NASA GRC and MSFC Space-Plasma Arc Testing Procedures

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Abstract—Tests of arcing and current collection in simulated space plasma conditions have been performed at the NASA Glenn Research Center (GRC) in Cleveland, Ohio, for over 30 years and at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama, for almost as long. During this period, proper test conditions for accurate and meaningful space simulation have been worked out, comparisons with actual space performance in spaceflight tests and with real operational satellites have been made, and NASA has achieved our own internal standards for test protocols. It is the purpose of this paper to communicate the test conditions, test procedures, and types of analysis used at NASA GRC and MSFC to the space environmental testing community at large, to help with international space-plasma arcing-testing standardization.

Discussed herein are neutral gas conditions, plasma densities and uniformity, vacuum chamber sizes, sample sizes and Debye lengths, biasing samples versus self-generated voltages, floating samples versus grounded samples, test electrical conditions, arc detection, preventing sustained discharges during testing, real samples versus idealized samples, validity of LEO tests for GEO samples, extracting arc threshold information from arc rate versus voltage tests, snapover, current collection, and glows at positive sample bias, Kapton® pyrolysis, thresholds for trigger arcs, sustained arcs, dielectric breakdown and Paschen discharge, tether arcing and testing in very dense plasmas (i.e. thruster plumes), arc mitigation strategies, charging mitigation strategies, models, and analysis of test results.

Finally, the necessity of testing will be emphasized, not to the exclusion of modeling, but as part of a complete strategy for determining when and if arcs will occur, and preventing them from occurring in space.

Index Terms— Arc discharges, Environmental testing, Aerospace simulation, Plasma measurements.

I. INTRODUCTION

Spacecraft collect current from the space plasma and sometimes arc into the space plasma. While models of these things are useful, it is the experience of all who have done space plasma testing that there are surprises along the way. Many times a seemingly well-thought out test will fail. Other times, some hardware design detail will make the test invalid. At other times, a completely unexpected phenomenon will appear. In other words, while models are useful as guides, only testing in simulated space plasmas will reveal what is likely to happen in space. The only thing better than a good simulated space plasma test is operation in the real space plasma, but this is expensive and difficult, and sometimes lacks the proper diagnostics to determine what really happened.

In the present paper, we talk only of arcing and current collection in space plasmas. This usually is very different than what happens in a pure vacuum. In other words, the space plasma modifies the test conditions, and can lead to unexpected arcing and current collection, due solely to the presence of an ambient plasma, that would not happen under vacuum conditions alone.

Space plasma testing has been done at the NASA Glenn Research Center (GRC) for over thirty years (see Grier and McKinzie [1]), and at the Marshall Space Flight Center (MSFC) for almost as long. During this period, proper test conditions for accurate and meaningful space simulation have been worked out, comparisons with actual space performance in spaceflight tests and with real operational satellites have been made, and NASA has achieved our own internal standards for test protocols. It is the purpose of this paper to communicate the test conditions, test procedures, and types of analysis used at NASA GRC and MSFC to the space environmental testing community at large, to help with standardization of international space-plasma arc-testing.

Unless otherwise specified, in this paper only MKS units will be used in all equations.

II. VACUUM CHAMBERS, PLASMAS AND NEUTRAL GASES – THE IMPORTANCE OF A COLLISIONLESS PLASMA

In order for a simulated space plasma test to be valid, the effects of ambient neutral gases must be minimized. One good start is to use a vacuum chamber, to keep ambient pressures very low. It is impossible to simulate in a vacuum chamber the very low neutral pressures in space. Therefore, one must keep the neutral gas from having an influence on the plasma generated. To do this, one must make the neutral gas

collisionless with the plasma – that is, make the mean-free path for electrons in the gas longer than some meaningful distance. In a plasma test, the chamber size is clearly the distance to use. If the electrons impact the chamber wall before they can ionize a neutral, the plasma in the chamber will be essentially collisionless.

The electron mean-free path in a thermal gas is given by the expression

$$L = R\, Tm/\, (N\, \sigma\, P) \qquad (1)$$

where R is the universal gas constant, Tm is the gas temperature (K), N is Avogadro's number, σ is the electron-atom collision cross-section and P is the pressure. In practice, eliminating electron-gas interactions means making the pressure low enough to prevent electron-neutral gas collisions from being important. For our purposes, let us take the neutral radius to be 2×10^{-10} m, which implies a cross-section of $\sigma = 1.3 \times 10^{-19}$ m^2. For typical test setups, where the gas temperature is about 300 K, this means making L larger than the plasma chamber width (see Section III below, and let us assume 1 m in our case), or the pressure lower than about 3.2×10^{-3} Pascals $= 2.4 \times 10^{-5}$ Torr.

It may not always be possible to maintain these low pressures, especially when the plasma source is operating. As a general rule of thumb, the neutral pressure in a plasma test should be kept lower than about 10^{-4} Torr if possible, or electron ionization of the neutral gas (Paschen discharge) may be a factor. When the neutral pressure is too high, and Paschen discharge occurs, it will be visible as a glow that extends for many centimeters through the vacuum chamber (see Ferguson et al [2]). If it is not possible to run at neutral pressures below about 10^{-4} Torr, one should be on the lookout for the Paschen glow. The Paschen glow has occurred many times in plasma chambers running at above about 10^{-4} Torr, and electron ionization has ruined current collection and arcing results in some notable tests. As most plasma chambers work by flowing a neutral gas through the plasma source, the neutral pressure condition must be maintained even when the plasma source is running. Neutral pressure gauges (ionization gauges) or RGAs (residual gas analyzers, usually quadrupole mass analyzers) may be used to monitor gas pressure during a test. Also, the local pressure near the sample can be much higher than measured by gauges installed on a plasma chamber wall due to outgassing and electron impact desorption. It is this local pressure that must be kept low.

In plasma testing, the gas which is being ionized by the plasma source should be chemically inert (such as the noble gases, neon, xenon, argon, krypton, and the like, although nitrogen gas has been used), and not be an electron sponge (such as sulfur hexafluoride). It is not important that the gas be representative of the gas species in the real space plasma, which is fortunate, since in LEO the gas is predominantly atomic oxygen, and in GEO it is the highly flammable hydrogen gas. When calculating ion fluxes, use the mass of the gas species actually being used. If ion collection is important, one should try to match the chamber ion flux to the ambient ram ion flux in orbit (see section IV below).

Many sorts of vacuum pumps have been used in plasma testing – oil diffusion pumps, turbopumps, and cryopumps. If oil diffusion pumps are used, oil back-streaming must be minimized, to avoid contaminating the samples. This means that, as a minimum, liquid nitrogen (or colder) cold traps must be used around the diffusion pump mouths. The importance of cleanliness of the chamber walls and inserted cables, instruments, etc., cannot be overestimated. Carbon contamination is common in vacuum chambers, and must be avoided; else the chamber walls must be cleaned before further testing.

III. ELECTRON AND ION DENSITIES AND TEMPERATURES, DEBYE LENGTHS AND SAMPLE SIZES

In Low Earth Orbit (LEO), the electron (and ion) density can vary from about 10^8 to about 10^{12}/m^3. Such densities are relatively easy to achieve in vacuum plasma chambers using Kauffman or hollow cathode sources. It is more difficult to reproduce the electron and ion temperatures in LEO (typically less than about 2300 K, or 0.2 eV) and it is even more difficult to measure temperatures so low. Most plasma sources have difficulty in producing plasmas of temperature less than about 5800 K (0.5 eV) for example. For many purposes, however, the plasma temperature is not extremely important, except in calculating thermal currents and currents collected by surfaces. One can often normalize by such fluxes to obtain arc rates, etc. that would be measured in a LEO plasma. However, for very detailed surface geometries, near the edge of a solar cell or for fine pinholes in dielectrics, for example, the electron temperature is very important for determining the currents that may be collected. The most modern plasma sources can produce temperatures lower than about 0.2 eV, but typically at the cost of having very dilute plasmas, where the plasma density is very low compared to LEO conditions, or at the cost of very high neutral pressures, where ionization of the neutral gas may severely affect the results.

Every surface in a plasma will be surrounded by a plasma sheath, where the plasma temperature allows electric fields to exist without immediate plasma neutralization. The plasma sheath for an unbiased surface has a thickness of about a Debye length, which is given by

$$\lambda d = (\varepsilon_0\, kT_e/ne^2)^{1/2}, \qquad (2)$$

where ε_0 is the permittivity of free space, k is Boltzmann's constant, T_e is the plasma temperature, n is the plasma number density, and e is the electron charge. (This formula is correct for typical LEO simulations when Te>>Ti. For a high density arcjet plasma, for example, where Te=Ti, the Debye length is half as great because of the ion contribution).

For typical plasma chamber conditions, n may be 10^{12} electrons/m^3 and the plasma temperature may be 11600 K (1 eV), and this gives a Debye length of about 0.0074 m (0.74 cm). Strictly speaking, the Debye length is only the plasma sheath thickness for a surface which is unbiased. For biased surfaces, the sheath will be thicker (the sheath thickness varies approximately as the square root of the ratio of the surface bias

to the electron temperature) and may reach 10 cm for a sample voltage of about 180 V with the above conditions.

Finally, the chamber used must be bigger than twice the sample size plus four times the sheath thickness, so that the plasma sheaths will not overlap. Remember, the inside chamber wall will also have a plasma sheath about a Debye length in thickness. Operationally, this means that for a sample of ½ m in size, a chamber of two meters diameter is more than sufficient for surface biases up to several hundred volts. In such a large chamber, with the sample centrally located, the sample will have the same conditions as if it were surrounded by the infinite plasma of space.

IV. FLOWING PLASMA VERSUS "STATIONARY" PLASMA

Most plasma sources will produce a plasma that is essentially stationary (has little bulk motion), and in fact this is often essential to guarantee a uniform plasma in the vacuum plasma chamber. However, the atomic oxygen plasma of LEO is being run into by an orbiting LEO spacecraft such that each oxygen ion impacts the surface with about 4.5 – 5.5 eV energy (7.6 km/s velocity). LEO spacecraft are supersonic with respect to the oxygen ions, but subsonic with respect to the electrons in the plasma. Thus, in calculating LEO electron and ion fluxes, one must assume that the ion flux is the ram flux, whereas the electron flux is omni-directional and thermal.

The one-sided thermal electron current flux density to a surface is given by the expression

$$J_{th} = nev_e, \tag{3}$$

where n is the electron number density, e is the electron charge, and v_e is the average electron velocity perpendicular to the surface.

$$v_e = (kT_e/2\pi m_e)^{1/2}, \tag{4}$$

so that

$$J_{th} = ne(kT_e/2\pi m_e)^{1/2}. \tag{5}$$

This amounts to $J_{th} = 2.49 \times 10^{-16}$ n $T_e^{1/2}$ A/m^2, where T_e is in Kelvins (MKS), or 2.68×10^{-14} n $T_e^{1/2}$ A/m^2 if T_e is given in eV (see for example Davis et al [3]).

Putting in some numbers typical of LEO plasma testing, taking $T_e = 1$ eV and n $= 10^{12}$/m^3, we have $J_{th} = 2.68 \times 10^{-2}$ A/m^2, or 26.8 mA/m^2. However, in a real LEO plasma of $T_e = 0.2$ eV, $J_{th} = 12.0$ mA/m^2.

It is instructive to compare the thermal electron flux to the ram ion flux in LEO. On the other hand, the ion ram current flux density is $J_{ram} = 7,600$ (m/s) x 10^{12} (m^{-3}) x 1.6×10^{-19} (C), or 1.2 mA/m^2. As a general rule of thumb, ram ions in LEO may be collected at about 1 mA/m^2. This is only about 1/10 as fast as ram electron collection. Thus, ram surfaces in LEO, if they are to remain in equilibrium, must repel about 90% of the electrons they encounter, and so must charge negative by a couple of times the electron temperature. In the plasma chamber with a non-flowing plasma, unbiased surfaces will

float even more negative, because the ratio of electron to ion thermal currents goes as the square root of the ion to electron mass ratio, and can be as high as 490 in a xenon plasma. Thus, in the chamber with a non-flowing plasma, unbiased surfaces float at 3 or more times the electron temperature negative.

If an unbaffled plasma source (such as an arcjet) is used in ground-testing, a flowing plasma may be achieved. In one such test done at GRC in a very large plasma chamber, the flow velocity of the ions in the plasma approximated that of LEO conditions.

V. SHEATH "SURFACE AREA" AND "SNAPOVER"

It is convenient to think of the edge of the plasma sheath surrounding an object in a plasma as a surface through which thermal currents are collected by the object. If a certain current is being collected, it can then be said that the "sheath surface area" is that current divided by the thermal current flux density. Using A_s as the sheath surface area, we may write:

$$A_s = I/J_{th}, \text{ where I is the collected current in amps.} \tag{6}$$

Comparison of the sheath surface area with the area of the collecting surface is a good way to get a feeling for how large the sheath has expanded into the plasma. Sometimes this comparison shows that current is being collected by more of a surface than the conductor area would indicate.

For instance, when a positively biased conductor adjacent to an insulator is placed in a plasma, secondary electrons produced by electrons missing the conductor and hitting the insulator can travel across the insulator surface and be collected by the conductor. Then, the surface of the insulator is acting for current collection purposes as if it were a conductor, and the surface of the insulator is said to be "snapped over". In a plasma with an elevated neutral pressure, such surfaces often glow from electron bombardment (apparently of desorbed gas near the surface), but in a hard vacuum, the glow may disappear. When snapover occurs, the electron current collected may increase many times. In a plot of current collected versus bias voltage, this snapover region exhibits a large derivative. Usually, snapover "saturates" when the entire insulating surface is acting as a conductor, and the derivative of current with voltage comes back down.

As an example, a large planar solar array (10 m^2) was recently tested in a very dense arcjet plasma (10^{13} m^{-3}) at about 0.1 eV electron temperature and collected about 300 mA of current at 100 V. According to the sheath surface area law, A_s was about 3 m^2, even though the amount of conducting surface on the array was only about 0.1 m^2. This indicates that about 1/3 of the insulating area of the coverglasses of the array was snapped over (3 m^2/10 m^2). Usually at higher voltages, snapover will progress until essentially the entire array surface area is snapped over. For the array in question, at its very high plasma densities, it would then collect nearly 1 A of current, which would challenge the current output of a hefty plasma source.

It was the prospect of a highly snapped-over solar array on the International Space Station (ISS) that led to the specification of

a plasma contactor that could emit 10 A of current to control ISS charging. At 12 mA/m², 10 A of electron current on ISS would require about 800 square meters of snapped-over array, well within the realm of possibility for the huge ISS solar arrays. As it turns out, the amount of snapover on the ISS arrays during normal operation is much lower than this, and the plasma contactor typically only needs to produce a fraction of an amp of current to balance electron current collection on the arrays.

Sometimes when snapover occurs during testing at high positive voltages, such large currents can be collected in such a small area of conductor that the temperatures on the conductor and adjacent insulators may become quite high. In one test at GRC of current collection by the Space Station solar array panels, an uncovered hole in the Kapton® covering a power trace, combined with a high degree of snapover at high positive voltages, led to temperatures high enough to char the edge of the kapton (Kapton pyrolysis) surrounding the hole. An application of Kapton® tape to cover the hole solved the problem.

VI. "FLOATING POTENTIALS" AND ARRAY GENERATED VOLTAGES

Some systems in the space plasma, such as solar arrays and electrodynamic tethers, generate their own system voltages. For such a system, some part of the system must necessarily be at a potential far from the ambient plasma potential. Often, such systems have conductors exposed to the plasma at these high potentials. For example, a typical solar array has exposed interconnects between the cells that may be at the same potential as the cells they are connected to. For a 100 V array, some part of the array will thus have exposed conductors 100 V different in potential from another part. Such an array will collect current from the plasma such that it will "float" at a potential where the electron thermal currents collected through the array plasma sheath will balance the ram ion currents. Because the electron thermal current density is typically many times the ram ion current density, only a small part of the array will float positive of the surrounding plasma, and collect electrons, whereas a large part will float negative, and collect ions. For an isolated array, not attached to any structure, a rule of thumb is that it will float about 90% negative; that is, the most negative part of the array will float 90% of the string voltage negative of the plasma, and the most positive part will be only 10% of the string voltage positive of the plasma.

For example, the ISS string voltage is about 160 V. An ISS array not electrically connected to any additional ion collecting area would be expected to float about 144 V negative, and only 16 V positive. Since the ISS was expected to have little if any exposed conductor on the negatively grounded structure, the ISS structure itself was expected to float 144 V negative, and would be in danger of continually breaking down its anodized aluminum thermal control surfaces, the tops of which would be floating at about the plasma potential (dielectric breakdown). This necessitated the addition of a plasma contactor to emit the electrons collected by the array and make ISS float highly positive, rather than highly negative.

As it turned out, ISS seems to have about 30 m² of ion collecting area on the structure, and many more square meters of collecting area on the array boom wires, and the ISS arrays were found to not snap over as much as expected. Consequently, ISS has floated only 20-30 volts negative of the plasma. With the addition of new solar array wings but not much more ion-collecting structure, ISS is expected to start floating more negative, except when the plasma contactor is in operation.

It should be emphasized that this LEO floating potential problem is due to the array generated voltages (see Ferguson and Hillard [4]), and is not related to the traditional spacecraft charging problem (see Purvis et al [5]). The traditional spacecraft charging problem comes in GEO orbits and in auroral zones, where the electrons may hit spacecraft surfaces at energies of thousands of electron volts. In that case, in order to maintain current balance to spacecraft surfaces, the spacecraft itself may sometimes charge to potentials of thousands of volts. Because of other effects which are unimportant in LEO equatorial orbits but may be dominant in GEO or auroral orbits, such as photoelectrons, secondary electron emission, and capacitances of surfaces relative to spacecraft ground, in those orbits differential voltages may build up between cells and coverglasses (for instance) of thousands of volts, and if the cells are negative of the coverglasses, arcs may ensue with these surfaces as electrodes.

VII. PLASMA ARCING AT NEGATIVE POTENTIALS

Solar cells, solar arrays, simulated solar cells and arrays, electrodynamic tethers, and anodized aluminum have been shown to arc into the space plasma or into simulated space plasmas when they are at negative potentials relative to the plasma. By definition, an arc (or electrostatic discharge) is a rapid, transient flow of current from a charged body. Although thresholds for the voltages of spacecraft arcing vary, most solar arrays can arc at voltages between -70 V and -250 V relative to a high density plasma, and at somewhat higher voltages relative to a tenuous plasma. These arcs are believed to be due to high electric fields inside dielectrics (in the case of the anodized aluminum) or at plasma-conductor-insulator junctions (so-called triple junctions) for the solar cells, solar arrays and tethers. There is some evidence that increases in the electric fields due to thin coverglasses, etc. decrease the threshold voltage for these arcs. Because these arcs sometimes trigger sustained discharges between spacecraft elements, the plasma arcs are sometimes called primary arcs or "trigger arcs."

Some have asked: What is the anode for these plasma arcs? The answer to that is the space plasma itself. It acts as a conducting medium that can transfer charges wherever there are biased surfaces. Without going into the theories for arcing, which are still at a rudimentary stage of development, we will concentrate on the laboratory and space operational aspects of the plasma arcs.

First of all, there is a negative voltage threshold for the phenomenon. The threshold shows up as a rapid increase in the stochastic arc rate, from seemingly zero at low voltages to many arcs per minute at high enough voltages. The threshold

varies, depending on details of the geometry, materials, etc., but does not seem to depend on the plasma itself, as long as the ambient plasma is dense enough to hold the coverglass surface near plasma potential despite charge bleedoff due to coverglass conductivity. It is believed that the function of the plasma in plasma arcing is to hold the surfaces at near zero potential, so the electric field will be concentrated in a narrow region, such as the gap between solar cells. As the plasma density increases, the recovery rate for recharging the surfaces increases, so the arc rate goes up. The arc rate strongly increases at a given voltage with an increase in plasma density. Thus, for arc threshold measurements, the more plasma of any type, the better. The threshold and the arc rate do not seem to depend on the area of the sample, so small samples are sufficient, if the plasma density is high enough that the time interval between consecutive arcs is determined only by the coverglass charging time. Theoretically, in a plasma test, one is looking for the minimal (negative) voltage that causes arcing. So, larger samples should provide a better chance to find this minimum voltage – the probability of arc inception increases with an increasing number of arc-sites. In practice, even small samples contain enough arc-sites that the threshold can be very well determined.

The arc threshold and arc rate do not depend on whether the sample is self-biased (as in an operating solar array) or is biased by an outside power supply (assuming the power supply is connected to the circuit appropriately). Usually, in ground tests, a power supply is connected between ground and the sample, which is otherwise left to float in the plasma. To prevent the power supply from continuously powering an arc once it has started, usually a large (kOhm-MOhm) resistor is placed between the power supply and the sample. This has the function of making the RC time constant of the power supply circuit long enough so that the arc is over before the power supply can sustain the current.

As an example, in a typical test on large samples (0.5 m^2) in the N-PI facility at NASA GRC, the ion collection current was 20-50 microAmps under negative sample bias. To constrain the voltage drop on the sample to less than half a volt, a 10 kOhm resistor was used. This limited the power supply current to less than 10 mA during an arc, and the capacitor size (1 microFarad) was chosen to make the charging time (10 ms) much longer than the arc current pulse width (50 μs maximum).

It is important that there be no large inductances in this part of the circuit, or one may get a ringing current trace in the arc, which is not representative of an arc on a real sample in space. Also, to provide energy to get the arc started, a capacitance is usually placed on the bias circuit between the sample and ground. It is a matter of some controversy how big this capacitor should be, but for arc threshold and rate measurements, it must only be big enough to allow arc detection by eye, high-speed camera, or current probe, and not so large that arc currents can damage or destroy the sample. Capacitance values between 0.03 microFarad and 1 microFarad have been used with success. The RC value should not be so large that it takes seconds to recharge the circuit, for this will invalidate the arc rate measurements. The true arc rate seems to depend mostly on the ion flux to the surfaces, which is why it is

really a rate of discharge of negatively biased surfaces by ions to reset the electric field. In order to make sure there are no circuit effects which may affect arc waveforms or rates, one should measure or accurately estimate the capacitance, inductance, and resistance in the arc circuit, including the bias cables, etc. Then, use SPICE or some other lumped element model to determine circuit effects during an arc (see Models, below).

There is only one way to accurately determine LEO arc thresholds. This is to bias the sample negatively in increments until arcs are detected. Increase the negative bias until the arc rate is appreciable, and sufficient arcs can be counted that statistics can be obtained on arc rates. Further increase the bias and obtain the arc rate at this higher bias (usually the arc rate goes up rapidly with increasingly negative bias). Obtain at least three statistically significant arc rate values in this way, and plot them versus bias voltage on a log-log plot. Extrapolate the results to a voltage just below where the arcs were first seen to start. Sit at that voltage until you have a statistically significant number of arcs, or the arc rate is more than 3 sigma below the prediction. If the arc rate is still significant, go to a slightly smaller negative voltage. Repeat until the arc rate is 3 sigma or more below the prediction (sigma for no arcs in Poisson statistics is 1 arc). The time to wait at each voltage may be found in advance from the length of time necessary to achieve a statistically significant absence of arcs. The threshold lies between the voltages where you found arcs and where your measurement was more than 3 sigma below the extrapolated prediction.

Many people have reported voltages where they saw no arcs as the "threshold voltage". Of course, such results depend on how long data were taken at that voltage, for a "no-arcs detected" result is really just a limit on the arc rate at that voltage. Sometimes this (more properly termed) "arc inception" voltage is near the true threshold, just because of the extremely rapid increase in the arc rate at voltages higher than the threshold. Sometimes, however, it is not. If the above procedure is followed, one can be assured of having found the "threshold".

In GEO testing, thresholds must be determined by charging the sample with electron beams, etc. and measuring the charging level before the arc. This can be done with a non-contacting (capacitively coupled) probe such as a Trek probe. Because the probe may disturb electric fields at the arc-site, probe readings should be taken before the arc occurs, not concurrently with arcing.

As was noted before, arc thresholds do not seem to depend on the type of plasma. However, they do depend strongly on the sample temperature, with a decrease in threshold with decreasing temperature. Thus, a measurement of sample (or at least chamber) temperature is useful.

The arc rate at a given voltage seems to be directly proportional to the ion flux onto the surface, whether the arcing is in the space plasma or in a laboratory plasma (see Ferguson [6]). Arc rates also usually decrease during an arcing test. It is not known whether this is due to a decrease in the number of available arc-sites after repeated arcing, a conditioning of surfaces by sputtering, an outgassing effect over extended

periods in a vacuum, or a combination of these and other causes.

It has been found that every plasma arc is initiated by a nanosecond timescale burst of electrons from the arc site (see Galofaro et al [7] and Vayner et al [8]). The total amount of charge in this burst is very small, and it may be missed altogether if the arc current measurement apparatus have insufficient time resolution. The arc itself usually takes several microseconds to develop, depending on details of the arc circuit. It is convenient to trigger recording equipment on the initial electron burst.
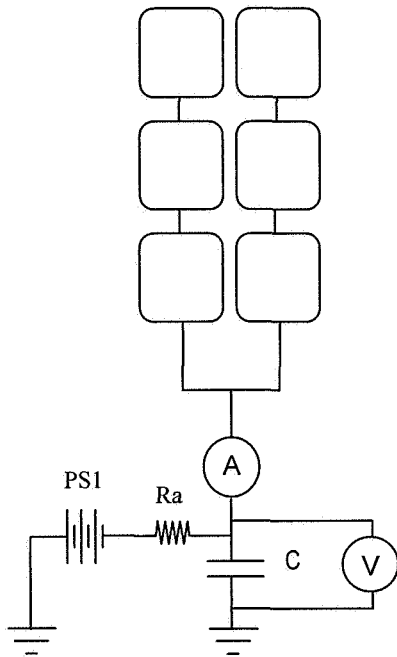

Fig. 1.   Typical Trigger Arc Circuit

When testing to determine the damage that may be produced by a trigger arc, one should use a capacitance that simulates the capacitance to space of the entire electrically connected space system (such as all connected solar array strings, or all anodized surfaces). It has been shown that regardless of whether the arc plasma can contact spacecraft surfaces, all surfaces may be discharged in a LEO trigger arc (see Vayner et al [9], [10], and Ferguson et al [11]). See Figure 1 for a typical trigger arc testing circuit.

VIII.   ARE LEO CONDITIONS VALID FOR GEO ARC THRESHOLD TESTING?

Since it is known that the electric field is the important factor in producing an arc at an appropriate arc site, the method of producing the electric field is relatively unimportant. In GEO, high electric fields are produced by spacecraft being charged highly negative by high energy electron streams, and the coverglasses, etc. may lag behind (because of capacitance effects, photoelectron and secondary electron emission, etc), producing a high field between the negatively charged array and the coverglass (or other) surface. In LEO, the coverglasses are discharged continuously by contact with the surrounding

plasma, while the array voltage charges the underlying cells negative. In either case, what is important is the potential between the coverglasses or anodized surface and the underlying cells or conductor. Thus, in testing, LEO conditions can be used to produce the electric field just as well as GEO conditions. Furthermore, under LEO test conditions, one can bias the underlying conductor to the desired potential, whereas under GEO conditions, an electron beam must be used to produce charging, and control of the conductor potential is not so reliable.

One difference might be if there were a somewhat conductive material between the conductor and coverglasses or anodize that would allow charges to bleed off. Then, the potential difference in GEO would be maintained better than in LEO, because the very low bleedoff currents in GEO conditions would amount to a smaller $\Delta V = I\,R$, where I is the bleedoff current and R is the resistance.

However, besides the electric field between the coverglass and the conductor (which has the same influence on the arc inception process in either LEO or GEO), and besides the leakage current through the dielectric, there is another important factor, namely the ion current density collected by the negative electrode. The high current density in LEO may cause electron emission from the metal surface, which generates a distributed surface charge on the side surface of the coverglass and creates an additional field enhancement under LEO conditions that is not seen under GEO conditions (see Jongeward and Katz, [12]). Thus, samples may arc at a less negative bias in LEO than in GEO. Cho et al [13] have shown that whereas standard array samples may show arcing at -150 to -200 V in a simulated LEO plasma, in a simulated GEO plasma similar samples may have an arcing threshold at about -400 V. Recently, Vayner et al [14] have shown a factor of three higher threshold voltage for solar arrays in simulated GEO conditions, compared to LEO.

IX.   SUSTAINED ARCING

A sustained arc between two closely adjacent surfaces at different potentials (like adjacent solar cells or power traces) can sometimes be caused when a plasma arc occurs on one of them and any source of current can continue to feed the arc at a current level of about 0.5 A or more, and at a voltage of 20 V or more. It is not known whether there are separate current and voltage thresholds for sustained arcs, or whether the threshold is a power threshold (see Schneider et al [15]). Real solar arrays on orbit have undergone sustained arcing (see Hoeber et al [16]), sometimes with the disastrous result that one or more array strings are totally grounded or become open circuits.

These sustained arcs are not really ambient-plasma arcs, because the original plasma becomes unimportant when a sustained arc gets started. However, since they can be initiated by ambient-plasma (trigger) arcs, and are devastating when they occur, they have been getting increasing attention in ground plasma testing. Recent tests have shown that the sustained arcs can be understood as Paschen discharge through the (usually metallic) neutral gas in the primary discharge (see Vayner et al [17]-[19]). The high local energy density of this discharge may

also cause Kapton® pyrolysis, surface outgassing, semiconductor decomposition, etc., and all of the evolved species can feed the discharge channel.

Even on samples where sustained arcing is possible, only a fraction of the "trigger arcs" lead to sustained arcing. What is particularly disturbing about the sustained arcs, however, is that they may be sustained by voltages between spacecraft elements that are significantly less than the trigger arc thresholds. For instance, one type of array tested showed trigger arcs only at biases more than 80 V negative (out of a total string voltage of 120 V), but the arcs could be sustained by only a 60 V difference between adjacent cells (see Hoeber et al [16]). Thus, if this array arced, there was a high likelihood that the arc would be sustained until the array strings involved were destroyed.

threshold if the testing is to be nondestructive. Current and voltage settings must be gradually increased until the duration of the discharge pulse between adjacent cells becomes significantly (say, ten times) longer than the primary arc pulse width. The next increase in voltage or current will usually lead to a sustained arc. While the amount of capacitance on the trigger arc supply is usually not important, our tests have shown that when more energy is pumped into the primary arc, the higher is the probability of having a sustained arc. Trigger arcs have turned into sustained arcs for capacitances as low as 0.1 microFarad. Of course if one had zero capacitance no arcs at all could be generated, but often the solar array sample plus the bias supply cabling contribute enough capacitance for trigger arcs to occur. See Figure 2 for a typical sustained arcing test circuit.
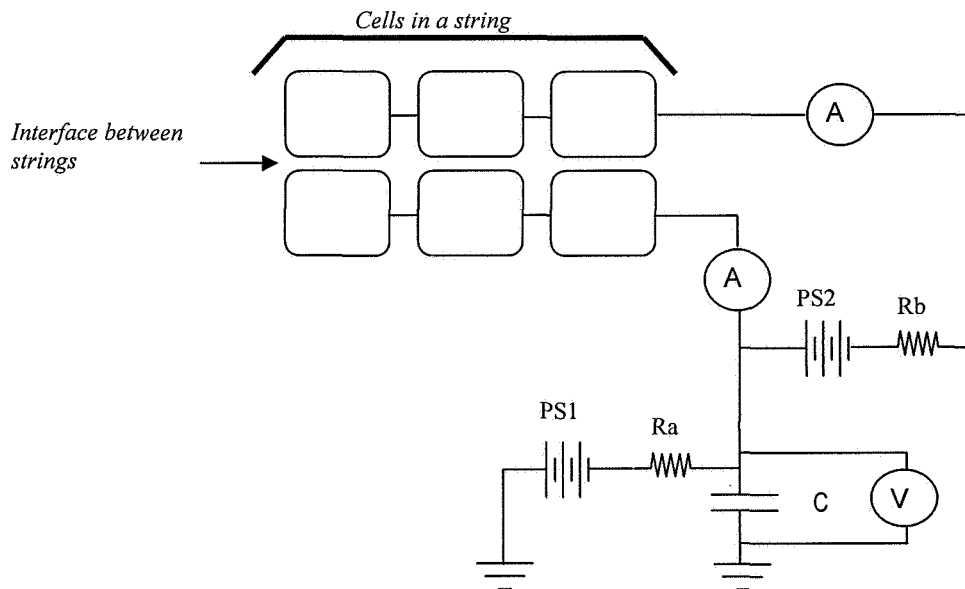

Fig. 2. Typical Sustained Arc Circuit

In ground testing, one can prevent the sustained arcs from damaging the array by limiting the current to at most a few amps (with a current limiting power source – a so-called solar array simulator) and by chopping the circuit for arcs that last longer than a few hundred milliseconds. This requires arc detection circuitry and a fast switch on the bias supply. It is very important to have a solar array simulator (SAS) that does not overshoot the current limit even for a short time of a few microseconds. The best electric current detectors are non-contacting ring coils that respond to changing magnetic fields around wires carrying currents. However, care must be taken to use current sensors that do not saturate if the product of peak current and pulse width is too large.

It is clear from our many tests over the years that a simple strategy must be applied to determine the sustained arcing

X. USING "REAL SAMPLES" VS. IDEALIZED SAMPLES

In many cases, testing has been performed on realistic samples (qualification test arrays, for example) or full arrays rather than small coupons. In other cases, not only have small coupons been used, but samples known not to be realistic (incorporating metal instead of silicon solar cells, for example). It is important that idealized samples only be used to investigate the physics of the phenomena. Since arc thresholds, rates, and even collection currents depend sensitively on the specific array materials and geometries, these must always be determined by using realistic, flight-like samples as much as possible. An effort should also be made for threshold testing to use realistic added capacitances, to simulate the other parts of the solar

array, and in the case of sustained arc testing, a good solar array simulator (without large current overshoots, for example) must be used to simulate the currents that may be provided by the rest of a large solar array during the sustained arc.

However, even in testing for arc thresholds, etc., it is allowable to use samples of only a few cells, rather than a full array. This is because it has been seen that the array area is of little concern in such testing. Of course, in testing for sustained arcing, realistic materials and geometries must be used around the arc site. Care should be taken that damage to the sample that occurs in the initial phases of testing will not influence the results of later testing. For this reason, non-destructive test techniques (shutting off sustained arcs before there is a great deal of damage, for instance) should be used in tests that will require statistics or when the test geometries or materials are critical.

XI. SYMPATHETIC ARCS

Independently-biased anodized aluminum plates in a plasma have exhibited "sympathetic arcs" (see Vayner et al [9]). The plates were mounted parallel to each other and separated by up to 30 cm. When both plates were biased negatively, the one that first arced (on the side toward the other plate) produced an arc almost simultaneously on the near-side of the other. The initial burst of electrons is apparently responsible for causing the second arc, as the very short time delay between the arcs is inconsistent with the major arc currents being responsible.

XII. TESTING FOR ARC THRESHOLDS FOR PASCHEN DISCHARGE

Paschen discharge is not, strictly speaking, an ambient-plasma arc, since it depends mainly on breakdown of the neutral gas. However, it is still an important consideration under space conditions. For example, the initial arcs that eventually destroyed the TSS-1R electrodynamic tether were Paschen discharges from the tether to the reel enclosures on the Shuttle (Szalai [20]).

Testing for Paschen breakdown requires accurate control of the neutral pressures, gas compositions, and distances between (and geometries of) the cathode and anode surfaces. The speed of onset of the voltage is also important, as it is well known that rapid transients in voltages (and AC voltages) produce Paschen discharges at lower voltages than do slow turn-ons (Dunbar [21], [22]). An attempt to reproduce realistic voltage transients for spacecraft systems will produce better results than uncontrolled turn-ons. For example, Paschen breakdowns at below the theoretical DC Paschen minimum were seen at GRC in thermal vacuum tests on heaters when the heaters were turned on rapidly, but were prevented by inserting a slow RC time constant in the heater circuit to prevent overshoot.

XIII. TESTING IN VERY DENSE PLASMAS (IE THRUSTER PLUMES)

Very dense plasmas, such as thruster plumes, pose many special challenges for testing. For one thing, the neutral densities in the plumes are likely to be very high, and this will make Paschen discharge more likely. Even outside the plume the pressure in the vacuum chamber may make chamber-wide Paschen discharge possible. Also, if the plasma density in the plume gets to be an order of magnitude or more higher than typical LEO plasma densities (10^{13} rather than $10^{12}/m^3$), currents collected and arc rates in the plume may become extremely high, overrunning power supplies and making the RC time constant in the circuit too long for accurately measuring arc rates.

Also, sputtering rates and/or electron bombardment in the plume may become quite high, and this may damage sample surfaces. Metals sputtered from thruster grids may plate out in the chamber on samples, diagnostics, and chamber walls, invalidating the measurements. If, however, the real space situation has solar arrays or other sensitive surfaces in such a plume, one has no alternative but to test in thruster plumes in the chamber.

If the particular array being tested always has a positive potential with respect to the plasma, perhaps because its negative terminal is connected to the arcjet or ion thruster anode, no arc inception on its triple junctions would be expected. However, this is correct for steady state operation only. Transitional processes can be much more complicated. When the arcjet or thruster is being turned on or off, the solar arrays may have an ill-defined set of coverglass and/or cell potentials, so arcing may be possible.

At very high plasma densities, sputtering may even become important on well-insulated AC wiring. The surface of insulators on AC wiring may float highly negative of the plasma (up to about the maximum AC voltage, due to much greater electron current collection in the positive part of the waveform compared to the ion collection during the negative part), and may become subject to sputtering from the chamber ions and/or thruster plume ions because of this. It is more important than ever to take account of these effects when testing in very dense plasmas.

Other considerations may also become important in thruster plume plasmas. For one thing, because these plasmas are highly directed, there will be plasma wakes produced behind blocking surfaces, and objects or diagnostics in the wake may charge differentially from surfaces in the ram. That is, traditional-looking spacecraft charging effects may occur, and arcs may jump between surfaces differentially charged with respect to each other. In addition, charge exchange within thruster plumes may produce low energy thermal plasmas of the acceleration grid materials. These may have different effects than the main ion beam constituents.

XIV. PLASMA SOURCES AND PLASMA DIAGNOSTICS

It is always important to produce the proper plasma with a plasma source. Traditionally, Kauffman-type sources or hollow cathode sources have been used to produce LEO type plasmas.

Flow rates and plasma source voltages and currents may be used to control plasma densities and temperatures. The plasma source ground or neutralizer should usually be connected to chamber ground to keep the plasma potential close to the chamber potential. Ion thrusters have been used as plasma sources in some plasma simulations, but if the thruster is not gridless, it is important to baffle the ion beam to produce a uniform plasma in the chamber.

Neutral pressures should be closely monitored using ionization gauges or residual gas analyzers (RGAs). RGAs are also very useful to determine when contamination in the chamber has dropped to acceptable levels, and when residual air pressure in the chamber is at a low enough level to allow valid testing.

During arc tests, and if there is a possibility of Paschen discharge in the chamber, low light level cameras should be used to pinpoint the location of the breakdown and/or to see the Paschen glow. During anodized aluminum arc tests using very high capacitances at GRC and MSFC, such cameras have been used to show molten blobs of metal flying through the chamber. A viewport on the chamber with a clear view of the samples being tested is also useful for confirming the camera results. Videotaping capabilities can be used to permanently record and time-stamp the camera results. After the fact, individual arc sites can be located from time stamps on the arc detection circuitry. In fact, Mengu Cho et al [13] have developed a special technique to image a sample on a CCD camera and to digitize the positions of arc-sites with a computer program.

Measuring the plasma conditions in the chamber during arc testing is essential. Traditional methods use Langmuir probes and/or retarding potential analyzers (RPAs) to determine the plasma densities and temperatures. Several such probes should be located throughout the chamber to determine the uniformity of the plasma, or in the case of thruster plumes, to map out the plume. For Langmuir probes, contamination may produce false electron temperature readings, so frequent cleaning of the probes by biasing to voltages high enough that electron bombardment will clean them will help to produce consistent and valid readings. Also, voltage sweeps both up and down in voltage will allow contamination to be detected by the hysteresis it produces in the probe readings. Langmuir probes or RPAs located too close to biased samples or grounded surfaces may produce false readings because they are inside a plasma sheath. As always, a calculation of the sheath thickness is key to locating probes and other diagnostics.

If a flowing plasma is used, such as an arcjet plume, a non-standard Langmuir probe analysis technique must be used (see Morton et al [23] and Katz et al [24]). This technique, proven to work for Langmuir probes on the SAMPIE and ISS Floating Potential Probe, was especially useful in a recent arcjet test, where the exact plume velocity was unknown. In this case, the flowing ion velocity was considered a free parameter in the fitting technique, and the technique yielded flow velocities very similar to what was expected from near-field plume measurements.

For a good description of experimental setups used at NASA GRC, see Vayner et al [25], [26]. For a description of test setups at NASA MSFC, see Schneider et al [27], [15].

XV. ARC MITIGATION STRATEGIES

There are many possible arc mitigation strategies, many of which will need to be tested in the laboratory, prior to implementation. For example, for mitigating trigger arcs, one may wish to try changing cell spacing, coverglass overhang, coverglass thickness or material, interconnect design, encapsulation, charging control, low voltage PMAD, etc. (see, for example, Hastings et al [28] and Ferguson and Hillard [5]). All of these and most others require strenuous control of the sample geometry and materials. For mitigating sustained arcs, one may wish to change cell string layout, coverglass overhang, interconnect design, encapsulation, arc detection and shutoff, substrate material, current-limiting diodes, etc. Again, detailed sample design is of utmost importance. Finally, for Paschen discharge mitigation, one may wish to change electrode spacing, insulation materials and thicknesses, enclosure ventilation schemes, etc. In this case, of primary concern during testing is that the neutral gas environment (pressure, temperature, composition) and the electrical details (net capacitance, inductance, resistance, and switching characteristics) be provided, measured and maintained during a test.

XVI. CHARGING MITIGATION STRATEGIES

Many strategies for preventing spacecraft charging or differential charging have also been proposed. Among them are array encapsulation, plasma contactors, field-emission devices, wrap-through interconnects, using thicker coverglasses or greater overhangs, etc. Many or most of these will involve measurement of electron collection currents, which should always be done for charging mitigation, but some will also involve electron emission (such as plasma contactors or field emission devices). In all cases, measurements of potentials and currents will be very important to testing for possible spacecraft charging effects.

It has been found that for many intricate array geometries, the electron temperature in the test plasma is very important for determining the electron collection. In such cases, a tradeoff may be needed between neutral density and electron temperature, since it is relatively easy to lower electron temperature by flowing excess gas through the plasma source. One must be very careful that no incursion is made into the Paschen discharge regime during such testing. A major test of the current collection of an ISS array was ruined by lowering electron temperature in this way, only to find that ionization in the chamber was swamping the currents that would be occurring under space conditions. Recently, new low electron-temperature plasma sources have been invented that do not rely on excess gas flow to achieve the low temperatures. It may be worthwhile to investigate their use.

XVII. MODELS

Various software models may be useful in space plasma testing. For instance, the Environments Workbench (EWB), and all of the NASA Air-Force Charging Analyzer Programs (NASCAP-2k, NASCAP, and NASCAP/LEO) have been used successfully to model plasma-tank experiments. In one important case, increased electron collection at very low electron temperatures on the ISS arrays was predicted by NASCAP/LEO before experiments were done to confirm it (Chock [29]). Furthermore, the correct "threshold" for increased collection was also successfully predicted. There are also models of solar array arcing that have had varying degrees of success in ground testing. The Cho/Hastings model for arc rates and arc thresholds (Cho and Hastings [30], [31], Hastings et al [32], Soldi et al [33], de la Cruz et al [34]) gives reasonable fits to the data with but one free adjustable parameter, for example. Trends of arc threshold with sample temperature have even been predicted by this model. However, detailed agreement with the data has been hard to achieve.

Models of the arc circuit are more plentiful and more mature. One model that has been used in the EWB code (Davis et al [35]) is the SPICE model, which is a lumped element circuit model. If correct estimates of inductance, capacitance, and resistance of all circuit elements (including wiring) are included in the model, SPICE can be used to assure that there is no ringing in the bias circuit, etc., and that the arc timescale and *arc rate are not affected by the circuit parameters.*

In order of difficulty from most difficult to easiest, we would rank the different aspects of modeling space plasma tests in the following way. Hardest would be arc thresholds and rates, because they depend on the most factors (geometry, materials, plasma densities and temperatures). Second would be electron and/or ion collection. Next, easier but still requiring testing, would be Paschen discharge thresholds. Finally, models of the arc circuit behavior are better developed and more reliable. Unfortunately, the best of the models available for space plasma testing are still very preliminary, and can't be relied upon for quantitatively determining these critical aspects of real space systems. In order to have confidence that our spacecraft will not charge, or arc, or will collect no more than a certain amount of current, it is still absolutely necessary to test the spacecraft systems in a simulated space plasma.

XVIII. ANALYZING AND REPORTING TEST RESULTS

Under no circumstances should test results that are unfavorable to the customer or to one's pet theories go unpublished. It is especially important that all results are reported in a test when some results were favorable to the customer and some not so favorable. While proprietary concerns are important, and should not be leaked to competitors, all results that are scientifically interesting should be reported to the entire space plasma testing community through publication of journal articles, books, public presentations and other publicly available sources. A government test lab should never agree to do a test if all of the results of the test must remain secret forever.

All relevant test conditions should be reported, so that important findings can be duplicated. It is important that whenever there is considerable uncertainty in a measurement or a test result, error bars or other indications of uncertainty should be reported along with the data. Also, whether the error bars are rms statistical errors, estimated errors, etc., or errors of some other type, must be reported. Many parameters that should be reported (i.e. plasma density and temperature) may be known only through modeling of probe readings. Whenever these parameters are reported, the technique(s) for deriving the quantities in question must also be reported. Statistically insignificant results should not be reported unless accompanied by a reminder that they are only suggestive. Data points that are significantly discrepant must always be reported, even if unexplained.

Reporting of raw data is not enough. The data must be analyzed by the original authors if it is to be of maximum usefulness to the scientific community. The analysis should show what ideas and/or hypotheses are supported and which are not supported by the evidence being reported. Was anything completely new found? Is there an explanation for it? If not, what kinds of tests might clarify the result? Analysis should be done as much as possible using standard scientific methods (correlation, statistical analysis, comparison with models and theories, etc.). Implications of the results for future spacecraft design should be pointed out.

Einstein once said, "Everything should be made as simple as possible, but not simpler." In other words, we must maintain clarity even when we must be brief. This should be a guideline for technical reporting in plasma testing (or for science in general).

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