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SPACE TEST PROGRAM OF HIGH-VOLTAGE SOLAR ARRAY/SPACE PLASMA INTERACTIONS

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Future spacecraft, notably the proposed Space Station, will require power systems much larger than have previously been flown. Efficiency, cost, mass and array size considerations demand the solar array operate at a higher voltage than previous spacecraft. It is recognized that at higher voltages, and at the relatively high plasma density present at low earth orbital altitudes, undesirable interactions between the high voltage solar array and the space plasma will occur. These can lead to parasitic power loss and/or arcing. Such interactions are complex and cannot be understood, properly simulated or evaluated by ground testing and modeling alone. Space experiments on high voltage solar array space plasma interactions in low earth orbit are an absolute requirement for confident design of a higher voltage solar array. Experiments are presently being identified to provide the necessary space data for calibration of ground testing, validation of analytical models, and development of design guidelines required for confident design of high voltage solar arrays in space. This paper summarizes one proposed flight experiment program which is designed to obtain the required data.

INTRODUCTION

Interactions between a spacecraft and its orbital particle and field environment can have significant impact on the spacecraft systems' operation and life. Radiation damage and aerodynamic drag, for example, must be considered in designing any space system. There are, however, a number of orbital environmental interactions which become important design considerations only for large and/or high power systems. Their impact must be assessed to ensure successful design. In particular, interactions between higher voltage solar arrays and the space plasma are of critical concern in designing large orbital power systems such as are required for a space station.

Most U. S. spacecraft to date have used low voltage solar arrays, generating power near 30 volts. The highest voltage array flown by NASA to date was on Skylab, which had a solar array with a normal operating voltage of 70 volts and generated 16 kW of power. Future large systems will require increasing power generation capability. For example, a solar array providing 35-50 kW of power for a low inclination, low altitude (500 km) space system will need to generate about 100 kW of power when in sunlight. As power levels increase, the mass, I^2R power loss and power distribution system complexity penalties for maintaining low solar array voltages become prohibitive, making higher voltage array designs mandatory (Ref. 1). It is thus necessary to thoroughly understand high voltage solar array operation in the space plasma environment. Unfortunately, no adequate simulation or model calibration can be achieved with ground based experiments alone.

Solar array systems consist of strings of solar cells with metallic interconnects between them. These interconnects are at voltages depending upon their positions in the array circuit and are usually exposed to the space environment. When such systems are placed in orbit, they will interact with the naturally occurring space plasma. Two types of potentially hazardous interactions to a higher voltage solar array in orbit are presently recognized: power loss from parasitic currents through the plasma; and arcing. Both of these interactions are plasma density dependent and present greater hazards at higher densities. The low temperature ionospheric plasma has a peak density (of 10^6 particles/cm^3) at about 300 km altitude. High voltage system-plasma interactions will therefore be most severe in low earth orbits. The power levels envisioned for such spacecraft as the proposed Space Station drive the design toward higher solar array operating voltages. When the spacecraft exits eclipse, this voltage will be even higher until the array warms up. Successful design of higher voltage arrays relies on understanding the limits imposed by plasma interactions.

NASA's Office of Aeronautics and Space Technology (OAST) is pursuing the needed technology development in photovoltaics, energy storage, and power management and distribution to enhance, enable, and ensure the environmental compatibility of high power systems. Technology programs are underway to develop and demonstrate advanced planar and concentrator solar cells and array designs. A joint NASA/U.S. Air Force Spacecraft Environmental Interactions Technology investigation is also underway to evaluate the impact of the plasma and field environments on system performance (Ref. 2). These programs are basically ground technology efforts involving ground experiments and model development. A complementary program of space flight experiments is required for several reasons. First, the ground test environment is necessarily an incomplete simulation of space conditions. The interactions are dependent on the plasma and neutral background parameters around the solar array. A space environment is therefore required. Because some of the interaction phenomena may extend many meters, there are concerns regarding the effect the chamber walls may introduce in ground testing. Also, most testing has involved applying a voltage bias on solar array segments and evaluating the interaction of such segments with the plasma. From these experiments, estimates of interactions impact on solar array performance have been made. However, the system level interactions can be very complex. Therefore, it is necessary to obtain a direct measure of the performance of a large solar array generating its own voltage and operating in the space environment, including the effects of parameters such as ram/wake which cannot be simulated. Also, it is clear from STS-3 data that the presence of a large body in orbit perturbs the ambient environment in ways which are as yet not fully understood, but which may have significant impact on system-environment interactions. Finally, flight data is absolutely critical to provide "space truth" information for use in calibrating ground simulations, demonstrating operating impacts and validating system level models which must be used to predict interactions impacts for proposed designs. This paper summarizes the interaction concerns for higher voltage arrays in orbit, the ongoing technology investigations, and describes a proposed series of Shuttle experiments designed to obtain the required flight data.

ENVIRONMENTAL INTERACTIONS BACKGROUND

The attention of the environmental interactions community was for several years focused on the investigation of spacecraft charging, an interaction which had been found to be hazardous for geosynchronous spacecraft and was intensively studied by NASA and the Air Force (Ref. 3). In the late 1970's, interest in high voltage interactions again intensified, and their study was resumed under the auspices of the joint NASA/USAF Spacecraft Environmental Interactions Technology investigation (ref. 2). The ground-technology program uses the experimental facilities at NASA and USAF centers, builds upon the modeling capabilities developed during the spacecraft charging investigation, and uses the earlier high-voltage study results (refs. 4 to 11). Among the goals of the technology program is the development of design guidelines and analytical tools for higher voltage solar arrays for Earth orbital applications.

This requires flight data to ensure that the phenomena observed in ground testing occur in orbit, to examine conditions not obtainable in ground facilities and to validate the models. To date, two small scale Plasma Interactions Experiments (PIX-I and PIX-II) have been designed, built and flown. Both were piggy-backs on second stage Delta vehicles and in approximately 900 km circular polar orbits. PIX-I, which flew in March 1978, and returned two hours of data, demonstrated that the current collection enhancement and arcing phenomena observed in ground testing of planar array segments also occur in orbit (Ref. 4). The 16 hours of planar array data returned by PIX-II, which flew in January 1983, are still under analysis. Preliminary results indicate that the minimum arcing onset voltage decreases with increasing plasma density and that tank wall effects influence current collection behavior at high positive voltages in ground tests.

No data is available on ram/wake effects, influence of the presence in orbit of a large system, or the effect of interactions on the operational characteristics of a large higher voltage array. Understanding these effects is critical to developing useful design guidelines for such solar arrays.

Solar Array Voltage Positive Relative to Plasma

Figure 1 represents experimental data for a solar array section biased positive with respect to the plasma in which it is immersed (Ref. 11). The left half of the figure illustrates that at voltages greater than 100-150 volts, the electron current collected by the solar array increases dramatically. The right half of the figure illustrates why. Even though the solar array surface is dielectric, the surfaces become highly positive and collect current as though the whole surface were a conductor. The explanation appears to be that as the plasma sheath grows around exposed interconnects or pinholes, the accelerated electrons strike the dielectric and low energy secondary electrons are released which are collected by the exposed metal. This leaves the dielectric cover glass positive, allowing the plasma sheath to grow over the solar cells. Therefore, the solar array collects electron current as though it were a conductor. As the voltage on the array segment and the effective collection area increases, the current collected rises, as indicated in figure 1. This current flow through the plasma is current which is not available to the spacecraft and therefore represents a power loss to this plasma shunt. Depending on the solar array voltage the power loss can be substantial and can seriously impact array performance.

No direct measure of the power loss exists because essentially all data consists of current collected by solar array segments with a potential impressed on them by a power supply. The power loss, which will be experienced in a solar array due to the collection of current from the plasma, has often been estimated by multiplying the collected solar array segment current by the voltage between the solar array segment and the plasma and summing over the segments. Such an estimation does not consider the current flow in the solar array. A solar array which is not in a plasma environment will have only the load current, I, flowing in it. The current is the same throughout the array and it can be operated at the maximum power point. However, a high voltage solar array immersed in a plasma will collect plasma current which will flow through the array in addition to the load current. The plasma current collected at a location on the array is a function of the potential between that location on the array and space. The current flowing through a specific point in the array is the load current and the sum of electron currents collected at points in the array at higher positive voltages. Therefore, nonuniform currents will flow within the array. To operate at the solar array maximum power point, each individual cell will operate off its individual maximum power point.

In ground tests, a voltage is impressed on test samples and the current collected from the plasma is measured. Because the voltage is applied, there is no differential voltage between the solar cells. However, for a solar array which is generating its own voltage by having solar cells placed in series, there will be voltage gradients on the surface of the cells due to difference in voltage between cells. The gradients may be quite high if the cells are strung such that solar cells at considerably different voltages lie next to each other. The electric field structure in the plasma sheath may be complex due to solar cell layout. Because such voltage gradients exist, there is the possibility of currents between cells due to field emissions and/or secondary electron emission and/or some other surface current mechanism not identified. These more localized currents may produce an additional shunting of portions of the solar array.

A discharge phenomena around the solar array has also been observed in some ground tests (Ref. 13). In these cases a bright glow appeared around the solar array and the electron currents collected by the solar array from the plasma increased by orders of magnitude. Such an increase in collected current will substantially affect the power loss in the solar array.

Because of the complex nature of high voltage solar array/plasma interactions, it is necessary to experimentally determine the power curve of a solar array operating in a plasma environment.

Solar Array Voltage Negative Relative to Plasma

Figure 1 illustrates the observed effects of a solar array segment biased positive of the surrounding plasma. Different effects are observed for a solar array segment biased to a negative voltage relative to the plasma. Unlike the positive voltage case, the solar cell cover glass voltage does not rise to the interconnect voltage as the solar cell voltage becomes more negative. A steep voltage gradient exists between the interconnect and other exposed metal parts of the solar cells and the solar cell surface. For impressed voltages of several hundred volts, arcing on the array is observed. Pictures of such arcing events are shown in figure 2 (Ref. 10). The arcing occurs at lower negative voltages for higher plasma densities. Arcing has been observed at voltages of -250 volts on a solar array segment in a plasma with a density of 10^4 electrons/cm^3 (Ref. 13). Ambient plasma densities of up to 10^6 electrons/cm^3 may be encountered in space. Such solar array arcing will introduce large current and voltage transients which may tend to collapse the array voltage. However, the effects of such arcing on the solar array performance is presently uncertain.

Solar Array-Spacecraft-Space Plasma Potentials

A spacecraft in orbit and immersed in the space plasma will come to a potential relative to the plasma such that no net current is collected. The solar array provides an additional complication since ambient charge particles can be collected. There are two solar array voltages to consider. One is the operating voltage generated by the solar cells in series. The other is the potential of the solar array relative to the surrounding space plasma. Some point on the array will be at space potential and the portions of the solar array positive of this point will collect electrons from the plasma while the negative part collects ions. Because of their higher temperature and mobility, electrons are much more easily collected than ions. Therefore, to collect equal electron and ion current, a much larger area at a negative potential relative to the plasma is required. For a spacecraft grounded to the negative side of the solar array, the situation on the right side of figure 3 will result. The spacecraft and negative side of the array will be driven below space potential. For an array of several hundred volts, solar array arcing may result, and since the spacecraft structure will be several hundred volts negative, it will experience a continuous ion bombardment for the spacecraft lifetime which may alter surface thermo-optical properties. Another spacecraft without such a solar array or an untethered astronaut will be near space potential. The resulting potential difference between such a free flyer and the highly negative spacecraft can pose serious safety concerns. The highly negative spacecraft potential will also interfere with some science, e.g., particle and plasma data acquisition.

If an electron gun or plasma source is operated on the spacecraft, electrons collected by the positive portion of the solar array will be released back to space. Large negative potentials will not result, and if electrons are freely released, the situation on the left in figure 3 will result.

Plasma Perturbation

Many sounding rocket experiments have been flown which investigated the magnetosphere by releasing electron beams along the earth's magnetic field lines (Ref. 14). It was anticipated that the rocket body would charge hundreds to thousands of volts positive due to the release of a high energy electron beam. This was not observed to be the case. The rocket potentials increased to only 30 to 100 volts positive. Plasma diagnostic devices indicate that the plasma density and temperature increased when the electron beam was released, and that a local discharge is created around the rocket either by electron bombardment ionization or a beam-plasma discharge (Ref. 14). The plasma is also observed to be perturbed at large distances from the rocket. An analogous situation can be expected with a spacecraft powered by a high voltage solar array. An electron gun or plasma source operation will raise the spacecraft potential to near space potential and will therefore drive the high voltage solar array very positive of the space plasma potential. As previously described, discharge phenomena for positive solar arrays in a plasma has been observed in ground tests (Ref. 13). The local discharge and plasma perturbations observed during rocket experiments can increase power loss due to parasitic currents and interfere with science data acquisition.

PROPOSED FLIGHT EXPERIMENTS: VOLTAGE OPERATING LIMIT TESTS

Recently, OAST proposed a new flight initiative, Voltage Operating Limit Tests (VOLT). The VOLT project is a comprehensive program composed of a series of four Shuttle based flight experiments which will provide the data base required to design successful higher voltage solar arrays for low earth orbit (LEO) power systems. Two of the experiments, VOLT-1 and VOLT-3 will utilize biased solar array segments of planar and concentrator designs, respectively, to scope the nature of the basic interactions in LEO, determine ram/wake effects and identify influences of the large STS vehicle on interactions. Results will be used in designing the other two, more comprehensive, experiments. VOLT-2 and VOLT-4 will test large area arrays of the planar and concentrator designs, respectively, to evaluate the impacts of interactions on array operation directly. VOLT-3 and VOLT-4 are similar in the plasma interactions portion of these experiments to VOLT-1 and VOLT-2 except that VOLT-3 and VOLT-4 both use concentrator solar arrays. Therefore, to prevent repetition, only a detailed discussion of the VOLT-1 and VOLT-2 plasma interaction experiments will be presented.

The VOLT-1 experiment, shown mounted in the Shuttle bay in figure 4, utilizes the backup hardware from the PIX-II experiment, with minor modifications for Shuttle flight compatibility. The objective of the VOLT-1 experiment is to evaluate plasma to solar array currents and arc thresholds for planar solar array segments in the LEO environment. Such data is like that collected in ground tests and will allow validation of basic interaction model predictions for the Shuttle LEO environment. Data will also be acquired in both ram and wake conditions. Because the experiment is hard mounted in the bay, the Shuttle attitude will provide ram and wake conditions for the experiment. The data acquired by VOLT-1 will allow better prediction of the interactions which will be expected on VOLT-2.

The VOLT-1 experiment is comprised of an electronics enclosure and an experiment plate, upon which is attached a 2000 cm solar array segment. The electronics enclosure houses the electrometers, power supply, sun and temperature sensor electronics, a Langmuir probe and associated electronics, experiment sequence controller and tape recorder. VOLT-1 is envisioned as being nearly completely self-contained and automatic, requiring only an electrical ground reference and experiment initiate signals. During operation positive and negative voltage biases will be impressed on the array in steps until potentials of ±1000 volts relative to ground are reached. Arcing onset and parasitic currents will be measured for both positive and negative biases.

A reflight of the Solar Array Flight Experiment (SAFE), with necessary modifications, has been proposed as a high voltage solar array/space plasma interactions experiment (Ref. 15). The basic SAFE experiment is a space test of a 12.5 kW size, lightweight solar array. It is primarily a demonstration of the solar array's ability to deploy and retract successfully and to obtain data on the dynamic response of such a large structure in space. A very small portion of the solar array consists of active solar cells with the majority of the area covered by thin aluminum squares to simulate the solar cell mass. The wing, shown in figure 5 in its fully deployed state, measures 4m by 32m. Also, a conceptual view of the experiment deployed from the Shuttle bay is shown in figure 6.

The VOLT-2 plasma interactions experiment utilizes the SAFE hardware with three primary modifications. These are: (1) that three solar cell panels, each consisting of two modules, will replace three of the present SAFE panels and will self-generate solar array operating voltages of from near 90 to in excess of 500 volts, (2) that electron release devices will be added to control the solar array potential to space and, (3) plasma diagnostic instruments will be added to determine the ambient and perturbed plasma conditions around the solar array.

The VOLT-2 experiment with retracted solar array, is shown in figure 7. This experiment will allow a direct measure of the solar array's performance by obtaining I-V curves as functions of solar array voltage, solar array-to-space potential, type of charge release device maintaining this potential and ram/wake orientation. It will also determine floating potentials for true distributed voltage solar array, arcing onset voltages and impact of arcing on the solar array. Such data from a functioning solar array will allow validation of system level model predictions of solar array performance.

The three active panels near the end of the solar array wing will provide about 14,500 cm^2 of solar array. Each panel will be composed of two modules. The modules will be placed in various parallel and series configurations to allow testing at solar array voltages from near 90 volts to in excess of 500 volts. Figure 8 indicates the change in module and maximum array voltage as a function of orbital position. When the solar array is floating in the plasma, such that it is collecting equal electron and ion current, 80-90% of it will have to float negative. Tests will be conducted by switching the floating solar array from lower to higher operating voltages and arcing phenomena, floating potential and solar array performance measurements will be obtained.

The high current hollow cathode and plasma source will be operated for tests of the solar array positive relative to space potential. These sources, with possibly the addition of an electron gun generating an energetic electron beam, will, independently, freely emit the solar array collected electrons back to space and will control to solar array to space potential. The majority of the solar array will be positive of the space potential allowing power loss evaluation as well as investigation of local discharge phenomena expected in the solar array vicinity. The array potential will be controlled by the spacecraft automatic active discharge system (SAADS) of which the charge release devices are an integral part. Because of their interest in the results of this experiment, the Air Force Geophysics Laboratory has offered to furnish this equipment to the VOLT-2 experiment. Some plasma diagnostics associated with SAADS will be located on the Mission Peculiar Experiment Support Structure (MPESS).

A minimum complement of three diagnostic instruments will be mounted on the end of the solar array. These are presently identified as a neutral density instrument, a Langmuir probe and a Differential Ion Flux Probe (Ref. 16). These instruments will allow determination of the ambient conditions in which the plasma interaction experiment is conducted as well as evaluation of perturbations to the plasma due to the high voltage solar array operation.

Figure 9 illustrates the anticipated orbital configuration of the VOLT-2 experiment. The figure indicates that the solar array and Shuttle tail will be pointed toward the sun. This configuration is more advantageous for experiments involving electron release by electron gun. The beam can be projected along the magnetic field line and not strike the solar array. The generated plasmas will also tend to diffuse along magnetic field lines and away from the solar array.

The orbital velocities of spacecraft for LEO are much greater than the thermal ion velocity but much less than the thermal electron velocity. The result is that as a spacecraft moves through the plasma it sweeps out the ions, leaving much decreased plasma density in its wake, which is occupied by an excess of electrons, relative to the ion population. As observed in figure 10, there will be positions in the orbit where the wake is on the solar cell side or the backside of the solar array and where no wake exists (when the spacecraft velocity vector and sun line are perpendicular). Data acquisition at these various positions will allow determination of power loss, arcing and plasma perturbation over the range of anticipated orbital plasma conditions.

CONCLUDING REMARKS

For a number of years NASA and the USAF have planned space missions utilizing solar arrays which generate orders of magnitude more power and operate at a much higher voltage than has been flown previously. During this same time ground technology programs have addressed the interactions between such a high voltage solar array and the ambient space plasma. These programs have given us a basic understanding of what interactions to anticipate and under what conditions. Ground test information has been augmented by flight tests which verified that the effects observed on the ground are observed in space. However, it has long been recognized that ground tests are limited by facility size, facility effects on plasma and electric field conditions and the capability to accurately simulate space plasma conditions. It is very important to test actual solar array performance with a large, self-generated voltage so that effects of large array area, surface voltage gradients and varying currents in the solar array can be evaluated. It is not possible to do this adequately in a ground test chamber.

The space test program described in this paper is designed to obtain critical information on solar array-plasma interactions and their impact on array performance for planar and concentrator arrays. Data will be obtained under conditions and at array sizes not obtainable in ground testing. These data are critical for validating the system level models which must be used to evaluate candidate large power system designs and for developing design guidelines for higher voltage arrays. The data will be obtained with a matrix of variables so that the maximum information on solar array interactions and performance in the LEO plasma environment will be collected. Experiments will be conducted with various applied and self-generated solar array voltages. These will be performed with the front of the solar array in plasma ram and wake conditions and with zero plasma drift normal to the solar cell face.

Without the crucial information this flight program will provide, designers of future spacecraft will be forced to be conservative and operate solar arrays at presently accepted voltages. This will seriously impact system efficiency and manageability.

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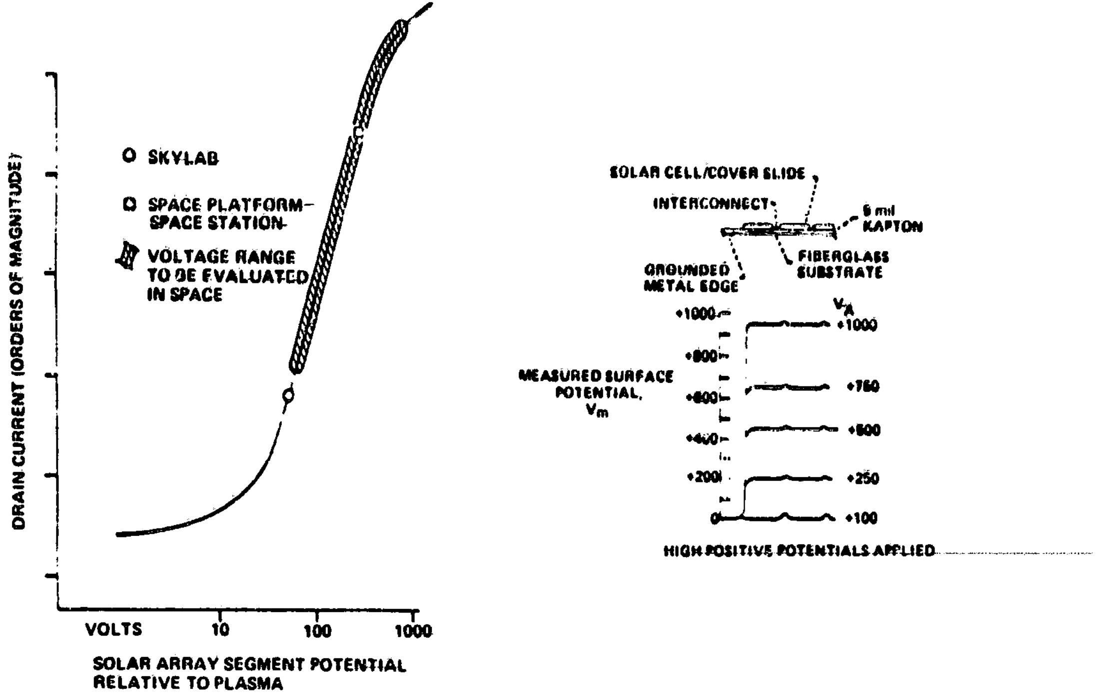
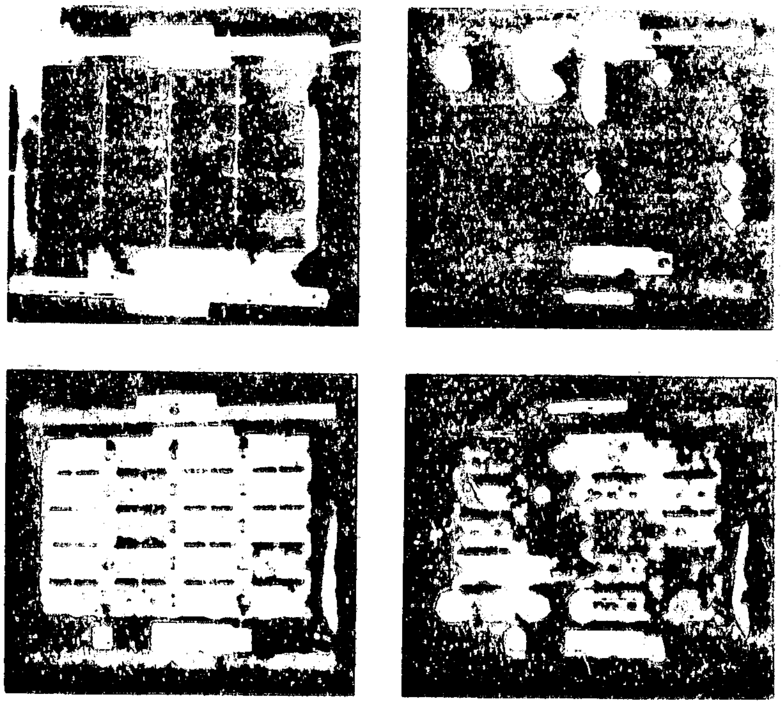


Figure 1. - Solar array positive relative to plasma.



- 2 x 4 ON WRAPAROUND CELLS ON KAPTON
- -1 KV BIAS
- 10^5 $\bar{e}/cm^3$ PLASMA

Figure 2. - Arcing on negatively biased solar cells.

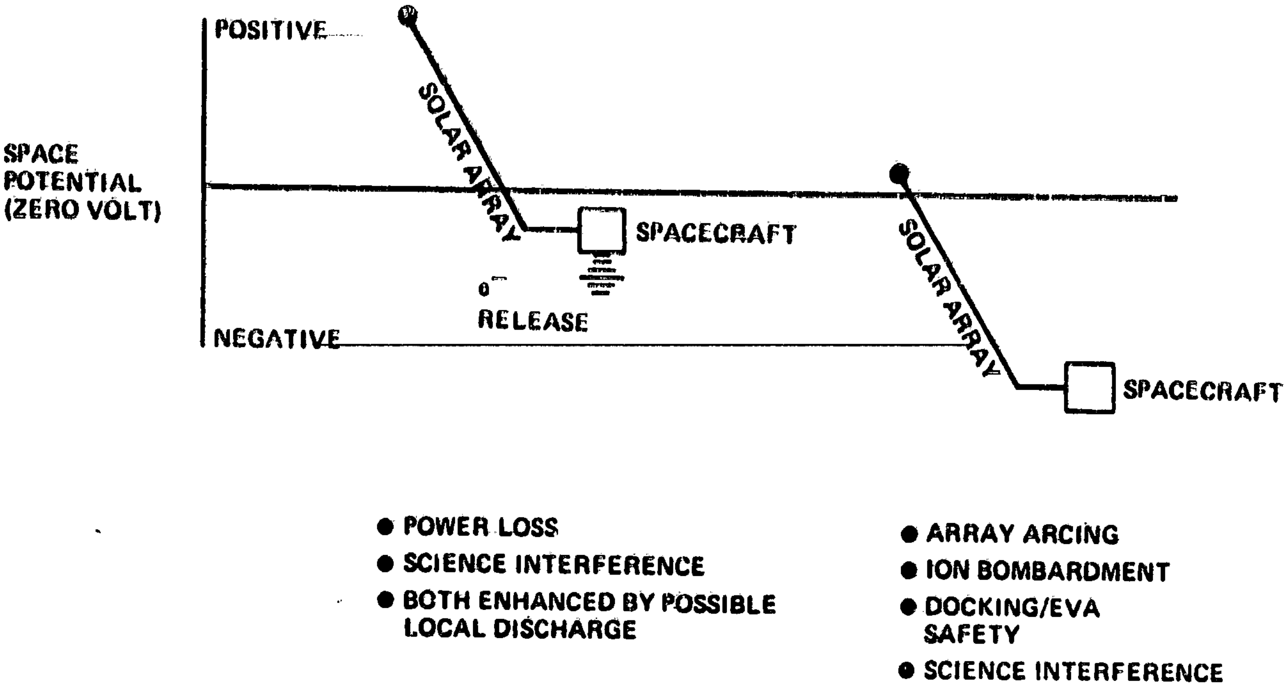


Figure 3. - Solar array - spacecraft - space plasma potentials.

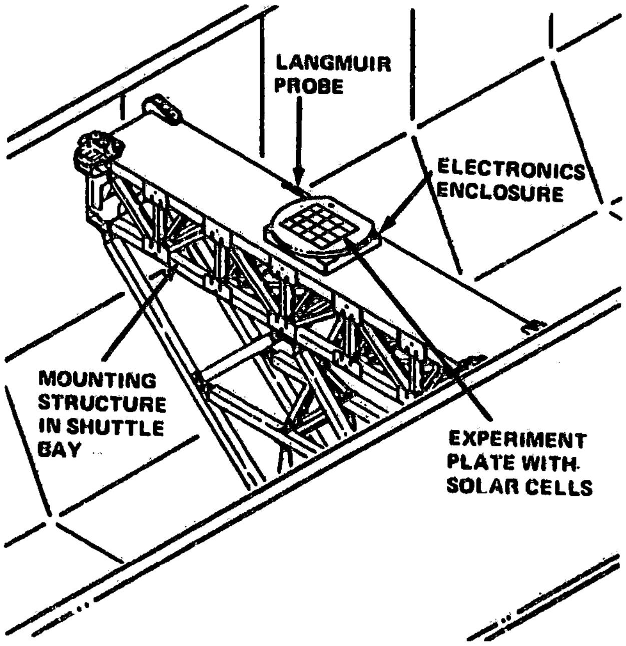


Figure 4. - VOLT-1.

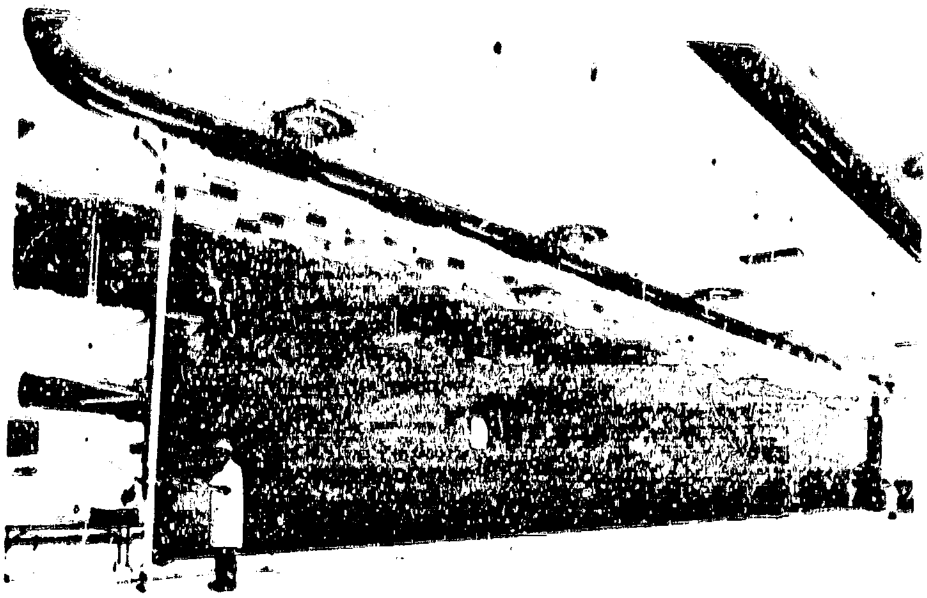


Figure 5. - SAFE wing.

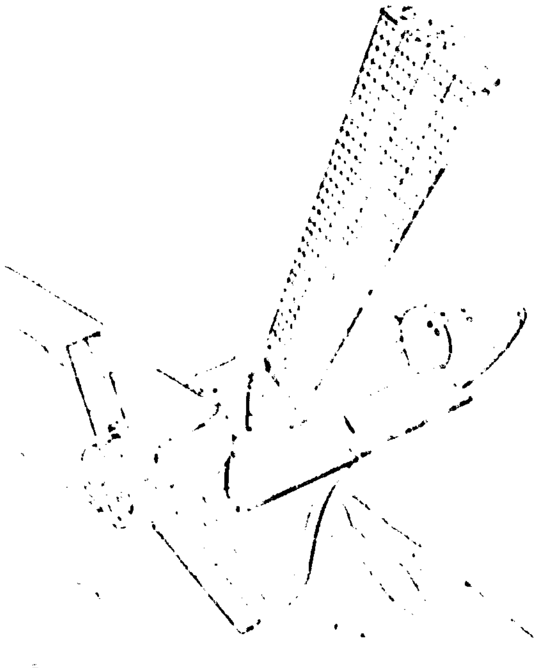


Figure 6. - Conceptual view of SAFE deployed.

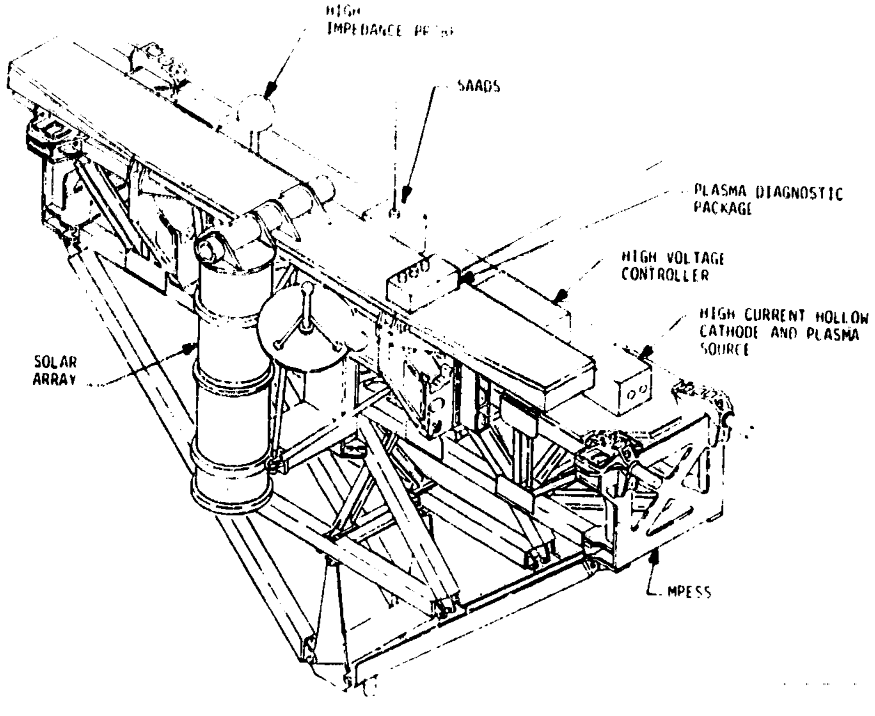
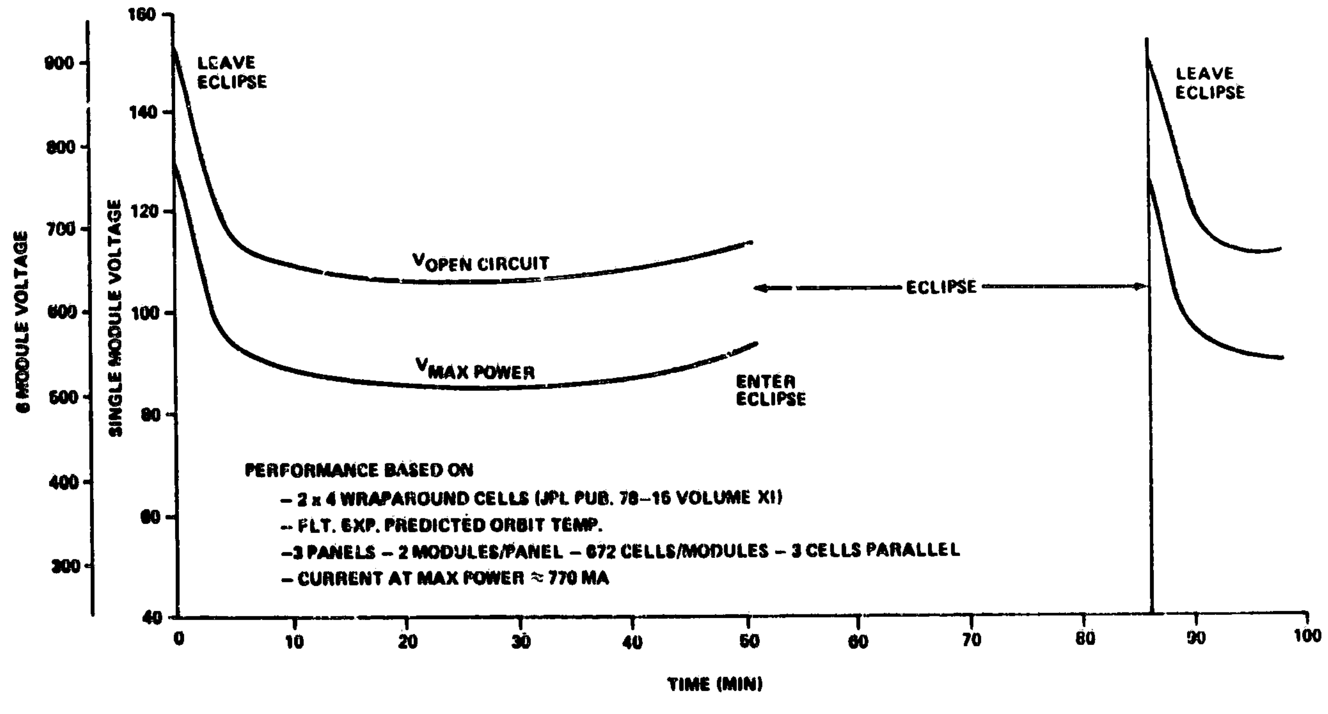


Figure 7. - VOLT-2.



PERFORMANCE BASED ON
- 2 x 4 WRAPAROUND CELLS (JPL PUB. 78-15 VOLUME XI)
- FLT. EXP. PREDICTED ORBIT TEMP.
- 3 PANELS - 2 MODULES/PANEL - 672 CELLS/MODULES - 3 CELLS PARALLEL
- CURRENT AT MAX POWER ≈ 770 MA

Figure 8. - Panel voltage as function of orbit.

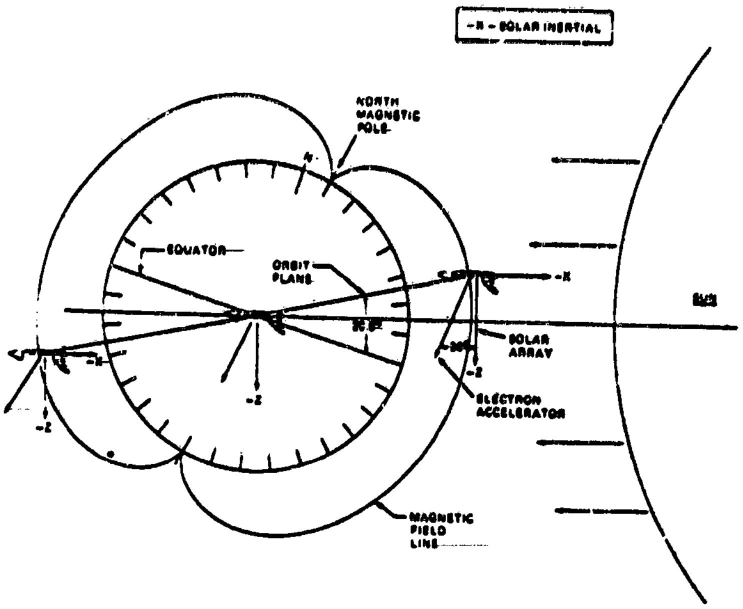


Figure 9. - Orbital configuration.

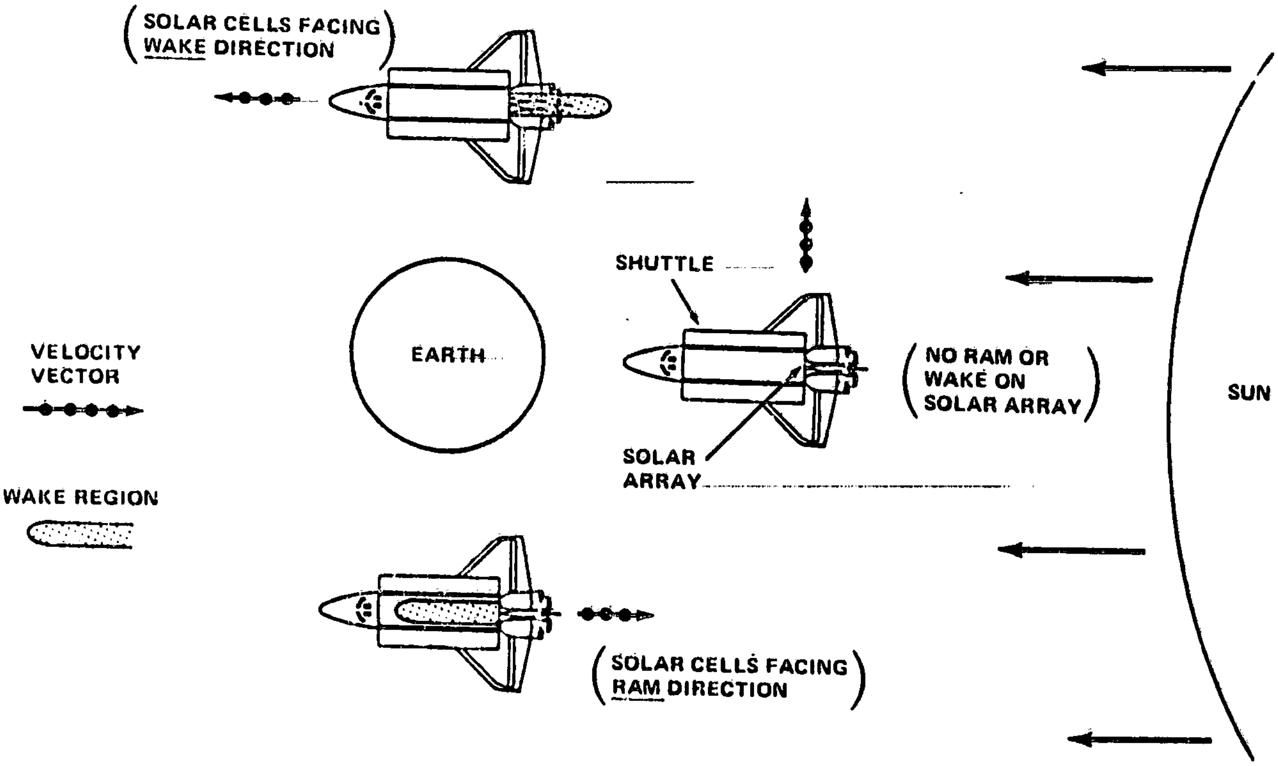


Figure 10. - Ram/wake conditions.