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Solar Array Module Plasma Interactions Experiment (SAMPIE): Science and Technology Objectives

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The solar array module plasma interactions experiment (SAMPIE) is an approved NASA flight experiment manifested for Shuttle deployment in early 1994. The SAMPIE experiment is designed to investigate the interaction of high voltage space power systems with ionospheric plasma. To study the behavior of solar cells, a number of solar cell coupons (representing design technologies of current interest) will be biased to high voltages to measure both arcing and current collection. Various theories of arc suppression will be tested by including several specially modified cell coupons. Finally, SAMPIE will include experiments to study the basic nature of arcing and current collection. This paper describes the rationale for a space flight experiment, the measurements to be made, and the significance of the expected results. A future paper will present a detailed discussion of the engineering design.

Introduction

HISTORICALLY, power systems on U.S. space vehicles have operated at the nominal 28-V dc inherited from the aircraft industry. At such low voltages, plasma interactions in low Earth orbit (LEO) are negligible and have not been a consideration in spacecraft design. High power systems now under development for space applications will operate at higher voltages in order to reduce power loss and system mass. The emergence of such systems is motivated primarily by a desire to save weight. Since the resistance of the necessary cabling is a strongly decreasing function of mass per unit length and cable losses are proportional to current squared, it is desirable to furnish power at higher voltages and lower currents. A further consideration is the reduced effect of magnetic interactions (torque and drag) that will follow from low current operation. Figure 1 shows past space power levels as well as some future trends. Going even beyond the figure are proposed power systems for orbit transfer that have been predicted to require thousands of volts. Vehicles for the space exploration initiative (SEI), which will experience plasma conditions in low Mars orbit (LMO) qualitatively similar to LEO, may also require very high voltage systems that will undergo similar plasma interactions.

Whereas high voltage systems are clearly desirable to the power system designer, they suffer the drawback of interacting with the ionospheric plasma[1,2] in several different ways (Fig. 2). First, conducting surfaces whose electrical potential is highly negative with respect to the plasma undergo arcing. Such arcing not only damages the material but results in current disruptions, significant electromagnetic interference (EMI), and large discontinuous changes in the array potential. For arrays using traditional silver-coated interconnects, a threshold potential for arcing of about −230 V relative to the plasma is believed[3] to exist. At least for solar cell interconnects, there are theoretical arguments[4] supported by limited ground tests[5] indicating that different metals will arc at different thresholds. Since new solar cell designs are emerging using copper traces, it is important to determine arcing thresholds, arc rates, and arc strengths for a variety of materials exposed to space plasma. Furthermore, inbound ions, accelerated by the high fields, will cause sputtering from surfaces with which they impact.

For solar arrays or other surfaces which are biased positively with respect to the plasma, a second effect occurs. Such surfaces collect electrons from the plasma, resulting in a parasitic loss to the power system. Since the mass of an electron is much less than an ion, the magnitude of current density is much greater for surfaces with positive bias. At bias potentials greater than about 200 V, sheath formation and secondary electron emission from the surface causes the entire surrounding surface, normally an insulator, to behave as if it were a conductor. This effect, often referred to as "snapover," is illustrated in Fig. 3 and results in large current collection from even a very small exposed area.

Besides producing a power loss, currents collected by biased surfaces will significantly affect the potentials at which different parts of the spacecraft will "float." Because of their large mass and low mobility, ions collected by negatively biased surfaces result in a relatively small plasma current density. The lightweight electrons, on the other hand, are readily collected by positively biased surfaces. Ram and wake effects further complicate the picture. Ram energy is considerably higher than ambient thermal energy so ram flow enhances ion collection relative to surfaces that are oblique to plasma flow. The spacecraft will reach equilibrium at whatever potential results in a net collected current of zero. The worst situations occur when the spacecraft power system uses a negative ground. In such a configuration, large surfaces are nega-

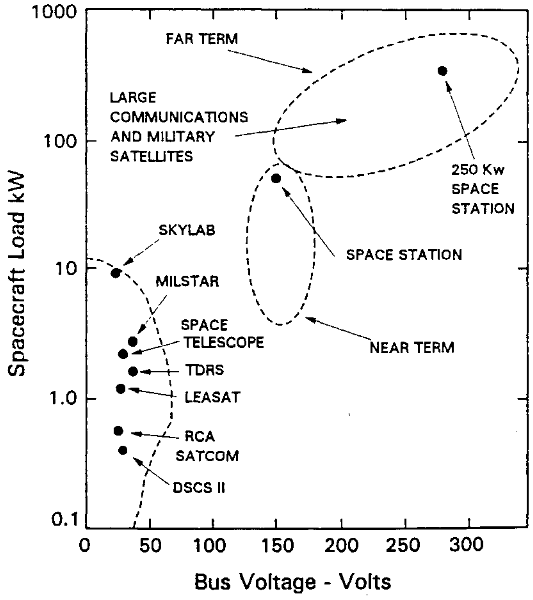

Fig. 1 Diagrammatic representation of present and future trends in space power (reproduced from Ref. 25).

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tive and must collect slow moving ions to balance the current from electron collection that now occurs only from relatively small areas of positive surface. In the worst case, parts of the spacecraft will be biased with respect to the ionosphere to a level very near the maximum voltage used on the solar arrays.

Two previous flight experiments involving conventional silicon arrays, plasma interactions experiments (PIX I and PIX II[1,2]) have shown many differences with ground tests. As shown in Fig. 4, arc rates in space were quite different and generally higher than in ground tests. For current collection, the current vs bias voltage curves obtained in space not only differed radically from the ground tests but differed depending on whether the data was taken with the array exposed to spacecraft ram or wake. It is desirable, therefore, that the behavior of various solar cell technologies be established with a suitable in-space test.

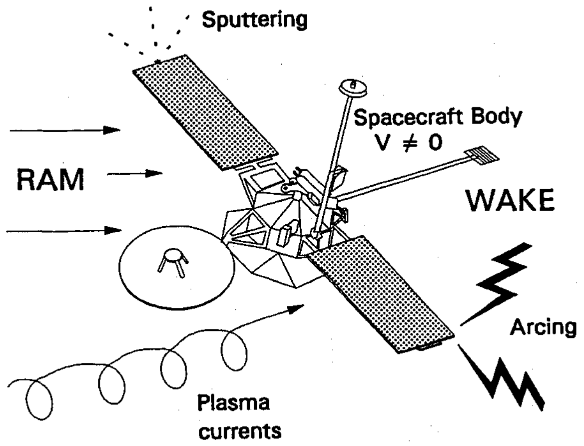


Fig. 2 Schematic representation of typical spacecraft high voltage interactions.

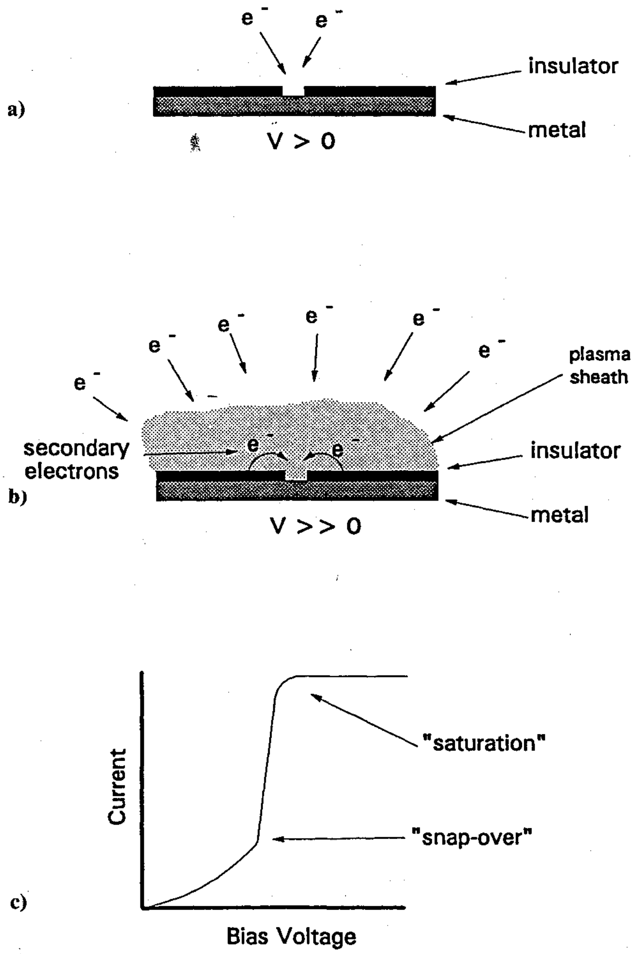


Fig. 3 Schematic representation of snapover effect: a) low voltage interactions of typical pinhole; b) high voltage interactions of typical pinhole; and c) schematic representation of I-V curve for high voltage pinhole.

In this paper, we have reviewed the background and justification for the solar array module plasma interactions experiment (SAMPIE) only briefly, since this has been presented previously.[6] We now present the status of the design and a discussion of the selected experiments.

Objectives

The general objective of the SAMPIE program is to investigate, with 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 LEO plasma on future high voltage space power systems. There are seven specific objectives of the SAMPIE experiment which are described in detail in the project's technical requirements document[7] (TRD).

1) For selected solar cell technologies, determine the arcing threshold, arc rates, and magnitude of arc current. As a minimum, the solar cells selected for flight must include the following: a) a sample array made of traditional silicon solar cells, which will provide a baseline for comparison with past experiments; b) a sample array using an advanced photovoltaic solar array (APSA); and c) a sample array using current Space Station Freedom (SSF) solar cell technology.

2) For these sample arrays, measure plasma current collection vs applied bias.

3) Design and test an arc mitigation strategy; i.e., modifications to standard design that may significantly improve the arcing threshold.

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.

5) Design an experiment to determine the dependence of arcing threshold, arc rates, and arc strengths on the choice of metal, with all other relevant parameters controlled.

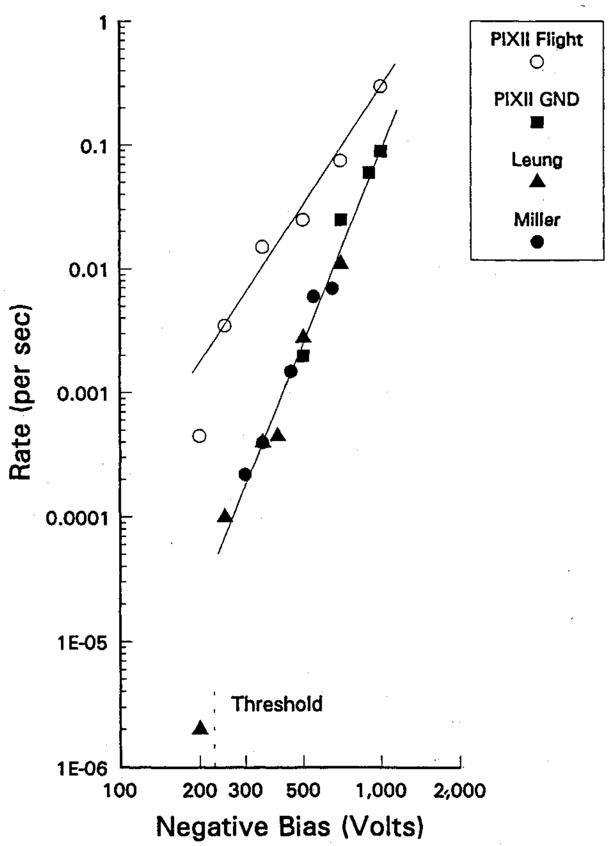


Fig. 4 Plot of PIX II data vs ground test results (reprinted with permission from Ref. 26).

6) Design controlled experiments to study basic phenomena related to arcing and its effects and add them on a space-available basis, subject to time and resource constraints. These may include (but are not limited to) the following: a) arcing from anodized aluminum using alloys and anodization processes typical of ones being considered for use on large space structures; b) arcing from pinholes in inidium tin oxide- (ITO-) coated conductors or from biased conductors covered with strips of ITO; and c) sputtering and degradation of metals or metal covered insulators biased to high negative potential in the atomic oxygen environment of LEO.

7) Measure a basic set of plasma parameters to permit data reduction and analysis. An additional requirement to aid data reduction is to obtain timely flight data (such as the Shuttle orientation and times of thruster firings) relevant to SAMPIE operations.

An objective that is implicit in most of the preceding is validation of computer models. Chief among these is the NASA charging analyzer program for low Earth orbit (NASCAP/LEO).[8] NASCAP/LEO is fundamentally a finite element Poisson's equation solver. As such, it is capable of dealing with complex geometries and can realistically model the arbitrary configurations of typical spacecraft. The code requires a specification of plasma conditions, spacecraft orientation and velocity, materials, and electrical biases. The code then calculates the equilibrium potential distribution on all surfaces and in the surrounding space, as well as the perturbed plasma conditions resulting from the interaction. Charge flow to the spacecraft and its effects are especially important and are readily calculated.

NASCAP/LEO has been under development since 1982 under a contract managed by the Lewis Research Center and will be released for public use in mid 1993. Despite its maturity, it has been validated only with data from PIX as well as sounding rockets and ground tests. All of the current collection measurements made on SAMPIE's various samples will be used to validate and refine the code.

Experiment Design

Package Layout

The SAMPIE experiment 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.[9] Figure 5 shows the carrier, as it is currently configured for the Office of Aeronautics and Space Technology (OAST-2) mission, with the SAMPIE enclosure on one of the four top mounting positions. As shown in more detail in Fig. 6, the package consists of a baseplate to which a card cage for printed circuit boards and various instrument boxes are attached. Most of the instruments and electrical subsystems are on cards mounted within the cage. The cover is a one piece case which provides a mounting surface for the experiment plate. Two electrical probes, one Langmuir probe to monitor plasma density and temperature, and a V-body probe to monitor Orbiter potential with respect to the ionosphere, are part of the package. Since SAMPIE will significantly disturb the ionosphere within an area estimated to be about 1 m in all directions, these probes have been moved to a side mounting position about 5 ft away. A comprehensive discussion of all instruments, subsystems, and design issues will be the subject of a future paper.

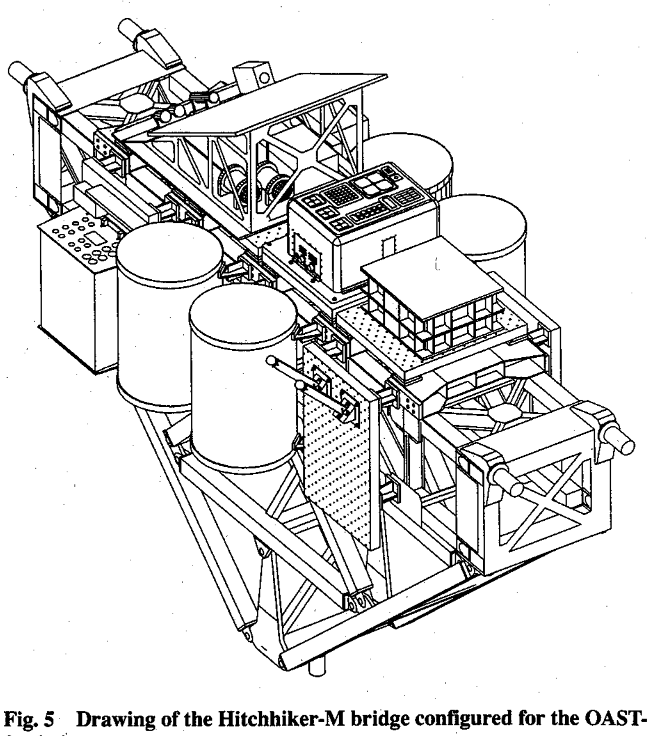
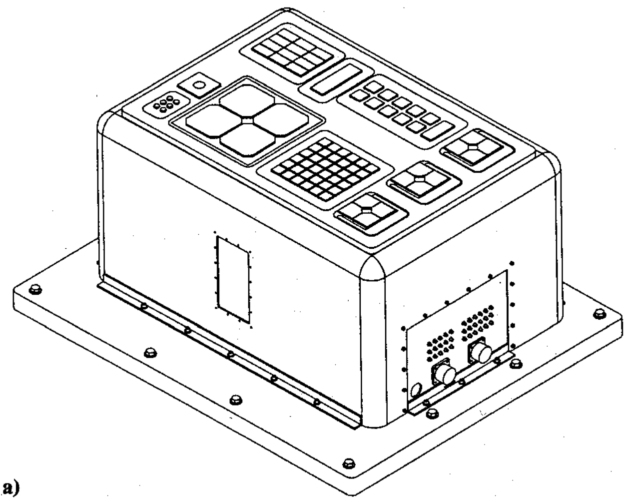
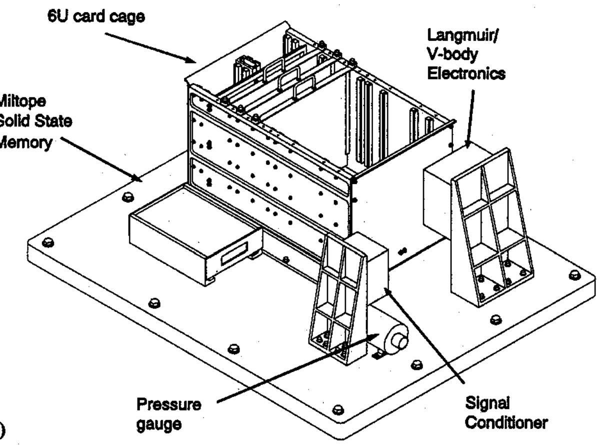


Fig. 5 Drawing of the Hitchhiker-M bridge configured for the OAST-2 mission.



a)



b)

Fig. 6 An external view of the SAMPIE package: a) with enclosure and experiment plate installed; and b) with enclosure cover removed.

Operations

In a simplified description of the experiment, one sample is biased to a particular voltage for a preset time whereas all remaining samples are held at ground potential. The power supply will bias the solar cell samples and other experiments to dc voltages as high as +300 and −600 V with respect to Shuttle ground. The bias time varies significantly with voltage and is specified in the TRD. 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 current collection vs voltage. A set of plasma diagnostics measurements is then taken and the procedure repeated at the other bias voltages. Diagnostic measurements consist of background pressure, plasma density and pressure, and the potential of the Orbiter with respect to the plasma. This last measurement is necessary because operation of SAMPIE will result in shifts of the

Table 1 Specific bias sequences for primary experiments

	Ram		Wake	
Experiment	Bias 1	Bias 2	Bias 2	Bias 3
APSA	2	2	—	1
SSF	2	2	—	1
Si-step 1	2	1	—	1
Si-step 2	—	1	—	1
Si-step 3	—	1	—	1
MBT-strips	1	—	—	—
MBT-Z93	1	1	—	1
SBT	1	—	—	—
Snapover	—	1	1	—
SSMOD-1	—	1	—	1
SSMOD-2	1	—	—	—
SSMOD-3	—	1	—	1

Table 2 Specific bias sequences for secondary experiments

	Ram		Wake	
Experiment	Bias 1	Bias 2	Bias 3	Bias 3
APSA	1	1	—	—
SSF	1	1	—	—
MBT-rod	1	—	—	—
Snapover	—	—	1	1
SSMOD-1	1	—	—	—
SSMOD-2	1	—	—	—
SSMOD-3	1	—	—	—

Orbiter ground potential. The data returned from the experiment will have bias voltage as the independent variable. We need this voltage to be the potential of the sample with respect to the ionosphere but the power supply only can set the voltage with respect to Orbiter ground. Therefore, Orbiter ground excursions are a highly nonlinear offset which must be corrected for. Extensive modeling has been done on this problem[10] and we expect ground excursions to be in the range of 10–25 V.

Vehicle orientation with respect to its velocity vector is critical since ram and wake effects are known to be significant. SAMPIE's operations plan will request control of Orbiter orientation such that one entire set of measurements is made with the payload bay held in the ram direction and a second set with the bay in the wake. Shuttle operational logs will be relied on 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. The experiment timeline is expected to require approximately 12 h of bay-to-ram and about 6 h of bay-to-wake.

Individual Experiments

Figure 7 shows the proposed layout of the experiment plate. The individual experiments will be described in detail in the following paragraphs. In addition to the experiment modules, Fig. 7 shows a sun sensor. This is a simple silicon photocell designed to aid data analysis by giving an indication of the degree of insolation. In the following experiment descriptions, the abbreviations in brackets serve as a key for Tables 1 and 2.

Space Station Cells

A four-cell coupon of 8 × 8-cm space station cells [SSF], having copper interconnects in the back, will allow a test of this technology. Arcing is expected to occur from the cell edges and there is considerable interest in arc rate vs bias curves as well as in the arcing threshold for these cells. Current collection from these cells will perhaps be even more interesting. As discussed earlier, current collection characteristics of solar cells can dramatically affect the floating potential of the spacecraft. An initial assessment of the implications for SSF was made by a workshop that included most of the recognized experts in NASA, industry, and academia.[11] That assessment showed that plasma effects are expected to have considerable impact on the performance and structural properties of SSF. As a result, a NASA "Tiger Team" was formed to comprehensively evaluate all related issues and to recommend any necessary action.[12] This team, consisting of more than 100 people including most of the experts just mentioned, worked for more than a year to study these issues. Extensive computer modeling and ground-based plasma testing was performed and incorporated into an exhaustive set of trade studies. NASCAP/LEO and similar codes played a key role in this effort.

The Tiger Team concluded that major parts of SSF would float at about 140-V negative with respect to the ionosphere, close to the 160-V maximum used by its power system. Such large potentials would be expected to involve major difficulties with arcing and sputtering and clearly cannot be tolerated. To address this problem, a plasma contactor is being added to SSF. It will be a hollow cathode device, grounded to SSF structure and emitting a continuous cloud of plasma. This plasma will be highly conductive and will effectively ground the structure to the ionosphere. A number of details, particularly the current capacity of the device, are being determined with considerable reliance on modeling results. It is important that data from SAMPIE be incorporated into the contactor design for SSF as soon as it is received.

Advanced Photovoltaic Solar Array

A 12-cell coupon of 2- × 4-cm APSA[13] cells will test the behavior of this relatively new, very thin (60 μm) technology. APSA normally uses a flexible blanket of carbon loaded Kapton® mounted in an external frame. The carbon loaded material provides a blanket that is slightly conducting and is necessary as an active charge control measure in geostationary applications. For use in LEO, the blanket will use germanium coated Kapton® for protection from atomic oxygen attack. On SAMPIE, a flexible, deployable geometry is not practical and the cell coupon will be hard mounted to a piece of aluminum. This should have no impact on the plasma interactions SAMPIE is designed to test since all cells, interconnects, and bus bars are on the front side.

Traditional Silicon

There are two reasons for including a coupon of traditional 2- × 2-cm silicon solar cells. First, a baseline for comparison is provided by including the technology that has been used exclusively in the U.S. space program to date. It was flown on PIX I and PIX II as well as being the subject of extensive ground-based testing and will provide a basis for continuity with past results. Second, computer codes which predict the results of plasma interactions are now mature but largely unvalidated. A key feature of such codes is the ability to predict current collection for solar arrays. Such predictions not only permit power system designers to deal with parasitic power losses but lead directly to a calculation of the floating potential of the vehicle. Unfortunately, plasma sheath effects make scaling the current collection to large arrays highly nonlinear and

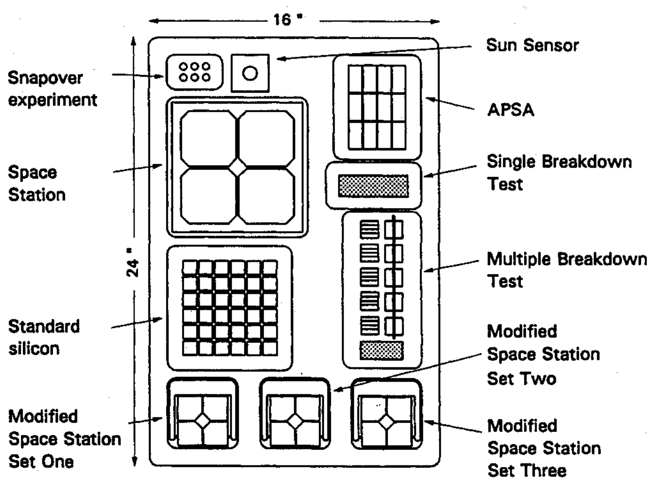


Fig. 7 SAMPIE experiment plate.

very difficult to predict. To study this effect and provide data for model validation, we have devised the experiment shown schematically in Fig. 8. Data is taken from a four-cell coupon of 2- × 2-cm silicon solar cells wired as a series string. A second independent series string of 12 cells surrounds the inner four. A third series string of 20 cells, also independent, surrounds the entire assembly.

The experiment is done in three parts. First, as illustrated in Fig. 8a, the outer strings are held at ground while the four-cell coupon is stepped through the entire bias sequence generating data on arc rates and electron and ion collection [Si-step 1]. The entire bias sequence is then repeated (Fig. 8b) with the 16-cell string always biased at the same potential as the inner four and the outer ring held at ground [Si-step 2]. It should be noted that, although the 16-cell string will be collecting current, this current is not measured. Data is taken only from the inner four cells which now collect more current because of the growing plasma sheath. Finally, the experiment is repeated a third time with all 36 cells biased together, data taken again only from the inner four [Si-step 3].

Modified Space Station

On the bottom of the experiment plate, Fig. 7, are three coupons of four cells. These are Space Station Freedom cells which have been cut from the normal 8- × 8-cm size to 4 × 4 cm. This size reduction is necessary to increase the number of experiments that can be done in the limited area provided by the experiment plate. The data returned from the selected experiments will not be impacted by the scaling. These cells are 0.0203 cm (8 mil) thick with a 0.0127-cm- (5-mil-) thick coverslide and are normally spaced 0.0813 cm (32 mil) apart. The coverslide overhangs the cell by an amount which can vary between zero and 0.0305 cm (12 mil) with 0.0089 cm (3.5 mil) nominal. Actual measurements of a sample of 120 such cells show the average overhang to be the nominal 0.0089 cm value.[14] When biased to negative potentials, the silicon collects ion current from the plasma and will be subject to arcing. At positive biases, the cells collect electrons. Several factors in the cell design are now known to significantly affect plasma interactions. The three coupons we will fly are designed to study these systematically.

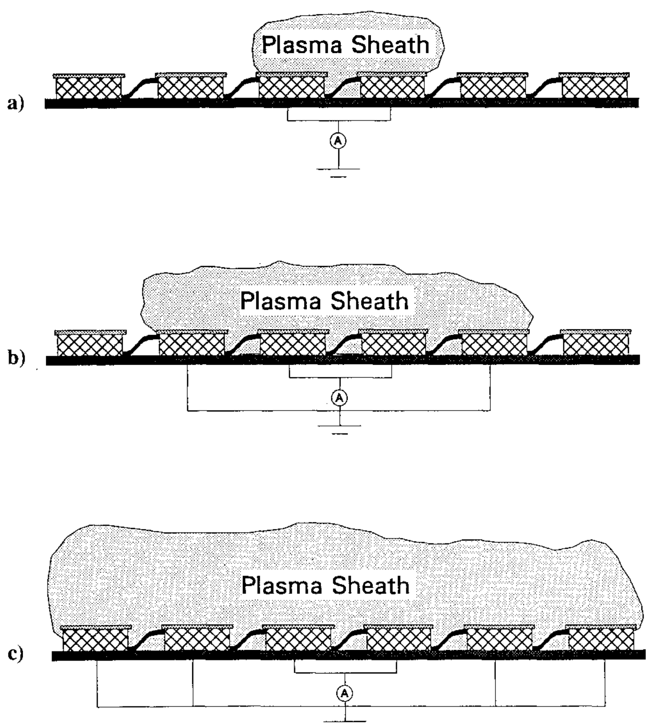


Fig. 8 Two-dimensional schematic representation of the array size scaling experiment: a) inner four cells biased, all others grounded; b) inner four cells and adjacent 16 biased, outer cells grounded; and c) all cells biased.

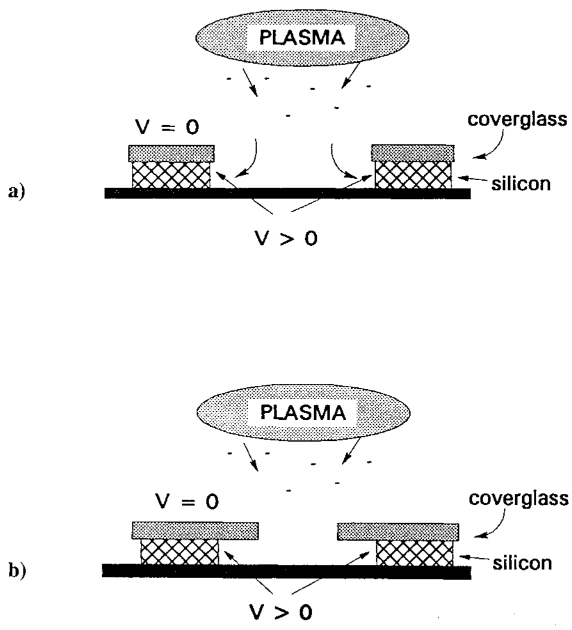


Fig. 9 Schematic representation of modified SSF overhang experiment: a) baseline overhang; and b) extended overhang.

The first factor we will test is the effect of the overhang distance [SSMOD-1]. Recent NASCAP/LEO[15] modeling indicates that extending the cover slides to cover a larger portion of the gap between cells is sufficient to choke off most of the current. Intuitively, as the overhang approaches a value close to the 0.0203-cm (8-mil) cell thickness, inbound particles will have an increasingly difficult time bending around the coverglass to reach the silicon (Fig. 9). This is borne out in the computer simulations which indicate that an overhang of 0.0229 cm (9 mil) is sufficient to effectively eliminate current collection. To test these results, the coupon has four cells, each wired as an independent experiment. The overhangs are chosen to be 0, 0.0102, 0.0178, and 0.0279 cm (0, 4, 7, and 11 mil).

The second coupon tests a proposed arc suppression technique [SSMOD-2]. For the past several years, research has been reported[16] indicating that a major factor in arcing is ion bombardment of excess coverglass adhesive which is inevitably present in the gap between cells. In this view, the actual arc is a breakdown in water vapor evolved from the adhesive.[17] Whether this mechanism is peculiar to this cell geometry or is more general is not yet clear. The authors of Ref. 16 have developed a unique facility and associated process for treating SSF solar cells to completely remove excess adhesive without structurally affecting the cell to coverglass bond. The coupon, which is wired as a series string, will be sent to them, subjected to their newly developed cleaning process, and returned for incorporation into the SAMPIE experiment.

The final coupon, shown on the bottom left in Fig. 7 [SSMOD-3], is designed to study current collection as a function of exposed edge area. Modified SSF cells will have their edges completely sealed with coverglass adhesive except for specified lengths that will be left free. The exposed lengths will be 0, 0.0203, 0.0406, and 0.0813 cm (0, 8, 16, and 32 mil). Data from this coupon will be used to verify NASCAP/LEO predictions that current collection is linear with exposed area.

Multiple Breakdown Test

The first of the two breakdown tests shown in Fig. 7 will explore the hypothesis that negative potential arcing is a special case of the classical vacuum arc.[18] With geometry and test conditions controlled, only the composition of the metal will be varied. We will do two different types of measurements of five different pure metals, chosen to be gold, silver, copper, aluminum, and tungsten. The family of curves (arc rate vs bias) produced by these samples will be correlated with various material properties such as vapor pressure, hardness, and work function and should give considerable insight into the basic nature of the arcing process.

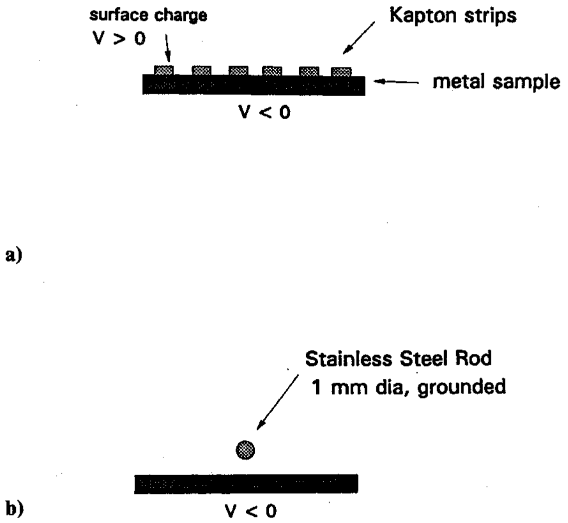


Fig. 10 Schematic representation of multiple breakdown test: a) metal-insulator breakdown test; and b) rod-plane discharge test.

The first set of five samples, illustrated in Fig. 10a [MBT-strips], consists of strips of 0.0025-cm- (1-mil-) thick Kapton® 0.1588 cm (1/16 in.) wide, spaced 0.1588 cm apart. This arrangement is typical of metal/insulator geometries widely found in space power applications including the solar cell/interconnect. When biased through a sequence of negative voltages, the exposed metal strips assume the full negative voltage and play the role of cathode in the resulting discharge. The Kapton® strips collect sufficient surface charge to cancel the electric field between the dielectric surface and the underlying metal, becoming strongly positive and assuming the role of anode. The nature of the resulting discharge is controversial. One possibility is that the arc propagates through space, originating as a vacuum arc on the metal surface, proceeding as a metal vapor discharge in the ejected material, and terminating on the dielectric surface. An alternate theory holds that such arcs are examples of surface flashover, proceeding along the metal surface, up the side of the insulator and terminating on its surface. It is hoped that detailed surface studies of returned samples will decide this issue.

A complication encountered with the foregoing test is the necessary use of adhesives to bond the Kapton® strips to the metal surface. In the event of a surface discharge, these adhesives will be intimately involved with the process and may react in ways difficult to predict. Therefore, a second set of five metals will be tested in a traditional rod-plane geometry [MBT-rod]. Shown schematically in Fig. 10b, a 1-mm-diam stainless steel rod is suspended 1 mm above the surface of the sample. This rod is grounded to the structure and plays the role of anode. The discharge between the metal surface and the rod now involves no dielectric or adhesive and is expected to produce data that depends only on the composition of the metal sample. In many ways this set provides a conceptually simpler experiment than the first set. Real space power systems, however, are much closer to the Kapton® strip experiments. For this reason, we decided to do both.

The final sample on the multiple breakdown coupon is the double-sized one at the bottom. It is placed on this coupon only for convenience and is not designed to test arcing phenomenon [MBT-Z93]. The sample is aluminum coated with Z93, a thermal coating widely used in the U.S. space program. Measurements of this material in a plasma chamber, performed at Lewis, indicate that under some conditions[19] it becomes conducting and may be used as an electron collecting surface. We will subject the sample to the positive bias sequence and measure the resulting electron collection.

Single Breakdown Test

The single breakdown test [SBT] consists of a sample of anodized aluminum. There is considerable concern that this material undergoes dielectric breakdown and arcing when biased to high voltages.[20] The particular alloy and sulfuric acid anodization process are chosen to be identical with that currently baselined for the SSF main truss structure.

Table 3 Definition of voltage bias sequences for experiment samples

Bias range	Purpose	Min, *V*	Max, *V*	Duration, min
1	Arcing/ ion current	0	−600	67
2	Electron current	0	+300	11
3	Electron and ion current	−300	+300	21

Snapover

To study current collection and snapover, we include six 1-cm-diam copper disks (Fig. 3a) covered with 0.0076-cm- (3-mil-) thick Kapton®. Each has a pinhole in the center with hole sizes tentatively chosen as 0.0025, 0.0127, 0.0254, 0.0381, 0.0508, and 0.0762 cm (1, 5, 10, 15, 20, and 30 mil). The use of such simple geometry will enable computer modeling of the essential physics without the complications introduced by geometrical complexities inherent in solar cells. The resulting family of current vs applied bias curves will be compared with predictions of NASCAP/LEO and other theoretical treatments. These curves, illustrated schematically in Fig. 3c, show the sudden onset of snapover as well as the approach to saturation. The physics underlying such curves is still a topic of academic research[21–24] and remains controversial. Reproducing the details of these curves will be a major challenge for modelers.

Experiment Timeline

The experiment timeline for SAMPIE is in two parts. The primary portion is that part of the experiment that will be guaranteed sufficient mission time, assuming normal Orbiter operations. Because of the challenge in coordinating conflicting requirements of the various OAST-2 experiments, this time is expected to be limited to 18 h. The second part of the timeline contains additional measurements that will be accommodated if mission operations can do so. For SAMPIE, this will require approximately 12 additional hours of experiment time.

The various experiments are subjected to three possible measurement sequences. These are summarized in Table 3. Table 1 summarizes the individual bias sequences, and the number of times the sequence is run, for the primary portion of the timeline. Three of the experiments, APSA, SSF, and the traditional silicon modules have been defined as the minimum necessary for a successful mission. Because of their importance, they are repeated a second time. All measurements are done at least once with the exception of the rod-plane discharge experiment. At this time, the 18-h mission frame will not allow this module to be tested as a primary experiment and it has been moved to the secondary portion. It is expected, however, that results from ground testing will allow a shorter arcing sequence than the 67 min required for solar cells. If this is borne out, the module will be moved back to the primary portion.

Table 2 shows the secondary measurements. With the exception just discussed, they are additional measurements that will be highly desirable but are not critical.

Summary

The SAMPIE flight experiment is the first orbital space power system/plasma interaction experiment since PIX II and is far more ambitious. Besides testing two emerging solar cell technologies, it will explore the viability of several arc suppression techniques. Using controlled experiments, it will provide basic data on arcing and current collection which can be used to validate and extend existing models and theories. SAMPIE will be designed and built in a highly modular way that will have easy reflight capability in mind. To this end, it can serve as a testbed for future technologies.

Acknowledgments

The authors wish to acknowledge and thank the members of the SAMPIE project team for their invaluable contributions in converting conceptual experiments to realistic hardware. In particular, the NASA Lewis Research Center project manager, Larry Wald, deserves considerable credit for somehow keeping the project on schedule despite our persistent efforts to expand its scope and complexity.

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