# Laboratory Tests of New Solar Array Designs

Boris Vayner
Ohio Aerospace Institute, Cleveland, Ohio 44142

Joel Galofaro
NASA Glenn Research Center, Cleveland, Ohio 44135

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## OUTLINE

- New Design- Low mass, High voltage;
- Tests in LEO: current collection, primary arc, sustained arc;
- Test in GEO: arcs, with/without ITO, arc sites;
- Temperature effects: LEO and GEO;
- Conclusions





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# ISSUES:

## High Voltage + New UltraFlex Design

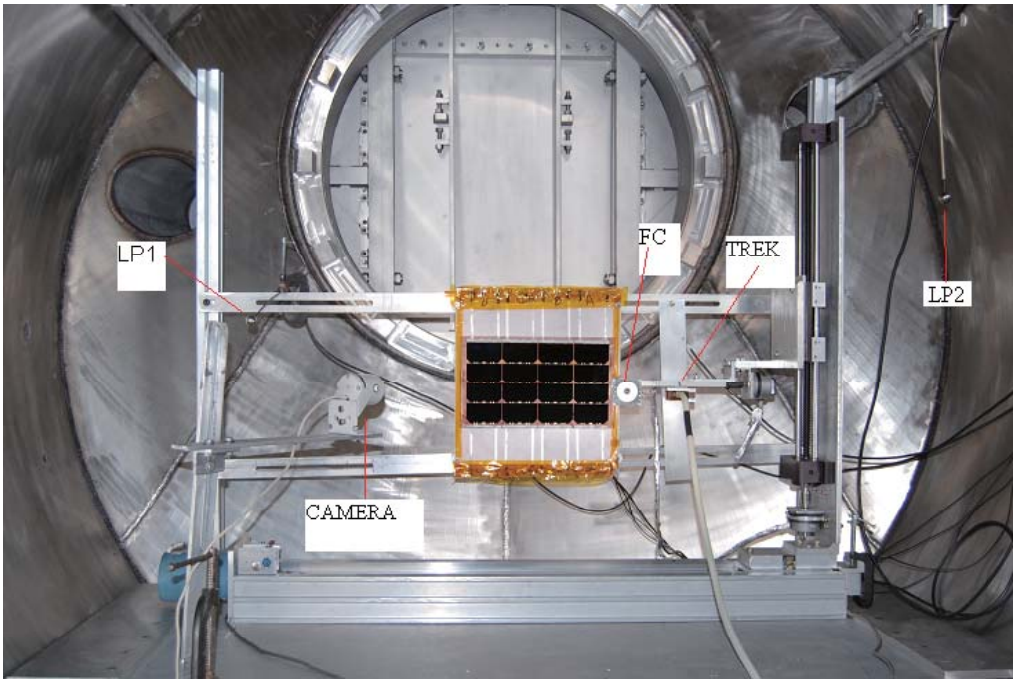
*Evaluation and testing of flexible thin-film photovoltaic (FTFPV) technology based on the UltraFlex solar array design*
Piszczor, M.F.; Spence, B.R.; Douglas, M.V.; White, S.F.;Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE 3-7 Jan. 2005 Page(s):814 – 817
*Next generation ultraflex solar array for NASA's New Millennium Program* Space Technology 8
Spence, B.; White, S.; Wilder, N.; Gregory, T.; Douglas, M.; Takeda, R.; Mardesich, N.; Peterson, T.; Hillard, B.; Sharps, P.; Fatemi, N.; Aerospace Conference, 2005 IEEE5-12 March 2005 Page(s):824 – 836
*Next generation UltraFlex (NGU) technology maturation for NASA's New Millennium Program (NMP)* Space Technology 8 (ST8)
Spence, B.; White, S.; Wilder, N.; Gregory, T.; Douglas, M.; Takeda, R.; Mardesich, N.; Peterson, T.; Hillard, B.; Sharps, P.; Fatermi, N.;
Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE
3-7 Jan. 2005 Page(s):826 – 829

## Low Temperature

1. Soldi, J.D., and Hastings, D.E. "*Arcing Predictions for PASP Plus Solar Arrays*", *PL-TR-94-2234*, 1994
2.Jongeward, G.A., and Katz. I. "*Effect of Conduction and Ion Currents on Solar Array Arc Threshold*", 6th Spacecraft Charging Technology Conference, Hanscom AFRL, MA, November 1998.
3.Guidice, D.A., Davis., V.A., Curtis, H.B., Ferguson, D.C., Hastings, D.E., Knight, F.L., Marvin, D.C., Ray, K.P., Severance, P.S., Soldi, J.D., and Riet, M.Van. "*Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) Experiment*", *PL-TR-97-1013*, 1997, p.5-11.
4.Katz, I., Davis, V.A., and Snyder, D.B. "*Mitigation Techniques for Spacecraft Charging Induced Arcing on Solar Arrays*", *AIAA Paper 99-16135*, Jan.1999.









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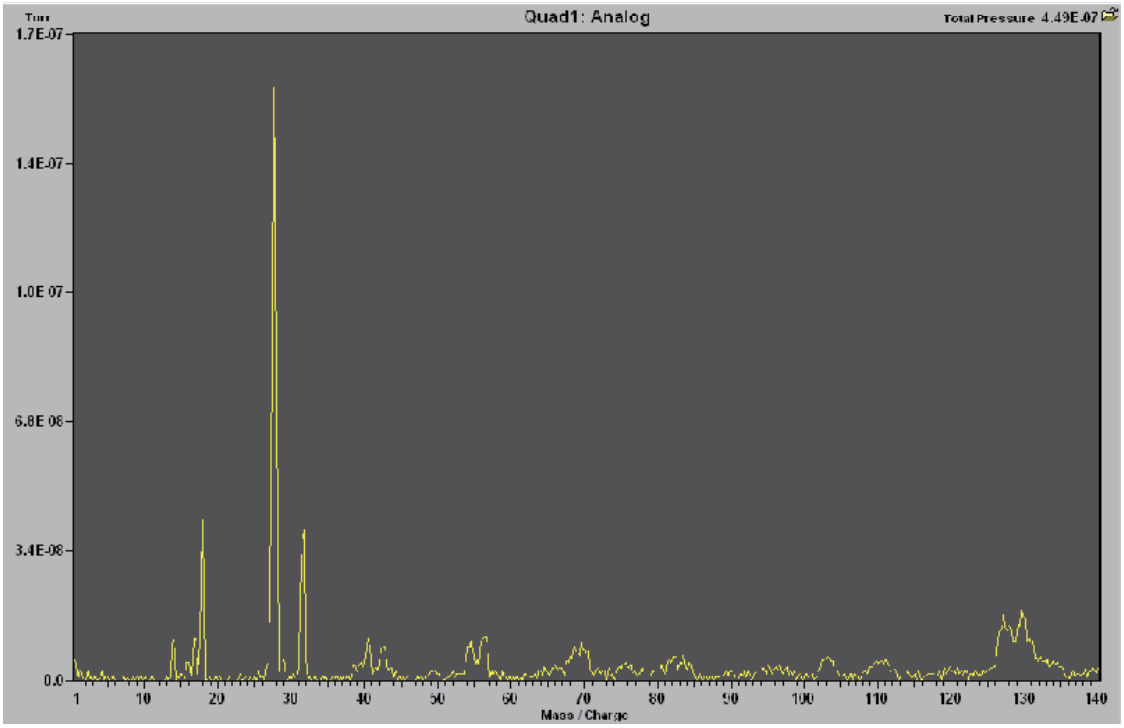
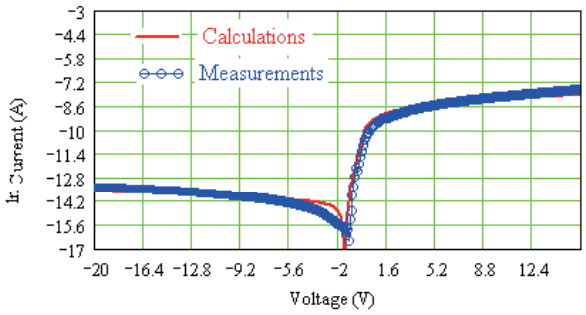


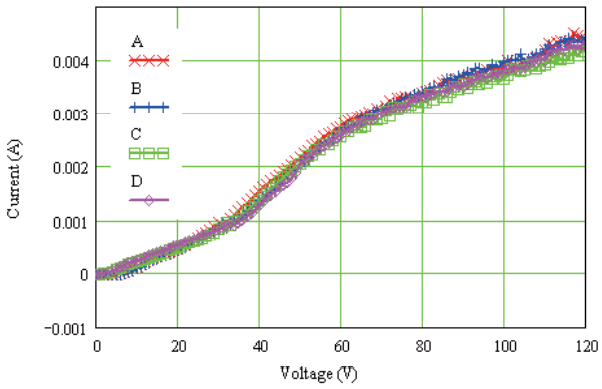

## Residual gas composition after 20 hours pumping








Plasma parameters were determined as the following (LP1/LP2): floating potential -1.2/-1.2 V; electron number density (4/3)*$10^6$ $cm^{-3}$ ; electron temperature 0.2/0.3 eV; plasma potential 3.2/3.4 V; ion temperature 0.058/0.058 eV; ion speed 0.92/0.92 km/s.




**Collection currents were measured for each string separately**





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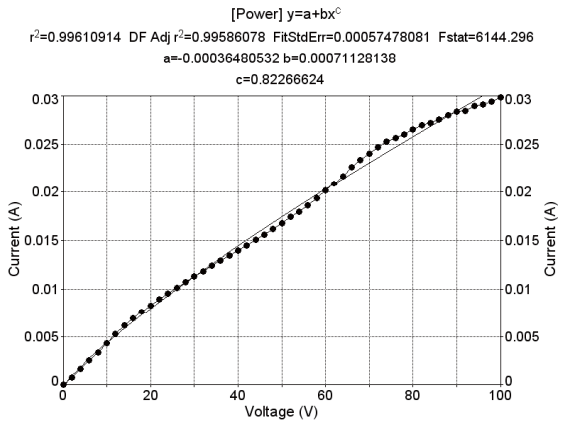
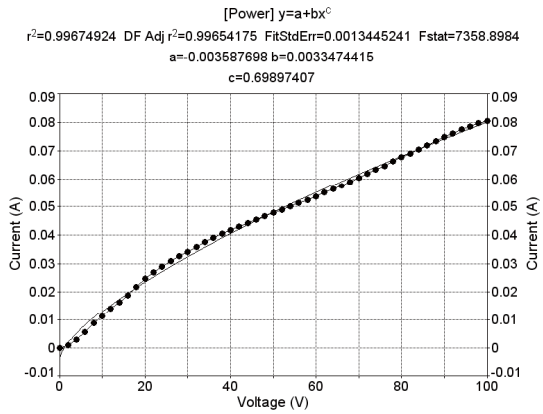
# Collected current per one string:

$$\sum_{i=1}^{N} I_i(V_i) = \int_0^U I_i(V)\frac{dN}{dV}dV = \frac{1}{UN_{sam}}\int_0^U I_{test}(V)dV$$

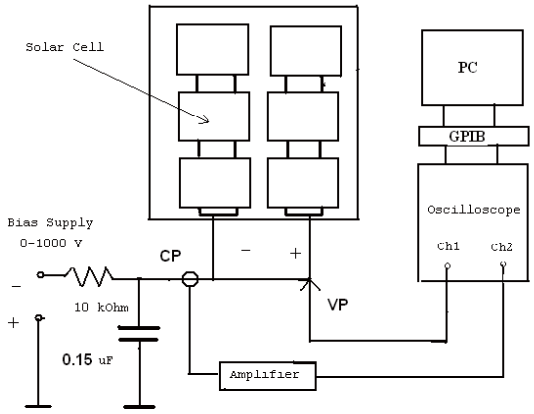
$I_{str} \leq 0.6$ mA. Thus, parasitic current does not exceed 0.1% of a string current



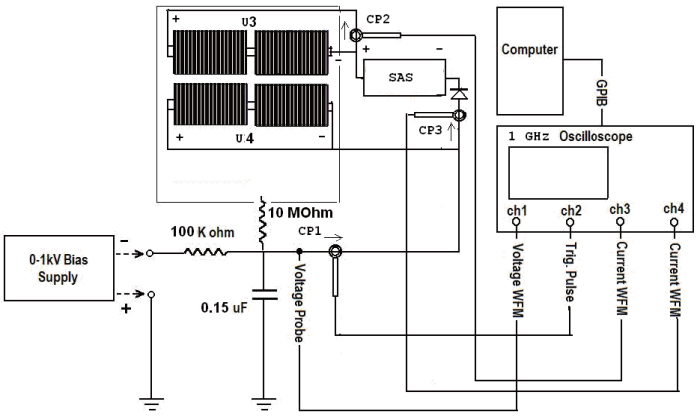








Circuitry diagram for determining a primary ESD inception voltage




Circuitry diagram for sustained arc inception measurements

***Equipment***: Oscilloscope LeCroy LC564 DL, 1 GHz bandwidth, 4 channels;
Tektronix TDS 460 A, 400 MHz, 4 channels;
Current probes: CP1-LeCroy AP015 DC 50 MHz;
CP2 & CP3 –HIOKI 3273-50 DC 50 MHz ;
Tektronix A6312 and A6302 current probes.
Voltage probe: Tektronix DCx100);
Solar Array Simulator (SAS): HP E4351B, 4 A, 120 V, $C_{out}$<50 nF;
Power Supply: Keithley K-237, 0-1.1 kV, 0-10 mA.
K-240, 0-100 V, 0-1 A.
Video cameras and VCR.





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## SOLAR ARRAY THERMAL BALANCE

$$\left(\sum_m c_m \rho_m h_m\right)\frac{dT}{dt} = (1-\chi)\cdot W - (\alpha_1+\alpha_2)\sigma T^4$$

**Thermal Properties**

| Material | Density $10^3$ kg/m$^3$ | Spec.Heat J/kgK | Therm. Conduct. W/mK | Thickness µm |
|---|---|---|---|---|
| Glass | 2.6 | 840 | 1.1 | 100 |
| Adhesive | 1.08 | 867 | 0.14 | 50 |
| Silicon | 2.33 | 712 | 149 | 100 |

$$\tau_e = \frac{\rho_m c_m h^2}{\kappa}$$

Time scale is in *ms* range

$$\sum_m c_m \rho_m h_m = 430 \quad \frac{J}{m^2 K}$$





$$\frac{d\theta}{dx} = (1-\chi)w - \theta^4 \qquad \theta = \frac{T}{T_0}; \qquad x = t\cdot\frac{(\alpha_1+\alpha_2)\sigma T_0^3}{\sum_m c_m \rho_m h_m} \qquad w = \frac{W}{(\alpha_1+\alpha_2)\sigma T_0^4}$$

$$\chi = 0.1; \qquad \alpha_1 = 0.85; \qquad \alpha_2 = 0.2$$

steady state temperature for a fully illuminated solar array is approximately equal to $T_{il}$=370 K ($\theta_{il}$=1.23).

When spacecraft is entering eclipse temperature decreases with the following rate

$$\theta(x) = \theta_{il}\left(1 + 3\cdot x\cdot\theta_{il}^3\right)^{-1/3}$$

During the time interval x≈1 (t≈4 min) temperature drops to Tec=200 K, and it stays practically steady until spacecraft starts coming out of the eclipse. Warming rate under full solar illumination can be found from the solution of balance equation.





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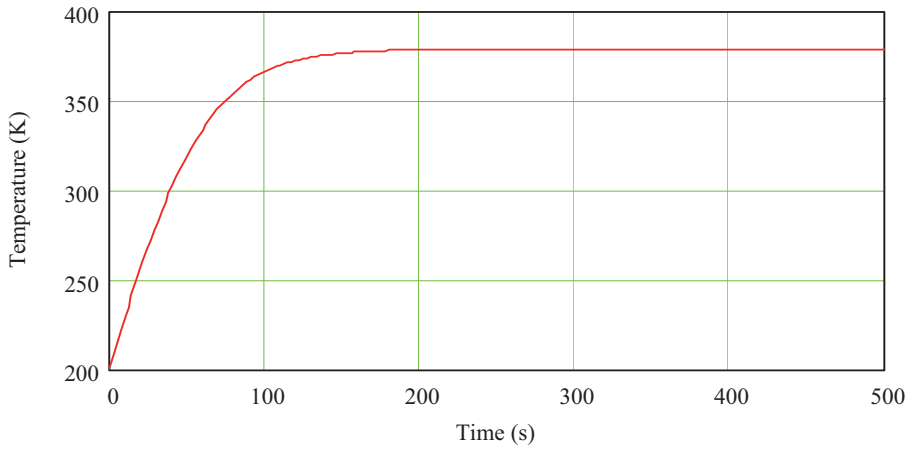
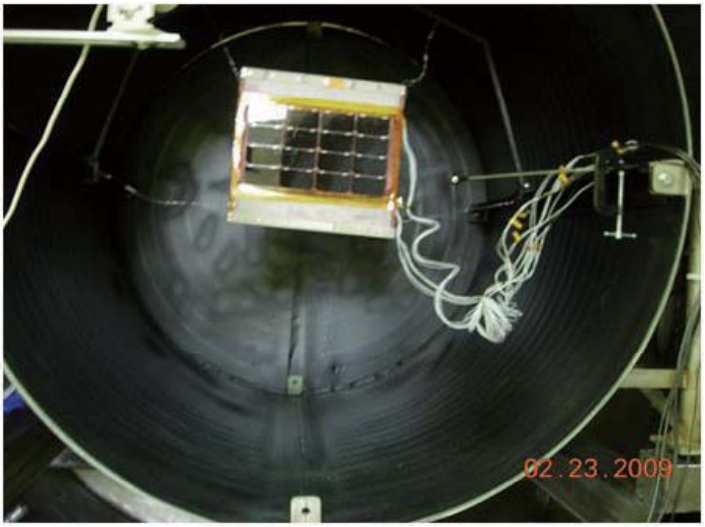



Thus, there is always a short time interval (≈ 1 min) during each orbit when array temperature is well below the room temperature





## ARCING ON SOLAR ARRAYS




Plasma parameters are measured with spherical Langmuir probe (LP). Arc sites are determined by camera and VCR.

Galofaro, J., Vayner, B., and Hillard, G. "*Experimental Tests of UltraFlex Array Designs in Low Earth Orbital and Geosynchronous Charging Environments*", AIAA Paper 2009-3525, June 2009.





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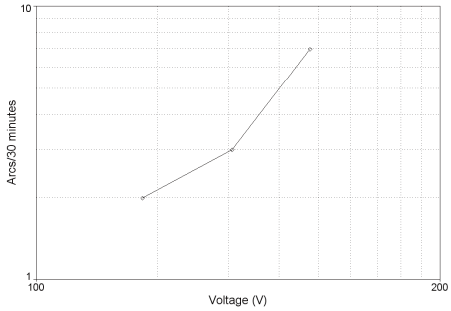
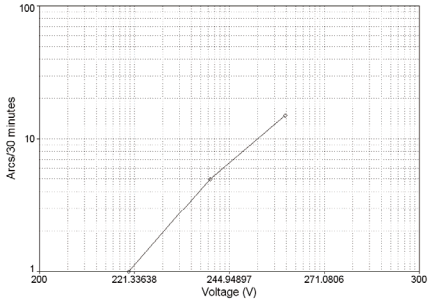
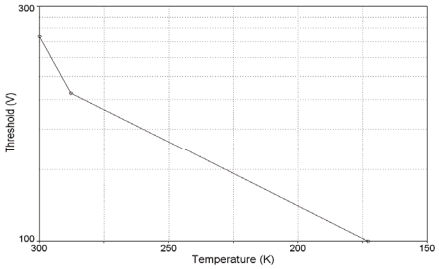
# LEO




Arc rate vs. bias voltage at low temperature (-100 C).




Arc rate vs. bias voltage at the temperature +10 C




Arc threshold vs. sample temperature



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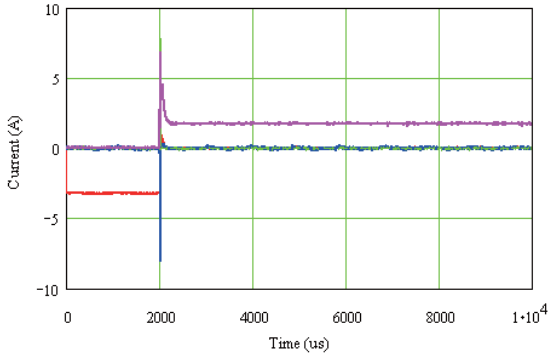
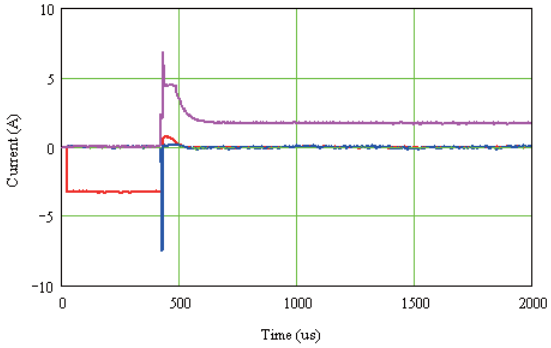
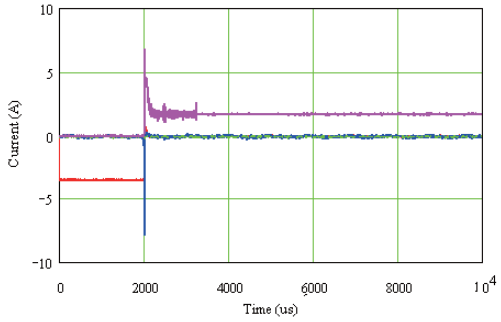
# SAS 120 V, 1.75 A- NO SA of 10 events



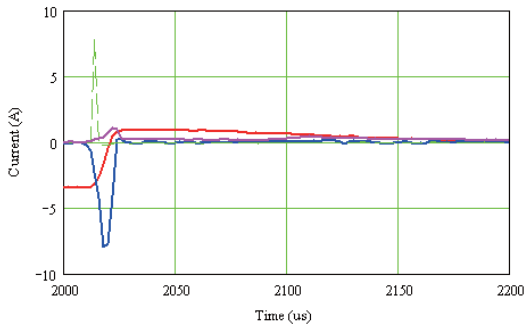

Event #2




Event #1




Event #7




Event #10





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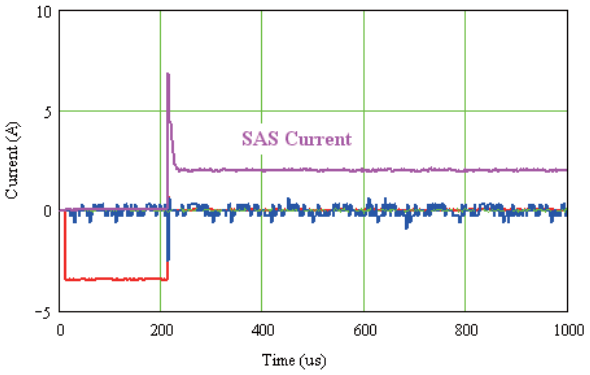
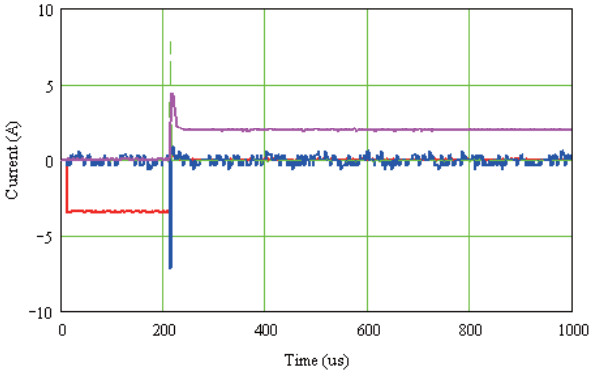



Event #4. SAS 120 V, 2 A. Temp. +15 C. t>8 ms




Event #6. SAS 120 V, 2 A. Temp. +15 C, t>8 ms

Events #5 and #7 were short. Event #8 was SA.

Voltage measured by SAS was 45-50 V during the SA.

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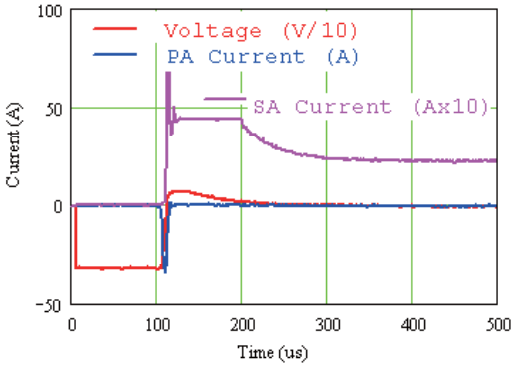
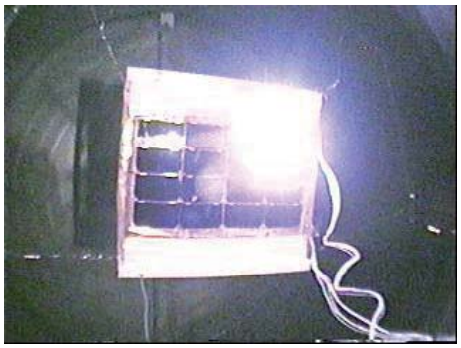
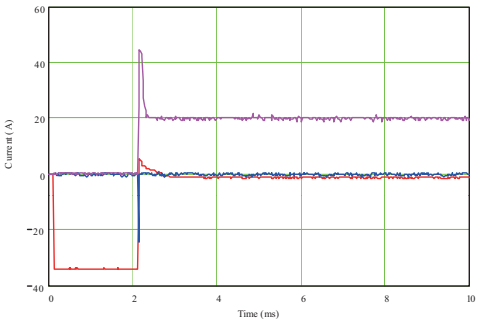


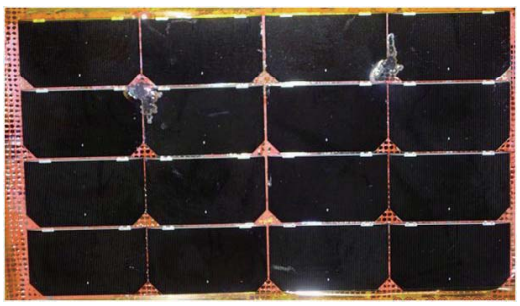

Sustained arc registered at -320 V bias, and 120 V and 2.25 A SAS parameters



Sustained arc with SAS parameters 120 V and 2.25 A (one frame).




Sustained arc with SAS parameters 120 V and 2.0 A, and sample temperature 16 C



The resulting damage from two sustained arcs

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**Table 3. Sustained arc current thresholds for different cathode materials**

| Material | Density g/cub.cm | Resistivity Ohm*cm | Th.Cond. W/m*K | Melting Temp. C | Melting Enthalpy J/g | Threshold Current A | Reference |
|---|---|---|---|---|---|---|---|
| Ag | 10.49 | 1.55E-6 | 419 | 962 | 105 | 1.2 | [24] |
| Cu | 8.96 | 1.7E-6 | 385 | 1083 | 204.8 | 1.6 | [24] |
| Ti | 4.5 | 5.5E-5 | 17 | 1670 | 435.4 | 2.0 | [24] |
| Si | '2.33 | 1E-2 | 124 | 1412 | 1800 | 1.6-2.0 | [33] |
| Ge | 5.32 | 5E-5 | 64 | 937 | 478 | 2.0-2.6 | [33] |


24. Mesyats, G.A. “Ectons and their role in plasma processes”, Plasma Physics and Controlled Fusion, Vol.47, No.2, 2005, pp.A109-A151.

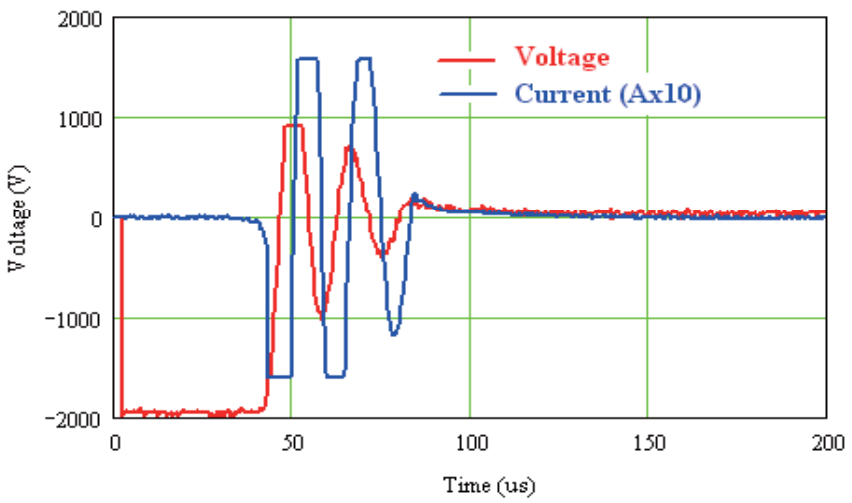
33. Vayner, B.V., Galofaro, J.T., and Ferguson, D.C. “Detrimental Effects of Arcing on Solar Array Surfaces”, 10th Spacecraft Charging Technology Conference, Biarritz, France, 2007, 14 p.






# GEO

beam of 2.8 keV energy and 1 nA/cm2 current density




Primary arc in GEO simulated environment on the sample with -70 0C temperature
No arcs with current density of 0.3 nA/cm^2.

$$E = \frac{\varepsilon_1}{\varepsilon_2 d_1 + \varepsilon_1 d_2}\left(\Phi_{cg} - U_b\right)$$

$E$=1.5 MV/m





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$$j = \beta \cdot \frac{E}{\rho_d} = 10^{-2}\beta \qquad nA/cm^2 \qquad \beta = 100\text{-}500$$

leakage current density is about 1.5-7.5 nA/cm.sq at room temperature

The resistivity of adhesive increases from ρ =10^15 Ohm*cm at 300 K to 10^17 Ohm*cm at the temperature of 200 K . Morgan, B.A. "Electrical Resistivity of DC93-500 Silicone Adhesive", *Aerospace Report No.* TR-*2003(1465)-1*, 2003,14 pp

## CONCLUSIONS

Tested solar arrays can be safely deployed in LEO providing operational voltages below 230 V. However, there is a short period of orbital time (about 1 min) when special care should be taken in order to prevent primary discharges on array surface. Current threshold for sustained arc inception is much higher than string current; thus, there is no concern regarding such catastrophic event as a sustained discharge between adjacent strings. Weakly conductive layer (ITO) should be implemented on top of cell coverglasses to avoid electrostatic discharges in GEO.

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