to ice crystal impacts were installed on a supersonic F-4D Phantom II aircraft. A total of eight sensors were installed on the aircraft. Four electrically isolated aluminum patches located on the radome of the aircraft were connected to current meters to monitor triboelectrically generated charge buildup. An electrometer to measure charge build up was installed on the outside of the left forward windshield to measure electrostatic charge buildup at this location. An induction probe was installed on the inside of the windshield to monitor streamer discharges. A field electrometer to measure aircraft potential was placed facing a hole in the belly of the instrumentation pod, a cylindrical metal container located below the aircraft. Finally, an electrometer sensor was installed in a region of undisturbed air below the nose of the aircraft to measure the charge and count the precipitation particles encountered as the aircraft flew through ice clouds.

To determine the way in which aerodynamics affect triboelectric charging, the four aluminum patches were installed along the aerodynamic contour of the nose radome of the aircraft. The patches were located at the 0, 30, 60, and 90 cm from the aircraft nose. The patches were fabricated from a 127 micrometers (5 mils) thick bare aluminum sheet and attached to the aircraft surface with epoxy polyamide adhesive. The patches, ranging in areas from 35 cm^2 to 60 cm^2, were surrounded by a guard ring to prevent any accumulation of charge from the surrounding radome.

Since the windshield of the aircraft is a large dielectric, charge generated on its surface will accumulate there until the surface electric fields become large enough to support streamer discharge across the surface. The induction sensor mounted on the inner surface of the windshield measured those discharges.

Due to the uncertainty in the ice cloud conditions through which the aircraft flew, the great majority of the data was collected during two flights, on December 30 and 31, 1970. On December 30, ice clouds were encountered from 15,000 to 30,000 ft in altitude and the aircraft flew at Mach 1.2 and 1.6. On December 31, the ice clouds were encountered at an altitude of 35,000 ft and the aircraft was flown at Mach 1.9.

The sensor that would best approximate the geometry of the Ares I rocket was the windshield electrometer. Unfortunately, brush discharges to the metal frame of the windshield periodically depleted any charge accumulated on the windshield. The configuration of the Ares I antenna assembly does not include any exposed metals in the vicinity and the windshield data could not be used.

Since the windshield sensor data was unusable, we decided that the Patch two location would provide us with a rough approximation to the Ares I antenna configuration. Since the December 30, 1970 flights encountered ice clouds at altitudes from 15,000 to 30,000 feet, we chose the Mach 1.6 data from that day as the basis for our tests. We stress that the use of this data is only to obtain a rough idea of the possible charging levels on the antenna housing. Thus, this study is only preliminary and provides us with a methodology to be used when actual data from a representative location can be obtained in the future.

3.0 Surface and Volume Resistivity Tests

The first series of tests that the Electrostatics and Surface Physics Laboratory performs to evaluate the electrostatic properties of a material surface resistance. Surface resistance measurements are the main test method used in industry to characterize the ESD properties of materials, since it is believed that charge deposited onto the surface of a material will "leave" (or decay) easier from a material with lower surface resistance than from a material with high surface resistance. Surface resistance is the ratio of the DC voltage to the current flowing between two electrodes of specified configuration that contact the same side of the material and is expressed in ohms (Ω). Volume resistance is the electrical resistance through the material and is expressed in ohm-cm (Ω-cm). Except for ambient humidity, the surface and volume resistivity tests are performed per the requirements of the ESD Association Standard Test Method ESD STM11.11 (surface) [1] and ESD Association Standard Test Method ESD STM 11.12-2000 (volume) [2]. These measurements are taken using a Prostat PRS-801 resistance system with a Prostat PRF-911 concentric ring resistance probe.

The tests require a five pound weight on top of concentric cylindrical electrodes and were conducted at ambient humidity conditions (~ 45% RH). Materials with a surface resistance less than 10^4 Ω are considered conductive. Materials between 10^4 Ω and 10^{11} Ω are statically dissipative and materials with a surface resistance above 10^{11} Ω are insulating according to ANSI/ESD standards. Materials with a volume resistivity less than 10^4 Ω-cm are conductive. Materials with a volume resistivity in the range 10^4 – 10^{11} Ω-cm are static dissipative while materials with a volume resistivity above 10^{11} Ω-cm are insulating. Raw surface and volume resistance values are reported as well as the surface and volume resistivity. Surface resistivity is calculated by multiplying the surface resistance by a factor of 10 which comes from the geometry of the PRF-911 concentric rings. Volume resistivity is calculated by the equation

$$\rho_V = (A/t)\, R_M.$$

A is the surface area of the probe, t is the material thickness, and R_M is the resistance measured by the Prostat meter. For the PRF-911 probe, $A = 6.9$ cm^2.

Materials tested were the bare SLA-220 foam, the SLA-220 foam coated with DC-1200 primer, SLA-220 foam coated with DC-1200 primer and Slygard 186.3, Eccofoam, as received housing SLA-220 foam, and the phenolic housing end cap. Surface resistivity test results are summarized in Table 1 and volume resistivity test results are summarized in Table 2. All materials are

insulating and under triboelectrification they should develop and maintain a surface charge density.

Table 1. Surface Resistivity Test Results of FTS Antenna Housing Materials

Material	Average R_S (TΩ)	Average ρ_S (TΩ/□)
SLA-220 (Bare)	2.01	20.1
SLA-220 (DC-1200 Primer)	3.66	36.6
SLA-220 (DC-1200 Primer + Slygard 186.3)	2.24	22.4
Eccofoam	1.74	17.4
Housing Foam (SLA-220)	2.17	21.7
Phenolic	0.244	2.44

Table 2. Volume Resistivity Test Results of FTS Antenna Housing Materials

Material	Average R_V (TΩ)	Average ρ_V (Ω - cm)
SLA-220 (Bare)	5.90	6.36×10^{13}
SLA-220 (DC-1200 Primer)	14.60	1.57×10^{14}
SLA-220 (DC-1200 Primer + Slygard 186.3)	6.16	6.07×10^{13}
Eccofoam	4.51	2.59×10^{13}
Housing Foam (SLA-220)	N/A	N/A
Phenolic	N/A	N/A

4.0 Determination of Charge on FTS Antenna Due to Surface Potentials

Experiments were performed to determine how much voltage an exterior surface charge density on the FTS antenna housing will induce on the electrically floating antenna vanes. A square Aluminum plate (approximately 5.0 in × 5.0 in × 0.125 in), attached to a HV power supply, was used to model an exterior electrostatic charge density caused by triboelectrification. Two test locations on the FTS antenna housing were used. The test positions were the top flat portion of the housing (location 1) and the slanted, forward facing, portion of the housing (location 2). Fig. 3 shows a schematic of the test set-up.

The housing was modified to attach a wire to one of the four antenna vanes. This wire was then attached to an external electrically floating Aluminum plate positioned below the housing. This test set-up is shown in Fig. 4. A Trek high speed electrostatic voltmeter was used to measure the voltage on the sense plate as voltage was applied to the exterior source plate. The tests were performed in the ESPL's large vacuum chamber. Fig. 5 shows the applied voltage on the exterior Aluminum plate versus the measured voltage on the interior antenna vanes.

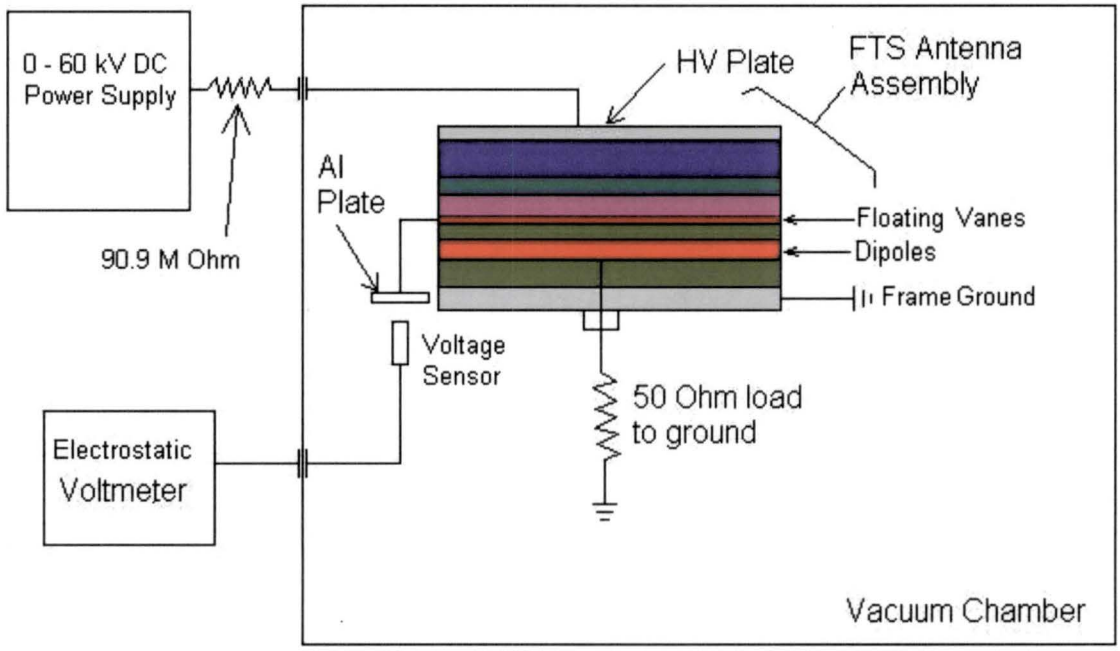


Figure 3. Ares I FTS Antenna Electrostatic Test Schematic.

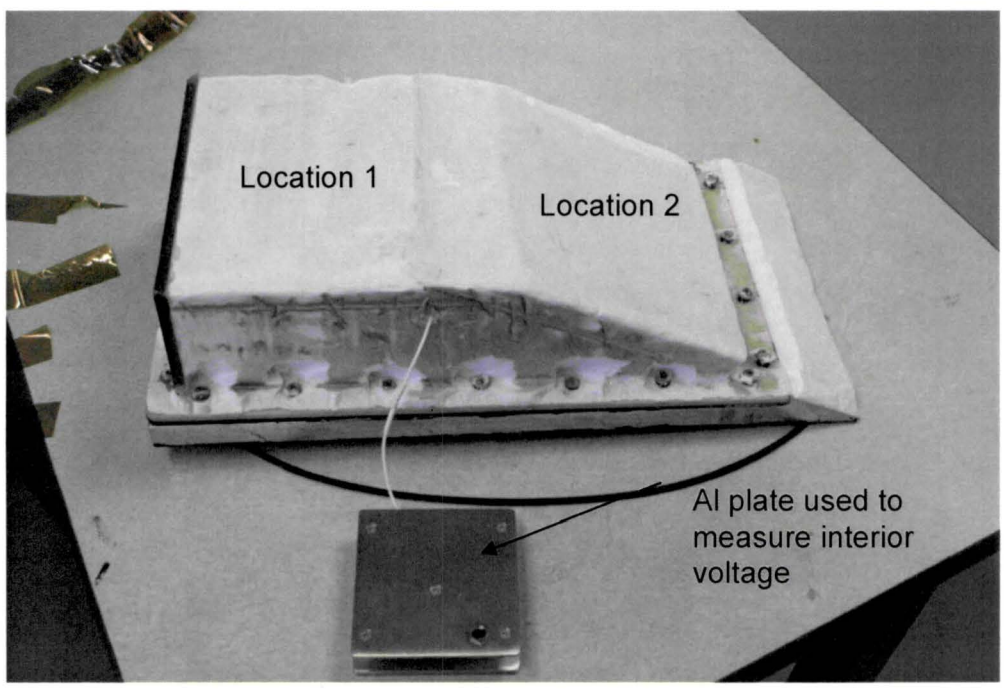


Figure 4. Test locations for the Aluminum plate used to model exterior surface charge on the Ares I FTS housing. Shows Aluminum plate used for interior voltage measurements.

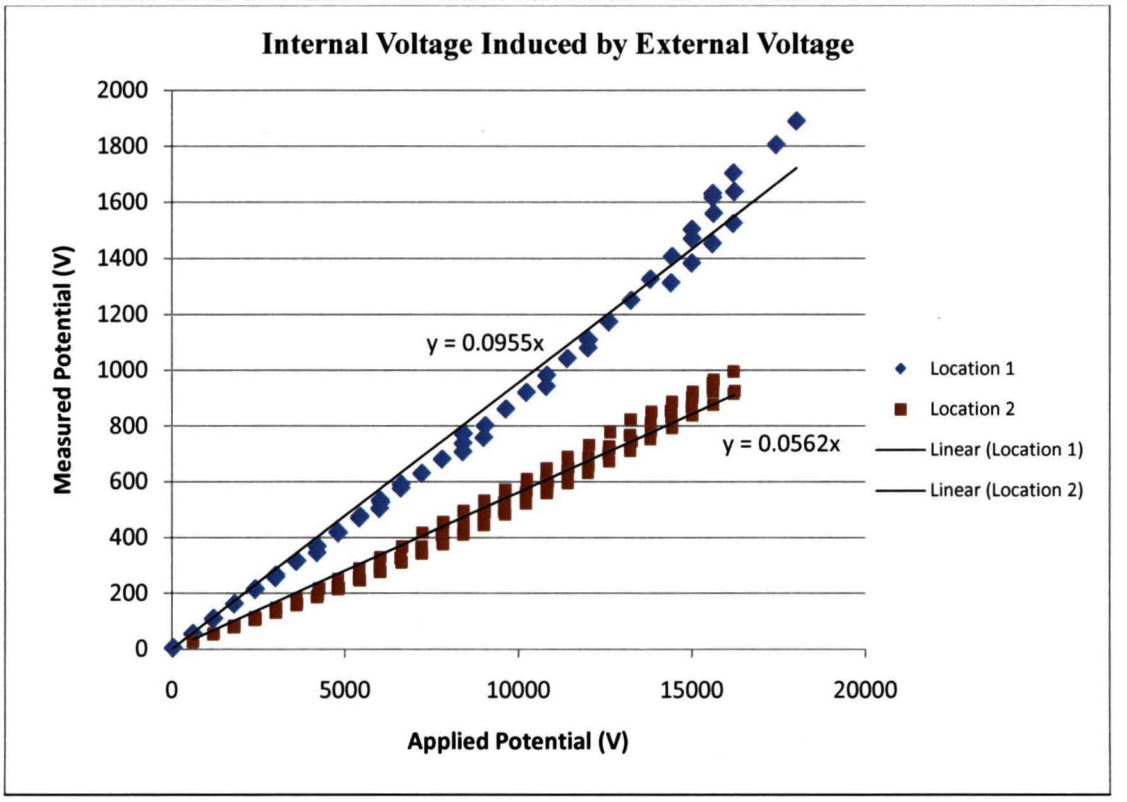


Figure 5. Measured voltage on the external Al plate versus the measured voltage on the internal antenna vane. Curve fits were calculated to get the slopes (correction factors).

The factors relating external voltage to internal induced voltage are ~ 0.1 for location 1 and ~ 0.06 for location 2. Since location 2 will receive most of the ice crystal impingement, 0.06 will be used for determining the worst case charge build-up on the vanes. Data from Patch 2 location from the 1.6 Mach flight of December 30, 1070 in the Air Force study [3] showed that the worst external charging due to ice crystal impingement was on the order of 10^5 V (100 kV). With this voltage applied to the external plate, the induced charge on the vanes will be on the order of 6000 V.

5.0 Vacuum Chamber Discharge Tests

Knowing the required voltage range to apply to the antenna vanes, the next step is to determine, at the different significant atmospheric pressures, whether or not sparking would occur. Fig. 6 shows the experimental set up for this test.

At the test pressure, voltage on the vane with the HV lead was slowly increased until a discharge was recorded As can be seen in Fig. 7, the range of discharge voltages are lower for lower pressures which is consistent with Paschen's curve [4] for sparking voltage versus pressure. A similar test was run where the voltage was raised until a visible discharge was observed, which

was at a higher potential as was expected. This voltage threshold was recorded at the same three atmospheric pressures and plotted in Fig. 8.

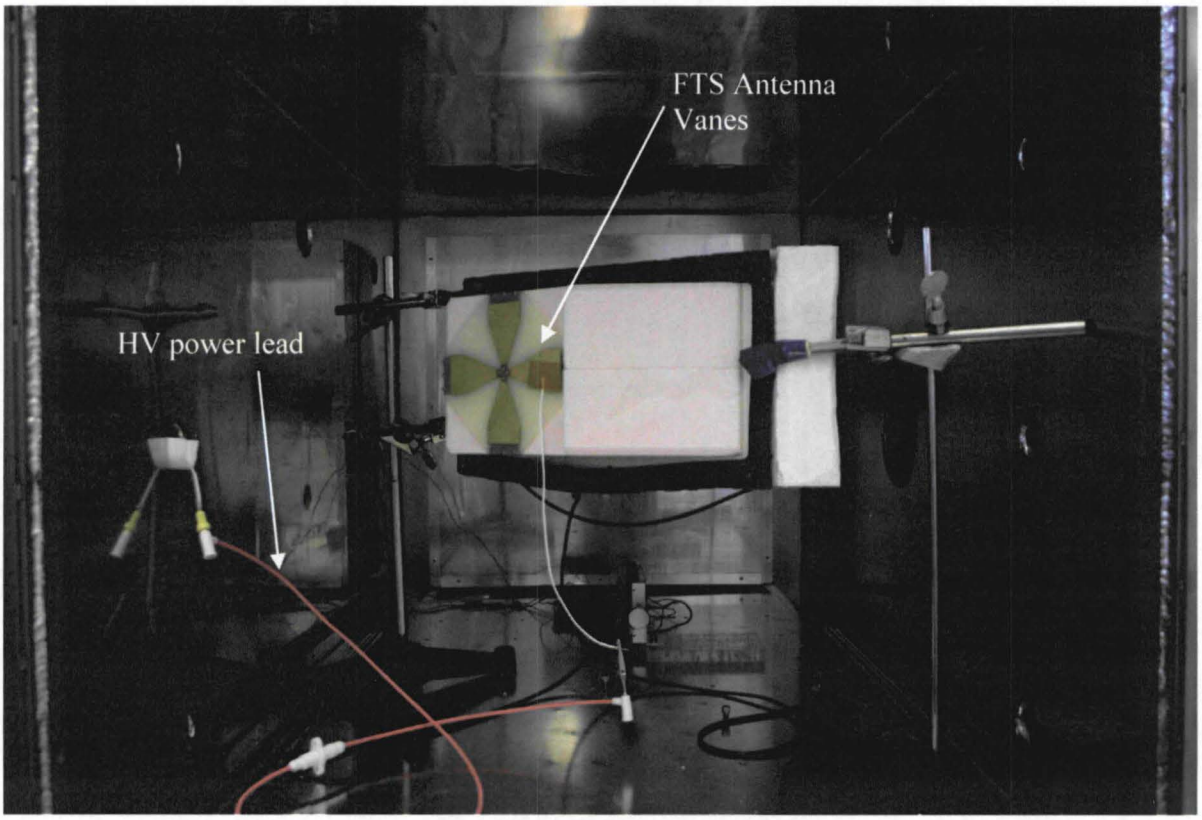


Figure 6. Test set-up inside the ESPL high vacuum chamber that was used to apply voltage directly to antenna vane modeling induced charge from external triboelectric charging.

Tests were run at 760, 480, and 88 Torr, the atmospheric pressure values for sea level and the upper and lower boundaries of the interested flight path. The voltage was turned progressively higher until an electrostatic discharge sensor (EMeye by Credence Technologies, Inc.) recorded a hit. The voltage where the hit occurred was recorded and the data was compiled to show where the lowest set of electrostatic discharges occurred, seen in Figs. 7 and 8.

At the 6000 V level, several visible discharges were noted between the energized vane and the nearest center screw head. An example of this discharge is shown in Fig. 9. Many discharges of this magnitude were generated in the course of this testing and resulted in only superficial damage to the outer edge of one of the vanes. This superficial damage is shown in Fig. 10.

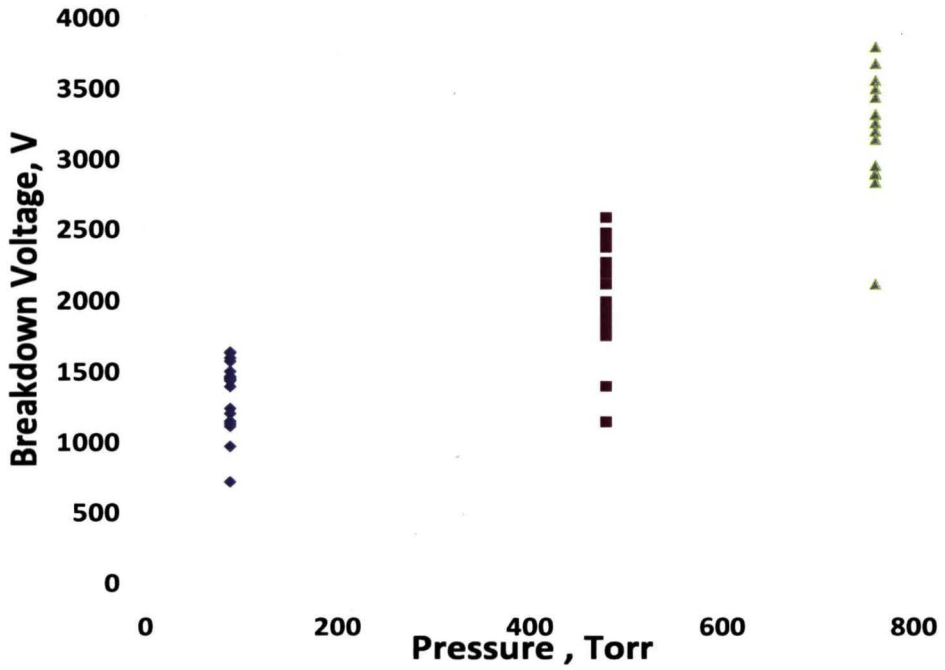


Figure 7. Breakdown voltage as a function of atmospheric pressure, based on an electrostatic discharge sensor.

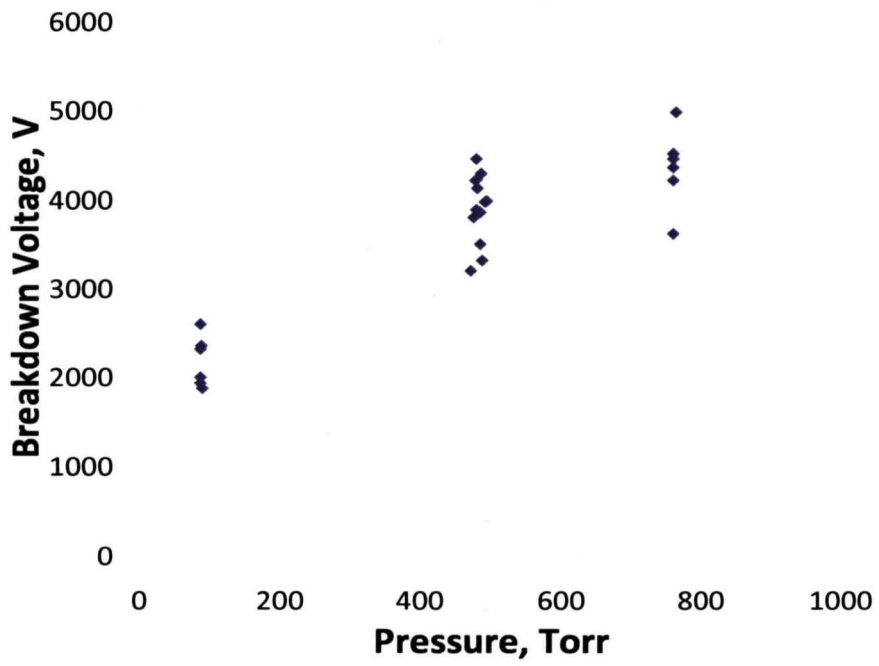


Figure 8. Breakdown voltage as a function of atmospheric pressure based on visual observations.

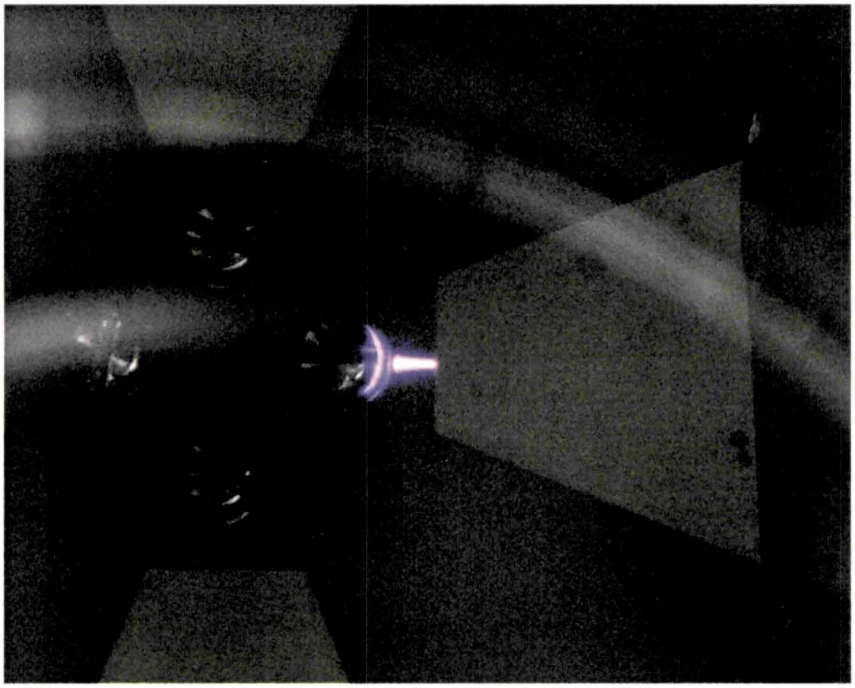


Figure 9. Electrostatic discharge between an FTS antenna vane at ~ 6 kV and a grounded center screw head.

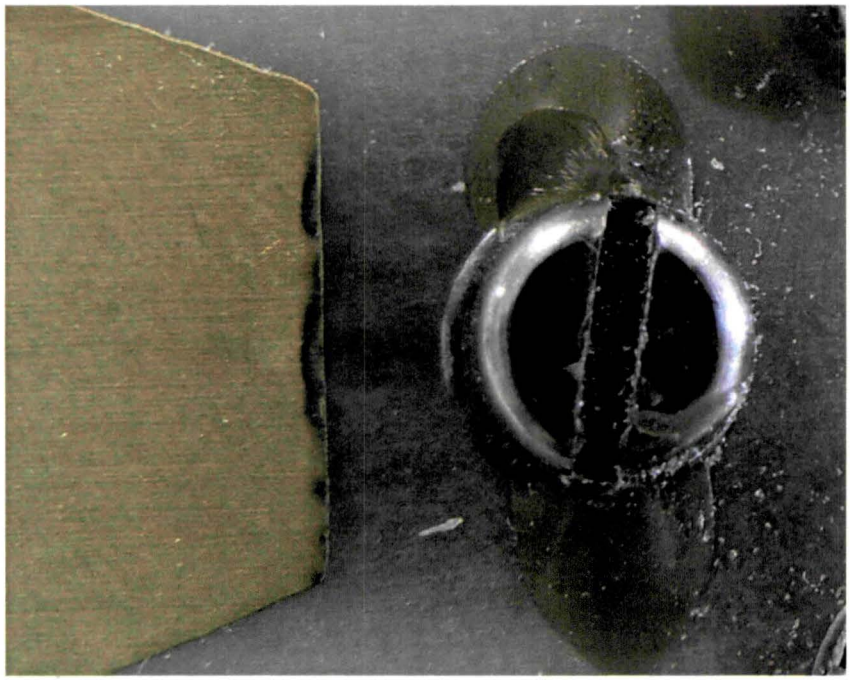


Figure 10. Superficial damage to an FTS antenna vane edge due to repeated electrostatic discharges in the 6 kV range.

For both sets of data, the relationship between decreased pressure leading to decreased threshold was anticipated due to the Paschen's law and having a set distance between the two points where discharge is occurring. Knowing that it was possible for the UHF antenna array to spark, under the estimated worst case conditions; the need arose to determine the characteristics of the discharge events. This information could be very vital to understanding possible damages to any of the communications equipment or any effects on signals being sent or received. Using an oscilloscope attached to the antenna output allowed analysis of the lower threshold discharges; primarily those invisible discharges observed using the EM Eye. While recording the potential going through the antenna in real time, the discharges were observed and recorded. Various configurations of the test were used from adding a 50Ω load and or a lightning stub to the antenna output. From this raw data, the peak-to-peak voltage and, more importantly, a Fast Fourier Transform (referred to as a FFT) analysis were performed, which determined the strengths of the radio-frequency noise created by the discharge.

6.0 Dielectric Breakdown Tests

Dielectric breakdown of the FTS antenna housing materials was measured using a Hypotronics 7100-SD149-P-B dielectric breakdown tester. This device can generate up to 100,000 volts and can measure the voltage necessary to penetrate dielectric materials. The layers between the exterior of the housing and the antenna vanes consist of the SLA-220 foam, fiberglass, and the Eccofoam. On the rear of the housing exterior is the phenolic cap. Test samples of these materials were cut. The phenolic and fiberglass samples were fairly thick and had to be milled thinner due to their large electrical resistance. All tests were performed in ambient conditions. At least three tests per material were performed and averages recorded. Dielectric breakdown tests are summarized in Table 3.

Table 3. Dielectric Breakdown Results for FTS Antenna Housing Materials

Material	Average V_{BD} (V/mil)
Eccofoam	62.59
SLA-220	37.51
SLA-220 w/ DC-1200 primer	37.43
SLA-220 w/ DC-1200 primer & Slygard 186.3	58.23
Fiberglass	458.68
Phenolic	387.25

From measurements of the thickness of the layers between the exterior of the housing and the floating antenna vanes gives 0.28 inch for the primed and coated SLA-220, ~ 0.25 inch for the fiberglass, and 0.39 inch for the Eccofoam. With the breakdown values from Table 3, a total electrical breakdown resistance from the exterior foam to the antenna vanes of about 155 kV is calculated. At sea level, air will ionize around 30 kV thus mitigating the surface charge and preventing this level (150 kV) of external voltage from occurring. Per Paschen's law [4], as the pressure is lowered, the discharge voltage gets lower so even at higher altitudes (in the range of

ice crystal impingement) such surface potentials are not possible. Using the values for the end cap materials (fiberglass ~ 0.25 inch, phenolic ~ 0.25 inch) gives a breakdown voltage of about 212 kV. Again this voltage cannot be attained due to air ionization.

7.0 Discussion and Conclusions

Surface resistivity and volume resistivity data show all the tested non-metallic materials of the Ares I FTS antenna assembly to be insulative. The external materials (White foam, phenolic) should be able to develop a large surface charge density upon tribocharging with ice crystal impingement.

Dielectric breakdown tests on the FTS antenna housing materials show that each of the insulative materials are very resistive to electrical breakdown. The thicknesses of these materials in a nominal housing should protect the antenna from direct breakdown from external triboelectric charging potentials.

Per data from the Air Force study, a maximum external electric potential in the range of 100kV can be developed on surfaces tribocharged by ice crystal impingement. Testing showed that under operational pressure ranges, this level of exterior voltage can result in a potential of about 6 kV induced on the electrically floating interior antenna vanes. Testing the vanes up to this voltage level showed that electrostatic discharges can occur between the electrically floating vanes and the center, grounded screw heads. Repeated tests with multiple invisible and visible discharges caused only superficial physical damage to the vanes. Fourier analysis of the discharge signals showed that the frequency range of credible discharges would not interfere with the nominal operation of the FTS antenna.

However, due to the limited scope, short timetable, and limited funding of this study, a direct measurement of the triboelectric charge that could be generated on the Ares I antenna housing when the rocket traverses an ice cloud at supersonic speeds was not performed. Instead, data for the limited Air Force study [3] was used as input for our experiments.

The Air Force data used was not collected with a sensor located to provide us with the best approximation at the geometry of the Ares I rocket, namely that of the windshield electrometer, because brush discharges to the metal frame of the windshield periodically depleted any charge accumulated. The configuration of the Ares I antenna assembly does not include any exposed metals in the vicinity and the windshield data could not be used.

Since the windshield sensor data was unusable, we decided that the Patch 2 location would provide us with a rough approximation to the Ares I antenna configuration and would give us an indication of the possible charging levels that would develop. This was the data that we used in this study. Whether these charging levels would be of the same order of magnitude as the actual charges developed by the Ares I traversing a cloud with ice particles is at this point unknown. An actual experimental test, requiring the acquisition of additional instrumentation, is strongly advised before a final recommendation can be formulated regarding the safe levels of electrostatic charging on the antenna housing. Thus the results of this study should be considered to be preliminary.

Acknowledgements

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