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Plasma Chamber Testing of APSA Coupons for the SAMPIE Flight Experiment

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PLASMA CHAMBER TESTING OF APSA COUPONS FOR THE SAMPIE FLIGHT EXPERIMENT

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Abstract

Among the solar cell technologies to be tested in space as part of the Solar Array Module Plasma Interactions Experiment (SAMPIE) will be the Advanced Photovoltaic Solar Array (APSA). Several prototype twelve cell coupons were built for NASA using different blanket materials and mounting techniques. The first conforms to the baseline design for APSA which calls for the cells to be mounted on a carbon loaded Kapton® blanket to control charging in GEO. When deployed, this design has a flexible blanket supported around the edges. A second coupon was built with the cells mounted on Kapton-H, which was in turn cemented to a solid aluminum substrate. A final coupon was identical to the latter but used germanium coated Kapton to control atomic oxygen attack in LEO. Ground testing of these coupons in a plasma chamber showed considerable differences in plasma current collection. The Kapton-H coupon demonstrated current collection consistent with exposed interconnects and some degree of cell snapover. The other two coupons experienced anomalously large collection currents. This behavior is believed to be a consequence of enhanced plasma sheaths supported by the weakly conducting carbon and germanium used in these coupons. The results reported here are the first experimental evidence that the use of such materials can result in power losses to high voltage space power systems.

Introduction

The Solar Array Module Plasma Interactions Experiment (SAMPIE)[1-3] is an approved NASA flight experiment manifested for shuttle deployment in early 1994. The SAMPIE experiment is designed to investigate the interaction of high voltage space power systems with ionospheric plasma. Among its various experiment samples, a number of solar cell coupons (representing design technologies of current interest) will be biased to high voltages to measure both arcing and current collection. One of the principal objectives of the experiment is to test the performance of the Advanced Photovoltaic Solar Array (APSA)[4].

APSA is characterized principally by the use of very thin (60 micron) solar cells mounted on a flexible deployable blanket. The resulting array has very high specific power, exceeding 130 W/kg beginning-of-life (BOL) even using silicon solar cells. To meet SAMPIE's objective, three twelve-cell prototype coupons of 2 cm by 4 cm silicon cells have been constructed. Originally designed for deployment in Geosynchronous orbit (GEO), APSA normally uses a flexible blanket of carbon loaded Kapton mounted in an external frame. The carbon loaded material provides a blanket which is slightly conducting and serves as an active charge control measure in geostationary applications. The first test sample was constructed as a flexible blanket using this material.

A second coupon, more appropriate for use in low Earth orbit (LEO), has a blanket of germanium coated Kapton for protection from atomic oxygen attack. The germanium coating provides a higher resistance than carbon loading but is still weakly conductive. Unlike the carbon loaded material, for which conductivity is a bulk property, this material uses germanium as a thin film deposited on a substrate of Kapton. On SAMPIE, a flexible, deployable geometry is not practical and the cell coupon will be hard mounted to a piece of aluminum. It was expected that the mounting scheme would have no impact on the plasma interactions SAMPIE is designed to test since all cells, interconnects, and bus bars are on the front side. As the data below show, this assumption is not strictly true.

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A final coupon uses Kapton-H, which we will henceforth refer to simply as "Kapton", cemented to an aluminum plate. This provides a baseline reference for comparison of plasma interactions of the two weakly conducting blankets. While the germanium coupon has been baselined and will be flown, it is necessary to test all three coupons in a space simulation chamber to quantify enhanced plasma current collection resulting from the use of these two materials.

Sample Construction

All three coupons were constructed using 2 cm by 4 cm silicon cells. The flexible module, designed to approximate baseline technology, used a 15.24 cm by 17.78 cm (6 inch by 7 inch) carbon loaded Kapton blanket. The outer 1.27 cm (.5) inch perimeter was covered front and back with Kapton tape to increase mechanical strength leaving a 12.7 cm by 15.24 cm (5 by 6 inch) area of carbon loaded material. The solar cells were wired as three parallel strings each having 4 cells in series. The module was suspended by 4 nonconducting bands in a frame made from nonconducting material.

The Kapton module used the same cells and wiring as above. The cells were mounted on a 15.24 cm by 17.78 cm (6 inch by 7 inch) piece of Kapton bonded to an aluminum substrate.

The germanium module used a 12.7 cm by 15.24 cm (5 by 6 inch) piece of Kapton with 150 nanometers of germanium coating on both sides. The aluminum substrate was anodized on the top and conversion coated on the back. This renders the top surface insulating and the bottom surface conducting. The Kapton was bonded using a nonconductive adhesive. The coupon is designed to allow it to be either grounded to the experiment or to be floating during operation. The grounding scheme was implemented by removing the anodization from a corner to expose bare metal, then covering this spot with nonconductive Kapton tape. Metal tabs were attached to both the upper and lower germanium coatings with conductive epoxy. This was done on two opposite corners of the coupon. The coupon in this condition, which is how it was received, is therefore isolated from the aluminum substrate. To ground it, one would remove the Kapton tape and use conductive epoxy to bond the tabs to the bare metal. The solar cells for this module were wired as a single series string.

In all three cases, electrical wires were attached to the two busbars and shorted together. Exposed busbars and turn-around strips are a major source of plasma current collection. All busbars were made from .32 cm (1/8 inch) wide strips but differed slightly in length because of the different wiring schemes. These properties are summarized in Table I.

For the germanium and carbon loaded samples, which have weakly conductive blankets, an additional operational mode was added. These two coupons were normally tested with their blankets electrically isolated from earth ground so that the only currents measured are due to the plasma, i.e. no leakage to ground is possible through the material. To test the importance of such ground leakage, a small metal clip was added to the corner of each of these two samples. By allowing this clip, which we will refer to as the "ground clip", to float freely or by grounding it to the tank wall, a direct measurement of the contribution from leakage is straightforward.

Table I: Coupon parameters

Blanket Properties			Array parameters	
Material	Thickness (10^{-5}m)	Exposed area (cm^2)	Wiring scheme	bus-bar area (mm^2)
Kapton - H	5.08 (2 mil)	145.7	series/ parallel	775
Carbon loaded	7.62 (3 mil)	Front: 70.3 Back: 189.2	series/ parallel	775
Ge coated	5.08 (2 mil)	76.8	series	692

Test Facility and Procedures

Testing was done in the Plasma Interaction Facility (PIF) at the Lewis Research Center. All measurements were made in a space simulation chamber offering a cylindrical volume 1.8 m (six feet) in diameter by 1.8 m long. A 91.4 cm (thirty six inch) diffusion pump provided an initial pumpdown to approximately 5 x 10^{-7} torr. Plasma was generated by a hollow cathode discharge source with a continuous flow of Argon. Pressure in the tank during operation of the plasma source was approximately 5 x 10^{-5} torr.

An electrometer, a Keithley model 237, was used to apply a bias voltage to the test sample and measure the resulting collected current. Ion currents were measured with applied biases from 0 to -200 V in 10 V increments while electron currents were measured with applied biases from 0 to +600 volts in 25 V increments. Ion and electron current collection sweeps were made separately, always beginning with zero volts bias and increasing the applied voltage magnitude. The negative bias range was restricted to -200 volts to avoid arcing and possible damage to the sample. A complete data set consisted of ten runs which were averaged to smooth random fluctuations in plasma density. Plasma density during the operation of hollow cathode sources is characterized by a relatively stable mean value with random fluctuation ranging from a few percent to occasional "bursts" which can exceed 15 or 20 percent. Additional precautions were taken to account for the small systematic drifts in plasma density caused by changing conditions in the plasma source. To this end, plasma density was monitored using a 1.9 cm (3/4 inch) Langmuir probe. At the beginning of each data run, the plasma source was adjusted to result in a current of 1.65 milliamps when this probe was biased to +100 volts. Plasma conditions corresponding to this value were measured and are shown in Table II. The procedure effectively normalizes all data to the plasma density indicated.

Table II - Plasma Parameters

Electron Density	7.96×10^5 cm^{-3}
Electron Temp	1.75 eV
Ion Temp	.56 eV
Plasma Potential	4.83 eV

Results and Discussion

Measurements of ion current were made from all three samples. The Kapton sample was measured only in a "floating" mode, i.e. with no attempt to account for leakage currents, which are assumed to be negligible. As will be shown below, equivalent measurements with the germanium coupon justify this assumption. The carbon and germanium coupons were also measured with the ground clip grounded to the tank wall. Table III shows a summary of the data.

Inspection of Table III shows several immediately apparent features. In particular, there is little difference in collected currents between floating and grounding the germanium coupon. By contrast, the carbon coupon shows a significant difference between these two operational modes. In both cases, current collected is significantly larger than for the Kapton coupon.

At this point it would seem well to clarify and quantify the several mechanisms operating for leakage current. For the Kapton coupon, the blanket is a uniform, highly insulating material. Leakage currents would consist of current flowing from the busbars, through the 2 mils of Kapton, to the metal substrate. For the carbon loaded case, we have a material which has been impregnated with carbon and may be expected to behave as a carbon resistor with bulk conduction occurring throughout the material. The germanium coupon is different from either of the others in that a highly insulating blanket has been coated with a weakly conducting semiconductor. Conduction through the blanket to the metal substrate should be comparable to that for the Kapton coupon. This mechanism can be quantified by biasing the coupon with the ground clip floating, turning the plasma sources off, and measuring the current with the back of the substrate grounded. When this was done, a maximum current of a little less than one microamp was recorded at the maximum bias of 600 volts. This effectively measures the resistance of the 2 mil Kapton to be in excess of 600 megohms. This mechanism, conduction through Kapton, is judged negligible and will not be considered further.

Table III: Ion Current Vs Applied Bias

Applied Bias volts	Kapton H μA	Carbon float μA	Carbon ground μA	Ge float μA	Ge ground μA
10	1.04	5.20	9.71	2.50	2.49
20	1.40	8.09	18.84	4.25	4.24
30	1.71	10.56	28.62	5.60	5.60
40	2.00	12.98	38.98	6.69	6.69
50	2.28	15.12	50.06	7.65	7.66
60	2.52	17.18	61.50	8.56	8.58
70	2.74	18.82	72.98	9.42	9.46
80	2.94	20.62	84.80	10.26	10.32
90	3.19	22.18	97.24	11.06	11.14
100	3.36	23.10	109.80	11.86	11.94
110	3.56	24.98	121.60	12.58	12.68
120	3.72	26.08	135.40	13.30	13.48
130	3.91	27.66	148.60	14.00	14.18
140	4.09	28.68	162.00	14.66	14.88
150	4.24	29.72	177.20	15.34	15.54
160	4.41	31.00	189.40	15.96	16.20
170	4.56	31.76	203.40	16.58	16.88
180	4.78	33.18	218.20	17.22	17.52
190	4.91	34.10	233.20	17.84	18.16
200	5.10	35.32	247.20	18.34	18.78

Mechanisms for leakage current can then be summarized as follows. For the Kapton coupon, no leakage path exists. Since the Kapton blanket has such high resistance, its surface potential in a plasma environment will remain uniformly close to the plasma potential. For the carbon loaded coupon, bulk conduction will occur through the material. If the ground clip is grounded, this will result in current to ground which is seen as enhanced collection during the measurements. Regardless of whether the coupon is floating or grounded, a complicated potential distribution will exist on the blanket surface which will affect plasma current collection. Since there is no substrate, such a potential distribution will occur on the backside as well as on the front. For the germanium coupon, conduction can only occur through the front surface layer. As with the carbon loaded sample, current will flow to ground when the clip is grounded and a complicated potential distribution on the surface will affect plasma current collection in all cases.

For the carbon loaded coupon, it remains to demonstrate explicitly that the difference in collected current between floating and grounded operation is due to leakage. To do this, we turn off the plasma source and use the electrometer to measure the collected current. This measurement was made for both polarities of applied bias. There was no difference in measured currents for the two polarities so only the negative bias results are presented. These results are shown in Table IV.

Comparison of Tables III and IV shows that the significantly larger current collection observed when the carbon loaded coupon is grounded is entirely accounted for by simple leakage through the material to ground. Applying Ohms' law to the data in Table IV

Table IV Ground Current Vs Bias
Carbon loaded coupon

Bias Volts	Current μA	Bias Volts	Current μA
10	5.7	110	97.8
20	12.5	120	109.0
30	20.1	130	120.7
40	28.1	140	133.3
50	36.7	150	146.0
60	45.9	160	157.0
70	55.6	170	169.4
80	65.8	180	182.2
90	76.0	190	195.1
100	86.6	200	208.3

shows that the effective resistance from the array to the ground clip is approximately 1 megohm. By comparison, a similar measurement for the germanium coupon yielded less than one microamp at 200 V implying that the effective resistance from the biased array to the ground clip is approximately 150 megohms.

Leakage current, as discussed above, is independent of the polarity of applied bias. Table V gives results for electron current collection for all three coupons. In this case, we are dealing with currents two to three orders of magnitude larger than for ion current. The effect of leakage current is negligible under these conditions.

Table V Electron Current Vs Applied Bias

Applied Bias volts	Kapton H mA	Carbon float mA	Carbon ground mA	Ge float mA	Ge ground mA
25	0.11	0.20	0.19	0.13	0.13
50	0.25	0.66	0.63	0.27	0.27
75	0.38	1.26	1.25	0.40	0.40
100	0.50	2.09	2.09	0.53	0.53
125	0.61	3.15	3.15	0.90	0.77
150	0.73	4.27	4.23	1.67	1.59
175	0.87	5.54	5.55	2.23	2.19
200	1.01	6.91	6.93	2.56	2.55
225	1.14	8.68	8.61	2.89	2.88
250	1.29	10.00	10.00	3.27	3.28
275	1.44	10.00	10.00	3.76	3.69
300	1.62	10.00	10.00	4.30	4.26
325	1.86	10.00	10.00	4.88	4.83
350	2.15	10.00	10.00	6.54	5.60
375	2.56	10.00	10.00	8.71	7.93
400	3.10	10.00	10.00	9.96	9.91
425	4.02	10.00	10.00	9.95	10.00
450	8.79	10.00	10.00	9.97	10.00
475	9.94	10.00	10.00	9.96	9.99
500	9.96	10.00	10.00	9.96	10.00
525	9.98	10.00	10.00	9.95	10.00
550	9.98	10.00	10.00	9.95	10.00
575	9.99	10.00	10.00	9.95	10.00
600	9.98	10.00	10.00	9.95	10.00

Having accounted for the effects of leakage current, we turn our attention back to comparing the characteristics of the three coupons. Since there is no other difference between floating and grounded operation, we will arbitrarily use the floating data for the remainder of our analysis.

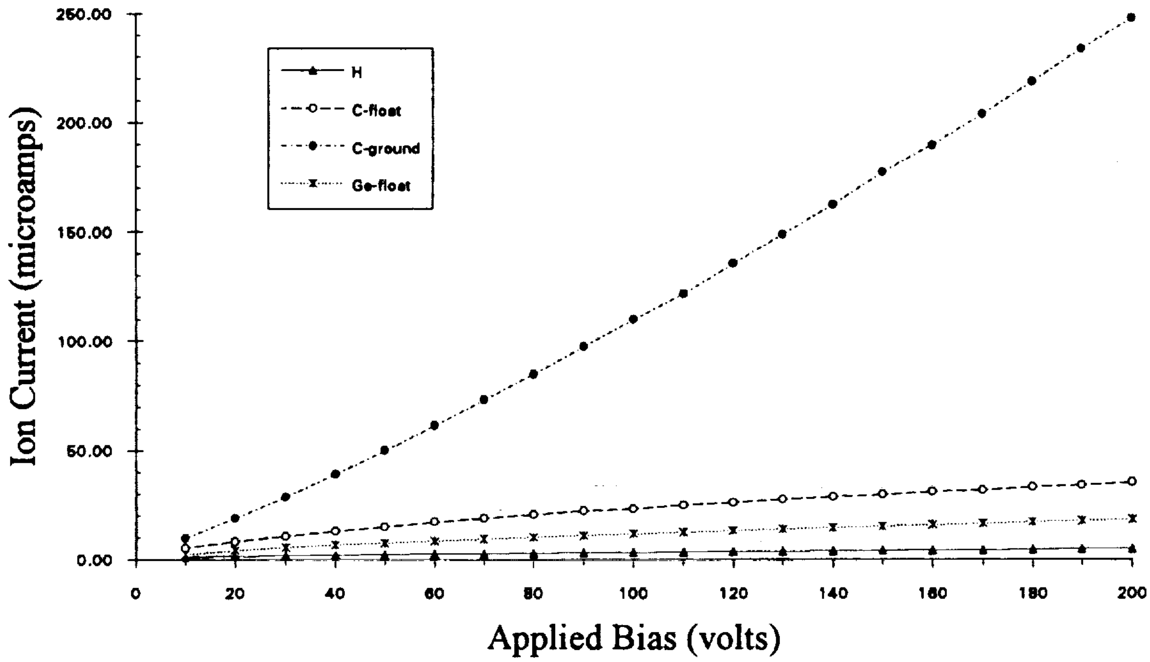

Fig.1. Ion Current vs Bias

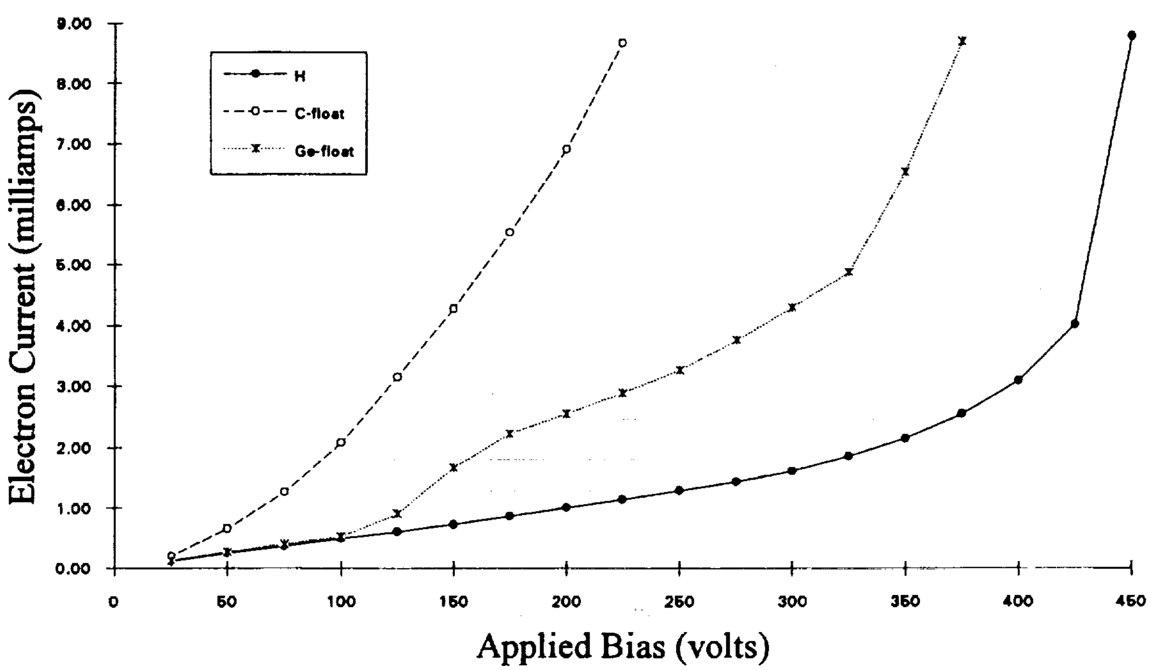

Fig. 2. Electron Current vs Bias.

The electrometer used for the measurements has a maximum current capacity of 10 milliamps. The data displayed in Table V exceeds this value at high voltages and saturates the instrument. The results for both electron and ion current are presented in graphical form in Figures 1 and 2.

As is immediately apparent from Figures 1 and 2, electron collection shows the effects of "snapover" in the steep increases in current that follow the sudden onset of this now well-known effect. Ion current, as is generally expected, is linear with bias. Comparing the behavior of the three coupons, we see that the same trend is present for both electron and ion collection. In particular, Kapton, which is highly insulating, collects the least current while the carbon loaded material, which has the least resistance, collects the most. The germanium coupon is a more complicated case. For ion collection, germanium is about midway between Kapton and carbon, collecting approximately 3 times as much current as kapton. For electron collection, it behaves as an insulator up to about 100 volts, being indistinguishable from kapton. Above this potential, current increases rapidly and the germanium coupon collects substantially more than the kapton blanket array.

In understanding these results we recall the point, mentioned above, that the highly insulating kapton will tend to remain near plasma potential at all points on its surface. The other two materials, since they are weakly conducting, will support potential distributions that are complicated by the geometry but in general will be close to the bias potential in the vicinity of the cell array and busbars while dropping to the plasma potential further away.

Such a potential distribution on the surface of the blanket may result in two different effects that can contribute to the enhanced current flow. First, charge may be simply collected by the blanket and conducted to the busbars. Second, such potential distributions will be expected to modify the plasma sheaths. For the Kapton case, the sheath is not likely to extend much beyond the area occupied by the actual cell array while for the two conducting coupons it may well cover the entire blanket. The effect of a large plasma sheath may be to "funnel" a significant current to the busbars and cell interconnects.

Our data were not able to quantitatively distinguish between these two effects which are undoubtedly both occurring. The data from the germanium coupon, however, strongly suggests that the sheath effect is the more important. This follows from the observation that there is no significant difference in current collection for the floating and grounded operating modes. As reported above, current from the cell array to the busbars in the absence of plasma was less that one microamp at 200 V bias. Yet Table V shows that at 200 V this coupon collected 2.5 milliamps compared to 1 milliamp for the Kapton module. The complicated geometry does not allow us to confidently bound current conduction through the entire blanket to the cell array from this fact. Nevertheless, we believe that conduction through the material is the lesser of the two effects and that the enhanced current collection we report is primarily a plasma phenomena.

One hopes eventually to gain insight into these effects through modeling. Unfortunately, the principal computer code available to the community, NASCAP/LEO[5], is unable to deal with weakly conductive blanket materials at this time.

Future Work

In order to better understand the effects reported here, it is desirable to replace the solar cell array with a simpler mockup. There are two reasons for this. First, the solar cells are themselves complicated objects involving exposed semiconductors, glass coverslides, and exposed interconnects. The cells are well known to be susceptible to snapover which makes it impossible to differentiate enhanced cell collection from collection by the blanket. Second, the geometry of cells, with exposed interconnects and busbars, in a rectangular array is fundamentally two dimensional.

We are now constructing a simple one dimensional experiment to study these effects. In essence, we will use a circular piece of the blanket material to be tested, tentatively chosen to be 24 cm in diameter. The center 2 cm will be covered by a metal disk. On the outer perimeter will be a metal ring with a 1 cm width, both metal parts being bonded with conductive epoxy. The center disk will be biased from the back and the ring can be either floated or grounded. This arrangement eliminates all the complications of solar cells since it has only metal and blanket material. In polar coordinates, it has symmetry in the angular variable and will offer a surface potential distribution that depends only on radius. The use of surface probes during operation will allow the surface potential to be mapped as a function of radius. It is hoped that the role of material conduction and plasma sheaths can be better sorted from such data. In any event, the one dimensional nature of the experiment will greatly facilitate efforts to model the relevant effects.

Conclusions

For the designer of real power systems, the relative importance of the two mechanisms discussed above may well be academic. Regardless of what is eventually shown to be the exact mechanism involved, it is clear that the use of weakly conductive blankets leads to enhanced plasma current collection. This is true even if the material has what is normally considered to be a large resistance, as does the germanium coating reported here. This enhanced current collection appears as a power loss to the system and is obviously of importance to the designer.

The magnitude of the loss that a photovoltaic power system may expect to incur as a result of this effect depends on its design. In particular, spacecraft are generally grounded to the negative end of the solar array which means that the majority of the system, including the spacecraft structure, will "float" negative with respect to the plasma and therefore collect ions. As our data shows, ion collection is enhanced with weakly conductive coatings but, as is always true of ion collection, the absolute magnitudes are small and the overall effect may be negligible. The use of a negative ground with a high voltage system, however, has serious implications for the final floating potential of the spacecraft[2], as has been amply demonstrated with Space Station Freedom (SSF). In the case of SSF, a plasma contactor had to be added to the baseline design to control potentially severe effects resulting from the grounding scheme. The final potential distribution on the solar arrays and structure resulting from the interplay of such a device with the power system is extremely complicated and beyond the scope of the present work, but we will point out that this is one case when large areas on the array can be driven to large positive potentials. It is in such a situation, however it occurs, that our results will need to be considered and the use of such coatings carefully evaluated.

The research community most affected by these results deals with atomic oxygen protective coatings. It was for this purpose that the germanium was initially added to the APSA coupon. Such coatings are not routinely tested for the effects we report and our results argue that they should be. For traditional low voltage systems this may not be necessary, but for solar arrays which will operate at 100 volts or more there is a clear potential for such coatings to lead directly to significant power losses on the array.

The simple apparatus discussed above, under future work, will offer an ideal way to test proposed coatings in a simulated space environment.

Acknowledgments

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