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Clint Thomson

JR Dennison
Utah State University

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SNAPOVER: ANOMALOUS PLASMA CURRENT COLLECTION BY POSITIVELY BIASED CONDUCTORS WHEN SURROUNDED BY A DIELECTRIC

C.D. Thomson

and J.R. Dennison

Utah State University, Logan, UT

ABSTRACT

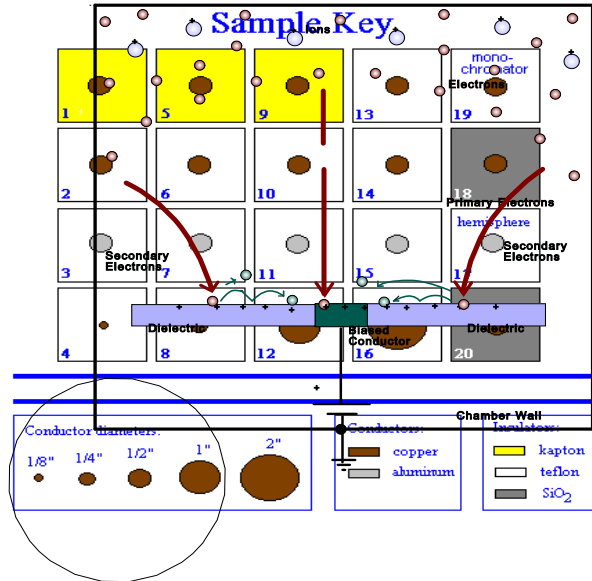
Over the last decade, high-powered spacecraft have been designed that will operate at voltages greater than 100 V. At these voltages, the solar arrays can undergo both destructive arcing at negative biases, and plasma electron current collection at positive biases. Furthermore, above some critical positive bias voltage (~100 V), the electron current collected by the array interconnects increases dramatically through a phenomenon termed "snapover". During snapover, large portions of the solar array cover glass charge positively, and begin to draw electron current from the plasma as if it were a conducting surface. This leads to substantial power losses for the spacecraft. We describe the results of an experimental investigation aimed at examining the importance of conducting material, insulating material, size and shape of the conductor, sample history, biasing rate, plasma density, and condition of the dielectric surface (contamination and smoothness) to the onset potential and magnitude of the parasitic snapover current. Theoretical investigations and computer simulations have proposed that the fundamental physical process underlying snapover is secondary electron emission from the dielectric. Our attempts to confirm the importance of secondary electron emission in the mechanism responsible for snapover were not conclusive, but in general did not support previous simple interpretations of the SE model. In addition, we observed much larger current jumps at biases from 350 V to 1000 V attributed to gas discharges. Both surface roughening and surface coatings were found to substantially inhibit snapover and gas discharge.

INTRODUCTION

In the past, satellite solar arrays have operated at voltages of less than 100 volts. However, over the last 20 years, plans have been made to launch larger and more complex spacecraft that will require much more power to operate. This shift in interest towards high powered spacecraft has presented new physics and engineering problems for designers. For example, operating at high currents inevitably leads to significant transmission line mass and I^2R power losses. Alternatively, operating at high voltages can result in detrimental interactions between the spacecraft and the ions and electrons that make up the space plasma environment.¹ To reduce cabling mass, power losses, and unwanted magnetic torque and drag effects it became mandatory to design arrays that operate at higher voltages and lower currents.^{2,3}

The International Space Station is an example of a high powered spacecraft that will operate at high voltages. In reaching equilibrium with the surrounding plasma (no net current flow from the environment) part of the solar array will float positive to collect electrons while other parts will float negative to collect ions. It is estimated that the most negative end of the space

station's arrays will float at ~140 V with respect to the surrounding plasma, while the most positive end will float at voltages over 100 V.⁴ At these voltages, a number of undesirable plasma interactions can ensue. First, high negatively biased solar arrays exhibit destructive arcing which can lead to both cover glass surface damage and sudden current pulses that can interfere with system instruments and control electronics.⁵ Second, positively biased arrays easily draw electron current from the plasma due to the relatively low mass (and high mobility) of the electrons.³ These currents may result in either surface charging or can be collected directly by exposed conductor interconnects or semiconductor solar cells.¹ Insulated conductors can be exposed to plasma currents when high energy meteoroids or orbital debris impact and punch tiny "pinholes" in the insulation. These currents effectively drain the system power supply and are therefore termed "parasitic" currents. At low positive voltages, parasitic electron currents are generally not a real concern; however, above a critical positive voltage (~100 V), solar arrays can undergo a phenomenon called "snapover" which further increases the electron current by a considerable amount.^{1,4}



During snapover, the electron current collected by exposed conducting interconnects exhibits a sudden increase at a critical positive bias voltage. Once this voltage threshold has been reached, the surrounding glass overlay charges positively and then draws electrons as if it were a conductor. Consequently, the effective current collecting surface area of the solar array is no longer limited to the conductor interconnects, but is greatly enlarged by the surrounding insulator. This results in substantial power losses for the spacecraft. In addition, snapover can cause high negative counter potentials on other parts of the spacecraft solar array that can lead to destructive arcing.³

MECHANISM

A number of researchers have addressed snapover theoretically and computationally.⁶⁻¹³ The majority of the theoretical formulations proposed over the past 15 years suggest that secondary electron emission, specifically from the dielectric surrounding the

If this model is correct, the voltage required to initiate snapover (termed the onset voltage) should depend heavily on the SE properties of the dielectric material. Specifically, it should depend on the PE incident energy (and therefore the closely related conductor bias voltage) above which the insulator's SE yield is greater than unity—the so called “first crossover energy”, E_1 (see Fig. 2).⁶

EXPERIMENT

As detailed as the theoretical explanations are, it is interesting that there has been little systematic

positively biased conductor, is the fundamental physical process responsible for the anomalous currents underlying snapover.⁶⁻⁸ Secondary electron (SE) emission is the emission of electrons from a surface as a result of energetic electron bombardment. The vast majority of the emitted secondary electrons possess low energies (less than ~20 eV), and the total number of SE's produced per incident primary electron (PE) is a function of both material and incident energy, E_p .

A simplistic explanation of the role of SE's in snapover can be summarized as follows. As the conductor bias is increased, ambient electrons from the plasma are accelerated radially inwards. Some of these electrons strike the dielectric immediately adjacent to the conductor with an energy equal to or somewhat less than the conductor bias (*i.e.*, for a conductor bias of +100 V, the electron kinetic energy upon striking the adjacent dielectric is E_p 100 eV), producing secondary electrons from the dielectric. Above some critical conductor bias the ratio of SE's to PE's (termed *SE yield*, δ) from the dielectric becomes greater than unity (see Figs. 1 and 2) causing the dielectric near the conductor to begin to charge positively.

Thus, the now positively biased dielectric begins to attract electrons from the plasma. Some of these electrons attracted by the charged dielectric strike immediately adjacent, uncharged portions of the dielectric, cascading the process until a larger region is positively charged.⁶⁻¹³ This entire process can lead to increased current since most of the low energy SE's emerging from the dielectric surface are drawn to the conductor in a “hopping” motion.^{6,7,10} Finally, within a very short time, a new equilibrium is established through a current balance between incoming primary electrons and outgoing secondaries which are collected by the conductor.^{6,13} This basic model describes many of the key features attributed to snapover; however, a more realistic model incorporates plasma sheath dynamics and the charge gradient along the dielectric.¹³

experimental investigation done on the basic parameters of the phenomena. In addition, previous ground based^{7,8,14} and flight¹⁵⁻¹⁷ experiments have been unable to confirm the detailed nature of snapover or the role played by SE emission. In response to the deficit of quantitative information, we designed a detailed systematic experimental research plan aimed at determining the fundamental parameters of the phenomenon. More detailed accounts of this work are provided elsewhere.¹⁸⁻²⁰ An array of twenty samples of various predetermined materials, shapes, and sizes was constructed as shown in Fig. 3. Each sample was comprised of a 10 cm x 10 cm dielectric (either

Figure 4. (Top) Current-voltage profile for a typical sample (1/2" Cu-Teflon™). Profile exhibits current jumps attributed to (a) pre-snapover, (b) primary snapover and (d) Paschen discharge. (Bottom) Derivative plot of the snapover peaks. Note the logarithmic vertical axes in both graphs. Teflon™, Teflon™ covered with Kapton™ tape, or SiO₂) with a conductor (Cu or Al) mounted in the center, flush with the front surface. One 1.27 cm diameter hemispherical Al conductor was also included for comparison with Al planar conductors.

The sample array was mounted vertically in the center of a 3 m high x 1.8 m diameter plasma chamber at the Plasma Interaction Facility (PIF) at NASA's John Glenn Research Center.²¹ The chamber was pumped to a base pressures of $\sim 10^{-6}$ Torr using three cold trapped oil diffusion pumps. Using Argon pressures of $\sim 1 \times 10^{-5}$ to 1×10^{-4} Torr, plasmas were produced with standard Penning sources. A 2 cm diameter Langmuir probe determined typical plasma densities of $\sim 1 \times 10^5$ to 4×10^5 cm⁻³ and temperatures of ~ 1 to 3 eV

Starting at bias voltages of -100 V and typically ending at +600 V, a series of current vs conductor bias curves (typically 10 sweeps per run) were recorded for each conductor/dielectric pair. Although the step size

Examination of the I-V profile data revealed that most samples exhibited more than one current jump over the voltage range of approximately +100 V to +1000 V. By

and ramping rate were varied from 1V/s to 50 V/s on a number of samples, 10 V/s (5 V steps with 500 ms delays) were standard. Currents up to 10 mA were measured. One additional sample was mounted in view of a spectrometer to analyze the glow that often accompanies the discharge phenomenon. The optical spectrum (350 nm to 600 nm) of a sample undergoing discharge was recorded.

Our experiments¹⁸ were designed to investigate the importance of:

1. How cycling a given sample through multiple snapovers changes sample surfaces and subsequent snapovers.
2. The effect of conductor biasing ramping rate (step size and time delay).
3. The effect of surface contamination (such as diffusion pump oil) of both insulator and conductor surfaces.
4. The effect of the ambient plasma density.
5. The type of insulating material. Teflon™, Kapton™, and SiO₂ were used.
6. The type of conductor material. Al and Cu were used.
7. The effect of the conductor size or shape (flat vs spherical).
8. The effect of roughening a strip of the surrounding insulator to try to inhibit snapover.
9. The effect of coating the surrounding insulator with other materials such as colloidal microcrystalline graphite (Aerodag™) or MgO.
10. The optical spectra of the glow that sometimes accompanies the phenomenon to determine the materials involved.¹⁴

A GENERAL DISCUSSION OF THE RESULTS

classifying these current jumps (based primarily on onset voltage and current jump magnitude) four major categories over the voltage range of 80 V to 1000 V were

identified:¹⁸

Preliminary Snapover: First, a small current jump ($\sim 1 \mu\text{A}$ to $10 \mu\text{A}$ for $\frac{1}{2}$ " conductors) could often be distinguished and occurred quite frequently over the voltage range of 150 V to 200 V, depending on the sample.

Primary Snapover: The second major current jumps ($\sim 10 \mu\text{A}$ to $100 \mu\text{A}$ for $\frac{1}{2}$ " conductors) occurred consistently in most runs at voltages ranging from 220 V to 350 V. These current jumps are the primary focus of this study. It was proposed that these current jumps were related to the SE emissions of the sample as discussed in the mechanism section above.¹⁸⁻²⁰

Gas Discharge: The third major category of current jumps ($\sim 0.1 \text{ mA}$ to 5 mA for $\frac{1}{2}$ " conductors) appeared in a sporadic fashion from one run to the next and had onset voltages ranging anywhere from 350 V to 600 V. These larger current jumps were attributed to gas discharge in the near vicinity of the sample conductor. Similar current jumps of this magnitude and onset voltage range have been observed in previous experiments with similar interpretations.^{7,8} Gas discharge may have resulted from ionization of sample out-gassing due to local heating or electron stimulated desorption.

Paschen Discharge: The fourth major category of current jumps ($\sim 2 \text{ mA}$ to $>10 \text{ mA}$ for $\frac{1}{2}$ " conductors) also appeared intermittently with onset voltages ranging from $\sim 500 \text{ V}$ to 1000 V . These larger current jumps were attributed to breakdown of the background Argon gas.¹⁹

Surface contamination presented a serious limitation to our experiments. After approximately ten cycles, samples would develop a visible yellow ring around the conductor, identified as diffusion pump oil originating from the vacuum system of the plasma chamber. We estimated the deposition rate of diffusion pump oil as $\sim 30 \text{ nm/cycle}$ (approximately half the wavelength of visible light per ten cycles).²² By contrast, the maximum escape depth of SE for diffusion pump oil is 2-3 nm.²³ Since SE emission of low energy electrons is very surface sensitive, even monolayers of contamination can significantly affect

These four categories are identified on I-V curves in Figs. 4 and 5 as (a) pre-snapover, (b) primary snapover, (c) gas discharge, and (d) Paschen discharge. In addition to these four major current jump categories, many smaller magnitude current jumps were observed throughout the voltage range of 80 V to 1000 V. Most of these jumps occurred irregularly and were attributed to contamination effects or as random gas discharges. Also, although these four categories provided a general framework, ambiguities in classification did occur.¹⁸

HIGHLIGHTS FROM OUR PARAMETER STUDY

A more detailed description of the results of our experimental investigation can be found in Thomson *et al.*¹⁸ and Vayner *et al.*¹⁹ Outlined here is a summary of key results from our experiment that point out the limitations of our data, lead to direct evaluation of the snapover model, or describe techniques developed to inhibit snapover and gas discharges.

Dependence on Surface Contamination

emission.^{24,25}

Therefore, the effects of chamber contamination on our data were undeniable. This impeached the verisimilitude of our studies of the dependence of snapover on sample materials, since in some ways all samples may have been effectively similar diffusion pump oil. SE emission properties of diffusion pump oil are $\delta_{\text{max}}=1.8-2.0$, $E_{\text{max}}=140-150 \text{ eV}$, $E_1 = 75 \text{ eV}$.²³

Dependence on Sample Dielectric Type

To determine the importance of sample dielectric

and conductor materials on snapover, multiple biasing cycles were performed at a constant ramping rate of 10 V/s under similar plasma conditions of 60-80 μ Torr Argon pressure, electron number density of $n_e=1-3 \times 10^5 \text{ cm}^{-3}$, and electron temperature $T_e=1-3 \text{ eV}$.

The measured primary snapover onset voltages for samples with 1/2" Cu conductors and different dielectrics are, in increasing order, Kapton™ (247" 23 eV), SiO₂ (259" 11 eV), and Teflon™ (275" 34 eV). The measured gas discharge onset voltages are, in increasing order, Kapton™ (433" 50 eV), Teflon™ (460" 33 eV), and SiO₂ (510" 60 eV). In contrast, literature values of the first crossover in increasing order, are SiO₂ (40-45 eV)²⁶, Teflon™ (69 eV)²⁷, and Kapton™ (75 eV).²⁷

These results suggest that measured primary snapover and gas discharge onset voltage were not dependant on the dielectric first crossover energy. Specifically:

- (i) Measured variations in the primary snapover or gas discharge onset voltages were not statistically different from one another.
- (ii) The order of increasing primary snapover or gas discharge onset voltage were not consistent with the order of first crossover energies. The values of crossover energies for insulators reported in the literature have large uncertainties, making it difficult to evaluate their effect on snapover in this manner.²⁶⁻²⁸
- (iii) The primary snapover onset voltage values were /180 V higher than the first crossover energies of any of the dielectrics or of diffusion pump oil. Even after corrections for sample, chamber ground, and plasma offset voltages, the measured onset voltages were still more than 100 V above the first crossover energies.^{18,19}

Finally, a dependance on dielectric first crossover energy could not be conclusively ruled out due to poor statistics resulting from an inadequate number of samples tested. Also, as discussed above the extensive contamination of the samples by diffusion pump oil may have masked any dependence on

dielectric SE emission properties.

Dependence on Sample Conductor Type

Comparison of results for 1/2" Cu-Teflon™ with 1/2" Al-Teflon™ samples suggested statistically significant differences due to conductor type. Aluminum conductor samples exhibited lower primary snapover and gas discharge onset voltages and current jump magnitudes than samples with copper conductors. Results for the current jump ratio are inconclusive.

Dependence of snapover or gas discharge current jumps with conductor type was not expected. These trends may reflect differences in the adsorption or removal of diffusion pump oil from the metals. For example, the Al had an insulating film of Al₂O₃ that may have led to surface charging and accumulation of the polarizable diffusion pump oil, while the oxide of Cu formed in a vacuum is conducting.²⁹ There may also have been differences in the surface roughness of the Al versus Cu conductors that could have affected SE emission and snapover directly or affected adsorption/desorption of contaminants.

The Effects of Sample Surface Treatments

To further test the secondary electron model of snapover and to explore methods to inhibit current jumps and stave off the onset of snapover, the insulator surfaces of several samples were treated and then tested through repeated cycling. Figure 6 compares typical I-V curves of the treated samples to an untreated 1/2" Cu-Teflon sample acquired under similar plasma environments and with consistent ramping profiles. Figure 6 also shows optical micrographs of the surfaces.

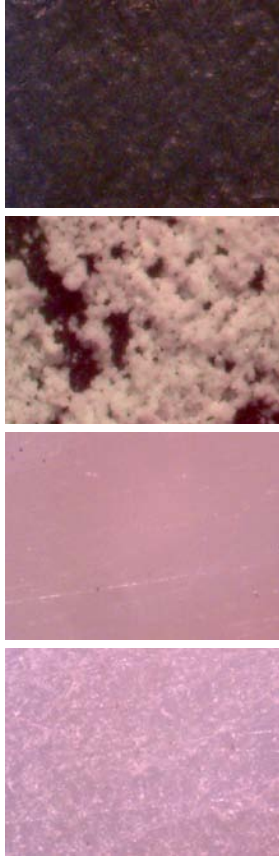


Figure 6. Current-voltage profiles showing the effects of surface modification on the primary snapover (b) and gas discharge (c) current jumps. Profiles shown are for: (1) an untreated 1/2" Cu-Teflon™; (2) a 1/2" Al-Teflon™ sample roughened with 70 μm grit sandpaper; (3) a 1/2" Al-Teflon™ sample with the dielectric coated with a thin film of ~50 μm sized cubic crystals of MgO; and (4) a 1/2" Cu-Teflon™ sample with the dielectric coated with a thin film of colloidal microcrystalline graphite (Aerodag™). Optical micrographs of these four samples (in order from left to right) shown below

are of ~900 μm x 500 μm areas. Rocky Mountain NASA Space Grant Consortium Symposium 2000

1/2" Al-Teflon™ samples were roughened using 70 Fm and 100 Fm grit sandpaper. By doing so, snapover current jumps were greatly reduced or eliminated. In addition, gas discharge current jumps were typically reduced by more than an order of magnitude. In some cases both snapover and gas discharge current jumps almost completely disappeared. Reduction in snapover is consistent with the fact that roughening can reduce SE collection by recapturing SE's on adjacent surfaces before they can be transported to the conductor or initiate the cascade. However, the observation that both snapover and gas discharge current jumps were suppressed suggest that surface modification had other effects on the processes. Previous experimental studies have reported inconsistent results for roughened surfaces, although Stillwell *et al.* reported similar findings that roughening decreases both snapover and gas discharge collection currents.^{7,30}

A 1/2" Al-Teflon™ sample was coated with a thin film of ~50 μm sized nearly-cubic crystals of MgO suspended in alcohol. The results were very similar to those for roughened surfaces, with snapover nearly fully suppressed and gas discharge current jumps delayed and greatly reduced in magnitude. Since thin film MgO has a maximum SE yield 2 to 8 times that of Teflon™, it is reasonable to expect SE-enhanced current jumps to increase rather than be suppressed.³²⁻³³ However, the MgO microcrystals can be considered an alternate way to roughen the surface, leading to diminishing effects similar to those described above.

Finally, we applied a thin film of Aerodag™ (colloidal microcrystalline graphite in isopropyl alcohol with a polymer based binder) on 2.3 cm and 4.3 cm OD regions of the dielectric of two 1/2" Cu-Teflon™ samples. The overall current flow to the conductor was

increased by almost two orders of magnitude, while the slope of the I-V curve (*i.e.*, the resistance) prior to discharge was reduced. The enhanced collection current resulted from the conducting properties of the graphite. In effect, the conductor size of the samples was increased, resulting in a corresponding increase in the sample collection currents. Because of the overall current increases, lower voltage snapovers appeared to be suppressed (see Fig. 6). However, closer inspection determined that they were still present with current jump magnitudes similar to those of untreated surfaces. The gas discharge current jump was

Solar arrays operated at high positive voltages can undergo a phenomenon called snapover where the electron current collected by the interconnects increases dramatically at some threshold voltage. This can lead to substantial power losses for high powered spacecraft such as the International Space Station. A series of experiments were conducted to test the mechanism of snapover. In general, more than one current jump was observed over the range of +100 V to 1000 V; these tended to grow in current jump magnitude with higher onset voltages. The current jumps were classified into four major categories based on value of onset voltage, magnitude of current jump, I-V curve behavior, and optical emission as follows: (a) pre-snapover, (b) primary snapover, (c) gas discharge, and (d) Paschen discharge.

Attempts to correlate primary snapover with the SE model of snapover were not successful for a number of reasons:

- (i) Primary snapover inception voltages occurred at much higher voltages than simple interpretation of the SE model suggests.
- (ii) SE values of the sample dielectric emission characteristics, including the first crossover energy were not known with the necessary

reduce by a factor of ~ 2 , while the onset voltage remained unchanged. Graphite does not have a first crossover energy; therefore, the SE model predicts a significant decrease in the snapover collection currents.³¹ The observed behavior that snapover did occur with current jump magnitudes similar to the untreated TeflonTM sample may have been due to the polymer binder in the AerodagTM or to the presence of diffusion pump oil contamination.

CONCLUSIONS

- accuracy to verify snapover inception voltage dependence on dielectric first crossover energies.
- (iii) Snapover onset voltage and current jump magnitude exhibited some dependence on conductor type, which is not expected from the SE model.
- (iv) Diffusion pump oil contamination by the plasma chamber may have obfuscated any snapover dependence on sample dielectric type.
- (v) An inadequate number of samples were tested to conclusively rule out dependence on dielectric first crossover energies.

Although the mechanism has not yet been clearly identified by our study, sample surface treatments to the surrounding dielectric were found to suppress snapover. Roughening the surface of the sample dielectric on the order of 50 Fm to 100 Fm—either by abrasives or by applying a thin layer of MgO—inhibited the collection currents of both snapover and gas discharge. These results suggest possible mitigation strategies for the snapover power loss problem.

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REFERENCES

- ¹ D.E. Hastings, H. Garrett, *Spacecraft Environment Interactions*, Cambridge University Press, 1996.
- ² N.J. Stevens, "Interactions Between Spacecraft and the Charged Particle Environment", *Spacecraft Charging Technology-1978*, NASA CP-2071, 1979, pp. 268-294.
- ³ G. Hillard and D.C. Ferguson, "The SAMPIE Flight Experimental Final Technical Requirements Document," NASA TM-106224, NASA Lewis Res. Center, 1993.
- ⁴ D.C. Ferguson, "Interactions Between Spacecraft and their Environments", Proc. 31st AIAA Aerospace Sciences Meeting and Exhibit, January 11-14, 1993, Reno, Nevada.
- ⁵ H. Thiemann, R.W. Schunk, K. Bogus, "Where Do Negatively Biased Solar Arrays Arc?", *Journal of Spacecraft and Rockets*, Vol. 27, No. 5, 1990, pp. 563-565.
- ⁶ D.E. Hastings, P. Chang, "The Physics of Positively Biased Conductors Surrounded by Dielectrics in Contact with a Plasma", *Phys. Fluids B*, Vol. 1, No. 5, 1989, pp. 1123-1132.
- ⁷ R.P. Stillwell, R.S. Robison, H.R. Kaufman, "Current Collection from the Space Plasma Through Defects in Solar Array", *Journal of Spacecraft and Rockets*, Vol. 30, No. 4, 1993, pp. 488-494.
- ¹⁶ G.B. Hillard, D.C. Ferguson, "Solar Array Module Plasma Interactions Experiment (SAMPIE): Science and Technology Objectives", *Journal of Spacecraft and Rockets*, Vol. 30, No. 4, 1993, pp. 488-494.
- ¹⁷ D.C. Ferguson, G.B. Hillard, "In-Space Measurement of Electron Current Collection by Space Station Solar Arrays", Proc. 33rd AIAA Aerospace Sciences Meeting and Exhibit, January 9-12, 1995, Reno, Nevada.
- ¹⁸ Thomson, C.D., Dennison, J.R., Davies, R.E., Vayner, B., Galofaro, J., Ferguson, D.C., de Groot, W., "Investigation of the Snapover of Positively Biased Conductors in a Plasma", Proc. 38th AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, 2000, Reno, Nevada.
- ¹⁹ B. Vayner, J. Galofaro, D. Ferguson, W. de Groot, "The Conductor-Dielectric Junction in a Low Density Plasma", Proc. 38th AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, 2000, Reno, Nevada.
- ²⁰ J. Galofaro, B. Vayner, W. de Groot, D. Ferguson, C. Thomson, J.R. Dennison and R.E. Davies, "Inception of snapover and glow induced discharges", Proc. 38th AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, 2000, Reno, NV.
- ²¹ B. Vayner, C.V. Doreswamy, D.C. Ferguson, J.T. Galofaro, D.B. Snyder, "Arcing on Aluminum Anodized Plates Array Insulation", *Journal of Spacecraft and Rockets*, Vol. 22, No. 6, 1985, pp. 631-641.
- ⁸ M.R. Carruth Jr., "Plasma Electron Collection Through Biased Slits in a Dielectric", *Journal of Spacecraft and Rockets*, Vol. 24, No. 1, 1987, pp. 79-85.
- ⁹ R.C. Chaky, J.H. Nonnast, J. Enoch, "Numerical Simulation of Sheath Structure and Current-Voltage Characteristics of a Conductor-Dielectric Disk in a Plasma", *Journal of Applied Physics*, Vol. 52, No. 12, 1981, 7092-7098.
- ¹⁰ R.L. Kessel, R.A. Murray, R. Hetzel, T.P. Armstrong, "Numerical Simulation of Positive-Potential Conductors in the Presence of a Plasma and a Secondary-Emitting Dielectric", *Journal of Applied Physics*, Vol. 57, No. 11, 1985, pp. 4991-4995.
- ¹¹ S.T. Brandon, R.L. Kessel, J. Enoch, T.P. Armstrong, "Numerical Simulations of Positively-Biased Probes and Dielectric-Conductor Disks in a Plasma", *Journal of Applied Physics*, Vol. 56, No. 11, 1984, pp. 3215-3222.
- ¹² M.J. Mandell, I. Katz, G.A. Jongeward, J.C. Roche, "Computer Simulations of Plasma Electron Collection by PIX-II", *Journal of Spacecraft and Rockets*, Vol.23, 1986, pp. 512-518.
- ¹³ H. Thiemann, R.W. Schunk, "Particle-in-Cell Simulations of Sheath Formation Around Biased Interconnectors in a Low-Earth-Orbit Plasma", *Journal of Spacecraft and Rockets*, Vol. 27, No. 5, 1990, pp. 554-562.
- ¹⁴ D. Ferguson, G. Hillard, D. Snyder, N. Grier, "The Inception of Snapover on Solar Arrays: A Visualization Technique", Proc. 36th AIAA Aerospace Sciences Meeting and Exhibit, January 12-15, 1998, Reno, Nevada.
- ¹⁵ N.T. Grier, "High Voltage Surface-Charged Particles Environment Test Results From Space Flight and Ground Simulation Experiments," NASA TM-79184, 1979.
- Immersed in Low Density Plasmas", *Journal of Spacecraft and Rockets*, Vol. 35, No. 6, 1998, pp. 805-811.
- ²² W.N. Hansen, Utah State University, private communications, 1999.
- ²³ K. Goto, K. Ishikawa, "Secondary Electron Emission from Diffusion Pump Oils II.: δ - η Analysis for DC-705", *Japanese Journal of Applied Physics*, Vol. 7, No. 3, 1968, pp. 226-231.

- ²⁴R.E. Davies, J.R. Dennison, "Evolution of secondary electron emission characteristics of spacecraft surfaces," *Journal of Spacecraft and Rockets*, Vol. 34, No. 4, 1997.
- ²⁵W.Y. Chang, J.R. Dennison, Jason Kite and R.E. Davies, "Effects of evolving surface contamination on spacecraft charging," Proc. 38th AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, 2000, Reno, NV.
- ²⁶C.W. Mueller, "The Secondary Electron Emission of Pyrex Glass", *Journal of Applied Physics*, Vol. 16, 1945, pp. 453-458.
- ²⁷I. Krainsky, W. Lundin, W.L. Gordon, R.W. Hoffmon, *Secondary Electron Emission Yield Annual Report for Period July 1, 1980 to June 30, 1981*, Case Western Reserve University, 1981.
- ²⁸R.F. Willis, D.K. Skinner, "Secondary Electron Emission Yield Behavior of Polymers", *Solid State Communications*, Vol. 13, 1973, pp. 685-688.
- ²⁹J.H. Moore, C.C. Davis and M.A. Copeland, *Building Scientific Apparatus*, 2nd Ed. (Addison-Wesley, Reading, MA, 1989), p. 335.
- ³⁰A.R. Krauss, "Localized Plasma Sheath Model on Dielectric Discharge of Spacecraft Polymers", *Air Force Weapons Laboratory (AFWL) Final Report*, 1989.
- ³¹H. Bruining, "Secondary Electron Emission", *Philips Technology Review*, Vol. 13, No. 3, 1938, p. 80.
- ³²P. Wargo, B.V. Haxby, W.G. Shepherd, "Preparation and Properties of Thin Film MgO Secondary Emitters", *Journal of Applied Physics*, Vol. 27, No. 11, 1956, pp. 1311-1316.
- ³³N. Rey Whetten, A.B. Laponsky, "Secondary Electron Emission from MgO Thin Films", *Journal of Applied Physics*. Vol. 30, No. 3, 1959, pp. 432-435.