NORTHROP GRUMMAN

Safe Current and Voltage Thresholds to Prevent Sustained Arcing in Power Systems

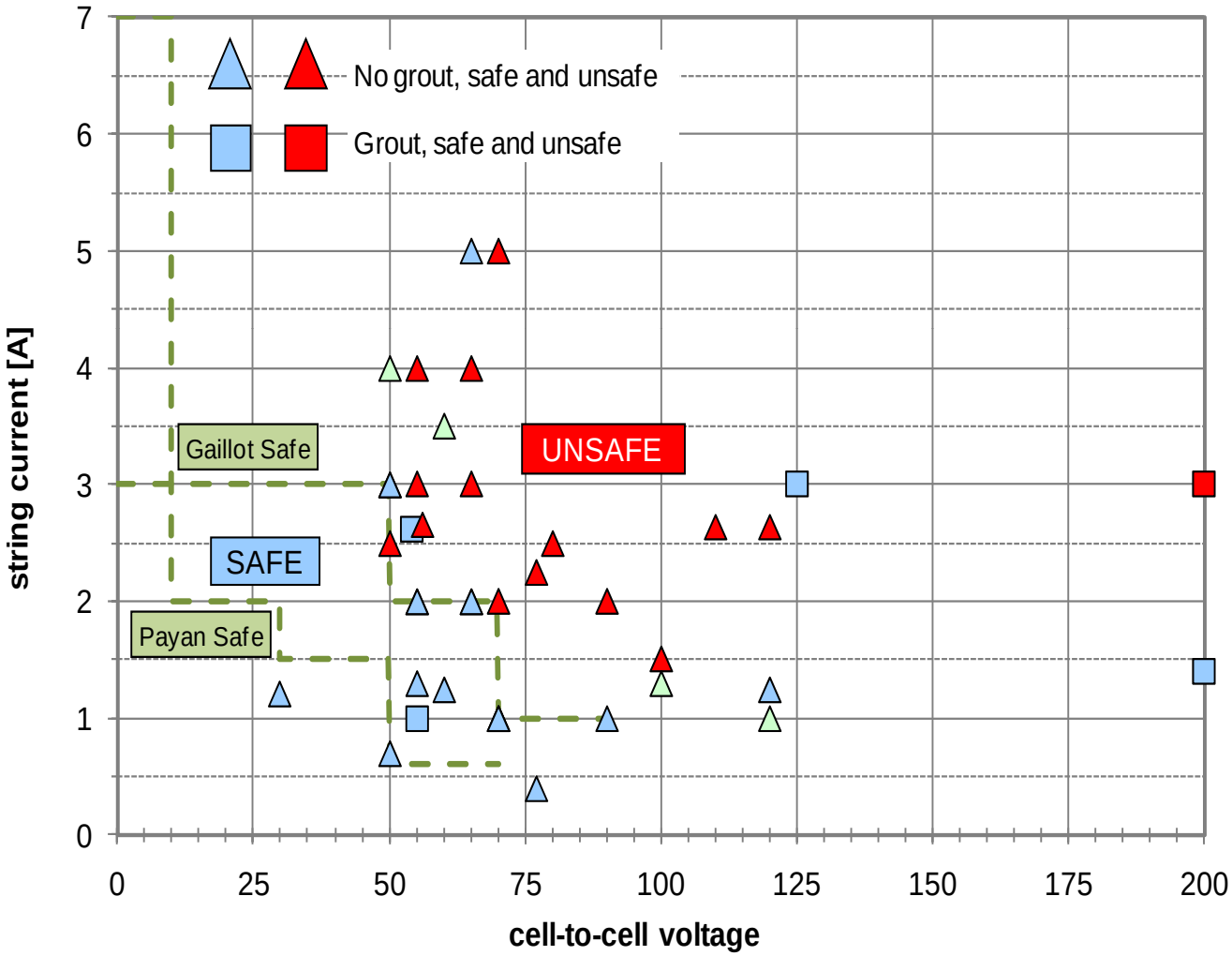
11th Spacecraft Charging Technology Conference

Albuquerque, New Mexico, September 20-24, 2010

Michael Bodeau
Technical Fellow

Decade of Tests Suggests I,V Safe Limits

- Test results since 1998 disclosure of spacecraft power loss induced by sustained arc on array front side
- 2 proposed safe I-V limit curves



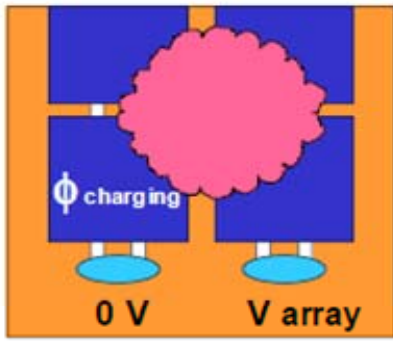


Figure 7. The spacecraft charging arc triggers a sustained discharge driven by the array string current and voltage.

Characteristics of Vacuum Arc

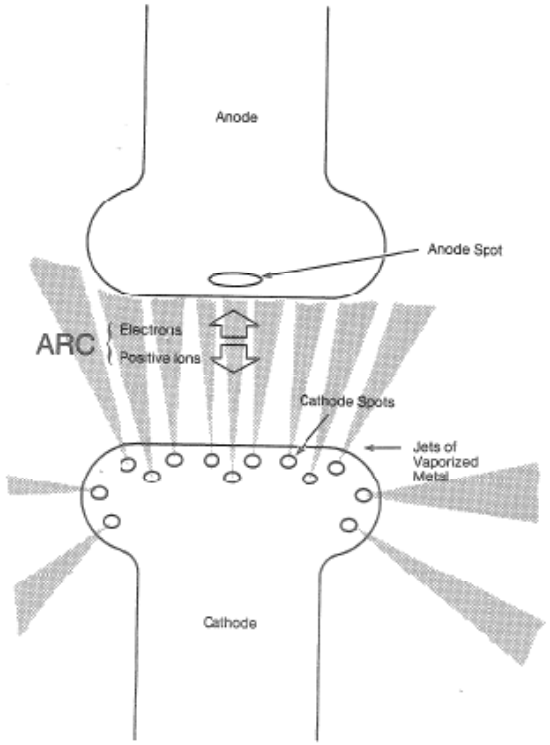
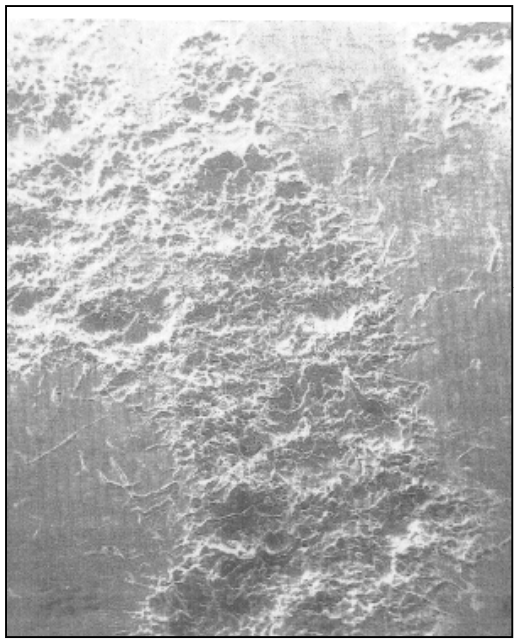
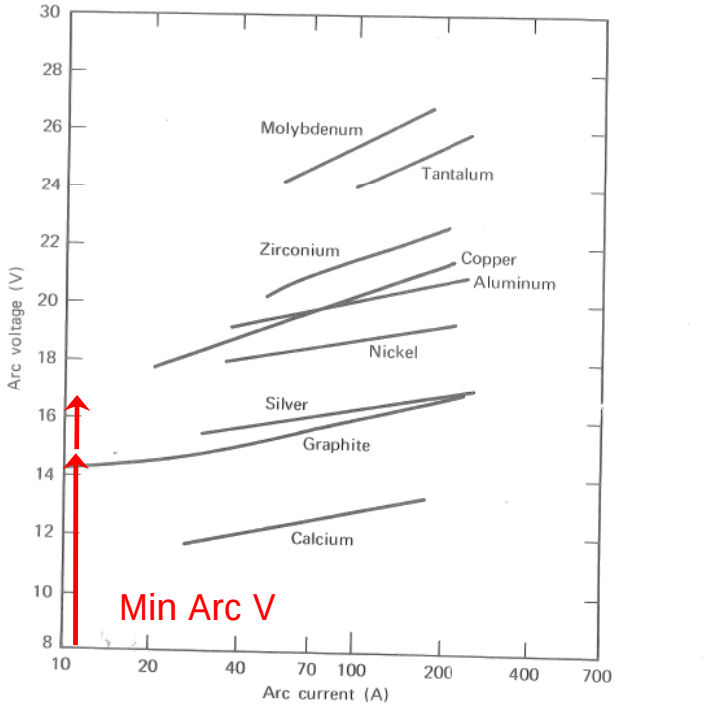


Fig. 1.2 Details of the vacuum arc.





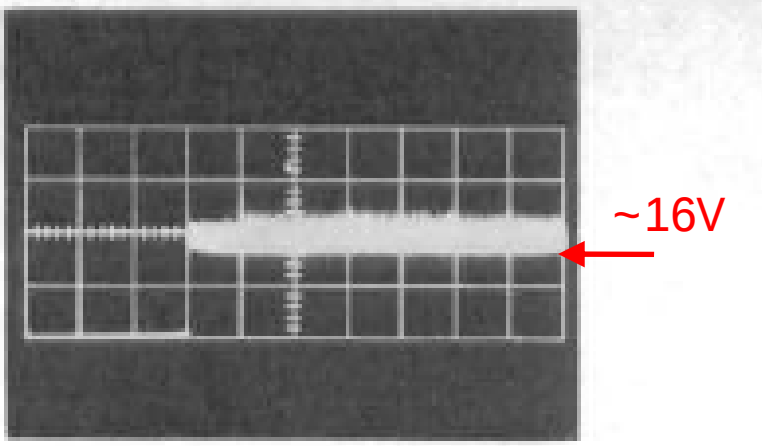
Dc volt-ampere characteristics of vacuum arcs measured by Davis and Miller.[19]

Arc current flows in plasma between electrodes; cathode spots of diameter 1-10μm with ~10^6 -10^8 A/cm^2

Tracks show that arc current vaporizes & ionizes cathode, new plasma sustains arc

S/C primary power systems have > min Arc voltage. When vacuum arc is established, arc resistance is low ($\Delta V/\Delta I$ = 4V/180A = 22mΩ for Cu)

Vacuum Arcs Sustain at a Minimum Voltage Well Below Array Voltage Threshold



Oscillogram showing arc voltage and noise for a copper vacuum arc (10 V/cm, 1 ms/div).

Table 1

Element	V_L (V)	s	Element	V_L (V)	s	Element	V_L (V)
Li	9·0	1·27	La	10·5	2·98	Sb	8·8
Na	7·0	1·41	Nd	11·5	3·3	Bi	7·5
Cu	15·5	2·05	Gd	11–11·5	3·0	Cr	15·5
Ag	12·5	1·93	Dy	11·5	3·02	Mo	23·0
Au	12·9	2·05	Er	11·5	2·9	W	23·2
Mg	11·0	2·04	Yb	6·6–7·1	1·28–1·5	Te	11·0
Ca	8·0	1·98	Tl	15·5	3·04	Mn	12·0
Sr	7·0	1·99	Zr	18·5	5·88	Fe	15·5
Ba	6·5–6·5	1·88	Hf	15·0–20·0	3·64–6·4	Co	13·9
Zn	9·1	0·91	C	12·0	0·93	Ni	16·5
Cd	8·1	1·02	Sn	10·5	2·14	Pd	16·0
Hg	7·5	1·00	Pb	8·0	1·41	Pt	13·5
Al	15·5	2·89	Nb	19–24·0	4·7–7·5		
Ga	10·0	1·43	Ta	20–23·0	5·2–6·9		
In	9·5	1·71					

- Min V threshold depends upon material's thermal properties
- Range of Min V values reported in literature

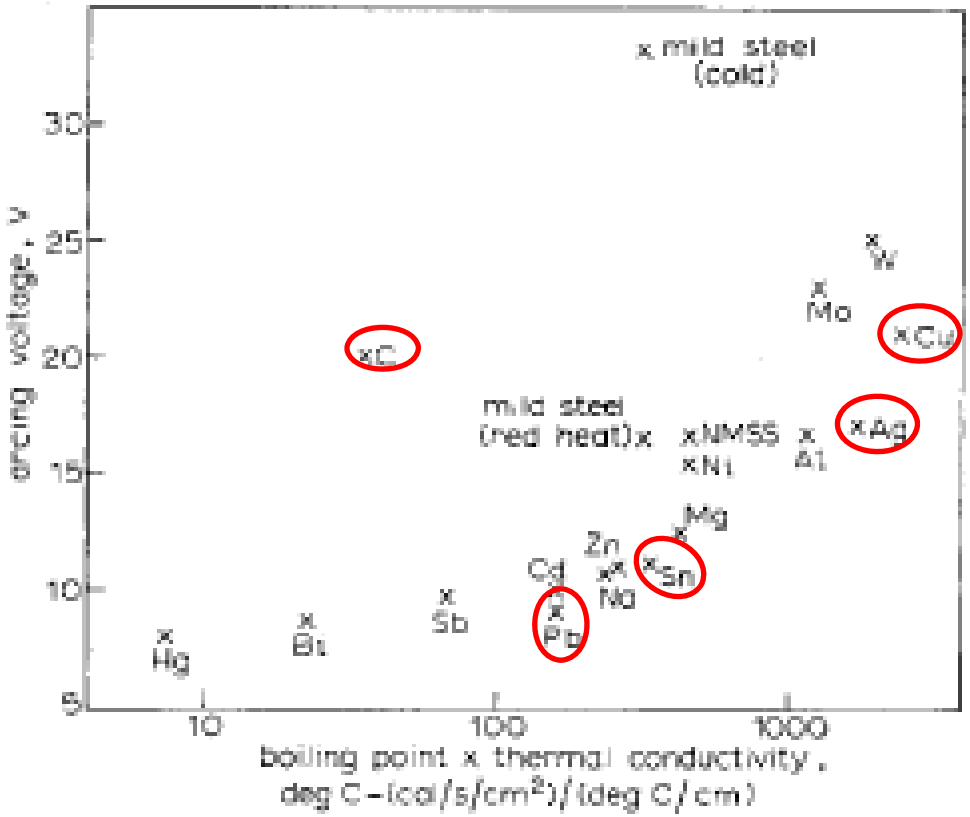


Fig. 5

Effect of thermal properties of cathode on arcing voltage

Arc Duration and Damage Depend Upon Current

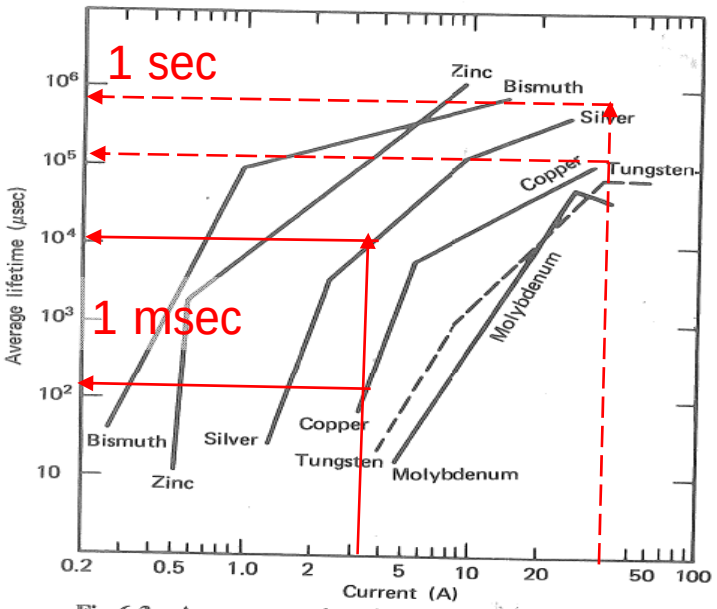
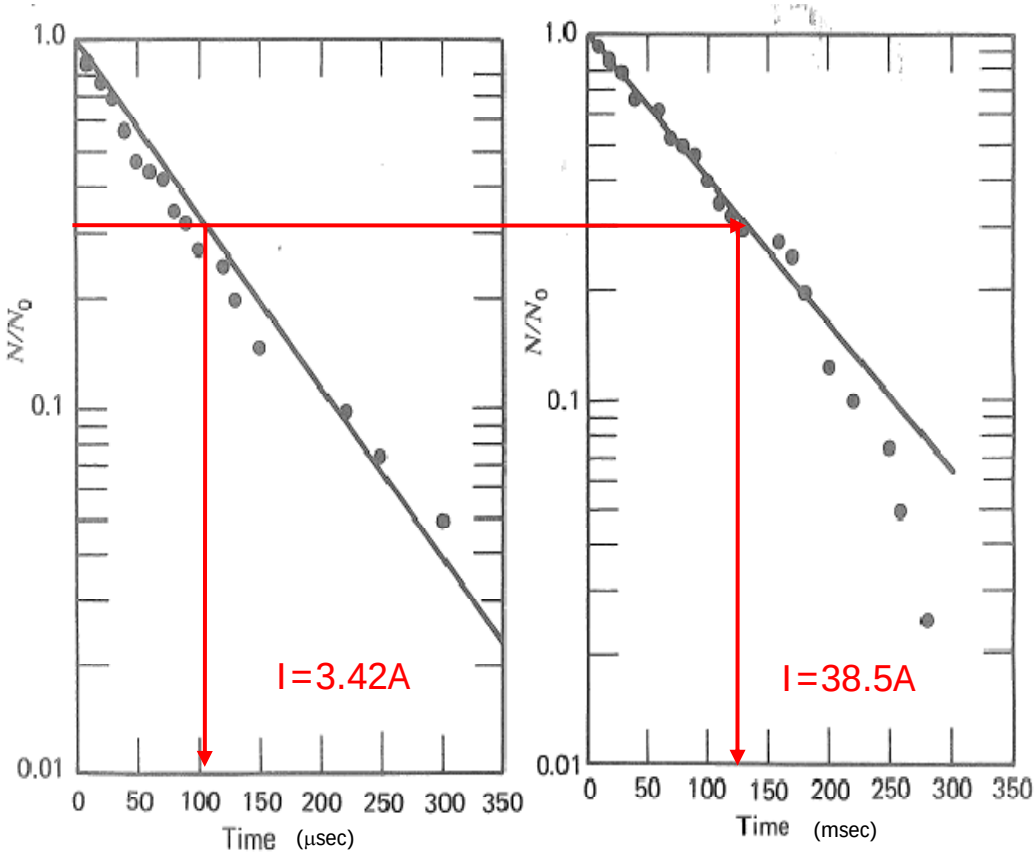


Fig.6.3 Average arc duration for various metals.

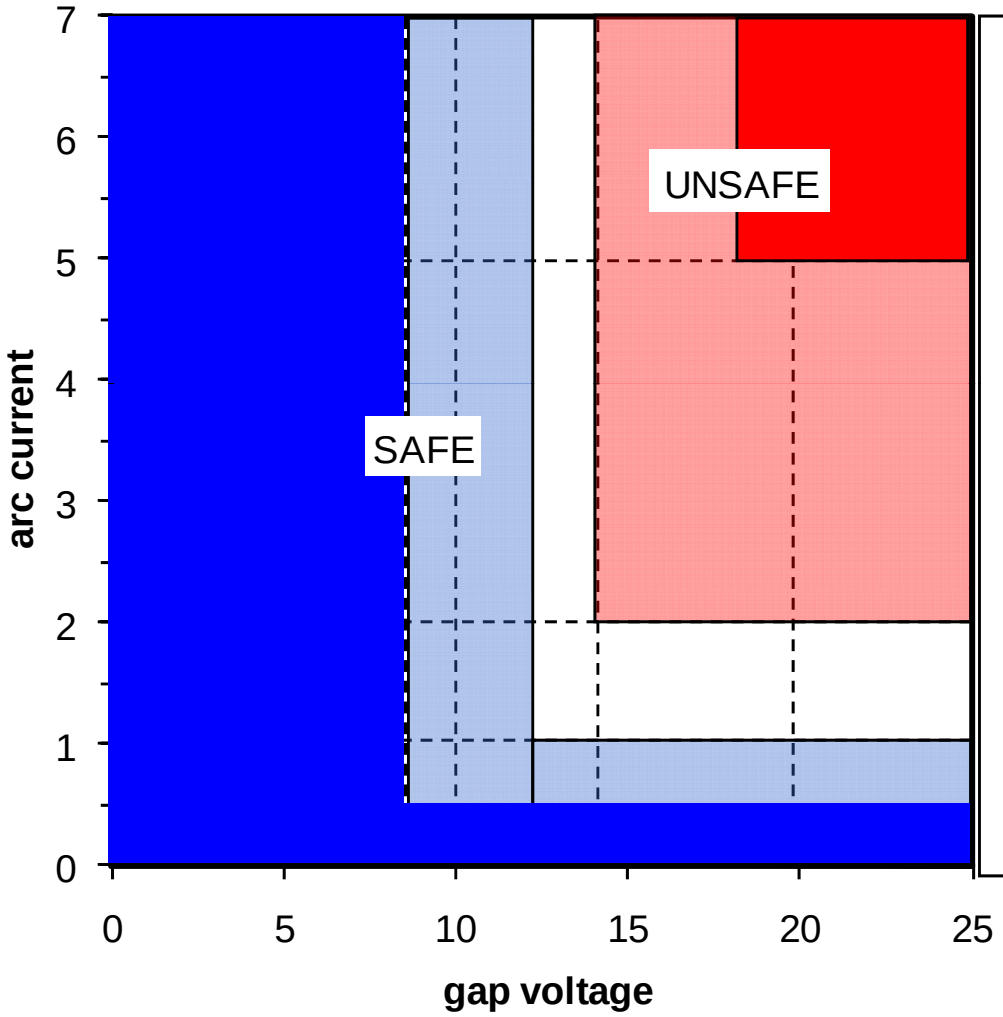
- Average arc lifetime @ 3⁺A is ~ 100us for Cu and ~10ms for Ag, 100-700ms @ 30A
- Lifetimes for fixed I&V follow exponential survival law distribution—possible that an arc lasts much longer (and shorter) than average

~10x increase in arc current causes ~1000x increase in arc



Fractional # of Arcs (Y-axis) Lasting Longer than Time t (X-axis: usec on left, msec on right)

Vacuum Arc Literature Shows a Lower Safe Voltage Threshold Than Array/Cell Testing



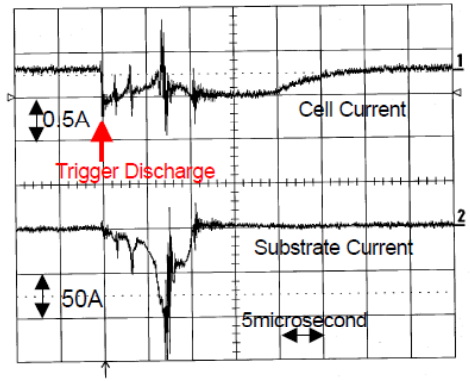
Loral in-orbit and on-ground sustained arcing data. Note string voltages are 80V and 75V, which exceeds the unsafe voltage threshold. We do not know what the arc voltage was during the ground tests, or the location of the arc in the strings and the delta V to the adjacent cell in orbit. So we cannot provide an arc voltage drop value.

Sustained arcs seen at 2.25, 2.75A with string voltage of 75-80V

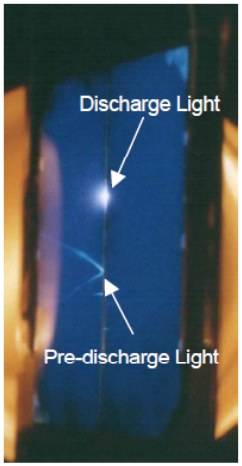
>1000 arcs at 0.2-0.4A last only 10-50us

Sustained arcing at string currents of <1A is not possible

Secondary Arcs of Duration ≤100us-1ms Are Not Harmful to Insulation, Even in Quantity

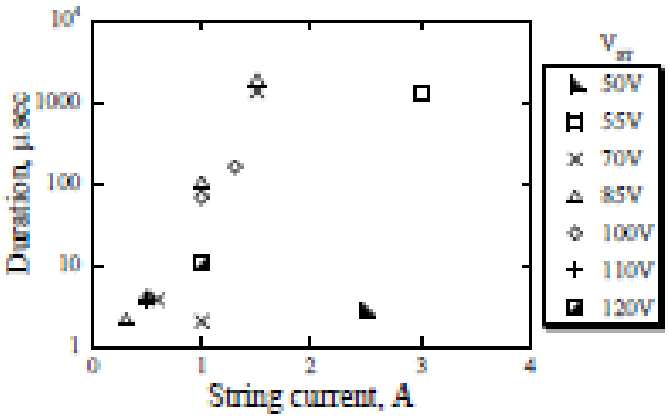


(a) Waveforms of transient currents



(b) Photograph of light

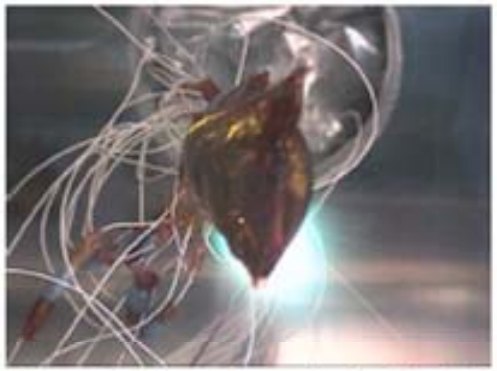
Figure 3. Example of the waveforms of transient currents and the discharge light in the case of d=0.8mm and V_a=77V.



Change of non-permanent sustained arc duration according to the string current

- [Fuji 03] About 100 rigger arcs with shunt current ≤30us. No detrimental damage to the cell gap. The cumulative duration of the 100 arcs is <3msec.
- [Kim 05] 1000's of primary and non-sustained secondary arcs did not degrade insulation, whereas a single 120sec sustained arc dropped isolation to <30ohms
- [Gaillot 05] 100usec secondary arcs are not harmful, even in quantity. Millisecond arcs degrade insulation slightly (no power effect) and progressively degrade cell I-V characteristics slightly (minor power effect) even in quantity.
- [Berthou 05] Secondary arcs began to appear at 60-80V and were systematic at 90V. No degradation of insulation occurred. Their frequency and duration increased as the cell-to-cell voltage increased, ranging from 30us to 145us and averaging 85us. At 120V, 1.25A, no sustained secondary arcs were observed. As Istr increased, the duration of the arc increased (from 30us to 3ms)
- CONCLUSION: need to look for conditions that promote longer duration (>100usec to >1msec) sustained vacuum arcs for damage

Vacuum Arcs Can be Triggered by Various Plasma Sources Wherever Sufficient V&I Exist



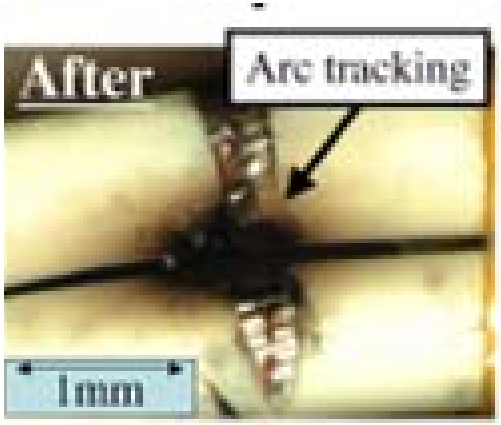
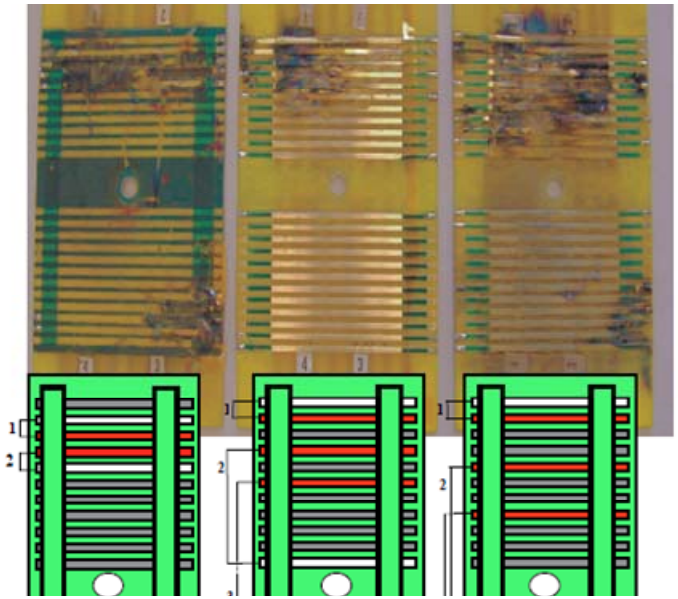


Figure 12 Plasma from the the hole of the MLI destroyed by ESD.

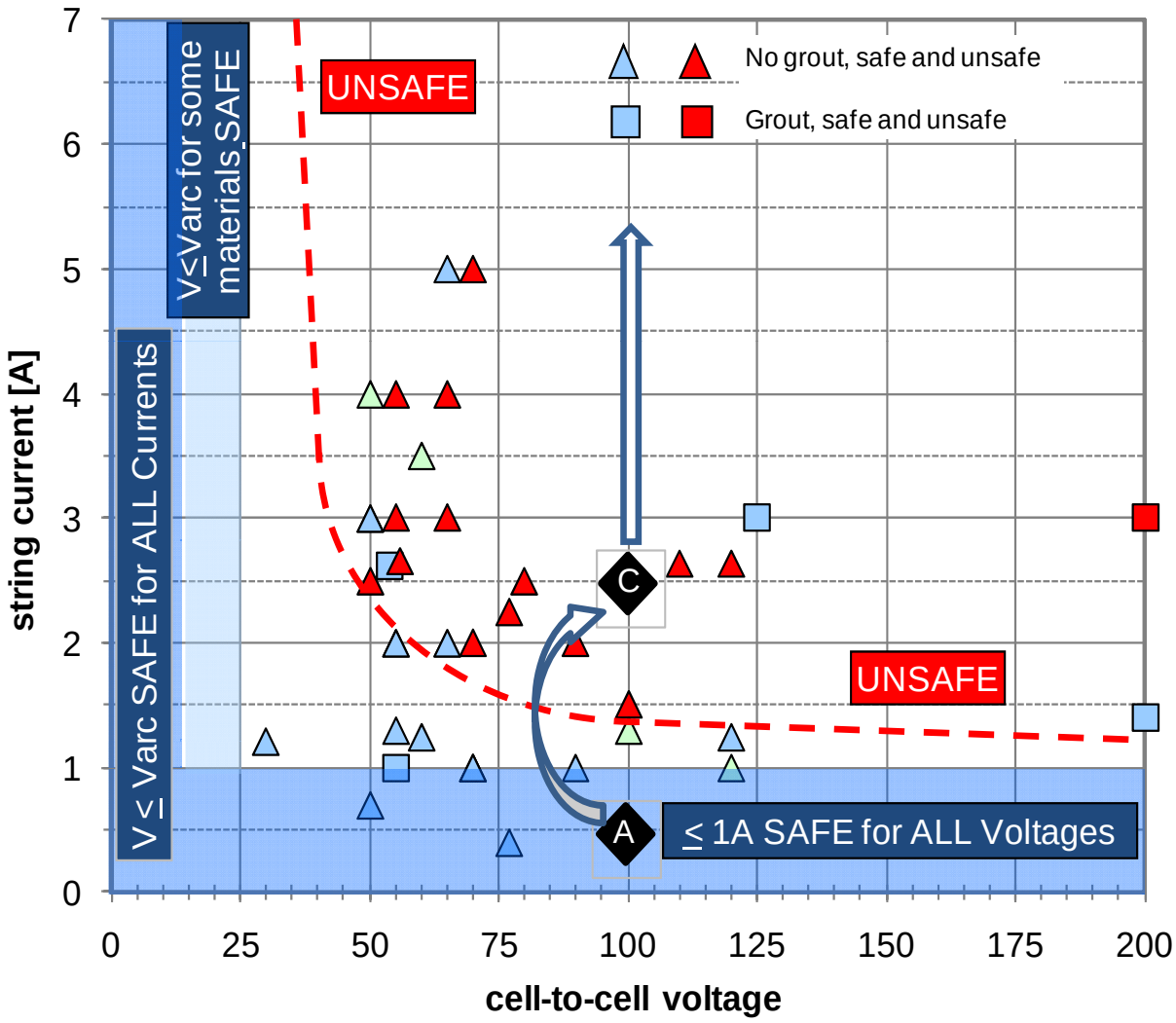
- In-orbit and ground test failures have occurred in harnesses, SADAs, power circuits of electronics
- Plasma from fusing tin whiskers, wires, debris impacts and ESD are all potential triggers



Tin whiskers can fuse into plasma that sustains vacuum arc

- Tin whisker (and wire) vacuum arcs have readily occurred in 30V and 50V primary power systems with high currents
- Consistent with vacuum arc literature, and lower V than solar array ESD tests

Conventional Solar Cell Arrays Operate in Safe Zone, Rest of Primary Power System Does Not



- 1 solar cell string ≤1A on anode side of its blocking diode is safe at any V
  - ISO test not needed
  - Risk increases rapidly as current reaches 1.5-2A
- Groups of strings joined beyond blocking diode cathodes are unsafe
  - Combined current is 2.5-4A or more
  - Sustained arc can draw current from primary power bus (>10's to 100's A) once arc voltage drops below bus V
- Primary power system in unsafe zone-fuses protect power bus
- Secondary power circuits are inherently safe
  - Min Varc > secondary V of 5-12V and lower

Summary

- Conventional arrays are safe--limit string current with 1 blocking diode/string to ~ <0.5-1A, far too low to sustain vacuum arc
  - Front-side array testing *for sustained arcing* is not needed
  - Continue to test for ESD degradation of cells per AIAA standards
- Beyond diode cathode, strings are combined into groups that are routed to array regulator electronics and primary power bus
  - Combined strings (e.g., 5-8) push short circuit current available for a vacuum arc up to 2.5-4A, in the high risk range
  - Much more current may be available from primary power bus, which will significantly extend arc lifetime and damage-add to testing
- Risks occur from blocking diode cathodes to slip ring assy to primary power bus & battery all the way to the primary power input to load secondary power converters
  - Double insulation and isolation help, but degrade over mission life--test protection of EOL coupons
  - Fusing can protect the power bus from single arc induced faults, but spares can be consumed before EOL
  - Vacuum arcs can propagate (e.g. arc tracking in wire bundles)

References

[Approx. Chronological Order]

- Hoeber et al., “Solar Array Augmented Electrostatic Discharge in GEO,” AIAA 98-1401, 17th Int’l Comm. Sat. Systems Conference and Exhibit, Yokohama Japan, Feb 1998
- Leung et al., “A test program to evaluate the immunity of HS702 solar array to sustained discharge,” 6th Spacecraft Charging Technology conference, Hanscom AFB, 1998 published in proceedings, AFRL-VS-TR-20001578, 1 September 2000
- Amorim et al., “Vacuum Arcs: Literature Review and Common Characteristics with Secondary Arcs on Solar Arrays,” 7th Spacecraft charging Technology Conference, Noordwijk, Netherlands, ESA SP-476 Nov 2001
- Amorim et al., Electrostatic Discharges on solar arrays: common characteristics with vacuum arcs,” J. Phys. D: Appl. Phys, Vol 35 2002
- Levy et al., “Secondary arcs on Solar Arrays: Occurrence, thresholds, characteristics and Induced Damage,” 7th Spacecraft charging Technology Conference, Noordwijk, Netherlands, ESA SP-476 Nov 2001
- Payan et al., “Electrostatic Discharges on Solar Arrays: Physical Model of Inverted Potential Gradient Electrostatic Discharge,” 7th Spacecraft charging Technology Conference, Noordwijk, Netherlands, ESA SP-476 Nov 2001
- Payan et al., Risks of low voltage arcs sustained by the photovoltaic power of the satellite solar arrays during an electrostatic discharge: Solar Array dynamic simulator,” 7th Spacecraft charging Technology Conference, Noordwijk, Netherlands, ESA SP-476 Nov 2001
- Toyoda et al, “Power reduction of solar Arrays due to arcing under simulated GEO Environment,” AIAA 2003-682, 41st Aerospace Sciences Meeting Jan 2003 Reno Nevada
- Leung, “Plasma Phenomena Associated with Solar Array Discharges and Their Role in Scaling Coupon Test Results to a full panel,”, 8th Spacecraft Charging Technology Conference, NASA CP-2004-213091
- Cho et al., “Issues for the Int’l standard of ESD ground test for geo satellite solar array,” 8th S/C charging tech. conference, Huntsville Ala. Oct 2003, NASA CP-2004-213091
- Toyoda et al., “Development of Solar array for WINDS: ESD tests,” 8th S/C charging tech. conference, Huntsville Ala. Oct 2003, NASA CP-2004-213091
- Sato et al., “Development of solar Array for a Wideband Internetworking Engineering Test and Demonstration Satellite (WINDS): System design,” 8th S/C charging tech. conference, Huntsville Ala. Oct 2003, NASA CP-2004-213091

References (continued)

- Fuji, “Electron-Beam-Induced ESD Triggering Discharge Tests of Solar Arrays for Space Use”, 8th spacecraft Charging Technology conference, Huntsville Ala. Oct 2003, NASA CP-2004-213091
- Fuji, “ESD-Triggered Arc Discharges on Solar Array by Electron-Beam Irradiation,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Kim, Aso, Hosada and Cho, “Threshold Conditions to Induce the Sustained Arc on the solar Array Panel of Leo Satellite,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Shikata, Hosoda, Cho, “Optical Spectral Analysis of arc plasma on solar array in GEO plasma environment,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Gaillot et al., “Secondary Arcs on Solar Array-Test results of EMAGS 2,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Berthou et al., “Plasma ESD Qualification Test Procedure of Alcatel Space Solar Array,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Amorim et al., “Electrostatic Discharges on 1m^2 Solar Array Coupon-Influence of the Energy Stored on Coverglass on Flashover Current,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Ferguson et al., “NASA GRC and MSFC Space-Plasma Arc Testing Procedures,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Cho, “Japanese Practices of Solar Array ESD Ground Tests,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Fuji, “Basic Experiment for Vacuum Arc Discharges Triggered by ESD,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005
- Payan and Schwander, “Solar Array Test Set-up Proposed by CNES in the Frame of European Standardization: Prevention of Secondary Arcing Induced by electrostatic Discharge,” 9th S/C Charging Technology Conference, JAXA SP-05-001E, April 2005


NORTHROP GRUMMAN