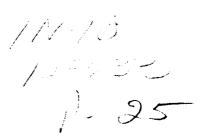# Solar Array Module Plasma Interaction Experiment (SAMPIE)

Technical Requirements Document

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TECHNICAL REQUIREMENTS DOCUMENT
SOLAR ARRAY MODULE PLASMA INTERACTION EXPERIMENT (SAMPIE)
A SHUTTLE BASED PLASMA INTERACTIONS EXPERIMENT

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1 Background and Justification for Space Flight Experiment

1.1 Snapover and Floating Voltages

Numerous ground experiments and two flight experiments (PIX I and PIX II) have shown that conducting surfaces at high electrical potentials relative to a plasma interact with the plasma in two fundamental ways. Firstly, they collect current from the plasma. Because the mass of an electron is much smaller than the mass of a positive ion, the electron current collected at positive bias relative to the plasma is much greater than the ion current collected at comparable negative biases. A further difference is that at positive biases greater than about two hundred volts relative to the plasma potential, insulating surfaces surrounding exposed conductors behave as if they were themselves conductors. This phenomenon, called "snapover", leads to greatly enhanced electron collection. On an operating solar array, for example, such currents collected from the plasma appear as losses in the array operating current and a reduction in the ability of the array to produce power. Pinholes in the insulation of cables transmitting power from any high voltage source will also be subject to snapover effects, robbing the system of power. Furthermore, the currents collected from the plasma will determine the potential at which different parts of the array will "float", relative to the plasma. It is therefore important to determine the manner in which solar arrays and other totally or partially conducting surfaces collect current from the space plasma, in order to evaluate power system operating efficiency and to predict and control spacecraft potentials relative to the plasma.

1.2 Negative Bias Arcing

Secondly, at high negative biases relative to the surrounding plasma, solar arrays (and other surfaces containing conductor-insulator junctions) arc into the plasma, leading to disruptions in the current produced, electromagnetic interference, and large discontinuous changes in the array and/or structure floating potentials relative to the plasma. Both

ground tests and flight tests have indicated that for solar arrays having silver-coated interconnects a threshold potential relative to the plasma exists, below which no arcing occurs, at about -230 volts. There are theoretical reasons and some indication from ground tests that different conducting materials exposed to the plasma have different arcing threshold potentials. It is important to determine the arcing threshold, arc strengths, and arc rates for solar arrays and other conductor-insulator junctions operating at high negative potentials in the space plasma.

1.3 High Voltage Array and Power System Operation

High power level solar arrays and other power sources now being considered for space applications will operate at high voltages, from end to end, in order to minimize the current which must be distributed. A major driver toward higher operating voltages is the mass of cabling which must be lofted into orbit to transmit the electrical power from the arrays or other power sources at high efficiencies. Because the resistance of the cable is a strongly decreasing function of the cable mass per unit length, and because the cable losses are proportional to the current squared, it is advantageous to operate at high voltages, where the currents will be low, and a larger resistance per unit length (less cable mass per unit length) may be employed. A further factor in operating at high voltage and low current is that magnetic interaction effects (such as magnetic torques and magnetic drag) are minimized with minimum current operation.

1.4 New Space Power Technologies

1.4.1 Because of snapover at high positive array potentials, which could compromise power system efficiency, and arcing at high negative potentials, which could lead to power disruptions, EMI, and rapid changes in floating potential, it is important to determine the potentials at which these interactions will occur for solar arrays and other exposed conductor-insulator junctions in the space plasma.

1.4.2 In order to save weight and manufacturing cost, new solar arrays being considered for NASA and ESA missions are of a new design and utilize new materials, which may change the currents collected and the arcing threshold. In particular, new arrays being considered for NASA missions have solar cells with interconnects in the back, bonded to lightweight flexible substrates, employing copper traces which may be exposed to the space plasma, in contrast to all of the solar arrays which have been flown in space to-date, which have had silver-coated interconnects exposed to the plasma between cells on the front of a rigid substrate.

1.4.3 A full panel of new array technology solar cells planned for Space Station Freedom application have been shown in ground tests to arc at biases as small as -210 V, relative to the plasma, in ground tests at the Lewis

2

Research Center. An in-space test of these arrays has not been done and is not currently funded.

1.4.4   An advanced technology solar array, emphasizing large areas and minimizing weight, which is currently being considered by NASA is the Advanced Photovoltaic Solar Array (APSA), which uses thin-film standard-interconnect silicon cell technology and high voltage, kapton-covered power distribution traces. It is expected, based on PIX and PIX-II experience, that such an array will experience arcing when used in low Earth orbit (LEO) applications. The insulation over the power distribution traces may also be subject to pinholes from micrometeoroid and debris impacts, etc., leading to parasitic current drains.

1.4.5   Non-solar space power systems, such as the SP-100 nuclear reactor, will be distributing power at potentials of several hundred volts, relative to the plasma, in order to realize the cable weight savings described above. Also, very high voltage solar arrays (generating thousands of volts) are being contemplated for Solar Electric Propulsion for use on orbital transfer vehicles and for planetary missions. In all such high voltage power schemes, the potential for pinholes in insulation exists, caused by micrometeoroid and/or debris impact, abrasion in handling, or chemical means from contamination or atomic oxygen. Also, every spacecraft built for operation in regions where spacecraft charging may be important, such as polar or geosynchronous orbits or interplanetary missions, has conductive surfaces to control spacecraft charging. Current collection from conducting surfaces and arcing from conductor-insulator junctions may be real problems for these advanced technology spacecraft, unless the plasma interaction effects may be characterized, understood and mitigated.

1.5   Differences Between Ground and Space Tests

1.5.1   Comparison of ground tests and flight tests of old-technology solar arrays have shown many differences between their behavior in vacuum tanks and in the real space plasma. On PIX II, for example, the same cells were tested in ground plasmas and in flight and showed that the shape of the collection current versus voltage curves were quite different in space than on the ground, and that two different types of curves were obtained, depending on whether the arrays were in the ram (forward facing) or wake (backward facing) orientation. Although the same arcing threshold seemed to obtain for the PIX II cells in orbit and in the ground-based plasma tests, the arc rate above the threshold potential was quite different (and much higher at voltages less than about 1000 V) in the space plasma than on the ground. The origin of the discrepancies is not known, due to

3

inadequacies in the theory of the arcing phenomenon and uncertainties about surface layers which may influence the arc rate. Thus, while ground tests may give us information about the arcing threshold potential, for instance, they will not give us the detailed information necessary to allow confident design of large future NASA and ESA solar arrays and other power systems.

1.5.2   LEO conditions are impossible to properly simulate in ground-based experiments, owing to the very low LEO neutral densities, the spacecraft velocity in LEO orbits, the changing local LEO magnetic fields with very large particle gyroradii, the infinite charged particle reservoir in LEO, etc. Theories to scale the ground-based results to LEO conditions are rudimentary, at best. In order to be confident of how space power systems will behave in LEO, they must be tested in LEO.

1.6   Arcing versus Snapover

1.6.1   The relative importance of the snapover and arcing issues for large space solar arrays and other power systems depends to some extent on the grounding scheme employed on the orbiting spacecraft. All spacecraft come to electrical equilibrium with their surrounding plasma in a very short period of time. The equilibrium is reached when positively charged portions of the spacecraft collect electrons at the same rate as the negatively charged portions collect ions from the plasma. For a solar array operating in the absence of other charge collecting surfaces, most of the array will float at a negative potential relative to the plasma, because only a small area collecting the low mass, mobile electrons may offset a much larger area collecting the heavy, slow-moving ions. For the ions encountered in low Earth orbit, as much as 95% of an isolated array may operate at negative potentials relative to the plasma. Because no part of the spacecraft will ordinarily float at a high positive potential, it is reasonable to "ground" the positive end of the solar arrays to the spacecraft. Then the additional charge collecting area of the spacecraft will make the spacecraft ground be even closer to the plasma potential, and vary even less with respect to the plasma. Thus, the snapover condition is unlikely to be reached for even very large array operating voltages before the negative end of the array reaches a potential beyond the arcing threshold. If the positive end of the array or spacecraft were to reach the snapover condition, the enhanced collection currents would "peg" the potential of this part of the spacecraft, effectively driving the negative end of the array even further into conditions of high arc rate. For these reasons, it is generally believed that array arcing is the limiting factor in array operating voltage, and it must be assigned the greater

4

importance in solar array design unless and until it can be proved that array arcing does not affect the array operating efficiency, lifetime, or generate unacceptable conditions of EMI or potential fluctuations.

1.6.2   If large space structures are grounded to the negative end of a high voltage solar array, it is still likely that the arrays plus structure will float mainly negative with respect to the plasma. This is because it is so easy to collect electrons at the positive end that the vast majority of the collecting area must still be devoted to collecting ions, and thus be at a negative potential. Furthermore, such a grounding scheme places the structure itself at a high negative potential, relative to the plasma, where unknown or unsuspected arc sites might develop. In any case, arcing may be expected to be a problem. In the case of a negative array "ground", arcing thresholds must be determined for a large number of possible structure materials and configurations. This would call for a number of space experiments to be done.

1.6.3   For new technology solar arrays, the way the cell geometry interplays with the plasma conditions may be very important in determining the relative amounts of electron collection at positive potentials and ion collection at negative potentials. For example, the SSF solar arrays tested in Tank 5 at the Lewis Research Center in 1989 collected very little electron current when biased positively, although the negative bias ion collection seemed normal. Through computer simulations performed with the NASCAP/LEO computer code, it was discovered that the close proximity of the coverslides of the solar cells prevented electrons in the test from reaching the cell edges, where they could be collected. This was due to the high electron temperatures in the tank test (> 1 eV compared to 0.1 to 0.2 Ev in LEO). After running the same code but using typical space conditions for electron temperatures, it was found that the electron collection would be increased by orders of magnitude, because electrons would no longer be excluded from the cell edges. It may be impractical or impossible to reach low enough electron temperatures in the laboratory to confirm the computer predictions. Furthermore, snapover was never reached in the laboratory tests, probably also because of the geometrical effects. The floating potential of the SSF, and possible effects for negatively grounded systems (such as sputtering and structure arcing), depend on a knowledge of the electron current collection of the solar arrays. Currents which may flow during reboost operations or other thruster firings depend on the snapover potential as well. Neither of these quantities may be found in ground test experiments, because of the unrealistically high electron temperatures which obtain.

1.7 Summary of Justification

For the reasons given above, it is important to determine the dependence of plasma collection currents, arc rates and strengths on potential relative to the plasma, and arcing potential thresholds for new technology solar arrays and other space power technologies in a real space plasma through one or more space flight experiments. The relevant plasma parameters, such as electron density and temperature, and spacecraft factors, such as orientation relative to the velocity vector, and potential relative to the plasma, must be concurrently measured along with the system performance, in order to be able to understand the interactions which take place, and to enable confident and reliable design and operation of future NASA and ESA space power systems.

2 Objectives of the Experiment

2.1 General Objective

The objective of SAMPIE is to investigate, by means of a Shuttle-based space flight experiment and relevant ground-based testing, the arcing and current collection behavior of materials and geometries likely to be exposed to the LEO plasma on high voltage space power systems, in order to minimize adverse environmental interactions.

2.2 Specific Objectives

There are seven specific objectives of the SAMPIE experiment:

2.2.1   For a selected number of solar cell technologies, determine the arcing threshold as well as arc rates and strengths. At a minimum, the solar cells selected for flight must include:

        2.2.1.1   A sample array made of traditional silicon solar cells. This will provide a baseline for comparison with past experiments.

        2.2.1.2   A sample array using APSA, the Advanced Photovoltaic Solar Array.

        2.2.1.3   A sample array using current space station solar cell technology.

        If space permits, other advanced solar cell technologies such as GaAs, InPs, or amorphous silicon may be included.

2.2.2 For these sample arrays, determine the plasma current collection characteristics.

2.2.3 Propose, demonstrate in ground tests, and fly an arc mitigation strategy, i.e. modifications to standard interconnect design which may significantly improve the arcing threshold.

2.2.4 Design simple metal/insulator mockups to allow the dependance of current collection on exposed area to be studied with all other relevant parameters controlled.

2.2.5 Design a simple arcing experiment to test the dependance of arcing threshold, arc rates, and arc strengths on the choice of metal with all other relevant parameters controlled.

2.2.6 Design, test, and fly simple controlled experiments to study basic phenomena related to arcing and its effects. Added on a space-available basis subject to time and resource constraints, these may include such things as:

2.2.6.1 Arcing from anodized aluminum using alloys and anodization processes typical of those being considered for use on large space structures.

2.2.6.2 Arcing from pinholes in Indium-Tin oxide (ITO) coated conductors or from biased conductors covered with strips of ITO.

2.2.6.3 Sputtering and degradation of metals or metal covered insulators biased to high negative potential in the atomic oxygen environment of LEO.

2.2.7 Measure a basic set of plasma parameters to permit data reduction and analysis. A further requirement to aid data reduction is to provide timely flight data (such as the Shuttle orientation, and times of thruster firings) relevant to SAMPIE flight conditions.

3 Description of the Experiment

3.1 Basics of the Experiment

SAMPIE will consist of a metal box with an experiment plate fixed to the top surface. It will mount directly to the Hitchhiker-M carrier and will have a suitable adapter to permit either top or side mounting. A power supply will bias the solar cell samples and other experiments to DC voltages as high as +300 volts and -700 volts with respect to shuttle ground. When biased negative, suitable instruments will detect the occurrence of arcing and measure the arc rate as a function of bias voltage. For both polarities of applied bias, measurements will be made of parasitic current collection versus voltage. Other instruments will measure the degree of solar insolation, plasma electron density and temperature, and monitor the potential of the shuttle with respect to the plasma. Shuttle operations logs will be relied upon for detailed information about the orientation of the experiment with respect to the vehicle's velocity vector as well as times and conditions of thruster firings.

3.2 Other Useful Measurements

Other measurements which might help further characterize the plasma and other test conditions, such as the array temperatures, the ion composition, the ion and electron energy distributions, the magnetic field strength and direction, electric and magnetic waves, the structure of the plasma sheath surrounding the biased arrays, etc., are desirable, and could be undertaken with instruments which are part of the Solar Array Module Plasma Interaction Experiment, or by co-flying experimenters.

3.3 Shuttle Operations

A limitation on Shuttle operations is imposed by the fact that the experiment ground will be tied to Shuttle Orbiter ground, which is tied to the plasma potential mainly through about 30 m^2 of exposed metal on the Shuttle Main Engines. When the arrays are biased to positive voltages higher than about 100 volts, the orientation of the Orbiter must be restricted such that the Main Engine nozzles are not in the vehicle wake, for large vehicle potential excursions would occur at those times, due to the low collectible ion density in the Orbiter wake. An operational constraint may also be imposed on the conduct of the experiment by the prospect of the Orbiter charging to high potentials. The maximum desirable positive array bias will be considered in this document under Scientific and Technological Constraints.

3.4 Hitchhiker

The experiment will be mounted on a Hitchhiker attachment plate within the Orbiter payload bay, and will use the standard Hitchhiker data recovery systems.

3.5 Experiment Operation

In a simplified description of the experiment, one solar cell sample is biased to a particular voltage for a preset time while measuring arcing and current collection data. A set of plasma diagnostics is then taken and the procedure is repeated at the other bias voltages until all measurements have been made.

3.5.1 Vehicle orientation is critical since ram and wake effects are known to be significant. SAMPIE will request control of the orbiter orientation such that various sets of measurements are made with the payload bay held in the ram direction while others are made with the bay in the wake.

3.5.2 The accuracy requirement for ram/wake operation can be arrived at by considering current collection to a plate which is initially oriented at zero degrees angle of attack, then rotated through a set of increasing angles. Geometrical considerations yield a cosine dependence of effective area with angle. NASCAP/LEO calculations by R. Chock of LeRC indicate that at high voltages current collection is unaffected by angle while at very low voltages the expected cosine dependence emerges. Since low voltages offer a worst case, we will require ram orientation to mean zero degrees plus or minus ten degrees.

3.5.3 The required view factor for SAMPIE can be arrived at by considering the effect of bow shocks from adjacent fixtures or experiments. Since the experiment plate is a horizontal top mount, such shocks would lead to turbulent conditions on the surface of the experiment plate. This would expose different samples to different plasma conditions and would clearly degrade the value of the data obtained. The angle formed by the shock wave can be calculated as $\sin\theta = v_s/v$ where v_s is the ion acoustic velocity and v is the vehicle speed. v_s can be calculated from

$$v_s = ((kt_e + \gamma kt_i)/M_i)^{1/2}$$

We will assume an electron temperature of .2 Ev, an ion temperature of .1 eV, and an ion mass of 16 atomic units (atomic oxygen). The factor γ is equal to $(2 + N)/N$ where N is the number of degrees of freedom. For one dimensional compression, $N = 1$ and $\gamma = 3$. Using these and assuming a vehicle speed of 7700 m/s, we calculate an angle 13 degrees. If we look at a worst case and assume an ion temperature of .2 eV (only

9

a few ions in the distribution would ever be this hot) the calculated angle becomes 16.5 degrees. To be safe, we will require that SAMPIE have a clear field of view of 20 degrees.

These last two requirements must be considered together. If an adjacent payload were 24 degrees from SAMPIE, for example, the orbiter would violate our field of view requirement if it were oriented more than 4 degrees from ram.

3.6 Diagnostics

The minimum diagnostic instruments are a neutral pressure gauge, Langmuir probe, v-body probe, and sun sensor.

3.6.1   The pressure gauge should be capable of measuring background pressures from 10^{-7} to 10^{-3} torr. In order to adequately track the influence of thruster firings, the instrument must have a time resolution of at least .05 seconds.

3.6.2   The Langmuir probe should be capable of measuring plasma densities from $10^3/cm^3$ to $10^6/cm^3$ and electron temperatures from .05 to .2 eV.

3.6.3   The v-body probe, which may be a separate unit, a function of the Langmuir probe, or both (for redundancy) will measure orbiter potential with respect to the plasma. It should do this with an accuracy of 3 volts or better.

3.6.4   The sun sensor is needed to allow proper determination of the I-V characteristic to use in modeling collection from biased solar cells. The short circuit reading from a calibrated solar cell or photocell may be used for this purpose. An accuracy of 5% is required for this reading.

3.7 Electromagnetic Interference Produced

Because the solar arrays at high negative potentials relative to the plasma will produce arcs, which are known to emit broadband electromagnetic interference, the capacitance of the arrays to space may need to be tailored to produce arcs of acceptable size and EMI production. Also, a waiver of the EMI specs for Orbiter payload bay experiments may need to be obtained. Finally, the electronics to measure arc strength must be designed to detect and measure arcs of the strength expected from the specified capacitance solar arrays.

3.8 Minimum Experiment Configuration

The minimum experiment configuration consists of the experiment plate, high voltage power supplies and switching gear, electrometers to measure the solar module collection currents, a transient current detector to detect arcs as they occur on the active solar panel, low voltage power supplies and controls, data acquisition and control equipment, a sun sensor, a pressure sensor to detect fluctuations in the pressure due to thruster firings, etc., and diagnostic instruments to measure electron density and temperature and vehicle potential.

4 Scientific and Technological Constraints

4.1 Orbit

The Solar Array Module Plasma Interaction Experiment must be placed in an orbit which keeps it from entering the auroral oval, for there occasional strong high energy electron fluxes and low thermal electron fluxes make conditions hard to measure, unpredictable, and therefore unsuitable for this experiment. This means that the orbiter orbital inclination during the Solar Array Module Plasma Interaction Experiment must be restricted to less than about 58° to the equator.

4.2 Solar Maximum Conditions and the Debye Length

The Solar Array Module Plasma Interaction Experiment is being considered for flight as soon as February, 1993, shortly after the time of the maximum of the solar activity cycle, in 1992. The plasma density in low Earth orbit depends on the level of solar activity, peaking at times of solar maximum. Recent estimates of the level of solar activity expected at the peak in 1991 or 1992 place the level unusually high, with some estimates of the averaged sunspot number as high as 200. For the purposes of experiment planning, the worst case of launch during the solar maximum in 1992 will be considered. Simulations of the ionosphere using the IRI-86 model place the maximum daytime electron density for such high solar activity levels as high as 3.8×10^6 electrons per cubic centimeter, at electron temperatures between 1100 K and 2300 K. Ion densities must be the same as the electron densities, but the ion temperatures are predicted to be in the range of 1100 K to 1400 K. Nighttime electron densities are predicted to be as low as 1.6×10^5. A temperature of 1200 K corresponds roughly to an electron energy of 0.1 electron volts. Under these conditions, the plasma will be capable of maintaining electric fields at low potentials over a distance of approximately one Debye length, which is given by

$$\lambda_D = (kT_e/4\pi n e^2)^{1/2} = 7.43 \times 10^2 \ (T_e/n)^{1/2}$$

11

where T_e is the electron temperature in eV, k is the Boltzmann constant, $\pi = 3.14159...$, e is the charge of the electron, and n is the electron density in cm^{-3}. Placing representative values from IRI-86 simulations in the above equation, one finds a minimum Debye length from 0.12 cm at 1100 K to 0.17 cm at 2300 K. Openings in the experiment electronics enclosure must be smaller than the minimum Debye length to prohibit plasma interactions with the experiment electronics. If it seems unlikely for the experiment electronics to have properly outgassed before the experiment is turned on with these small openings, larger openings may be used if covered with an electrically connected conductive wire mesh of spacing less than the minimum Debye length.

4.3 Plasma Sheath Radius and Experiment Operation

4.3.1 It would be desirable in the Solar Array Module Plasma Interaction Experiment to place the plasma diagnostic instruments outside the plasma sheath (the sheath being the region where the plasma is significantly disturbed by the applied electric fields) of the array being biased. For large potentials, assuming orbit-limited collection, the plasma sheath radius may be taken to be the radius of a sphere with the same area as the area of the collecting array segment, multiplied by the square root of the quantity, the applied bias in volts divided by the electron energy in eV. Under ram conditions, the ion sheath may be somewhat smaller than this (perhaps 1/4 the radius), because the flux of ram ions is greater than the thermal flux. For a voltage of 700 V, this implies a sheath radius of more than a meter under all reasonable plasma densities. At even moderate voltages, such as two hundred volts, the sheath will extend for a distance of more than 45 cm, using orbit-limited theory.

4.3.2 Alternatively, one may assume that the flow of charged particles to the solar arrays is limited by a build-up of space charge around the collecting array. In this case, calculations indicate that at 200 V, the sheath radius will be at least 30 cm for electron collection and/or ion collection without ram ion impingement, and at least 9 cm collecting ions in the ram direction. In the case of electron and non-ram ions, this indicates that the sheath radius is much greater than the array dimensions discussed below, so that orbit-limited theory should apply. Recent experiments of Thiemann and Bogus, indicating much smaller plasma sheaths, may have been influenced by electron ionization of the dense background gas, or by ram ion impingement in their high energy streaming plasma. The discrepancies should be investigated by means of a numerical code such as NASCAP/LEO.

4.3.3 From the above considerations, it may not be possible to have the Langmuir probe or other instruments measure the undisturbed plasma

density and temperature and "ground" potential on the array structure when an array segment is being biased to significant voltages because the plasma sheath will have dimensions exceeding the dimensions of the array structure. In order to be able to monitor plasma conditions when either array segment is biased it may be necessary to switch the array bias off for a short time, to allow sensors mounted on the structure to measure the undisturbed plasma, before going on to the next bias voltage.

4.4 Rate of Change of Orbital Conditions and Experiment Timescale

Calculations of the rate of change of plasma parameters in the IRI-86 model of the ionosphere show that within 5 degrees of orbit, the plasma densities and temperatures may change by 25%. If it is desired to measure the plasma conditions to within about 50%, it will be necessary to restrict each bias voltage interval to less than about 10 degrees in the orbit, or about 3 minutes of time. The Langmuir probe scan, for example, could then be done in a matter of seconds, between array bias voltages. It is important to measure the vehicle potential continuously, perhaps from a sensor mounted at least one meter from the biased array segments.

4.5 Orbiter Floating Potential and Collection Currents

4.5.1 Of great interest to the Solar Array Module Plasma Interaction Experiment is a calculation of what the floating potential of the Shuttle Orbiter will be when the array segments are biased to high voltages. Not only do the true potentials of the array segments with respect to the plasma depend on the potential of the spacecraft "ground" relative to the plasma, but it may be possible to charge the Orbiter up to potentials where non-array material junctions could arc into the plasma. We require, in particular, that the Orbiter potential, $V_.$, never exceed -75 V, the Skylab proven "safe" operating potential. To establish this, we require a calculation of the expected Orbiter floating potential. A series of such calculations have been performed by R. Chock of LeRC. Using the NASCAP/LEO computer code, these calculations assumed that current balance is maintained by matching electron collection by SAMPIE with ion collection from the shuttle main engine nozzles. Critical assumptions included that the nozzles were never in the vehicle wake and that the SAMPIE experiment plate was in the ram. These calculations proceeded by assuming that the entire experiment plate was collecting current, then gradually reducing the area. By this means, it was explicitly shown that the current collection is linear with plate area. Using these results and assuming that the largest single experiment on SAMPIE, the four cell SSF coupon, is fully snapped over, the calculations showed that at a bias of +600V the shuttle charges to about -25V. Since shuttle charging is within

13

acceptable limits even at voltages as high as 600 V, the capability of the power supply to deal with large currents resulting from snapover becomes the limiting factor.

4.5.2   There is evidence from ground tests that the plasma current collection characteristics of solar arrays depend on the potential of the surrounding material, as well as on the speed with which the bias is applied. The surrounding material may alter the orbits of the electrons to be collected, and thus change the currents reaching the exposed biased conductors. For this reason, to simulate a large solar array, where large adjacent areas are at about the same potential, it is desirable to bias up all adjacent array segments when measuring the electron collection current of any of them, to give a surrounding potential nearly the same as that of the array segment being measured. This should help evaluate the "worst case" collection currents. If this is impractical because of power supply limitations (see below), then an alternate means of simulating the effects of a large array would be acceptable. One possibility would be for one or more cell coupons to be surrounded by metal strips which would be biased at the same time as the cells. Modeling, using NASCAP/LEO, would be required to determine the size, placement, and appropriate bias, not necessarily the same as the cells, in order to best simulate a large array. When biasing positive, to collect electrons, it is also recommended that the bias voltage be applied with a time constant of 100 milliseconds or more, to simulate the slow build-up of voltage on the array when it comes out of Earth's shadow.

4.6   Positive Bias Limitations from Practical Power Supplies

4.6.1   A possibly more serious limitation on the positive bias of the arrays will be current limitations on practical power supplies. Again, using Staskus's measurements, the thermal current is collected at a potential of about +150 V. This corresponds to about 3 mA, for a Solar Array Module Plasma Interaction Experiment 1000 cm^2 array at a plasma density of 3.7 x 10^6 cm^{-3} and a temperature of 1100 K. At about +200 V, the current in Staskus's experiments increased to about 3/10 the full snapover current, or about 1.8 A in terms of the Solar Array Module Plasma Interaction Experiment. At +300 V, full snapover was reached, implying currents of several amps and power levels of over 1000 W, clearly impractical for the mass and power constraints on the Solar Array Module Plasma Interaction Experiment power supply. One might expect that at about +175 V potential, the array may sometimes be drawing as much current as a 100 mA power supply (for example) could provide. Assuming that,

14

at this potential, the effective array current collecting area is about 300 cm^2, gives V$_-$ = -30 V. Then V$_+$-V$_-$, the bias voltage, is 205 V.

4.6.2   From these considerations, it appears that a positive bias of from +205 V to +335 V is the maximum practical for the bias voltages which may be used in the Solar Array Module Plasma Interaction Experiment. This will restrict the ability of the Solar Array Module Plasma Interaction Experiment to explore the snapover regime fully, but under ordinary conditions, voltage limitations on arrays imposed by the possibility of arcing on the negative end may make snapover unreachable on the positive end, so that space measurements of full snapover may not be as immediately important as measurements of arcing thresholds. Ground tests may help further illuminate the snapover voltage for the new technology solar cells, and computer modeling may help to specify the maximum usable bias voltage in the Solar Array Module Plasma Interaction Experiment. On the Solar Array Module Plasma Interaction Experiment, since instruments will be measuring the "ground" potential V$_-$ relative to the plasma, it may be well to design so as to stop increasing the array positive bias when the Shuttle Orbiter goes a specified number of volts (such as -75 V), away from plasma potential. Biases should be applied to the cell strings in the middle of the string, so that the potentials of the cells furthest from the bias point will be affected in offsetting ways by plasma interactions. For strings of only one cell, the bias point should be on the positive side of the cell, between the cell and the load.

4.6.3   Another consideration for the Solar Array Module Plasma Interaction Experiment is Shuttle floating voltage excursions due to RCS thruster firings. The effective Shuttle current collection area is greatly increased during RCS firings, due to the large amount of ionized and ionizable gas emitted. It is expected that during RCS firings, the Shuttle may suddenly return to near plasma ground potential, making the potential of the array segments with respect to the plasma become the full amount of their bias voltage. This may drive their collection currents up, or drive them over the arcing threshold voltage. For these reasons, it is important to know exactly when RCS thruster firings occur during the experiment, and at what potential the Orbiter is floating at all times.

4.7   Negative Bias Limitations from Arcing Rates

4.7.1   On the negative bias side, constraints on the experiment may be imposed by the expected arc rate of the solar panels. In the only quantitative, large scale ground tests of new technology, welded-through interconnect solar

panels to date, Norman Grier's measurements may be interpreted to yield an arc rate versus voltage law of

$$R = 6.6 \times 10^{-27} \, V^{8.1} \, n \, T^{0.5} \, m^{-0.5}$$

where T is the plasma temperature in eV, V is negative potential in volts, n is the plasma density in cm^{-3}, and m is the ion mass in amu. Taking n to be 3.8×10^6, the maximum expected in orbit, T to be 5 eV (the ram ion energy), and m to be 16 (atomic oxygen), one finds that the expected arc rate at -700 V is 1552 arcs per second! Because of the strong dependence of arc rate on voltage, the expected arc rate drops to 0.06 arcs per second at -200 V, and 0.00022 arcs per second at -100 V. It may be argued that these rates are based on extrapolations from ground test data, and may not apply in space. For the PIX II type solar cells, the arc rate in space was higher at all voltages than the arc rate in ground tests, normalized to the same plasma conditions, but a threshold for arcing was found at around -230 V. Two of the objectives of the Solar Array Module Plasma Interaction Experiment are to determine the threshold and arc rates for the new technology solar arrays in space conditions. Nevertheless, one must design the experiment with some expectations in mind.

4.7.2   Ground experiments done by David Snyder, of LeRC, have shown that for simulated silver solar cell interconnects, the potential after arcing drops to about -230 V, the same as the arcing voltage threshold found from PIX II and ground tests. Similar tests done for copper, the material likely to be exposed to the plasma in the new technology solar cells, show that the potential after arcing drops to a much lower voltage, on the order of -100 V, suggesting that the arcing threshold for copper may be as low as -100 V. Thus, it is important for the Solar Array Module Plasma Interaction Experiment to be able to measure arc rates as low as they may be at -100 V in orbit.

4.7.3   In order to be able to expect a single arc at -100 V, at the arc rates calculated above, the Solar Array Module Plasma Interaction Experiment would need to dwell at -100 V for 76 minutes, the greater part of a complete orbit, even at the maximum possible plasma density. This seems to be impractical, given the time constraints on any experiment in orbit. Because of the strong dependence on voltage, however, a dwell time of only about 20 minutes would be necessary to expect one arc at -120 V. Thus, an experiment timeline should be set up which would allow at least a twenty minute dwell time at -120 V, and correspondingly shorter times at higher voltages. If one allows one complete orbit to do all of the measurements at both positive and negative voltages, and a limit of +300 V is imposed on the positive side, with current measurements every

16

minute at increments of 30 V, a suggested set of times follows, with expected numbers of arcs at the maximum plasma density of 3.8×10^6 and at a density of 10^6 cm^{-3}:

Array bias	Dwell time	N (n=n$_{max}$)	N (n=10^6)
+300 V	1 minute	0	0
+270 V	1 minute	0	0
+240 V	1 minute	0	0
+210 V	1 minute	0	0
+180 V	1 minute	0	0
+150 V	1 minute	0	0
+120 V	1 minute	0	0
+90 V	1 minute	0	0
+60 V	1 minute	0	0
+30 V	1 minute	0	0
0 V	1 minute	0	0
-30 V	1 minute	0	0
-60 V	1 minute	0	0
-90 V	1 minute	0	0
-120 V	40 minutes	2.3	0.6
-150 V	20 minutes	7.0	1.8
-180 V	5 minutes	7.7	2.0
-210 V	2 minutes	11.0	2.9
-240 V	1 minute	16.0	4.2
-270 V	1 minute	42.0	11.0
-300 V	1 minute	98.0	26.0
-400 V	30 seconds	500.0	130.0
-500 V	5 seconds	500.0	130.0
-600 V	2 seconds	875.0	230.0

4.7.4   I believe it is unnecessary to test for arcs at a voltage greater than -600 V. At this voltage, the arc counter may be filled up at the end of two seconds, and it may be impractical to reset the high voltage power supply on a time scale shorter than a few milliseconds, as will be seen below. The times shown above do not contain provision for Langmuir probe sweeps between voltages, yet they add up to 85 minutes per full set of 24 voltages. If the Langmuir probe sweeps take only 10 seconds between voltages, this makes up 4 minutes, essentially making a full set of voltages take one full orbit. In order to follow the plasma density during the long dwell times, it may be necessary to break them up into increments of 3 minutes or less, with Langmuir probe sweeps in between.

4.8   Arc Detection and Avoidance of Damage to Arrays

In order to keep the solar arrays from being damaged by large arcs powered by the high voltage power supply, it will be necessary to place a large impedance in the bias voltage

17

circuit, between the high voltage power supply and the biased array segment. This will keep the array segment isolated from the power supply during the short duration arcs. To tailor the size of the arcs to something that the transient detector can comfortably detect, it is also necessary to specify the capacitance of the array segment to the Orbiter. These considerations will limit the ability of circuit to recover rapidly after an arc takes place, and may limit the highest negative voltage to be used in arcing studies because of the expected high arc rates at high negative voltages. Because the arcs are likely to last for about 20 microseconds at the most, it is desirable to have an RC time constant in the bias circuit of at least 100 microseconds.

4.9   Attainment of Steady State Conditions

There is evidence that the arc rate of a solar array in a plasma decreases to a steady state value on a time scale of a few hours. Also, outgassing from the Orbiter payload bay may make neutral densities abnormally high for a matter of many hours after the Orbiter is in orbit. Under such conditions, electron ionization of the neutral gas may make collection currents and arc rates and strengths uncharacteristic of the values obtained in a long-lived solar array in orbit. For these reasons, it seems important to delay the start of the Solar Array Module Plasma Interaction Experiment for at least 24 hours after the Orbiter is in orbit with the payload bay doors open.

4.10   Arcing and the Bias Sequence

There is evidence that the previous history of an array undergoing arcing and current collection may influence its behavior in the plasma. In particular, the prior presence of arcing seems to influence the arcing threshold and collection currents seen in laboratory experiments. The sequence of bias voltages should, therefore, start with the positive voltages, where arcing is less likely, and proceed to the negative voltages. If time allows, a second time through the sequence will permit the collection currents of the now pre-arced arrays to be tested. In order to compile good statistics and to cover an adequate range of plasma conditions and Orbiter attitudes, it is desirable that the entire voltage bias sequence be done at least twice with each array segment. For arcing, measurements need be taken only in the ram orientation since both theory and PIX II results indicate that arcing will not be observed in the highly depleted wake region. Current collection measurements, however, require both ram and wake measurements sequences. An arcing sequence, as given above, will therefore require a full orbit while a current collection sequence will require only about 25 minutes.

4.11   Electric Fields, Grounding, and Arcing

Finally, arcing may be exacerbated by the presence of strong electric fields in the vicinity of the arc site. For this reason, when one of the array segments is being biased negative, the other segment should be grounded, to strengthen the local fields. This also will help simulate the possible adjacency of different parts of the large area array string in future

large space power systems. In ground experiments, arcs sometimes have also occurred between adjacent conductors at high relative potentials. The arc detector on the SAMPIE should be capable of discriminating these two types of arcs, based on characteristics found in ground experiments. Also, because the array voltages are likely to recover rapidly after negative voltage arcs, the negative biases to the Solar Array Module Plasma Interaction Experiment array segments should be turned on rapidly, without the 100 millisecond time constant recommended for the positive biases.

4.12 Loads on Array Segments

Biased array segments should be fully resistance-loaded to near their maximum power point. Ground tests and theory have shown that only in this configuration (as opposed to being shorted or left open-circuited) are the dynamic resistances of the array modules proper to simulate an active array for arcing purposes.

5 Summary of Science and Technology Requirements

5.1 Experiment Configuration

5.1.1 The minimum experiment configuration agreed on consists of the experiment plate, high voltage power supplies and switching gear, electrometers to measure the solar panel collection currents, a transient current detector to detect arcs as they occur on the active solar panel, low voltage power supplies and controls, data acquisition and control equipment, a sun sensor, a pressure sensor to detect fluctuations in the pressure due to thruster firings, etc., and diagnostic instruments to measure electron density and temperature and vehicle potential.

5.1.2 The experiment will be mounted on a Hitchhiker attachment plate within the Orbiter payload bay, and will use the standard Hitchhiker data recovery systems.

5.1.3 When the arrays are biased to positive voltages higher than about 100 volts, the orientation of the Orbiter must be restricted such that the Main Engine nozzles are not in the vehicle wake. Control of the Orbiter orientation is necessary.

5.1.4 A waiver of the EMI specs for Orbiter payload bay experiments may need to be obtained.

5.1.5 All arcing experiments need be done in ram only, while current collection experiments require both ram and wake. It is desirable that the entire experiment timeline be repeated a second time, if possible, to allow better

statistics and to permit identical measurements to be made under different conditions of solar insulation.

5.2 Scientific and Technological Constraints

5.2.1 The Orbiter orbital inclination during the Solar Array Module Plasma Interaction Experiment must be restricted to less than about 58° to the equator.

5.2.2 Openings in the experiment electronics enclosure must be smaller than the minimum Debye length, 0.12 cm. If wire mesh is used to cover larger openings, it must be electrically connected to the enclosure, and have a mesh spacing smaller than the minimum Debye length.

5.2.3 In order to be able to monitor plasma conditions when either array segment is biased it may be necessary to switch the array bias off for a short time, to allow sensors mounted on the structure to measure the undisturbed plasma, before going on to the next bias voltage.

5.2.4 It will be necessary to restrict each bias voltage interval to less than about 10 degrees in the orbit, or about 3 minutes of time. The Langmuir probe scan can then be done in a matter of seconds, between array bias voltages. It is important to measure the vehicle potential continuously.

5.2.5 The high voltage power supply must be capable of producing at least 30 mA, and more desirably 100 mA, when biasing to positive voltages (electron collection), and of producing at least 1 mA when biasing to negative voltages. Electrometers to measure the current collected must be capable of measuring from 10^{-6} to 3×10^{-2} amp in the positive biases and 10^{-8} to 10^{-3} amps in the negative biases, based on the above considerations, with errors of 10% or less.

5.2.6 It is desirable to bias up all adjacent array segments when measuring the (positive bias) electron collection current of any one of them. When biasing positive, to collect electrons, it is also recommended that the bias voltage be applied with a time constant of 100 milliseconds or more.

5.2.7 The array bias relative to the Orbiter must be limited to below about +335 V. A positive bias of from +205 V to +335 V is the maximum practical. It may be well to design so as to stop increasing the array positive bias when the Shuttle Orbiter goes a specified number of volts (such as -75 V), away from plasma potential. Biases should be applied

20

to the cell strings in the middle of the string. Strings of one cell should be biased on the positive side of the cell.

5.2.8   Allowing one complete orbit to do all of the measurements at both positive and negative voltages, and imposing a limit of +300 V on the positive side, with current measurements every minute at increments of 30 V, a suggested set of times follows:

Array bias	Dwell time
+300 V	1 minute
+270 V	1 minute
+240 V	1 minute
+210 V	1 minute
+180 V	1 minute
+150 V	1 minute
+120 V	1 minute
+90 V	1 minute
+60 V	1 minute
+30 V	1 minute
0 V	1 minute
-30 V	1 minute
-60 V	1 minute
-90 V	1 minute
-120 V	40 minutes
-150 V	20 minutes
-180 V	5 minutes
-210 V	2 minutes
-240 V	1 minute
-270 V	1 minute
-300 V	1 minute
-400 V	30 seconds
-500 V	5 seconds
-600 V	2 seconds

5.2.9   The times shown above do not contain provision for Langmuir probe sweeps between voltages. If the Langmuir probe sweeps take only 10 seconds between voltages, this makes up 4 minutes, making a full set of voltages take one full orbit. It may be necessary to break them up into increments of 3 minutes or less, with Langmuir probe sweeps in between.

5.2.10   It will be necessary to place a large impedance in the bias voltage circuit, between the high voltage power supply and the negatively biased array segment. It is also necessary to specify the capacitance of the array segment to the Orbiter. It is desirable to have an RC time constant in the bias circuit of at least 100 microseconds.

5.2.11 It is important to delay the start of the Solar Array Module Plasma Interaction Experiment for at least 24 hours after the Orbiter is in orbit with the payload bay doors open.

5.2.12 The sequence of bias voltages should start with the positive voltages and proceed to the negative voltages. It is desirable that the voltage bias sequence be done for at least twice with each array segment.

5.2.13 When one of the array segments is being biased negative, all others should be grounded. The arc detector should be capable of discriminating between arcs to the plasma and between adjacent solar array cells at different potentials. The negative biases to the Solar Array Module Plasma Interaction Experiment array segments should be turned on rapidly, without the 100 millisecond time constant recommended for the positive biases.

5.2.14 Biased array segments should be fully resistance-loaded to near their
5.2.15 maximum power point.

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13. ABSTRACT (Maximum 200 words)

The Solar Array Module Plasma Interactions Experiment (SAMPIE) is a NASA shuttle space flight experiment scheduled for launch in early 1994. The SAMPIE experiment will investigate plasma interactions of high voltage space power systems in low earth orbit. Solar cell modules, representing several technologies, will be biased to high voltages to characterize both arcing and plasma current collection. Other solar modules, specially modified in accordance with current theories of arcing and breakdown, will demonstrate the possibility of arc suppression. Finally, several test modules will be included to study the basic nature of these interactions. The science and technology goals for the project are defined in the Technical Requirements Document (TRD) which is presented here. The experiment is being developed at the National Aeronautics and Space Administration (NASA) Lewis Research Center in Cleveland, Ohio, and is sponsored by the NASA Office of Aeronautics and Space Technology (OAST).

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