Solar Array at Very High Temperatures: Ground Tests

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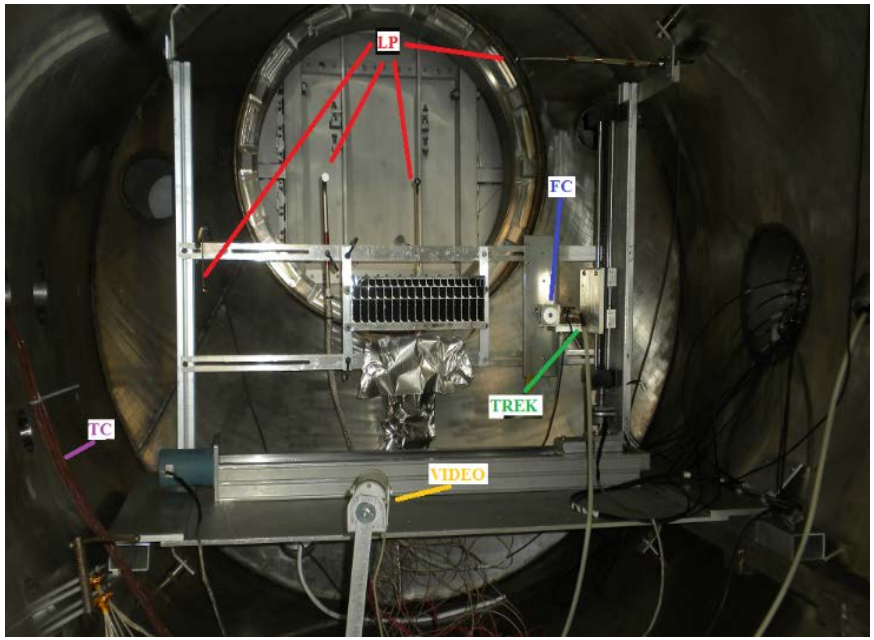
OUTLINE

- Coupon at high temperature
- Outgassing and contamination
- Arcing in simulated LEO and GEO
- Fully encapsulated coupon
- Electrostatic cleanness
- AR over ITO
- Conclusions

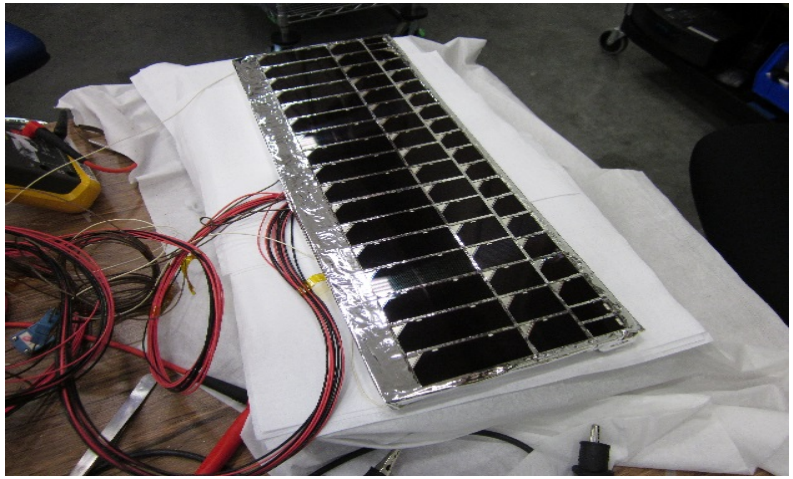
SETUP #1

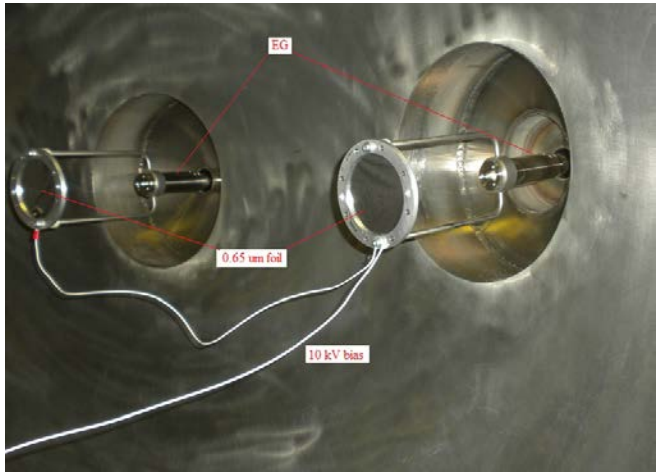


Test coupon with fully encapsulated all dielectric-conductor junctions

1. Donegan, M., Decker, R., Raouafi, N., Lario, D., and Bernasconi, P. "Surface Charging Analyses for the Solar Probe Plus Mission", 11th Spacecraft Charging Technology Conference, Albuquerque, NM, 2010.

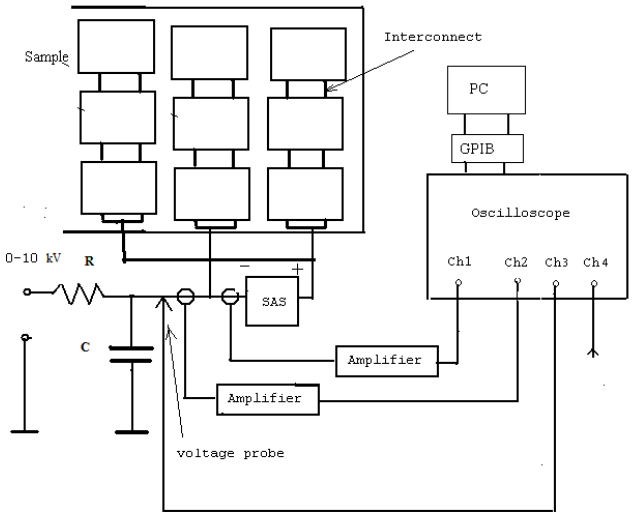
3 strings with 17 cells each, no ITO

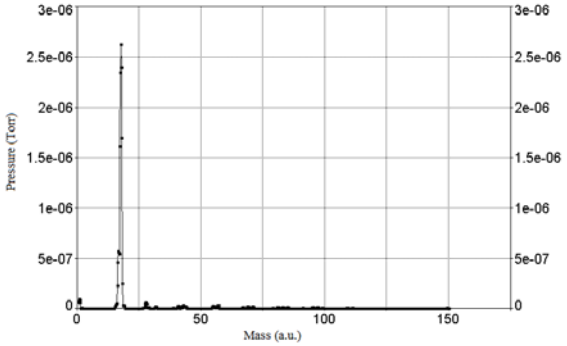




Two EGs with 0.65 um foil

LEO Simulated Environment



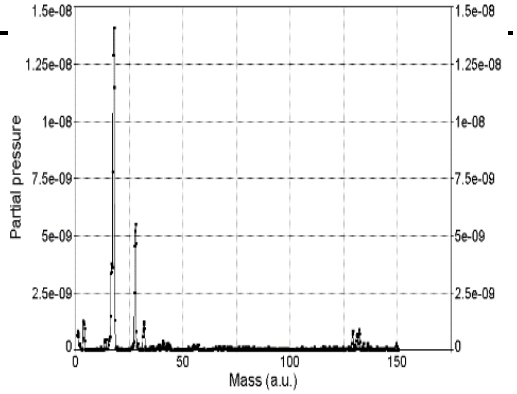


initial

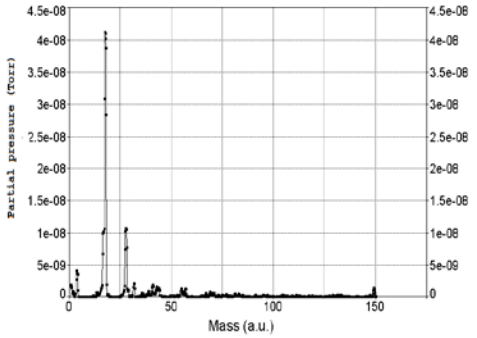
number density of N_e=10^6 cm^{-3} and electron temperature of T_e=0.2 eV.

1. Vayner, B., Galofaro, J., and Ferguson, D. "Interactions of High-Voltage Solar Arrays with Their Plasma Environment: Ground Tests", *Journal of Spacecraft and Rockets*, Vol.41, No.6, 2004, pp.1042-1050

No	:Bias: (V)	Temperature: °C	Time: (min)	Numb. of arcs:
1.	120	176	30	0
2.	160	176	30	0
3.	200	178	30	0
4.	240	177	30	0
5.	280	179	30	0
6.	320	180	30	0
7.	280	148	30	0
8.	320	148	30	2
9.	160	9	30	0
10.	200	9	30	0
11.	240	10	30	0
12.	280	11	30	0
13.	320	11	30	2

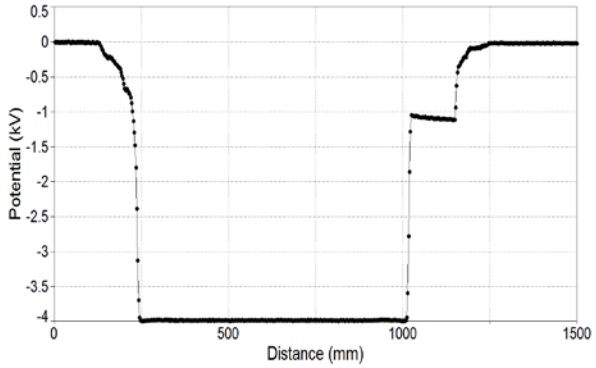


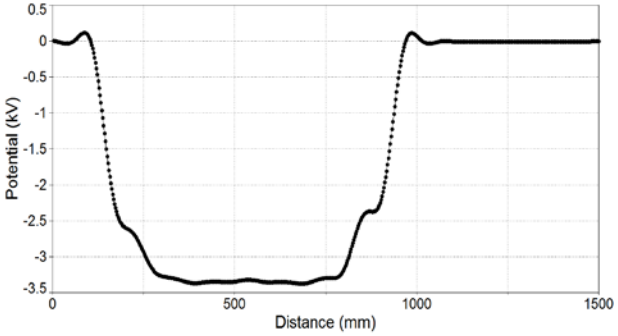
At15 C



Final at 175 C

GEO Simulated Environment



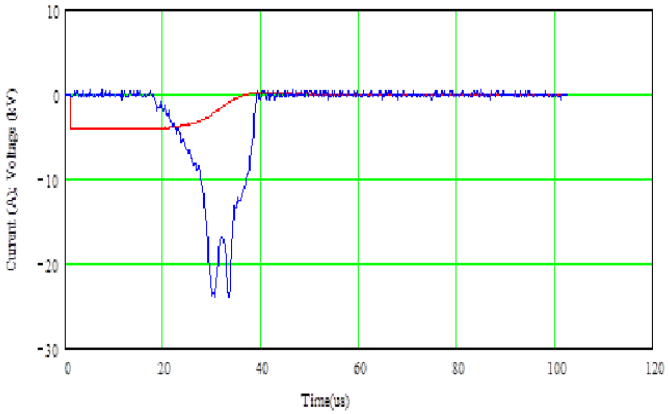


4.8 keV energy and 6 nA/cm^2 current density.

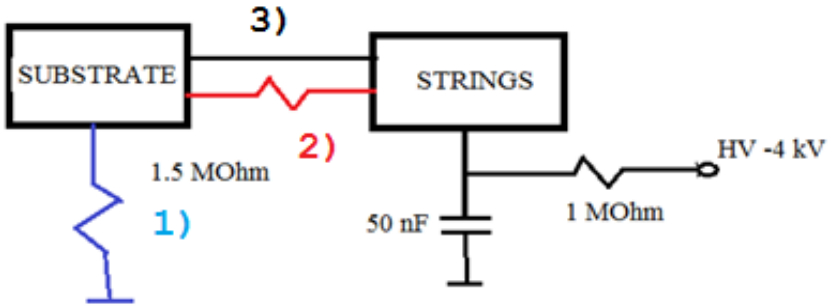
Biased before irradiation

After 20 minutes irradiation
(600 V dif.charging)

Arc sites are shown for test at 175 C (red), and for test at 9 C (green).



One example of discharge initiated at coupon temperature of 175^0 C



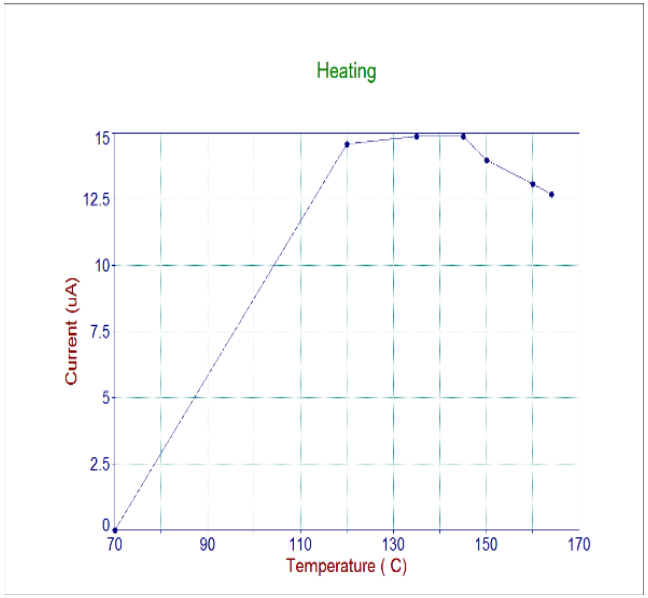
Three different circuitry diagrams that were used in GEO arcing tests

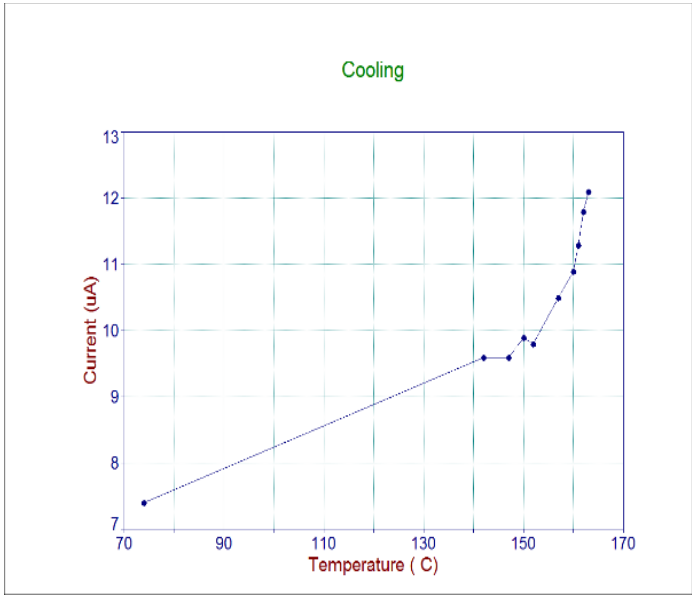
1. Grounded substrate-NO ARCS at all.
2. Substrate connected to strings through 1.5 MΩ resistor: 8 arcs for 46 minutes at 8° C; 8 arcs for 4 minutes at 160° C.
3. Substrate connected to strings: 3 arcs for 30 minutes at 8° C; 9 arcs for 5 minutes at 160° C.

Table 2. The Results of GEO Testing

No.:	Bias kV	:Beam Energy: keV	Curr. Dens: nA/cm^2	Temperature: °C	Diff.Voltage: V	No. of arcs:	:Remarks:
1.	4	4.8	9	6	500	0	
2.	4.5	5.3	6.7	8	700	0	
3.	4.5	5.3	10	8	800	3	
4.	4	4.8	6	176		9 for 5 minutes	
5.	4	4.8	3.5	38		0 for 30 min.	Grnd.Substrat
6.	4	4.8	10	8		8 for 46 min.	Subst.to cells With R=1.5MΩ
7.	4	4.8	10	9		0 for 30 min.	Grnd.Substr.
8.	4	4.8	10	153		0 for 30 min	Subst.grnd. With R=1.5MΩ
9.	4	4.8	10	160		8 for 5 min	Substr.to cells With R=1.5MΩ
10.	4	4.8	10	160		4 for 14 min	Subst.to cells

One visible trace of arc was found on edge of foil





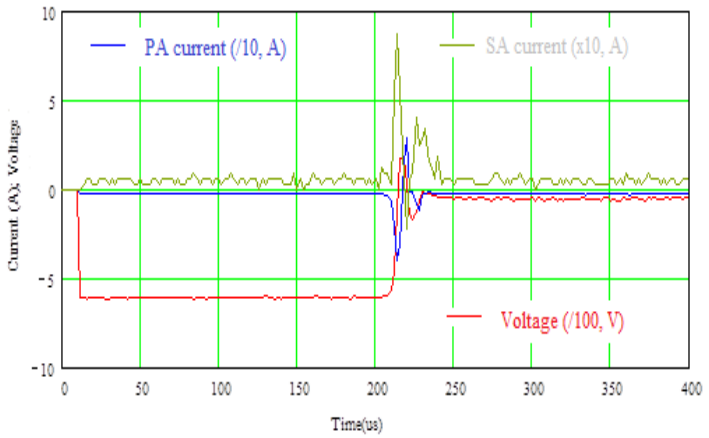
Voltage of 300 V was applied between strings and substrate

Leakage current of 10-15 μA cannot influence solar array performance at elevated temperatures.

Finally, internal resistance was measured between strings and substrate with FLUKE:
At coupon temperature of 10° C the resistance was $R=\infty$, and at 160° C it was R=0.9 MΩ.

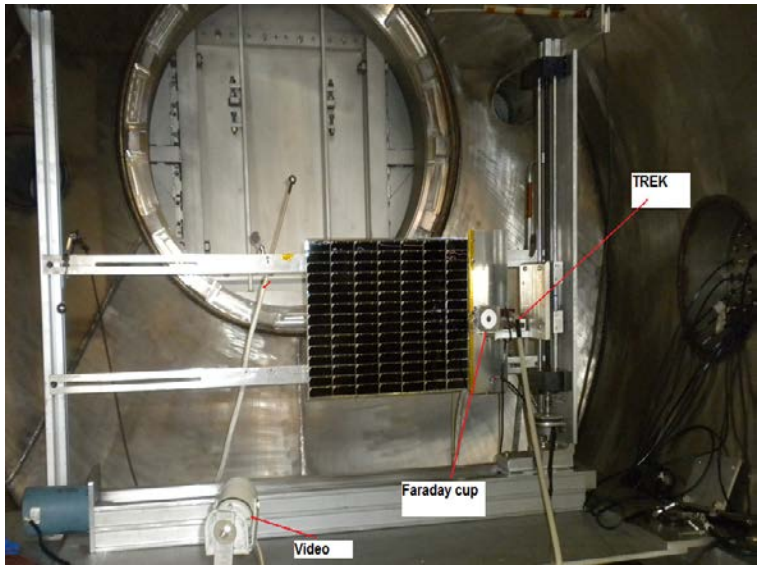
Table 3. SUSTAINED ARC TEST

No.	Bias: V	SAS V	SAS A	:No.of PAs :	No. of SAs :	:Temp. : °C
1.	300	100	0.1	9	0	13
2.	320	50	1.6	10	0	170
	540					
3.	500	50	2	10	0	160
4.	500	50	2	10	0	180
5.	600	50	2.4	10	0	180
6.	600	50	2.4	10	0	180



One example of pulses for SA test: bias-600 V, PA peak -40 A, SAS current peak 0.8 A

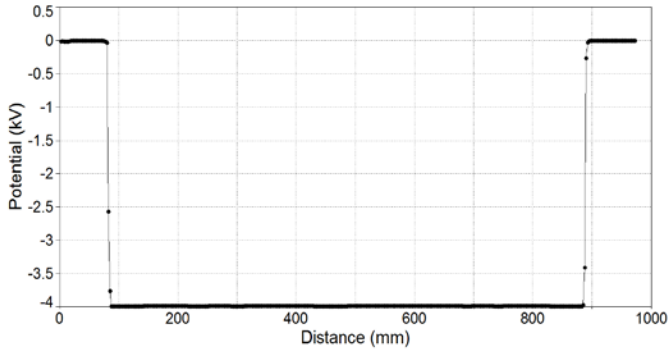
Electrostatically Clean Coupon- Setup #2



7 strings with 15 cells each
ITO+AR

Boca, A., Blumenfeld, P., Crist, K., Flynn, G., McCarty, J., Patel, P.,Sarver, C., Sharps, P., Stall, R., Mark Stan, M., and Tourino, C. "Array-Design Considerations for The Solar Probe Plus Mission", 37th Photovoltaic Specialist Conference, Seattle, WA, June 19-24, 2011.

Coupon was biased -4kV and surface potential was measured with TREK probe

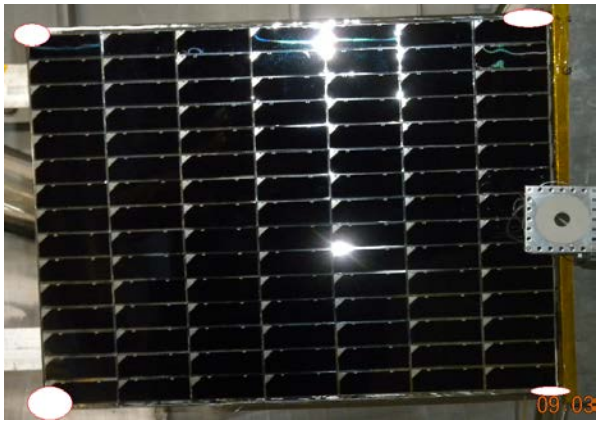


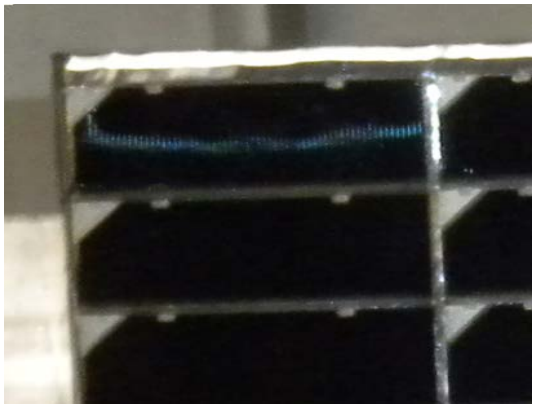
$$\delta_{sys} = \frac{\Delta U_{sys}}{U} = 0.325\%$$

$$\delta_{st} = \frac{\Delta U_{st}}{U} = 0.0035\%$$

At the second stage, coupon was biased -3.5 kV and irradiated with electron beam of 4.3.keV energy and 3 nA/cm^2 current density. One more scan was performed after 15 minutes of irradiation. Statistical analysis resulted in systematic error of 18 V (δ_{sys}=0.51%) and dispersion of 4.8 V (δ_{st}=0.14%) . Systematic error can be caused by: 1) differences in readings between power supply voltmeter and TREK probe; 2) residual surface charge.

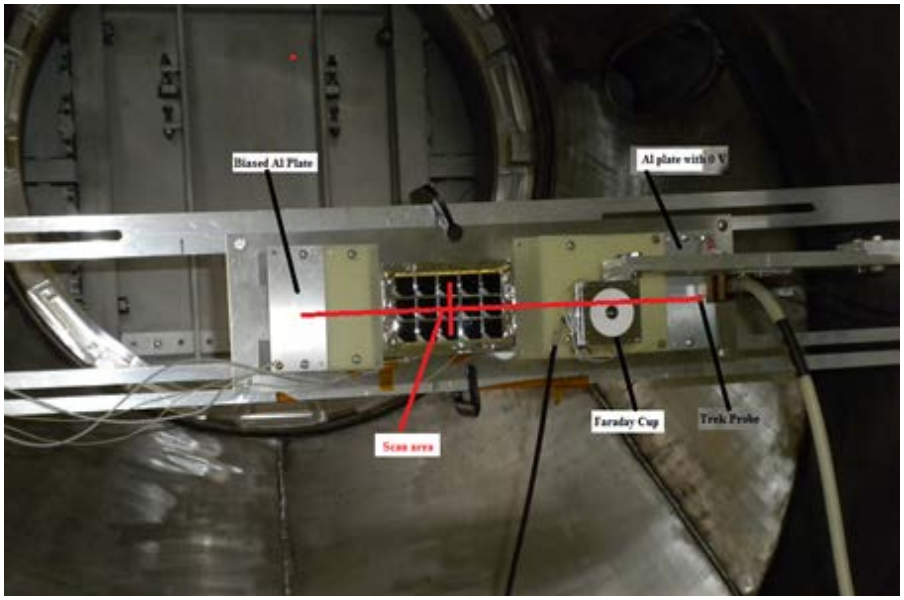
Last scan was performed after 15 minutes of irradiation with beam current density of 10 nA/cm^2. The result was U=3.481 (0.002) kV. Thus, standard deviation was determined as 2 V across coupon. Maximum voltage was 3.487 kV and minimum voltage was 3.475 kV. These numbers allow concluding that the variations of residual differential potential did not exceed 6 V (3σ). After comparing systematic errors from the first scan (13 V, no irradiation) and from the last scan (18 V, 15 minutes irradiation) one can conclude that residual homogeneous potential did not exceed 5 V.





Arcs were observed in circled areas

Setup #3



ITO+AR

Al plate grounded on right side
Al plate biased on left side
Scan time about 2 minutes

Table 4. Residual potentials for ITO+AR layers.

No.	:Bias : (kV) :	Beam Energy (keV):	Curr.(nA/cm^2)	: Time : (min) :	Res. Potential: (V)	Stdv : (V) :	String :
1.	3	3.8	10	20	16	6	middle
2.	5	5.8	10	20	11	7	middle
3.	5	5.8	10	30	13	8.5	upper
4.	0	-	-	-	21	3.8	upper
5.	3	3.8	10	30	1	6.2	upper
6.	3	3.8	10	30	14	6	bottom
7.	5	5.8	10	30	0	3.2	bottom

$$\tau = \frac{\varepsilon\varepsilon_0}{\sigma} >> 60s$$

Dielectric permittivity of magnesium fluoride is ε=5.5, and

$$\sigma_{\max} = 8 \cdot 10^{-13}\ S/m$$

$$j_{\max} = \sigma_{\max} \cdot \frac{U}{d}$$

d=100 nm and voltage drop U=20 V

j_{max}=16 nA/cm^2.

$\sigma \approx 10^{-12}$ S/m *from*

1. Vayner, B., Ferguson, D., and Galofaro, J. "Quartz-Indium Tin Oxide-Magnesium Fluoride Sandwich in a Low Density Plasma", Proceedings of the 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 4-8, 2006.

Conclusions

The tests demonstrated clearly that conductive heating of solar array coupon allowed testing against differential charging at high temperatures even in comparatively small plasma chamber. Contamination of chamber volume due to outgassing was absolutely insignificant, and decrease in dielectric resistivity did not cause any substantial leakage current. RTV grouting of all gaps between strings resulted in rising arc threshold well above differential voltages expected for spacecraft in LEO. However, in order to avoid arcing in GEO coverglass should be covered with weakly conductive layer (ITO). Full encapsulation of coupon with ITO connected to substrate allowed achieving a very high electrostatic cleanness. Influence of cosmic radiation and thermal cycling on RTV properties (aging) needs additional investigations.