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NASA Technical Memorandum 106224

IN-18

P-28

The Sampie Flight Experiment Final Technical Requirements Document

G. Barry Hillard and Dale C. Ferguson
Lewis Research Center
Cleveland, Ohio

(NASA-TM-106224) THE SAMPIE FLIGHT EXPERIMENTAL FINAL TECHNICAL REQUIREMENTS DOCUMENT (NASA. Lewis Research Center) 28 p

N94-34729

Unclas

G3/18 0015266

June 1993

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THE SAMPIE FLIGHT EXPERIMENT
FINAL TECHNICAL REQUIREMENTS DOCUMENT

G. Barry Hillard and Dale C. Ferguson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

The Solar Array Module Plasma Interactions Experiment (SAMPIE) is a shuttle based flight experiment scheduled for launch in early 1994. SAMPIE will investigate plasma interactions of high voltage space power systems in low Earth orbit. Solar cell modules, representing several technologies, will be biased through a series of 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 in its final form. 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).

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)[1,2] have shown that conducting surfaces, at high electrical potentials relative to a plasma, interact with the plasma in two fundamental ways: First, 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 a comparable negative bias. Furthermore, 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, currents collected from the plasma appear as losses in the array operating current and reduce the ability of the array to produce power. Pinholes in the insulation of cables transmitting power from any high voltage source and subject to snapover effects, will also rob the system of power. Additionally, 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

Second, at high negative biases relative to the surrounding plasma, solar arrays (and other surfaces containing conductor-insulator junctions) arc[3] into the plasma, disrupting current, producing electromagnetic interference, and causing 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 indications from ground testing that different conducting materials exposed to the plasma have different arcing thresholds. It is therefore 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 cable resistance 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 effects (such as torque and 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 under development by NASA use designs and materials which may change both plasma current collection and the arcing threshold. Arrays now baselined for Space Station Freedom (SSF), for example, have solar cells with interconnects in the back. These are bonded to lightweight flexible substrates and employ copper traces which may be exposed to the space plasma. In this document, we occasionally refer to such solar cells or arrays made from these cells as "new technology". All of the solar arrays flown in space to-date, which we refer to as "old technology", 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[4] to arc at biases as small as -210 volts relative to the plasma. An in-space test of these arrays has not been done and is not currently funded. With the baselining of a plasma contactor for Space Station Freedom, it is important to determine the electron current collection of its solar arrays, in order to specify plasma contactor requirements.

1.4.4 An advanced technology solar array emphasizing large areas and minimizing weight, currently being considered by NASA, is the Advanced Photovoltaic Solar Array (APSA)[5]. APSA 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 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 possibility exists for insulation pinholes, caused by micrometeoroid and/or debris impact, abrasion in handling, or chemical means from contamination or atomic oxygen. Also, spacecraft built to operate in regions where spacecraft charging may be important, such as polar or geosynchronous orbits or interplanetary missions, have conductive surfaces to control spacecraft charging. Current collection from conducting surfaces and arcing from conductor-insulator junctions may be significant problems for these advanced technology spacecraft, unless the plasma interaction effects are 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 space. On PIX II, the same cells tested in ground plasmas and in flight showed that the shape of the collection current versus voltage curves were quite different in space than on the ground. Furthermore, 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 space than on the ground. The origin of the discrepancies is not known, due to inadequacies in the theory of the arcing phenomenon and uncertainties about surface layers which may influence the arc rate. While ground tests may therefore give some indication of the arcing threshold, for example, they will not provide the detailed information necessary to allow confident design of large 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, and the infinite charged particle reservoir in LEO. Theories to scale the ground-based results to LEO conditions are rudimentary. 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. 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. In this case 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. The snapover condition is therefore 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 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 be devoted to collecting ions, and therefore 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 requiring a number of space experiments to be done.

1.6.3 For new technology solar arrays, the interplay of cell geometry and plasma 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 simulations performed with the NASCAP/LEO computer code, it was discovered that the close proximity of the solar cell coverslides prevented electrons in the test from reaching the cell edges, where they could be collected. This effect 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. Recently, ground tests conducted in tank 5 using advanced hollow cathode based plasma sources[6] have achieved an electron temperature of .2 eV. Data from these tests confirm predictions of enhanced current collection at low temperatures. The floating potential of the SSF, and possible effects for negatively grounded systems (sputtering and structure arcing), depend on 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 impracticality of reproducing the ram-flow condition.

1.7 Summary of Justification

For the reasons given above, it is important to determine the dependence of plasma collection currents, arc rates and arc strengths on electrical 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 understand the interactions which take place and to enable confident and reliable design and operation of future 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 selected 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 to 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 Freedom solar cell technology.

2.2.2 For each sample array, 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 design which may significantly improve the arcing threshold.

2.2.4 Design simple metal/insulator mockups to allow the dependence 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 dependence 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 experiments 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 SSF.

2.2.6.2 Arcing and current collection behavior of Z-93 thermal control paint. Substrate and coating specifications should be the same as for radiators on SSF.

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

2.2.7 Measure a basic set of plasma parameters to permit data reduction and analysis. To aid data reduction, flight data (such as the Shuttle orientation, and times of thruster firings) relevant to SAMPIE flight conditions are required.

2.3 Success Criteria

The experiment timeline, presented in the appendix, divides the various measurements into two classes: essential and secondary. The essential measurements comprise the heart of the SAMPIE experiment and, if completed, allow all primary science objectives to be met. The secondary measurements consist of repeats from the first list and a few arcing measurements that are highly desirable but are not considered to be absolutely essential. The time allotted to the essential measurement sequence (18 hours) is considered to be a hard requirement for purposes of mission integration and planning. The secondary measurements will be accommodated by mission planners subject to the needs of other experiments on the flight. This list remains flexible. The completion of the first block of measurements will be sufficient to characterize SAMPIE as **FULLY SUCCESSFUL**. In the event that the mission cannot be completed and must be terminated early, key measurements are prioritized. Three experiment samples, the SSF coupon, APSA, and standard silicon are collectively sufficient to meet the most critical of SAMPIE's goals. Completion of one full measurement sequence on each of these, requiring 4 hours and 16 minutes of experiment time, will be sufficient to characterize SAMPIE as **MINIMALLY SUCCESSFUL**.

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 top of a Hitchhiker-M carrier[7]. A power supply will bias the solar cell samples and other experiments to dc voltages ranging from +300 volts to -600 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 solar insolation, plasma electron density and temperature, and monitor the shuttle potential 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 array temperatures, ion composition, ion and electron energy distributions, magnetic field strength and direction, electric and magnetic waves, and plasma sheath structure surrounding the biased arrays are desirable and could be undertaken with instruments which are part of SAMPIE, 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 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 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 an attachment plate to a Hitchhiker-M carrier within the Orbiter payload bay, and will use the standard Hitchhiker uplink and downlink capability.

3.5 Experiment Operation

In a simplified description of the experiment, one 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[8] indicate that current collection at high voltages is unaffected by angle while at very low voltages the expected cosine dependence emerges. Since low voltages offer a worst case, ram orientation will be required 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, exposing different samples to different plasma conditions and clearly degrading 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

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

We will assume an electron temperature t_e of .2 eV, an ion temperature t_i of .1 eV, and an ion mass M_i 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 γ = 3. Using these numbers and assuming a vehicle speed of 7700 m/s, we calculate a shock angle of 13 degrees. If a worst case is considered and we assume an ion temperature of .2 eV (only a few ions in the distribution would ever be this hot) the calculated angle becomes 16.5 degrees. To be safe, SAMPIE will be required to have a clear field of view of 20 degrees.

These last two requirements (3.5.2 and 3.5.3) must be considered together. If an adjacent payload were 24 degrees from SAMPIE, for example, the Orbiter would violate the 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) should measure Orbiter potential with respect to the plasma 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. 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 sample 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

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

4.2 Solar Maximum Conditions and the Debye Length

SAMPIE is being considered for flight as soon as February, 1994, after the time of the maximum of the solar activity cycle, in 1991. The plasma density in low Earth orbit depends on the level of solar activity, peaking at times of solar maximum. The level of solar activity at the peak in 1991 was unusually high, with averaged sunspot number as high as 200. For the purposes of experiment planning, the worst case of launch during solar maximum conditions will be considered. Simulations of the ionosphere using the International Reference Ionosphere (IRI-86) model place the maximum daytime electron density for such high solar activity levels at 3.8×10^6 electrons per cubic centimeter, at 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 λ_D, which is given by

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

where T_e is the electron temperature in eV, k is the Boltzmann constant, π = 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 have smaller dimensions than this minimum to prohibit plasma interactions with the experiment electronics. If it seems unlikely for the experiment electronics to have properly outgassed with these small openings before the experiment is turned on, 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

It would be desirable 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 sample being biased. Calculations done using NASCAP/LEO have shown that for large potentials these sheaths may extend for a half meter or more from the edge of the sample. Under ram conditions, the ion sheath may be somewhat smaller because the flux of ram ions is greater than the thermal flux. If the instruments cannot be removed from the immediate vicinity of the sample, it may not be possible to measure the undisturbed plasma parameters and "ground" potential of the Orbiter when an array segment is being biased to significant voltages. Under these conditions, it may be necessary to periodically switch the array bias off for a short time to measure the undisturbed plasma parameters. This is not possible for the measurement of vehicle potential which, by definition, must be made while the samples are biased. It is therefore considered necessary that the Langmuir and v-body probes be removed at least .7 meters from the experiment plate.

4.4 Experiment Timescale and Rate of Change of Orbital Conditions

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 that Langmuir probe scans be taken about every 10 degrees in the orbit, or about every 3 minutes. It is important to measure the vehicle potential frequently enough to resolve transient changes in Orbiter potential. We will require that this measurement be made once per second with five times per second desirable. The sun sensor should be monitored once per second.

4.5 Orbiter Floating Potential and Collection Currents

4.5.1 Of great interest to SAMPIE is a calculation of what the Orbiter floating potential 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 the Orbiter may be charged to potentials where non-array material junctions could arc into the plasma. The Orbiter potential, V_{-}, must therefore never exceed -75 volts, the Skylab proven "safe" operating potential. A calculation is required to ensure that this requirement is adequately met. A series of such calculations[9] have been performed using NASCAP/LEO. These calculations assume 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 area was collecting current, then gradually reducing area. 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 +600 volts the shuttle charges to about -25 volts. Since shuttle charging is within acceptable limits even at voltages as high as 600 volts, 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 rate of change of applied bias. The surrounding material may alter electron orbits and change the currents reaching the exposed biased conductors. To simulate a large solar array, where large areas are at about the same potential, it is desirable to bias all adjacent array segments when measuring electron collection from any of them, to give a surrounding potential nearly the same as that of the array segment being measured. Doing so 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 approach would be for one or more cell coupons to be surrounded by cells independently biased at the same time as the cells of interest. Modeling, using NASCAP/LEO, would be required to determine the size, placement, and appropriate bias, 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 more serious limitation on the positive bias of the arrays will be current limitations on practical power supplies. For a 1000 cm^2 array at a plasma density of 3.7×10^6 cm^{-3} and a temperature of 1100 K, the thermal current collected at +150 V is about 3 mA. This current increases to about 1.8 A at +200 V and to several amps (full snapover) at +300 V. (These numbers are based on measurements performed by J. Staskus at LeRC). These currents and the associated power levels of over 1000 W are clearly impractical for the mass and power constraints on SAMPIE's power supply. At about +175 V, the array may be drawing as much current as a 100 mA power supply (for example) could provide. Assuming that the effective array current collecting area is about 300 cm^2, gives $V_- = -30$ V. Then the bias voltage, $V_+ - V_-$, 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 which may be used. The ability of SAMPIE to fully explore the snapover regime will therefore be restricted. Array voltage limitations imposed by arcing may make snapover unreachable, so that space measurements of full snapover may not be as important as measurements of arcing thresholds. Ground tests may further illuminate snapover for the new technology solar cells, and computer modeling may help to specify the maximum usable bias voltage for SAMPIE. Since instruments will be measuring the "ground" potential V_- relative to the plasma, it may be well to stop increasing the array positive bias when the Shuttle Orbiter departs from plasma ground by a specified number of volts (such as -75 V). The bias should be applied to the arrays in the middle of the string, so that the potential 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 Shuttle floating voltage excursions may occur 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 potential, causing the potential of the array segments with respect to the plasma to become the full amount of their bias voltage. Their collection currents may be driven 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 For negative bias, constraints on the experiment are imposed by the expected arc rate of the solar panels. Large scale ground tests of new technology solar panels with welded-through interconnects yield an arc rate versus voltage law of

$$R = 6.6 \times 10^{-27} V^{8.1} n T^{1/2} m^{-1/2} \quad (3)$$

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 arc rate depends strongly 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 in ground tests normalized to the same plasma conditions. PIX II also yielded a threshold for arcing at around -230 V. Two objectives of SAMPIE are to determine the threshold and arc rates for the new technology solar arrays in space conditions.

4.7.2 Ground experiments[10] have shown that for simulated silver solar cell interconnects, electrical 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. It is important, therefore, for SAMPIE 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, equation 3 indicates that SAMPIE 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. An experiment timeline should therefore be specified which would allow at least a twenty minute dwell time at -120 V with correspondingly shorter times at higher voltages. Electron current measurements will require at least 10 seconds at increments of 5 V. For ion currents, which are generally in the microamp range, measurements will be made simultaneously with measurements of arcing parameters. In order to ensure good data these measurements should have a minimum dwell time of one minute.

Equation 3 may be used to estimate the number of arcs expected for a given bias and assumed plasma conditions. For most negative biases, the dwell time is determined by the expected arc rate and should be particularly chosen to allow as much time as possible near the expected threshold of -120 V. At higher voltages, equation 3 predicts a large number of arcs and the dwell time is determined by the 1 minute minimum required to accomplish the current measurement. The experiment timeline, presented in the appendix, takes all of these factors into account.

4.7.4 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.

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 supply, it will be necessary to place a large impedance in the bias voltage circuit, between the high voltage supply and the biased array segment. The array segment will be kept 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 the circuit to recover after an arc takes place, and may limit the highest voltage used in arcing studies because of the large expected 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 from a larger initial value to a steady state value on a time scale of a few hours. 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, arc rates, and arc strengths uncharacteristic of the values obtained in a long-lived solar array in orbit. Therefore, it is important to delay the start of the experiment for at least 48 hours after the Orbiter is in orbit with the payload bay doors open.

4.10 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, a prior history of arcing seems to influence the arcing threshold and collection currents seen in laboratory experiments. The sequence of bias voltages should, therefore, start with positive voltages where arcing is less likely, and be followed by negative voltages. In all cases, a bias sequence should begin with zero volts and step to higher voltage. If the sequence were to begin at a high positive voltage such as +300 V and step through to -600 V, large plasma sheaths would form and require some time to decay. It is important to avoid this effect. If time allows, a second run through the entire 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, however, requires both ram and wake measurements.

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 samples is being biased negative, the others should be grounded, to strengthen the local fields and help simulate the effect of adjacent parts of a large area array in a space power system. Because voltages are likely to recover rapidly after negative voltage arcs, the negative biases to the various experimental segments should be turned on rapidly, without the 100 millisecond time constant recommended for the positive biases.

4.12 Loads on Array Segments

Two of the solar cell samples (APSA and the SSF coupon) are intended to behave as closely as possible to a large array which is using these cells to generate power. It is necessary that these coupons be resistance-loaded to near their maximum power point. Ground tests and theory have shown that in this configuration the dynamic resistance of the array modules will allow proper simulation of an active array for arcing purposes. This loading is required to be within 10% of the maximum power point.

5 Summary of Science and Technology Requirements

5.1 Experiment Configuration

5.1.1 The minimum experiment configuration consists of the experiment plate, high voltage power supplies and switch 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 an attachment plate to a Hitchhiker-M carrier within the Orbiter payload bay, and will use standard Hitchhiker uplink and downlink capability.

5.1.3 When the arrays are biased to positive voltages higher than about 100 volts, the orientation of the Orbiter must keep the Main Engine nozzles out of the vehicle wake. Control of the Orbiter orientation is necessary.

5.1.4 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 insolation.

5.2 Scientific and Technological Constraints

5.2.1 Orbital inclination 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 of 0.12 cm. If wire mesh is used to cover large openings, it must be electrically connected to the enclosure, and have a mesh spacing smaller than the minimum Debye length.

5.2.3 Langmuir and v-body probes should be located at least 0.7 meters from the experiment plate.

5.2.4 Langmuir probe scans must be done every 10 degrees of orbit, or about every 3 minutes. Vehicle potential must be monitored once per second with five time per second desirable. The sun sensor should be monitored once per second.

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 current collection 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 with errors of 10% or less.

5.2.6 It is desirable to bias all adjacent array segments when measuring the (positive bias) electron collection current of any one of them. When biasing positive, it is 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 +335 V. A positive bias 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 to the cell strings in the middle of the string. Single cell strings should be biased on the positive side of the cell.

5.2.8 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.

5.2.9 It is important to delay the start of operations for at least 48 hours after the Orbiter is in orbit with the payload bay doors open.

5.2.10 The bias sequence should begin with zero volts and step to higher voltage starting with the positive voltages and proceeding to the negative voltages. It is desirable that the voltage bias sequence be done at least twice with each array segment.

5.2.11 When one of the array segments is biased negative, all others should be grounded. The negative biases to the experiment modules should be turned on rapidly, without the 100 millisecond time constant recommended for the positive biases.

5.2.12 Negatively biased array segments should be resistance-loaded to within 10% of their maximum power point.

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APPENDIX - Module Summary, Relay Assignments, and Experiment Timeline*

* The experiment timeline assumes that 18 hours of on-orbit experiment time will be made available. This number results from discussions with the OAST-2 mission integration team and is an attempt to balance the requirements of the various experiments on the mission. Additional experiment time may requested and will be provided if possible.

SAMPIE Experiment Plate
Module Summary

APSA	2x4 cm cells, 12 cells in series mounted on Germanium coated Kapton.
SSF	Baseline 8x8 cm cells, four cell coupon on Kapton-H.
Si 2x2	2x2 cm old technology (exposed interconnects). 36 cells in a six by six coupon. Inner four cells wired in series. Twelve surrounding cells wired as series string and biased separately, refered to as G1 (guard ring 1). Outer 20 cells wired as series string and biased separately, refered to as G2 (guard ring 2). Inner four cells without guardrings denoted as G0.
SSMIN 1,x	4 cut down space station cells, 3.5 cm by 3.5 cm each. Denoted by x = 1 - 4. Edge coatings nominally controlled to systematically measure current collection. Each cell wired as separate experiment.
SSMIN 2	4 cut down cells, as above. All cells shorted together as a single experiment. Coupon processed by PSI to suppress arcing.
SSMIN 3,x	4 cut down cells, as above. Each cell wired as separate experiment, denoted by x = 1 - 4. Coverglass overhang varied from cell to cell to suppress current collection.
Metal Samples	11 metal samples, 10 are 1 inch squares to test arcing theories. Five samples, denoted MS 1 - MS 5 are different pure metals covered with strips of kapton 1/16 inch wide and 1/16 inch apart. Five others, denoted MS 6 - MS 10, are different pure metals in a rod-plane discharge geometry. The remaining sample, 1 inch by 2.5 inch aluminum, is Z93 covered. Different pure metals are Cu, Au, Ag, W, Al
Snapover	Six 1 cm diameter copper disks covered with Kapton. Each has a pinhole of varying size. Denoted Snap 1 - Snap 6
Anodized Aluminum	One sample of anodized aluminum for arcing measurements.

Relay Assignments

Relay #	Board #1 (100 mA)	Board #2 (12.5 mA)
1	APSA	MS 1
2	SSF	MS 2
3	G0	MS 3
4	SSMIN 2	MS 4
5	SSMIN 1,1	MS 5
6	SSMIN 1,2	MS 6
7	SSMIN 1,3	MS 7
8	SSMIN 1,4	MS 8
9	SSMIN 3,1	MS 9
10	SSMIN 3,2	MS 10
11	SSMIN 3,3	Al Z93
12	SSMIN 3,4	G1
13	SNAP 1	G2
14	SNAP 2	Anod Al
15	SNAP 3	unused
16	SNAP 4	unused
17	SNAP 5	
18	SNAP 6	

Bias Range 1: 0 V to -600 V, 67 min total, (Arcing & ion current)

Bias Level (Volts)	Dwell Time (Minutes)	Sum	Total # arcs $n = 3.8 \times 10^6$	Total # arcs $n = 10^6$
0	1	1	0	0
-30	1	2	7.8E-07	2.0E-07
-60	1	3	2.1E-04	5.6E-05
-90	1	4	5.7E-03	1.5E-03
-120	30	34	1.8	0.5
-150	20	54	10.0	1.9
-180	5	59	7.8	2.1
-210	2	61	10.9	2.9
-240	1	62	16.0	4.2
-270	1	63	41.6	10.9
-300	1	64	97.6	25.7
-400	1	65	1003.7	264.1
-500	1	66	6117.3	1609.8
-600	1	67	26787.3	7049.3

Bias Range 1S: Identical to Range 1 but limited to -500 V maximum. Accomodates expected voltage limitation on power supply #2

Bias Range 2: 0 V to +300 V, 5 V increments, 10 second dwell, 11 min total, (electron current)

Bias Range 3: -300 V to +300 V, 5 V increments, 10 second dwell, 21 min total, (electron & ion current)

Essential Measurements

Orbiter Orientation	Power Supply #1 (100 mA)	Bias Range	Power Supply #2 (12.5 mA)	Bias Range	Duration minutes	Sum	Mission Time: Hours	Minutes
Ram	APSA	1	MS 1	1S	67	67	1	7
Ram	APSA	2	idle	-	11	78	1	18
Ram	SSF	1	MS 2	1S	67	145	2	25
Ram	SSF	2	idle	-	11	156	2	36
Ram	Si G0	1	MS 3	1S	67	223	3	43
Ram	Si G0	2	idle	-	11	234	3	54
Ram	Si G0	2	G1	2	11	245	4	5
Ram	Si G0	2	G1 & G2	2	11	256	4	16
Ram	APSA	1	Anod Al	1S	67	323	5	23
Ram	SSMIN 1,1	2	idle	-	11	334	5	34
Ram	SSMIN 1,2	2	idle	-	11	345	5	45
Ram	SSF	1	MS 4	1S	67	412	6	52
Ram	SSMIN 1,3	2	idle	-	11	423	7	3
Ram	Si G0	1	MS 5	1S	67	490	8	10
Ram	SSMIN 1,4	2	idle	-	11	501	8	21
Ram	APSA	2	idle	-	11	512	8	32
Ram	SSMIN 3,1	2	idle	-	11	523	8	43
Ram	SSF	2	idle	-	11	534	8	54
Ram	SSMIN 3,2	2	idle	-	11	545	9	5
Ram	SSMIN 3,3	2	idle	-	11	556	9	16
Ram	SSMIN 3,4	2	idle	-	11	567	9	27
Ram	idle	-	Al Z93	2	11	578	9	38
Ram	SSMIN 2	1	Al Z93	1S	67	645	10	45
Ram	SNAP 1	2	idle	-	11	656	10	56
Ram	SNAP 2	2	idle	-	11	667	11	7
Ram	SNAP 3	2	idle	-	11	678	11	18
Ram	SNAP 4	2	idle	-	11	689	11	29
Ram	SNAP 5	2	idle	-	11	700	11	40
Ram	SNAP 6	2	idle	-	11	711	11	51
Wake	APSA	3	idle	-	21	732	12	12
Wake	SSF	3	idle	-	21	753	12	33
Wake	SSMIN 1,1	3	idle	-	21	774	12	54
Wake	SSMIN 1,2	3	idle	-	21	795	13	15
Wake	SSMIN 1,3	3	idle	-	21	816	13	36
Wake	SSMIN 1,4	3	idle	-	21	837	13	57
Wake	SSMIN 3,1	3	idle	-	21	858	14	18
Wake	SSMIN 3,2	3	idle	-	21	879	14	39
Wake	SSMIN 3,3	3	idle	-	21	900	15	0
Wake	SSMIN 3,4	3	idle	-	21	921	15	21
Wake	idle	-	Al Z93	3	21	942	15	42
Wake	Si G0	3	idle	-	21	963	16	3
Wake	Si G0	3	G1	3	21	984	16	24
Wake	Si G0	3	G1 & G2	3	21	1005	16	45
Wake	SNAP 1	2	idle	-	11	1016	16	56
Wake	SNAP 2	2	idle	-	11	1027	17	7
Wake	SNAP 3	2	idle	-	11	1038	17	18
Wake	SNAP 4	2	idle	-	11	1049	17	29
Wake	SNAP 5	2	idle	-	11	1060	17	40
Wake	SNAP 6	2	idle	-	11	1071	17	51

Secondary Measurements

Orbiter Orientation	Power Supply #1 (100 mA)	Bias Range	Power Supply #2 (12.5 mA)	Bias Range	Duration minutes	Sum	Mission Time: Hours	Minutes
Ram	SSMIN 1,1	1	MS 6	1S	67	1138	18	58
Ram	SSMIN 1,4	1	MS 7	1S	67	1205	20	5
Ram	SSMIN 3,1	1	MS 8	1S	67	1272	21	12
Ram	SSMIN 3,4	1	MS 9	1S	67	1339	22	19
Ram	SSF	1	MS 10	1S	67	1406	23	26
Ram	SSMIN 2	1	Anod Al	1S	67	1473	24	33
Ram	APSA	1	Al Z93	1S	67	1540	25	40
Ram	SSF	2	idle	-	11	1551	25	51
Ram	APSA	2	idle	-	23	1574	26	14
Ram	SNAP 1	3	idle	-	23	1597	26	37
Ram	SNAP 2	3	idle	-	23	1620	27	0
Ram	SNAP 3	3	idle	-	23	1643	27	23
Ram	SNAP 4	3	idle	-	23	1666	27	46
Ram	SNAP 5	3	idle	-	23	1689	28	9
Ram	SNAP 6	3	idle	-	23	1712	28	32
WAKE	SNAP 1	3	idle	-	23	1735	28	55
WAKE	SNAP 2	3	idle	-	23	1758	29	18
WAKE	SNAP 3	3	idle	-	23	1781	29	41
WAKE	SNAP 4	3	idle	-	23	1804	30	4
WAKE	SNAP 5	3	idle	-	23	1827	30	27
WAKE	SNAP 6	3	idle	-	23	1850	30	50

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1993

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Sampie Flight Experiment Final Technical Requirements Document

5. FUNDING NUMBERS
WU–506–48–2B

6. AUTHOR(S)
G. Barry Hillard and Dale C. Ferguson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–7942

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–106224

11. SUPPLEMENTARY NOTES
Responsible person, G. Barry Hillard, (216) 433–2220.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Solar Array Module Plasma Interactions Experiment (SAMPIE) is a shuttle based flight experiment scheduled for launch in early 1994. SAMPIE will investigate plasma interactions of high voltage space power systems in low earth orbit. Solar cell modules, representing several technologies, will be biased through a series of 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 in its final form. 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).

14. SUBJECT TERMS
Space environment interaction; Space power; Space experiments

15. NUMBER OF PAGES
28

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	