N92-22369

EXPERIMENTAL BREAKDOWN OF SELECTED ANODIZED ALUMINUM SAMPLES IN DILUTE PLASMAS

Norman T. Grier and Stanley Domitz
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

ABSTRACT

Anodized aluminum samples representative of Space Station structural material were tested for electrical breakdown under space plasma conditions. In space, this potential arises across the insulating anodized coating when the spacecraft structure is driven to a negative bias relative to the external plasma potential due to plasma-surface interaction phenomena. For anodized materials used in the tests reported herein, it was found that break-down voltage varied from 100 volts to 2000 volts depending on the sample. The current in the arcs depended on the sample, the capacitor, and the voltage. The level of the arc currents varied from 60 to 1000 amperes. The plasma number density varied from $3x10^6$ to 10^3 ions per cc. The time between arcs increased as the number density was lowered. Corona testing of the anodized samples revealed that samples with higher corona inception voltage had higher arcing inception voltages. From this it is concluded that corona testing may provide a method of screening the samples.

INTRODUCTION

Anodized aluminum surfaces are proposed for use as the outer skin for many of the components on Space Station Freedom (SSF). These structural components are electrically connected to the negative terminal of the SSF solar array. The proposed operating voltage for the solar array is 160 volts. Due to the plasma-array interactions, the spacecraft structure is predicted from numerical simulations calculations to be driven to approximately 140 volts negatively with respect to the surrounding plasma potential. Since anodized aluminum is an insulator, the plasma-anodized-aluminum form a capacitor with the plasma and the aluminum forming the two electrodes. Thus, the anodized layer is expected to withstand a voltage of 140 volts during the spacecraft operations. Breakdowns of this thin anodized layer can initiate arcs with the current being supplied by the discharge of the large plasma-anodized-aluminum capacitor. The interaction of charged spacecraft surfaces with the space environment at low earth orbit has been the subject of many studies (references 1-8). The studies, however, are primarily focus on determining the current to the surface from plasma rather than the breakdown of insulators in plasmas.

Previous experiments at Marshall Space Flight Center (MSFC) have demonstrated that some anodized coatings breakdown and arc at voltages as low as 80 volts in plasma, causing very large currents in the circuit. (References 9 and 10.) This result was unexpected since "normal" arcs which occur at metal-insulator interfaces, are initiated at voltages greater than 200 volts and usually in the range of 300 to 1000 volts. The present experiments were performed to extend the measurements obtained at MSFC to other anodized aluminum samples. Samples tested here included two samples that were obtained from MSFC along with other samples. All the other samples had breakdown strengths greater than 200 volts. The two MSFC samples had breakdown strengths less than 200 volts. These results agree the those obtained at Marshall for these type of samples. The thermal and optical properties of the samples were not measured, therefore, the relative merits of one over the other for SSF thermal control purposes was not discerned.

There apparently are two type of arc sites, (1) virgin sites that are initiated during the breakdown process, and (2) repeating sites that are initiated at previous breakdown sites. Each type seem to have its own threshold voltage. It was expected that if arcs are initiated at previously arc sites, the threshold voltages at these sites would increase as the plasma number density is lowered. For the JSC and the SSF samples, this was found to be true. It is therefore concluded that the arcs occurring on these samples, mostly occur at previous breakdown sites. For the MSFC samples the arc inception voltage did not vary with density. It is concluded from this that each arc produced a new breakdown site. And due to the longer time for the anodized surfaces to become charged to the applied voltage, a lower density cause the arc rates to be reduced . The measurements were performed at number densities ranging from 3×10^3 to 3×10^6 e/cc.

It would be advantageous to perform bench tests of anodized samples that are predictive of their behavior in a plasma. Corona (partial discharge) testing is a nondestructive test that can usually predict insulator breakdown behavior when ordinary metallic electrodes are used. The corona inception voltage is always lower than breakdown voltage. Corona tests were performed on each of the samples used herein. A correlation between corona inception voltage and breakdown voltage was found.

EXPERIMENTAL TESTS

The tests were performed in the NASA LeRC vertical vacuum chamber, which was oil diffusion pumped to a base pressure of 2×10^{-7} torr. The plasma sources were an argon hollow cathode that are commonly used in ion thrusters and/or and two Penning type hot filament discharge chambers. When both sources were operated simultaneously, the plasma densities ranged from 1 to 3×10^{6} e/cc. To obtain lower densities, the hot filament Penning type chambers were used alone. These sources are controllable down to very low densities, and provided number densities from approximately 1000 to 3×10^5 electrons per cubic centimeter. The plasma density was measured using spherical Langmuir probes. The anodized aluminum samples were attached to an approximately 12-inch long Kapton coated wire pigtail which were in turn connected to the center conductor of a coaxial cables. A sketch of the experimental setup is shown in Figure 1. All the exposed edges and connections to the samples were covered to prevent breakdown and current collection in these areas. To test the integrity of the seal, the samples were biased from -200 to either +200 or +300 volts in a plasma and the current measured.

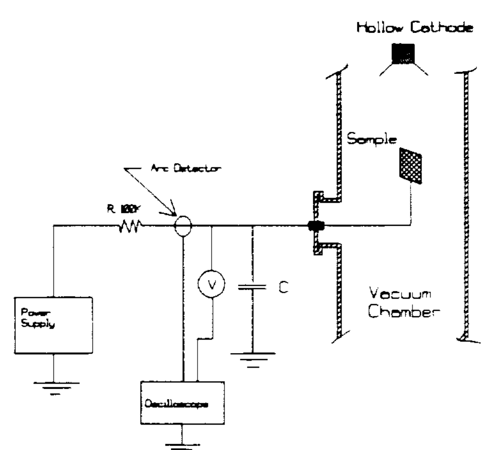

Figure 1 Test Setup

Table I Description of Samples Tested

Sample	Size	Electrolyte	Thickness, mils
MSFC-1	6x6 in	Chromic	0.20
MSFC-F	6x6 in	Chromic	0.20
JSC-1	3x3 in	Sulfuric	0.99
JSC-2	2x2 in	Sulfuric	0.20
JSC-3	6x6 in	Sulfuric	0.20
SSF-M1	3x3 in	Sulfuric	0.20

A typical test was initiated by introducing the argon plasma and applying a negative bias to the anodized sample until an arc occurred. The arc current was detected using a Pearson current transformer. The output was fed to one channel of a Hewlett Packard oscilloscope. The other channel of the oscilloscope received the signal from a Textronic 100:1 voltage probe, which was used to measured the voltage applied to the sample. The capacitors used in the circuit ranged from .25 µf to 100 µf. They were high voltage dry film type. All tests were performed at a plasma density of $2.5x10^6$ e/cc. To determine the effect of density on the arc inception voltage, additional tests were repeated using a capacitor of 25 µf at lower plasma densities.

Corona measurements were also made on each sample using a Biddle Partial Discharge Detector with a sensitivity of 1 picocoulomb. The corona measurements were made using a flat metal electrode to provide the electrical contact to the anodized layer. Realizing that plasma electrodes may perform differently than metal electrodes, attempts were made to perform the measurements using an electrolyte electrode, in this case salt water, as one of the electrodes. It was hoped that this would simulate the plasma as being one the electrodes. In some tests, these measurements were not useful since at times they indicated a corona inception voltages less than 20 volts less than the sensitivity of the instrument.

TEST SAMPLES

The test samples are listed in Table I. The two samples obtained from MSEC were used as a baseline for comparing test results. The SSF sample is a sample of one of anodized aluminum that is being considered for use by LeRC on SSF. Samples JSC-1, -2, and -3 were obtained from NASA Johnson Spaceflight Center (JSC) and were made from aluminum 5657 and used sulfuric acid as the electrolyte. These samples were pretreated for 20 seconds in bright-dip at 97°C, anodized in 20% H_2SO_4 and sealed in water at 95°. The two SSF samples were made of Type IIClass 1 aluminum 6061T6 and sulfuric acid was also used as the electrolyte. The anodization was done on these samples according to Mil Spec 8625-E.

TEST RESULTS

It was found that breakdown voltage of the anodized aluminum samples varied considerably in a plasma, from 100 volts to over 2000 volts. The maximum current varied from 60 to 1100 amperes. The current depended on the sample, the capacitance, and the applied voltage. Table II summarizes the tests the results. Figure 2 shows a typical oscilloscope trace obtained during an arc.
Results were complicated by the fact that two types of arc discharges can occur. One initiated by the breakdown of the anodized film and the other, the "normal"

Table II Test Results

Sample	Inception, V	IMAX, A	I*dt, Coul	C, μF	CV
MSFC-1	200	5	$1.81 x 10^{-4}$	5.0	$1.0 x 10^{-3}$
(6x6 in)	200	20	$4.13 x 10^{-3}$	20	$4 x 10^{-3}$
	120	25	$2.74 x 10^{-3}$	25	$3 x 10^{-3}$
	180	100	$1.10 x 10^{-2}$	100	$1.8 x 10^{-2}$
MSFC-F	200	110	$2.2 X 10^{-3}$	20	$4 X 10^{-3}$
(6x6 in)					
JSC-1	600	80	$6.0 x 10^{-4}$	0.25	$1.5 x 10^{-4}$
(3x3 in)	600	100	$1.0 x 10^{-3}$	0.5	$3.0 x 10^{-4}$
	500	350	$5.0 x 10^{-3}$	5	$2.5 x 10^{-3}$
	800	600	$9.0 x 10^{-3}$	10	$8.0 x 10^{-3}$
	600	500	$8.9 x 10^{-3}$	25	$1.5 x 10^{-2}$
	700	1100	$7.2 x 10^{-2}$	100	$7.o x 10^{-2}$
JSC-2	400	48	$4.6 x 10^{-4}$	0.5	$2.0 x 10^{-4}$
(2x2 in)	400	85	$9.2 x 10^{-4}$	1	$4.o x 10^{-4}$
	400	160	$2.9 x 10^{-3}$	5	$2.0 x 10^{-3}$
	400	206	$6.4 x 10^{-3}$	15	$6.0 x 10^{-3}$
	400	293	$1.8 x 10^{-2}$	45	$1.8 x 10^{-2}$
	400	400	$4.4 x 10^{-2}$	100	$4.0 x 10^{-2}$
JSC-3	300	38	$3.5 x 10^{-4}$	0.5	$1.5 x 10^{-4}$
(6x6 in)	300	57	$6.0 x 10^{-4}$	1.0	$3.0 x 10^{-4}$
	300	120	$2.1 x 10^{-3}$	5	$1.5 x 10^{-3}$
	300	183	$6.8 x 10^{-3}$	15	$4.5 x 10^{-3}$
	300	320	$1.7 x 10^{-3}$	45	$1.35 x 10^{-2}$
	300	400	$3.3 x 10^{-2}$	100	$3.0 x 10^{-2}$
SSF-M1	600	48	$5.9 x 10^{-4}$	0.5	$3.0 x 10^{-4}$
(3x3 in)	600	146	$1.4 x 10^{-3}$	1.0	$6.0 x 10^{-4}$
	600	233	$4.4 x 10^{-3}$	5	$3.0 x 10^{-3}$
	600	360	$1.3 x 10^{-2}$	15	$9,0 x 10^{-3}$
	600	533	$2.7 x 10^{-2}$	45	$2.7 x 10^{-2}$
	600	626	6.5x10-2	100	$6.0 x 10^{-2}$

type occurring at bare metal sites that have become exposed after breakdown. This latter type occurs at the junction of a metal-insulator interface when it is biased negatively relative to plasma potential. the breakdown voltage of these two types can be quite different. For example, for the JSC-1 sample the initial breakdown voltage was approximately 2000 volts. However, subsequent arcing occurred at approximately 600 volts at the now exposed metal site. As a result, the potential required for film breakdown could no longer be reached and only one hole appeared in the insulator.

On the other hand, for MSFC-1 and MSFC-2 samples, the film breakdown strengths were in the 100 to 200 voltage range. These voltages were not high enough for breakdowns to reoccur at ametal site. Each arc, created therefore, a new site. For other samples both types of breakdowns were in the same range, so

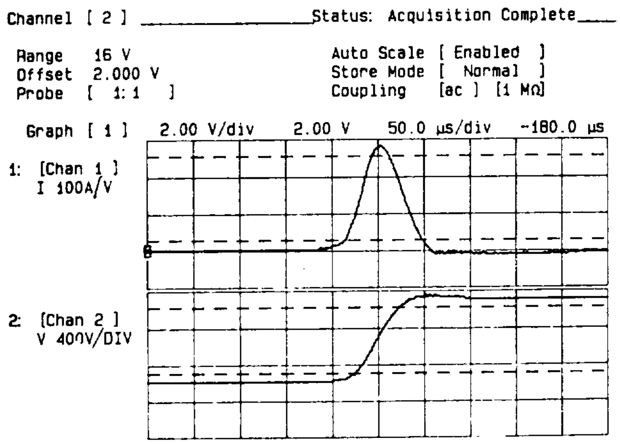

Figure 2. Typical oscilloscope traces.

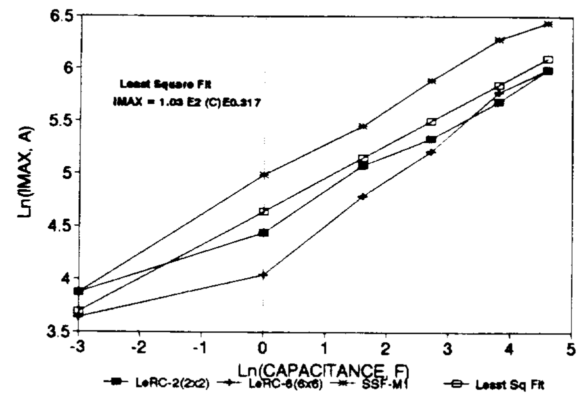

Figure 3. The logarithm of the maximum current as a function of log of capacitance, C.

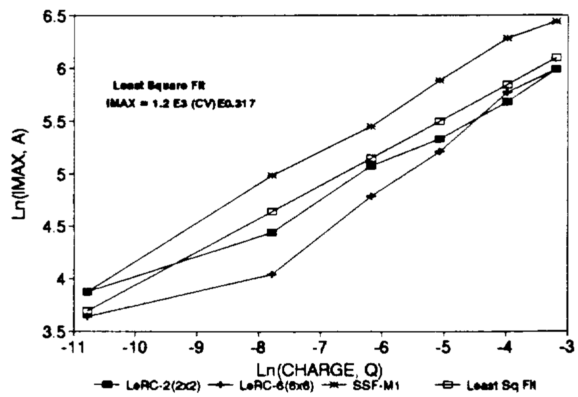

Figure 4. The logarithm of the maximum Current as a function of log of total charge, CV.

arcing occurred through both insulation breakdown and at bare metal sites. The maximum arc current depended on the capacitor size and the voltage reached at breakdown. Figures 3 and 4 show respectively the maximum current, I_{MAX}, as a function of the capacitance and the maximum current as a function of the total charge stored in the capacitor at discharge, CV. Both plots are log-log plots. The results indicate the maximum current varies as 0.317 power of either the capacitance, C, or the charge , CV.

From the transient current-voltage oscilloscope traces, (a typical one is shown in figure 2), it was found that the total integrated current is about the same as the charge stored on the capacitor before discharging. This implies that the capacitor was fully discharged in each arc. This is shown in Table II in columns labeled I*dt and CV. As can be seen, the larger the capacitor the better the agreement.

Comparing the maximum current measured from the oscilloscope traces and that found by using the maximum dv/dt showed relatively good agreement. The difference is attributed to the inductance in the circuit. The circuit inductance was determined to be in the range of 20-30 microhenries. It is felt that most of this inductance is due to the inductance in the capacitors.

Density Effects

By using the hot filament Penning type discharge sources, the density could be varied down to approximately $3x10^3$ e/cc. Tests were run to determine breakdown strength as a function of density. The results are shown in Table III. For the three samples shown, the breakdown strength increases with decreasing number densities. This indicates that arcing is occurring at bare metal sites. This agrees with previous investigations performed using negatively biased pinholes and solar arrays. (References 11 and 12.)

On the other hand arcs initiated by breakdown of the anodizing layer should be independent of the number density. The only requirement is that the thermal flux of ions to the surface be sufficient to keep the surface charged while also providing for leakage current through the

Table III Effect of Density on Breakdown Voltages

Density, e/cc	LeRC-3 V_{bk}	LeRC-2 V_{bk}	SSF-M1 V_{bk}
$2x10^6$	300	400	600
$5x10^4$	350	600	700
$7x10^3$	400	800	900

insulator and the opened arc sites. This is demonstrated for sample MSFC-F in Figure 5. The data for this figure was obtained by holding the voltage at -200 volts while the number density was lowered and recording the time between arcs at several density levels. the lowest density where arcs were observed was approximately $2x10^3$ e/cc. As can be seen, as the density increases arc rate increases sharply.

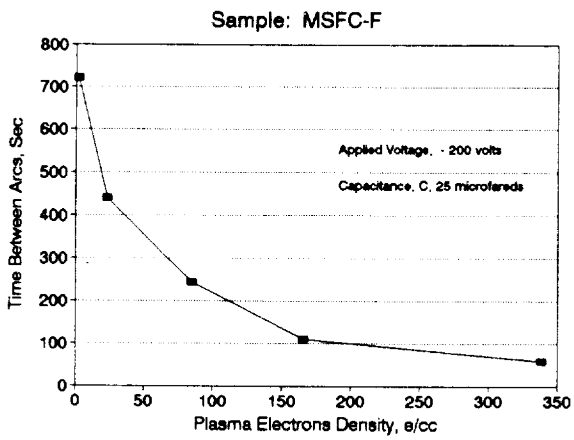

Figure 5. Average time between arcs as a function of plasma density for sample MSFC-F.

Corona Measurements

Corona inception voltages for various samples using metal electrodes are shown in Table IV together with the breakdown potential in the plasma experiments. It can be seen that the corona inception voltages followed the plasma breakdown potentials in that the higher the corona inception voltage the higher the breakdown voltage. Many of the samples, however, are grouped around a corona inception voltage of near 250 volts rms. (350 volts peak) although their breakdown values varied. What can be said is that samples that showed a corona inception voltage of 200 volts and higher had plasma breakdown voltages of greater than 300 volts. This indicates a possible screening method for testing of anodization breakdown strengths.

Corona measurements using a liquid electrode, salt water, to simulate plasma contact gave unusual results. Corona initiation for all samples started at extremely low voltages, a few volts, and in some cases no measurements were possible because a short circuit appeared as the liquid made direct contact. A possible explanation of this may be as follows. In the process of manufacturing the anodized layer, a very thin solid "barrier layer" grows first, and then oxide columnar with open pores in between columns grows. (References 13-15.) The indicated thickness of oxide corresponds to the height of the columns and the barrier layer thickness. However, the true insulation thickness is the barrier layer only, which is much thinner. It is this layer that can easily break down. It is believed that the liquid electrolyte penetrates down to the thin barrier layer whereas the plasma sheath prevents the plasma from penetrating.

Table IV Corona Inception Voltage

Sample	Corona Inception Voltage, V(rms)	Breakdown Inception Voltage, V
MSFC-1	38	120
MSFC-F	66	200
LeRC-1	270	600
LeRC-2	250	400
LeRC-3	230	300
SSF-M1	270	600

CONCLUSIONS

Anodized films vary greatly in their ability to withstand applied voltages, varying in breakdown strength from 100 volts to 2000 volts in the films tested here. Therefore it is possible to choose anodized films that will not breakdown under the potentials imposed on the space station structure, but the relation between the desired optical and thermal properties and the desired breakdown strength has not been established. The second type of arcing, that initiating at exposed metal sites, is not a factor since the inception voltage is above 200 volts and usually much higher.

Maximum arc current depends on the size of the capacitor used and the applied voltage, that is on the total capacitor charge. The maximum current varied approximately to the one-third power with the capacitance or total charge.

Experiments at low plasma density show that arcing that are initiated at bare metal sites occur at higher voltages as number density is lowered. Arcs triggered by insulation breakdown are independent of density. This confirms that true vacuums arcs are occurring in these ground tests, and the ambient plasma only as a trigger mechanism. For space plasma conditions where the metallic anode is not present some of the unusual phenomena of vacuum arcs will not appear and a type of arc not seen in ground experiments may occur.

Corona tests on anodized samples show that corona inception follows breakdown voltage, and can be used to screen new samples.

REFERENCES

1. Stevens, N. J., Berkopec, F. D., Grier, N. T., and Staskus, J., "Investigation of High-Voltage Spacecraft System Interactions with Plasma Environments," AIAA Paper 78-672, 1978.

2. Katz, I., Mandell, M. J., Schnulle, G. W., Parks, D. E., and Steen, P. G., "Plasma Collection by High-Voltage Spacecraft at Low Earth Orbit," Journal of Spacecraft and Rockets, Vol. 18, Jan-Feb. 1981, p. 79.

3. Grier, N., "Experimental Results on Plasma Interactions with Large Surfaces at High Voltages," NASA TM-81423, 1980.

4. N. J. Stevens, "Interactions between Large Space Power Systems and Low-Earth Orbit Plasmas," in Spacecraft Environmental Technology 1983, (C. K. Purvis and C. P. Pike, eds). NASA CP-2359 and AFGL-TR-85-0018, March 1985.

5. Kennerud, K. L., "High Voltage Solar Array Experiments," NADA CR-121280, March 1974.

6. Stillwell, R. P., Robinson, R. S., Kaufman, H. R., "Current Collection from the Space Plasma through Defects in high Voltage Solar Array Insulation," J. Spacecraft and Rockets 22, 1985, pp. 631-641.

7. Thiemann, H. and Bogus, K., "High-Voltage Solar Cell Modules in Simulated Low-Earth-Orbit Plasma," J. Spacecraft and Rockets, Vol 25, No. 4, July-August, 1988.

8. Mandell, J. J. and Katz, I., "Potentials in a Plasma Over a Biased Pinhole," IEEE Transactions on Nuclear Science, Vol. NS-30, 1983, pp. 4307-4310.

9. Vaughn, J., "SSF Chromic Acid Anodized Aluminum Arc Tests," Electrical Grounding Tiger Team Meeting, Huntsville, A., May 14-17, 1991.

10. Vaughn, J. "Experimental Investigation of Current Flow Dring Dielectric Breakdown," Electrical Grounding Tiger Team Meeting, Huntsville, Al, May 14-17, 1991.

11. Synder, D. B., "Characteristics of Arc Currents on a Negatively Biased Solar Array," NASA TM-83728, June 1984.

12. Jongeward, G. A., Katz, I., Mandell, M. J., and Parks, D. E.,"The Role of Unneutralzed Surface Ions in Nagative Potential Arcing," presented at chr 1985 IEEE 22nd Annual Conference, NSRE, Monterey, CA, July 22-24, 1985.

13. Symposium on Anodized Aluminum, Cleveland, OHio 1965. American Society for Testing Materials 1965, ASTM Sp Pub. 388.

14. Young, L., "Anodic Oxide Films," Academic Press, New York, 1961.

15. Lacey, E. A. and Sonnino, C., "Testing of Anodic Coatings on Aluminum alloys: A Review," *Testing of Metalic and Inorganic Coatings*, ASTM STP 947, W. B. Harding and G. A. Di Bari, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 150-166.