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COMPUTER AND LABORATORY SIMULATION OF INTERACTIONS BETWEEN SPACECRAFT SURFACES AND CHARGED-PARTICLE ENVIRONMENTS

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ABSTRACT

There are two categories of interactions considered in this report. The first, spacecraft passive, refers to cases where the charged-particle environment acts on the spacecraft (e.g., spacecraft charging phenomena). The second, spacecraft active, refers to cases where a system on the spacecraft causes the interaction (e.g., high voltage space power systems). Both categories are studied in ground simulation facilities to understand the processes involved and to measure the pertinent parameters. Computer simulations are based on the NASA Charging Analyzer Program (NASCAP) code. Analytical models are developed in this code and verified against the experimental data. Extrapolation from the small test samples to space conditions are made with this code. Typical results from laboratory and computer simulations are presented for both types of interactions. Extrapolations from these simulations to performance in space environments are discussed.

INTRODUCTION

Spacecraft systems must function in a tenuous charged-particle, space environment. Normally, this has not been a troublesome constraint on these systems. However, under certain conditions, the environment can have a profound effect on the performance of these systems.

The first indication of charged-particle environment interactions arose in the late sixties with geosynchronous satellites. These satellites experienced anomalous behavior in their electronic systems at various times in their operational life.[1] These anomalies ranged from spurious switching of electrical circuits (which is correctable) to complete failure of a power system (which terminated the satellite operations). An explanation for these anomalies was derived from the data from the Applications Technology Satellites (ATS-5 and -6). This data indicated that geosynchronous satellites were encountering plasma clouds containing kilovolt energy particles.[2,3] These clouds were charging the satellite ground surfaces to multikilovolts negative during eclipse periods and to hundreds of volts negative during sunlight encounters.[4-6] A satellite, immersed in an ambient plasma, will come into electrical equilibrium with that plasma by developing surface charges of the proper sign and magnitude to reduce the net current between the satellite and ambient plasma to zero (see fig. 1(a)). Hence, in sunlight conditions, the photoemission from the sunlit surfaces must be sufficient to maintain the lower spacecraft ground potential relative to space. However, there can be shaded insulator surfaces on these satellites. So, it is conceivable that a geosynchronous satellite could encounter a plasma could (or geomagnetic substorm) and become differentially charged, that is, the electrical ground surfaces would be between about -100 volts while shaded insulators could be a few thousand volts negative. If this voltage difference exceeds a breakdown threshold, then a discharge will occur. The resulting electromagnetic pulse can couple into the electrical harness and this noise pulse be interpreted by the logic circuit as a command to switch functions. These transients are rapid and of rather low amplitude. So, it is probable that geosynchronous satellites have been experiencing discharges since the first one was placed in orbit. But, the anomalies only started occurring when the low level logic (0 and 5 V) replaced relays.

This phenomenon is referred to as spacecraft charging.[3] It is the subject of an AF/NASA investigation to develop the means to control or eliminate the absolute and differential charging of satellite surfaces by geomagnetic substorms.[7] Since this type of environmental charging occurs because the satellite encounters a geomagnetic substorm, it has been categorized as a spacecraft-passive interaction.[8]

There is another category of interactions between the charged-particle environments and spacecraft surfaces. These interactions occur when an on-board system attracts particle flows which can influence system performance. This category is called spacecraft-active interactions.[8] While the spacecraft charging interactions are limited to geosynchronous altitude, the spacecraft-active interactions can occur at all altitudes. Hence, it is important to understand these interactions in order to be able to operate successfully the large systems proposed for future missions.[9-12] A typical example of the large systems proposed are the space power systems that will function either in low Earth or geosynchronous orbits.[13-15] These systems would generate power at levels that vary from 25 kW to multimegawatts. It will be necessary for these systems to operate at elevated voltages to reduce line losses and minimize system weight.[8] At these elevated operating voltages (>100 V), interactions with the charged-particle environment are possible. These interactions are illustrated in figure 1(b) which shows a solar array system in a space environment. In the standard construction of this array, cover slides do not completely cover the metallic interconnects between the solar cells. These cell interconnects are at various voltages depending on their location in the array circuits. Hence, the interconnects can act as plasma probes attracting or repelling charged particles. At some location on the array, the generated voltage will be equal to the space plasma potential. Cell interconnects at voltages above this space plasma potential will collect electrons while those at voltages below the space potential will collect ions. The voltage distribution in the interconnects relative to space must be such that these electron and ion currents are equal (i.e., the net current is zero). This flow of particles can be considered to be a current loop through the power system to space that is in parallel with the operating system and hence, is a power loss.

Interactions with the charged-particle environment are not limited to plasma-coupling currents. The possible confinement of voltages (and electric fields) to cavities formed by the cover slides and interconnects could conceivably give rise to breakdowns especially in the negative voltage regions (analogous to the spacecraft charging interactions). Even if breakdowns are avoided, the detrimental effects of depositing charges in insulators for long periods of charge (due to the accelerating electric fields from the operating voltages) must be assessed.

Since the highest operating voltage reported for space power systems is the 100 volts used on Skylab,[16] there is limited space experience to guide the system designer in constructing a high-voltage, space-power system. There has been ground-simulation testing of biased-surface behavior in plasma environments to determine possible interactions,[17-22] and several analytical treatments of the impact of these interactions on system performance.[23-28] These tests and analyses can serve as indicators to what could happen in space.

Laboratory simulations and analytical evaluation of interaction phenomena in both categories have been conducted at the Lewis Research Center for the past 10 years. The basic philosophy in these investigations is to conduct tests to determine the interaction processes, model the processes with the available analytical tools, compare the model results to experimental data and then use the verified analytical tool to extrapolate to system performance in space. Modification required to control detrimental spacecraft-environment interactions are developed with the analytical model. Wherever possible, the analytical model is checked against space results. In this report the laboratory and modelling simulation results obtained for both spacecraft charging and high voltage system-plasma environment interactions are summarized and discussed.

SIMULATION CAPABILITIES

The analytical tools and laboratory facilities used in simulation of both categories of interactions are essentially the same. The analytical tool is the NASA Charging Analyzer Program (NASCAP) which treats the surface interactions with charged-particle environments. The laboratory simulations are conducted in chambers utilizing similar instrumentation. In this section of the report these simulation tools are summarized.

Analytical Modelling Tool - NASCAP

The NASA Charging Analyzer Program (NASCAP) computer code was developed specifically for the AF/NASA Spacecraft Charging Investigation to predict the response of 3-dimensional spacecraft bodies to environmental fluxes.[27] It can also compute the currents collected by biased conductors (in a geosynchronous environment) and so it can be used to simulate the high voltage system interactions. The code flow chart is shown in figure 2.

NASCAP is a quasi-static computational code; that is, it assumes that currents are functions of environmental parameters, electrostatic potentials and magnetostatic fields. It is capable of analyzing the charging of a 3-dimensional, complex body as a function of time and system generated voltages for given space environmental conditions. It includes consideration of the dielectric material properties (e.g., secondary emission, backscatter, photoemission and conductivities-bulk and surface) and computes currents involving these materials in determining the potential distributions around the body.

The body must be defined in terms of rectangular parallelipiped or sections of parallelipipeds within a 17 by 17 by 33 point grid. Only seven separate conductors can be specified in the present version of the code. The first conductor can either float electrically relative to the environment, or be at some fixed voltage.

The code functions either in a ground simulation or space environment modes. The ground simulation mode evaluates the surface potentials of test specimen subjected to particle beams (up to 20 keV) or collection phenomena due to high voltage surfaces in a tenuous thermal plasma ($T \sim 1$ eV, and $n_e \sim 10$ cm^{-3}). In the space environment mode, the environment can be defined in terms of Maxwellian distributions or double Maxwellian descriptions of geomagnetic substorms.[28] It is also possible to use an actual spectra description of substorms and compute potentials on spacecraft by reverse trajectory computations.

The code output includes a variety of graphical and printed data displays. Graphical output includes the material and perspective object definition plots, potential contour plots and particle trajectory plots. The printed output includes a summary of all cell voltages, listing of currents to specified surfaces and compilation of electric fields through the dielectric.

Experimental Simulation Facilities

The principal simulation facility to evaluate environmental interactions is shown in figure 3.[29] This facility is housed in a 1.8 m diameter by 1.8 m long vacuum chamber capable of operating in the 10^{-7} torr range. The schematic diagram for spacecraft charging tests is shown in figure 4(a) and for high voltage surface-plasma tests in figure 4(b).

Spacecraft charging test facility description. - The substorm environment is simulated by bombarding a test sample with monoenergetic electrons only. This is done to force the insulator surface to negative potentials similar to that experienced by spacecraft. Monoenergetic electrons are used rather than a distribution of energies to enhance the understanding of the processes involved and to ease the experimental difficulties in building, operating and calibrating a distributed flux source. The monoenergetic source can be operated at any accelerating energy between 2 and 25 kV. The current density at the test plane can be controlled to be any value between 0.5 and 5 nA/cm^2. This is a reasonable simulation of a substorm electron flux. The beam is uniform, within a factor of 2, over a 3000 cm^2 area.

Low energy plasmas are generated in the chamber by means of a gaseous nitrogen electron bombardment plasma source. This source is routinely used to discharge sample surfaces after exposure to the electron fluxes.

Solar simulation can be obtained from a Xenon lamp system. This simulator is located outside the chamber and the illumination is transmitted through a quartz window.

Samples to be tested can be mounted on a three-position sample rotator or assembled in any given planar configuration. The rotator fixture allows three separate samples to be tested during each pumpdown of the facility. Samples up to 30 by 30 cm can be accommodated on the rotator and single configuration tests up to 50 by 50 cm can be handled. Substrates of the test samples can either be grounded, allowed to float electrically or be biased by external power supplies.

Electron current densities at the test location are measured with a Faraday cup. This cup is mounted on a 30 by 30 cm plate which shields the sample while the gun parameters are being established.

The surface voltage across the insulator surface is measured by sweeping an electrostatic voltage probe (TREK Model 320 HV) across the sample. This probe is a noncontacting, capacitance-coupled device and usually traverses the sample about 3 mm above the surface. The probe functions while the beam is on so that continual charging curves can be obtained without interrupting the electron flow.

When the test sample substrate is grounded, the total leakage current through the dielectric and around the sample edges is measured by an electrometer in the ground line. From the time dependent leakage current and surface voltages, the charge and energy stored in the sample can be computed for given beam conditions.

When discharges occur additional measurements are taken. Loop antennas are used to sense and quantify discharge activity. The signals received by the antenna are amplitude discriminated into 3 separate ranges (>1, >2.5, and >5 V) and counted. Inductively coupled current probes (with the current sensing electrometers switched out) and a transient analyzer (Biomation Model 8100) are used to record and measure the replacement currents resulting from arcs. This measurement allows the computation of charge being drawn from ground to neutralize image charges in the test sample. This replacement charge can then be compared to the charge lost during a discharge as computed from leakage current transients and surface voltage measurements.

Discharges are routinely photographed with a Polaroid portrait camera. These photographs can be either multiple exposure to obtain the complete discharge history of a given test condition or a single discharge exposure.

This facility has been duplicated in other chambers at the LeRC. These chambers range from an 18" bell jar for quick turn-around evaluations of materials or techniques to a 4.5 m diameter chamber to conduct large sample testing. The discussion in this report will be limited to test results obtained in the principal facility.

High voltage surface-plasma test facility description. - The experimental evaluation of this phenomena is conducted in the same facilities as those used for spacecraft charging tests. For these high voltage surface-plasma tests the electron beam remains off and the low energy plasma source is used to generate the thermal plasma density desired. The nitrogen plasma can be controlled to maintain a plasma density of any value between 10^6 to ~10 particles cm^{-3} with characteristic electron and ion temperatures between 0.5 and 5 eV. These plasma characteristics are measured with a Faraday cup and spherical Langmuir probes. The uniformity is within a factor of 2 throughout the test area in the chamber. This environment simulates the thermal plasma environment in space from about 300 km altitude to about synchronous.

For these tests a bias voltage (positive or negative) is applied to an electrode and/or solar array circuit. The current collected is measured by an ammeter in the high voltage line. The purpose of these tests is to determine the coupling mechanisms between a surface at some voltage relative to space and the space plasma. Ideally, the tests should be conducted with the solar array generating its own voltage while floating electrically. This requires a very large array and even larger facility. The study to understand the interactions can be conducted with power supplies as long as the influence of the supply on the interaction can be assumed to be minimal.

The surface voltage probes can also be used in these tests to provide data on the insulator behavior for given bias voltages. Discharges, when they occur, are treated in the same manner as in the spacecraft charging tests.

SPACECRAFT CHARGING: EXPERIMENTAL AND ANALYTICAL EVALUATION

Approach

The charging of spacecraft insulator surfaces involves a current balance process. The surface voltage will reach a value such that the net current to the surface is zero. The understanding of this phenomenon, then, depends upon the knowledge of insulator properties (e.g., conductivities, secondary yields, backscatter and photoemission) and effects of surroundings on the incident flux of charged-particles.

The evaluation being conducted at the Lewis Research Center involves a combined analytical and experimental approach dealing first with single insulator surfaces and then with multiple insulator samples. The single insulator surfaces are tested in the laboratory simulation facility previously described to obtain the total leakage current and surface voltage profiles as functions of time under fixed electron beam conditions. These samples are modelled using the analytical simulation code, NASCAP, and predictions are compared to the experimental data. The code material parameters are varied, to obtain agreement with the data. This procedure allows for the determination of lumped or effective values for these parameters. By comparing analytical predictions to experimental results for multiple insulator surfaces, the effects of surroundings or boundary conditions can be evaluated. The final comparison (which has not yet been attempted) should be between analytical and experimental results for a spacecraft-like model in a ground simulation facility. These comparisons are made for both charging and discharging conditions.

The final output of this evaluation is a computer code that will have been calibrated for predicting spacecraft surface voltages (at least for electron fluxes) and can be used for predicting voltages in space. This philosophy assumes that the transition from monoenergetic to distributed fluxes as well as the effect of proton impact on the surfaces can be treated reasonably well analytically. This assumption will be evaluated by comparing code predictions to spacecraft flight results.

The work undertaken in this evaluation is not complete and in continuing. The present status of the Lewis analytical and experimental investigations is summarized in the following sections of this report. The investigation of photoemission effects is still in a preliminary stage and will not be further discussed.

Material Charging Simulation

Single insulator samples. - The comparison of experimental results with a simple 1-dimensional model[30] and the initial comparison of these results with NASCAP predictions[31] have been published. In this report NASCAP comparisons are summarized for silver Teflon samples irradiated by a 10 kV electron beam to illustrate the effects of lumped material parameters on surface voltage predictions.

The silvered Teflon sample was about 300 cm^2 (15 by 20 cm) and was made by mounting 3 strips of 5 cm wide Teflon (0.0127 cm thick) to an aluminum substrate with conductive adhesive. The electron beam conditions were 1 nA/cm^2 electron current density at the test plane at 10 keV accelerating potential. The tests were conducted without solar simulation.

The typical output of the computer code for this type of sample is shown in figure 5. This figure shows the steady-state electron particle trajectories (fig. 5(a)) and a detail of the steady-state voltage profile around the sample (fig. 5(b)). Note that, in the trajectory plots (fig. 4(a)), NASCAP computes the beam deflection due to the surface charging. Additional plots of steady-state or transient data can also be obtained.

The charging of the sample is illustrated in figure 6 which shows the surface voltage of the center of the sample as a function of time. The experimental results are shown as the data points with their associated error bars and the solid line represents the NASCAP predictions. The agreement is excellent.

The steady-state values have been found to depend primarily upon secondary emission from the surface. This emission was set at values reported in the literature with the resulting good agreement. The steady-state voltage profile across the sample can be used to evaluate the surface resistivity of the sample (see fig. 7). The data points are shown with their associated error bars along with the NASCAP predictions for surface resistivity of 10^{16}, 10^{14}, and 10^{13} ohms/square. As shown there is a threshold for surface resistivity effects and a reasonable value would be between 5 and 10×10^{13} ohms/square. The apparent lack of agreement at the edge of the sample is probably due to two effects: the size of the grid in the NASCAP model (2.5 cm) influences the accuracy of the predictions at edges and the physical size of the surface voltage probe influences the measurements.

The rate of charging depends upon the incident current flux and the capacitance of the sample. If it is assumed that the beam current flux is constant, then a 40% increase in the capacitance would produce a prediction shown by the dashed in figure 6. Even this result is reasonable: the largest difference is 20% at the 3 minute time interval.

The results of these test comparison indicate that it is possible to estimate the lumped material parameters in such a manner that charging behavior can be predicted. The defintion of these lumped parameters for the various classes of spacecraft materials is still underway.

Multiple insulator samples. - Once the charging behavior of single insulator samples can be reasonably well predicted, then a next logical step would be to evaluate the effect of having different insulators and conductors next to each other. This has been accomplished with the four sample set shown in the facility (see fig. 8(a)). The four samples were aluminized Kapton (0.015 cm thick), silvered Teflon (0.015 cm thick), Optical Solar Reflectors (Silica, 0.02 cm thick) and a gold plate magnesium plate electrically floating. The frame around the samples was a conductor electrically grounded. The NASCAP model for the four sample set is shown in figure 8(b).

The results of these tests are summarized by comparing the experimental data with predictions under steady-state conditions for 10 kV beam condition (see fig. 9). As shown in this figure both the data and predictions indicate an asymmetric voltage profile across the Kapton insulator (and to a lesser extent across the Teflon sample) that was not in the single sample tests. The surface voltage at ends of adjacent insulators tends to be more negative than the ends adjacent to space. Even though this surface voltage profile is skewed, the peak value is about the same as the single sample results. The model does predict a more rapid falling of voltage at the space end of the sample than indicated by the data. This could be due to an overcompensation in the beam spreading routine of the computer code. It will be further evaluated.

These comparisons do illustrate the differences between the idealized surfaces used in the NASCAP simulation and actual test surfaces. The optical solar reflectors (OSR's) are 2.5 cm squares with gaps between them. NASCAP cannot treat such gaps and so assumes that the surface is continuous. Therefore, the code cannot predict the variations in potential due to the individual nature of the OSR's. The data points shown are for the peak voltages on the center of the OSR's. Another illustration of this effect is the Kapton sample. This sample was a single surface but apparently developed surface imperfections that caused the voltage variations shown in these data points (e.g., the surface could have developed blisters). Again, NASCAP predicts behavior based on the assumption of uniform surfaces.

Material Discharging Simulation

When insulators are charged above a certain threshold voltage, they will discharge. These discharges are visible and have been photographed[32,33] (see fig. 10). The available experimental data indicates that the discharge is triggered at an insulator edges and removes charge from the whole insulator surface.

There seems to be two types of discharges that can occur. The first, called a minor discharge, occurs at lower beam voltages (those that are just above threshold conditions) and results in charge removal only in the local area around the discharge site. The second, called a major discharge, occurs around the higher (16-20 kV) accelerating potential tests and results in significant charge loss over the entire test sample.

This phenomenon can be approximated with NASCAP by specifying the threshold voltage (relative to the substrate) and by estimating the depth of discharge (percent of the total charge stored). Using the hypothesis that discharges can occur when the voltage gradient at the sample edge is about 2×10^5 V/cm[34] and assuming that the 67% of the charge is removed,[35] then the NASCAP predictions for a 0.0127 cm thick silvered Teflon are shown in figure 11(a). In figure 11(b) the experimental results for a silver Teflon sample are shown.

As shown in the NASCAP simulation (see fig. 11(a)), cells in the central region of the Teflon sample charge more rapidly than the cells on the sample edges. Breakdown threshold is reached in about 5-1/2 minutes. Thereafter, breakdowns occur in this region approximately every four minutes (the computer simulation was run for 20 minutes to verify this trend). Cells on the edges of the sample reached breakdown conditions about a half minute after the first central region breakdown and repeated the charging-discharging cycle about every 5 minutes. It is important to realize that the NASCAP voltages used here are average values for the center of each cell. The breakdown conditions apply only at an insulator edge or seam. Hence, the criteria imposed here was breakdown at -12 kV which corresponds to the desired edge voltage gradient.[34]

Comparison of these predictions to test data (see fig. 11(b)) shows that predictions of times to reach first breakdown are long, but are in reasonable agreement for subsequent breakdowns. The discrepancy in time for first breakdown could be due to experimental electron flux variations in the initial charging cycle, the sample being precharged initially or errors in the material properties used in the code.

The actual test results show that separate breakdowns in the central regions and edge regions do not occur as predicted by NASCAP. In the testing the whole sample surface discharges at once. This indicates that the model should be modified to include a coupling mechanism. Another discrepancy is the amount of charge left on the sample after discharge. NASCAP model predicts much more charge remaining compared to the data. This condition could be alleviated by increasing the depth of discharge in the NASCAP model from the 67% to 85%. Parametric evaluations of effect of depth of discharge are being conducted.

It is also interesting to note the role surface resistivity plays in this simulation. The predictions shown here were computed with resistivity values of 10^{14} ohms/square. In a preliminary series of computations, a resistivity of 10^{13} ohms/square was used. The predictions for this resistivity value showed that the edge cells did not reach breakdown conditions. Apparently small increases in surface currents can control voltage buildup and prevent breakdowns. This may be an indication of why grounded metal picture frames on insulator samples prevent discharges. The surface resistivity effect may also aid in developing the mechanism to cause simultaneous charge removal on the sample when discharges occur.

The simulation of discharges presented here must be considered to be a first approximation to actual processes. It is encouraging that NASCAP results are as close to experiment data. However, there is still considerable work to be done before a good discharge model will be available.

Analysis of Spacecraft Behavior in Geosynchronous Orbits

The NASCAP simulation predicts surface voltages reasonably well for the ground test conditions. The computer program has been developed primarily as a designer's tool to evaluate spacecraft behavior in geomagnetic substorms. Therefore, it would be informative to use NASCAP to compute surface voltages for an idealized geosynchronous satellite experiencing a geomagnetic substorm.

The satellite considered is shown in figure 12. This satellite has two solar array wings, each 3 by 1.8 m, capable of generating about 550 watts (1100 W total). The satellite body is an octagon (a NASCAP cylinder) equivalent to about 1.8 m diameter by 1.5 m long. An apogee insertion motor remains with the satellite. Two antennas are simulated on the satellite which is assumed to be 3-axis stabilized.

The satellite surfaces are covered with patterns of Teflon, Kapton, Aluminum, and OSR's (silica) as shown in the figure. The solar cells are simulated by the silica cover glass. Interconnects are considered to be lumped in regions designated by the aluminum patches which corresponds to about 10% of the solar array - a reasonable approximation. These solar arrays are assumed to be mounted on a flexible Kapton substrate. Finally, it is assumed that the solar array voltage is +25 volts for the upper wing and -25 volts for the lower wing (relative to the satellite body which floats electrically relative to the space plasma potential).

This satellite was subjected first to a geomagnetic substorm in eclipse conditions (no sunlight and no operational voltages on solar arrays). A Maxwellian approximation to a substorm was used in the computations. This substorm assumed that the electron temperature was 5.6 keV and ion temperature was 14 keV. The particle densities were 0.2 cm^{-3}. These results are shown in figure 13.

Under these substorm conditions the spacecraft ground potential drops to approximately -3500 volts. When exposed to a substorm of this magnitude, the ATS-5 ground potential fell to about -3800 volts. Since it has been shown that geosynchronous satellites experiencing similar substorms in eclipse come to about the same ground potential regardless of size,[36] it can be assumed that the NASCAP simulation is reasonable. Differential charging can exist due to the different current generating characteristics of the various insulators. The silica on the solar arrays and OSR's achieve a surface voltage of about -3300 volts while the Kapton reaches -3900 volts and Teflon, -3600 volts. Hence, the differential charging is only about 100 to 400 volts: it should not be sufficient to cause breakdowns.

An analysis was also conducted to evaluate charging in sunlight conditions. The sunlight was assumed to be incident at a shallow angle (27^{o}) simulating a June or January condition. A substorm having the Maxwellian approximation of T_e = 5.6 keV, T_i = 10.0 keV, $n_e = n_i$ = 0.2 cm^{-3} was used. This substorm was measured by the ATS-6 and charged the ground to about -700 volts. The results of this computation is shown in figure 14.

In the sunlight charging example, NASCAP predicts that the spacecraft potential decays slowly to about -690 volts in about 40 minutes. Hence, the time history of substorm characteristics becomes very important in analyzing satellite behavior under sunlight, spacecraft-charging environments. The voltage profiles shown here graphically illustrate the stronger fields that exists on the shaded portions of the solar array, the shadowed insulators behind the antennas and the shadowed Kapton and Teflon at the apogee motor. It is in these areas that arcing could occur.

This example indicates that there is still much to do in establishing the guidelines for designing future geosynchronous satellite that will be immune to charging anomalies. The final validation of the tools used to develop these guidelines will be the comparison of the predictions to the flight data from the P78-2 SCATHA spacecraft.[37]

HIGH VOLTAGE SURFACE-PLASMA INTERACTION: EXPERIMENTAL AND ANALYTICAL EVALUATION

Approach

In the spacecraft charging interactions the geomagnetic substorm environment charge the satellite surfaces. It is a condition that exists because the satellite happens to be at a location where it can encounter this environment. For high voltage space power systems, electric fields that can accelerate charged particles into the structure will exist at all times and at all orbits. Hence, the evaluation of this phenomena will require an understanding of how electric fields propogate in plasmas and a determination of the influence of the insulators surrounding biased conductors on particle interactions.

For these high-voltage surface/plasma interaction evaluation the basic philosophy is the same as that for the spacecraft charging investigation: an iterative experimental-analytical approach is to be used. At this time, the experiments are well underway[21,22] while the modelling tool development is just starting. Until this computer code is developed, the NASCAP code can be used to approximate the experimental behavior, at least for the low plasma density cases.

In this section applied bias test results using small solar array segments are briefly summarized. The comparison of these experimental trends with a NASCAP model illustrates the areas where additional modelling is required. Finally, the behavior of a large space power system operating at high voltages is computed as a initial indicator of regions where additional technology development is required.

Experimental and Modelling Results

The experimental results obtained when solar array segments are biased in plasma environments have been detailed in other reports.[21,23,25,26] These results are only summarized here, the trends identified and the initial attempts to model these interactions illustrated.

When a solar array segment, similar to that shown in figure 15, is biased positively and negatively in plasmas, there are phenomena that occur due to the insulation surrounding the biased conductors. The plasma coupling currents collected in three different plasma densities is shown in figure 15(a) (for positive bias voltage-electron collection) and figure 15(b) (for negative bias voltage-ion collection). For the positive bias case, at voltages below 100 volts, the current collection appears to be low and proportional to the interconnect (biased conductor) area, the applied voltage and plasma properties. Above bias voltages of 100 volts there is a transition such that the currents collection is orders of magnitude higher. It appears that the area dependance has transferred from the interconnect area to the whole panel area. For the negative bias voltage case, there appears to be no such stable transition, but a rapid transition into an arc at some plasma density dependent threshold.

The surface voltage profiles taken during these tests give an indication of the processes that may be occurring. This data is given in figure 17. At the low positive voltages the quartz cover slides assume a slightly negative voltage required to maintain a net current to that surface of zero. This surface voltage appears to suppress the field due to the biased interconnect and effectively limits the collection to just the interconnect area. As the bias is raised above 100 volts, the electric field from the biased surface appears to grow over the quartz and encompasses it. The quartz surface voltage then becomes about 50 volts less than the bias voltage. It is believed that the electric field expands during this transition period and accelerates electrons into the quartz surface with sufficient energy to create secondaries which are collected by the biased conductor. This represents an additional current from the quartz and causes the surface voltage to reach a new equilibrium potential.

For the negative bias voltage case the electric fields due to the biased conductor appear to be confined to the cavity formed by the interconnect and quartz cover slides. This causes the voltage gradients to increase until values greater than 10^6 V/cm are reached. At these voltage gradients, breakdowns triggered by field emission are possible.

While this general explanation of phenomena can be made, there is still considerable work to be done to be able to understand in detail what is happening, why it occur and how can these effects be converted to power system behavior in space.

The NASCAP code can be used to explore some of these effects and examine the validity of the beliefs. This work has just started and so only the initial results are available at this time. The present version of NASCAP is designed to be valid for the cases where the plasma Debye length is large compared with the model dimensions. There is a screening expression in the code that can approximate conditions where the plasma density is higher. This screening expression is used in the following modelling discussion. There is also no means in the present version of NASCAP to model the processes involved in the encompassing of the quartz surface voltage at bias voltages greater than 100 volts. This effect can be simulated by allowing the quartz surface resistance to drop drastically and thus form effective conduction layer which enhances particle collection and hence, matches the experimental results.

Analysis of Space Power Systems

Even though the modelling techniques for these high voltage surface-plasma interactions are just being initiated, it would be informative to use the preliminary techniques to evaluate the behavior of such a system in geosynchronous orbit.

The NASCAP model of such a high voltage space power system is shown in figure 18. This system consists of two solar array wings, each 50 by 60 m, with a central body, a 20 m octagonal antenna. The antenna, which is assumed to be the system electrical ground and float relative to space, has aluminum top and bottom surfaces with 0.01 cm Kapton on the sides.

Each solar array wing is assumed to be divided into three sections, 20 by 20 m, with each section operating at 7000 volts. The interconnects are assumed to be aluminum and exposed on the front and back of the array similar to the Solar Electric Propulsion (SEP) solar array design. Since the NASCAP code cannot treat small gaps, the interconnects are assumed to be concentrated at two locations in each section as shown. This exposed area represents 5% of the front and back areas of each section and is a reasonable approximation for these interconnect areas. Quartz cover slides, 0.015 cm thick, are used for the solar cells. The substrate and sides of the array are covered with 0.01 cm thick Kapton.

The electrical circuit for this power system is assumed to be such that there is a 42 kV potential difference across the array (see fig. 19). The overall power output of this system is on the order of 600 kW with each section generating 100 kW.

The behavior of this system is computed in a normal geosynchronous environment having plasma densities of 10 cm^{-3} and particle temperatures of 1 eV. The array is assumed to be in full sunlight and only steady-state conditions are considered. The high surface resistivity simulation of the plasma sheath or secondary collection phenomenon (mentioned in the last section) was applied only to the +21 kV section of the array in this analysis. It was found that this was the only section on the positive-voltage wing to remain positive relative to space plasma potential and warrent such collection mechanisms. The detailed voltage profiles in space around this system is shown in figure 20.

The voltage distribution in space along the surface of the solar array is shown in figure 21. The operating voltage of this system has caused the central body to assume a very negative value (-17.9 kV) relative to space plasma potential. This establishes a negative voltage distribution around the system. The +21 kV section of the array floats at +3.1 kV (relative to space) and is the only positive voltage section. The current collected through space for this system represents less than 1% of the operating current. Hence, power loss through this environment can be neglected.

This type of analysis indicates the areas where additional work is required in order to operate these systems in space. The region of the interconnects show that voltage gradients of greater than 10^6 V/cm are possible. At these gradients breakdowns will occur. Furthermore, since the insulators surface voltage seems to remain closer to space than to the operating voltage, very strong electric fields are established within the insulators. These electric fields can give rise to the possibility of bulk breakdown thru the dielectric, excessive energy storage in the dielectrics and strong, induced mechanical stresses within the dielectric.

While these effects are serious and could prevent successful operation of the high voltage systems in space, they can be controlled. This control requires the capability of modelling systems accurately, and then conducting trade-off studies, such as reducing the electric fields by increasing the conduction against increased current collection or shielding against weight. Magnetic field shielding obtained from optimized routing of operating current flows could also be evaluated with a good analytical model.

It should be repeated that NASCAP, in its present state, is just an approximation of high voltage system interactions. The concentration of interconnects at specified cells instead of allowing them to be distributed around the array, the limitation of using just 6 voltage stops and the restraint of computing coupling currents with simple spherical probe theory, must be relaxed in future modelling programs. However, NASCAP does give the material surface voltages for these conditions and therefore, does provide information on possible problems with high voltage power systems.

CONCLUSIONS

Laboratory and computer simulations of interactions between spacecraft surfaces and charged-particle environments are being conducted at the Lewis Research Center. There are two types of interactions being studied. The first is that due to the charging of surfaces by the geomagnetic substorms at geosynchronous orbits (spacecraft charging). The second is that due to the existence of high operating voltages on future, large space power systems. In both cases an iterative approach is being taken with the experiments being conducted to support the analytical modelling development and vice-versa.

In the spacecraft charging studies the experimental investigation is concentrating on collecting data on the charging of insulators, in various configurations, when subjected to monoenergetic electron fluxes. The analytical modelling code is NASCAP (NASA Charging Analyzer Program). The physical processes within the code has been verified and the effort now is concentrating on validating the material properties required to predict insulator charging. This is being done by comparing experimental results to the analytical predictions and adjusting properties to improve the fit to the data.

The modelling of discharge phenomena is limited to an empirical approach. A preliminary criteria has been established for breakdown thresholds and depth of discharge which seems to work for the limited available data base. Additional work is needed in this area.

The modelling code can be used to investigate spacecraft behavior, but additional flight results are required to verify the accuracy of the predictions. The AF P78-2 flight (SCATHA) can provide the necessary information for this validation.

The high-voltage surface/plasma interaction investigation has a long experimental history. These tests have shown that the insulators surrounding the biased conductors can have a profound effect on the interactions with charged-particle environments. When the voltage and solar array segment is positive with respect to space, the insulation can increase the current collection. For negative bias voltages, arcing can occur. These interactions are plasma density dependent and are more severe at low Earth orbit.

The modelling of these interactions is just starting. Eventually, a realistic code to predict these interactions will exist. As an indicator of the effect of the interactions on space power systems the NASCAP code can be used for evaluation an geosynchronous environments. The predictions of such a model indicate strong electric fields exist at interconnects and through the dielectrics. By conducting a technology investigation and having a realistic analytical tool it will be possible to optimize the techniques to relax these constraining interactions.

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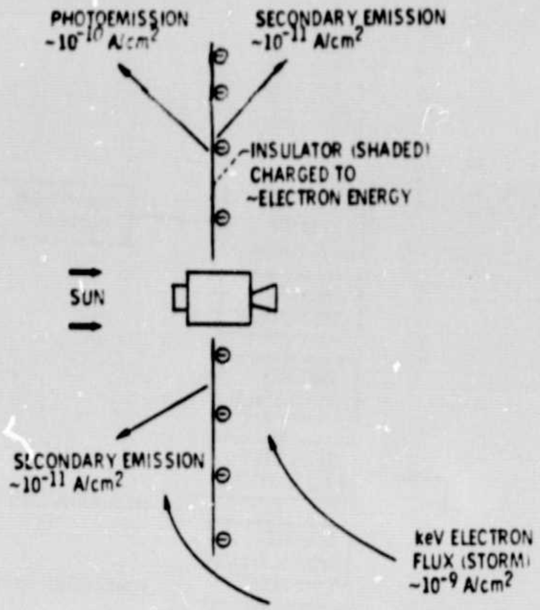
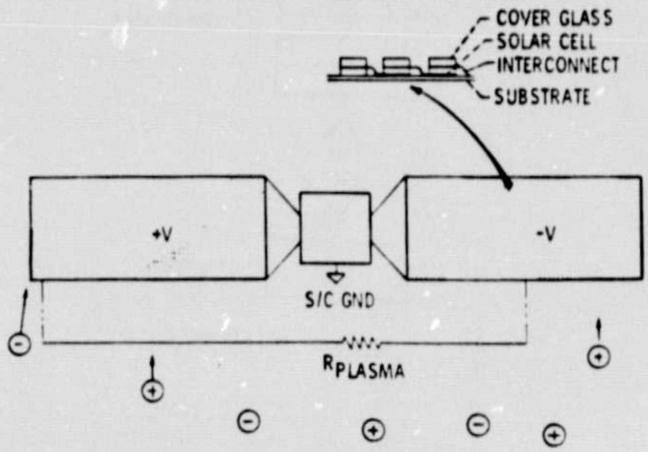


(a) SPACECRAFT CHARGING INTERACTIONS.



(b) SPACECRAFT HIGHER VOLTAGE SYSTEM-ENVIRONMENT INTERACTIONS.

Figure 1. - Environmental interactions.

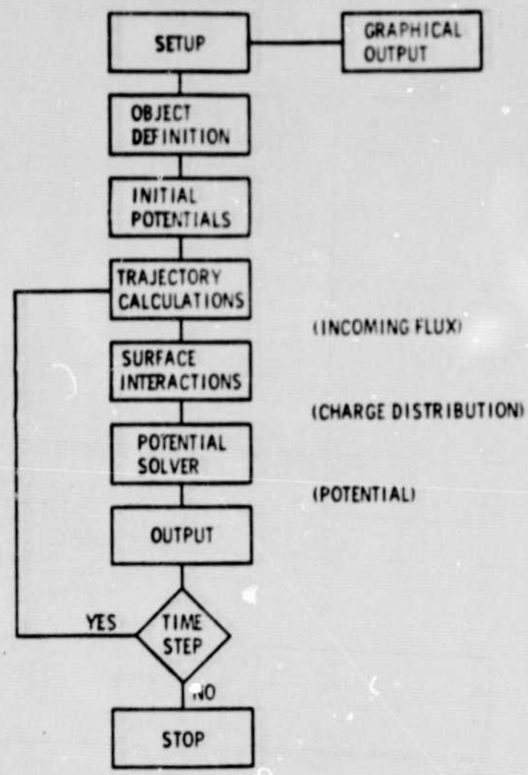


Figure 2. - NASCAP flow diagram.

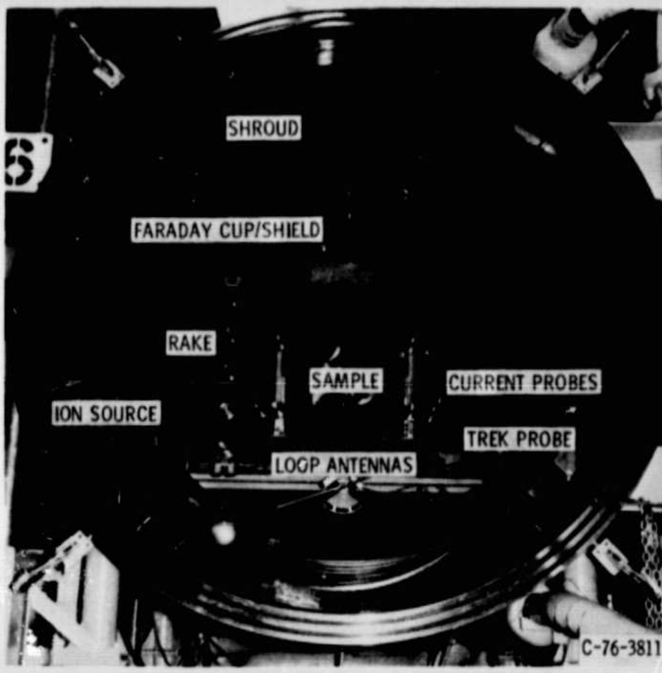
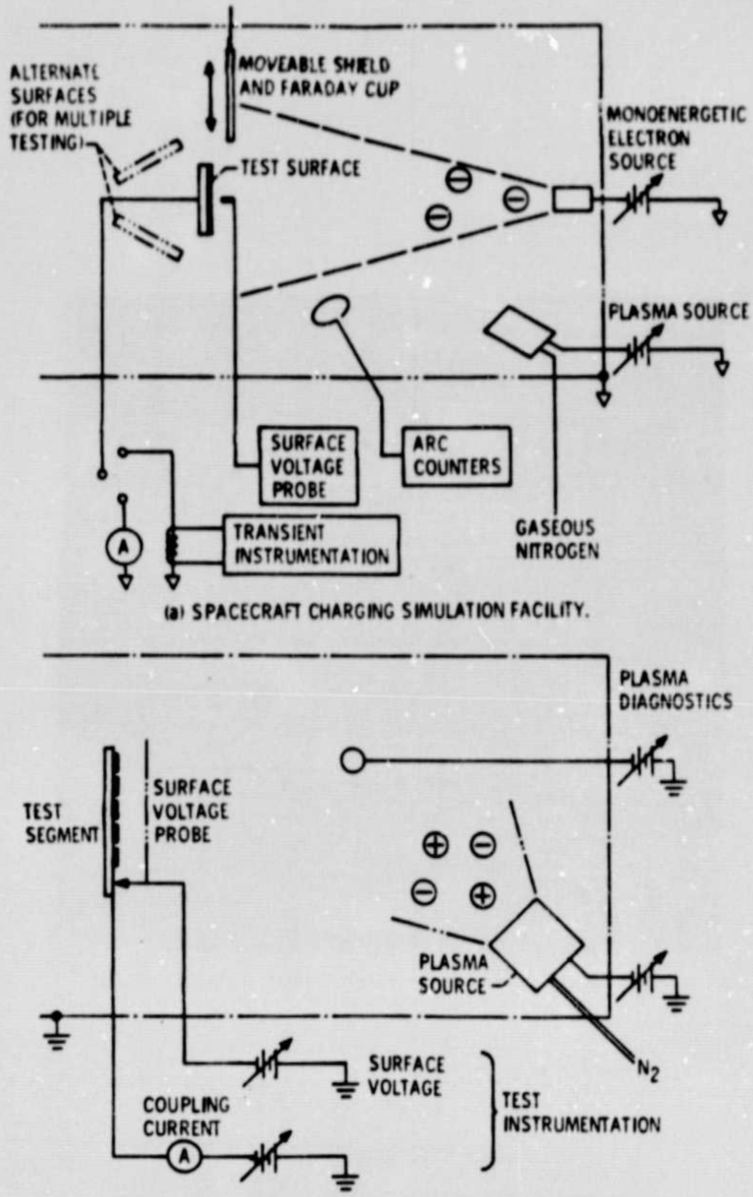


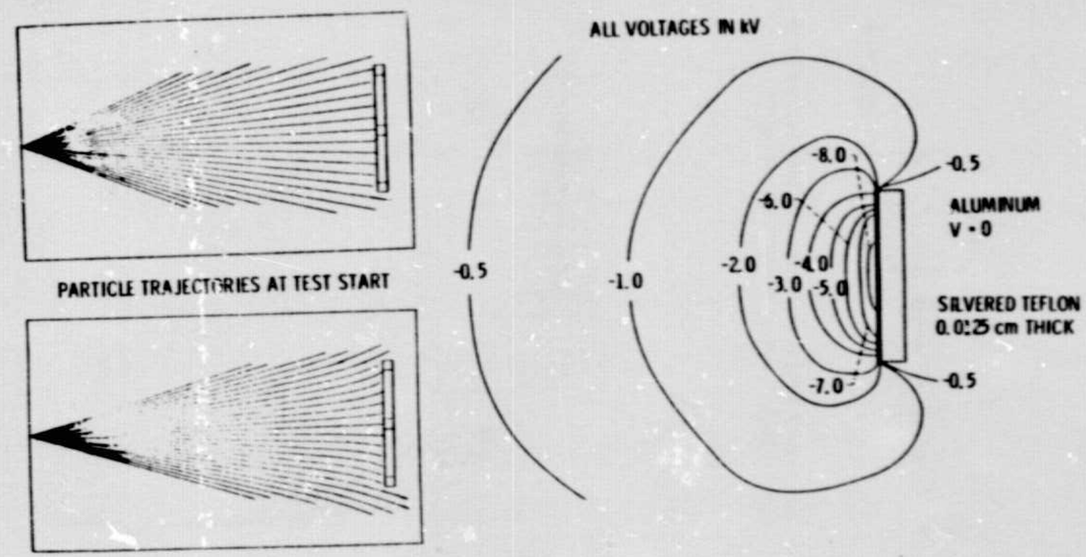
Figure 3. - LeRC Substorm Simulation Facility test chamber interior.



(a) SPACECRAFT CHARGING SIMULATION FACILITY.

(b) HIGH VOLTAGE SURFACE-PLASMA TEST FACILITY.

Figure 4. - Schematic diagram of test arrangements.



(a) INCIDENT ELECTRON BEAM TRAJECTORIES.

(b) TYPICAL VOLTAGE DISTRIBUTIONS - STEADY-STATE GROUND NASCAP SIMULATION SILVERED TEFLON SAMPLE - 10 kV BEAM VOLTAGE, $1 nA/cm^2$ CURRENT DENSITY.

Figure 5. - NASCAP output.

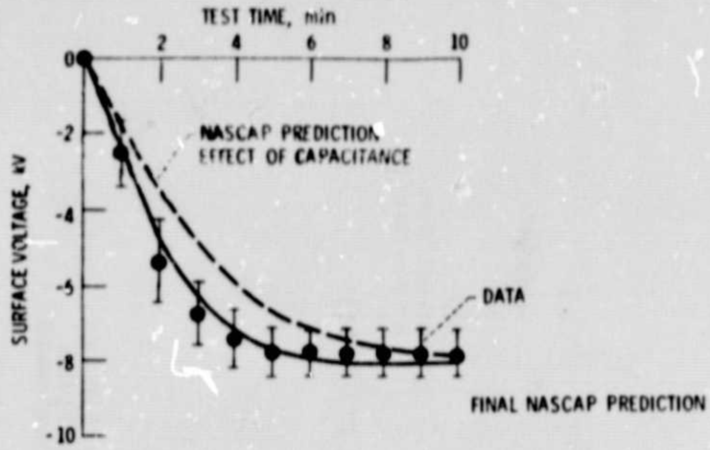


Figure 6. - Comparison of NASCAP predictions with data. Silvered teflon sample, 0.0125 cm thick, 10 kV beam voltage, 1 nA/cm^2 current density.

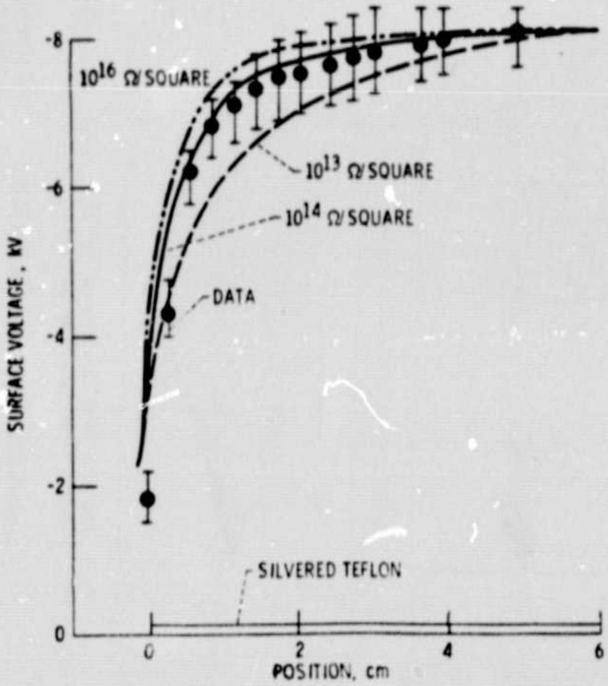
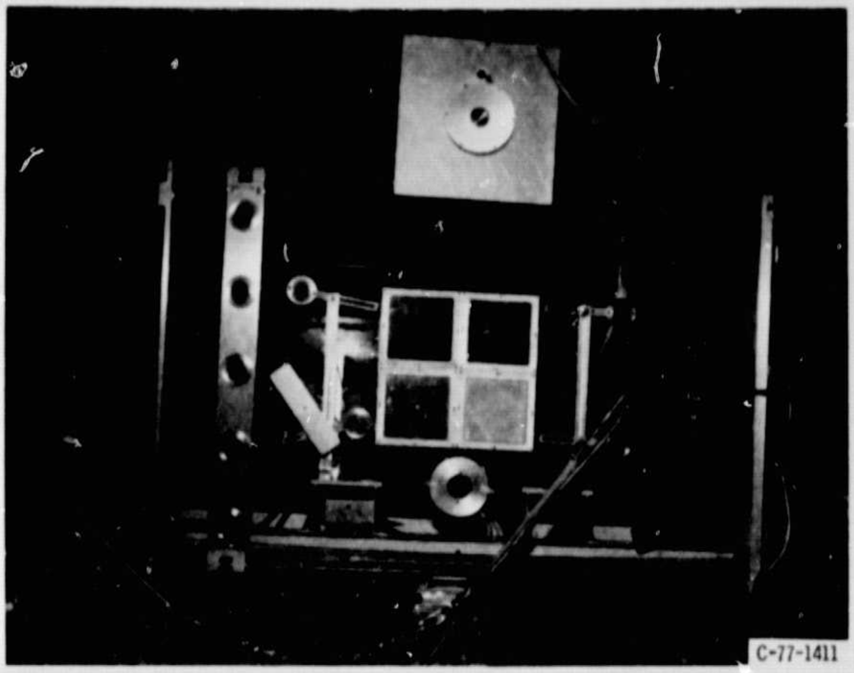
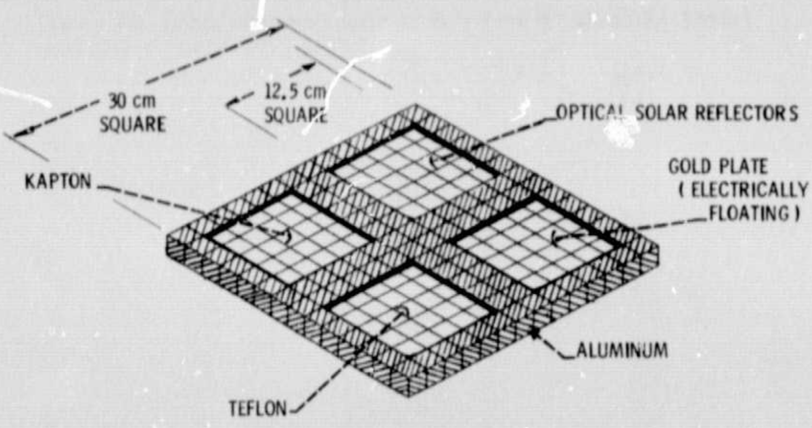


Figure 7. - NASCAP predictions of edge voltage profiles; effect of surface resistivity. Silvered teflon sample, 0.0125 cm thick, 10 kV beam voltage, 1 nA/cm^2 current density.



(a) Test surfaces in experimental facility.

Figure 8. - Multiple insulator test surfaces.



(b) Analytical model.

Figure 8. - Concluded.

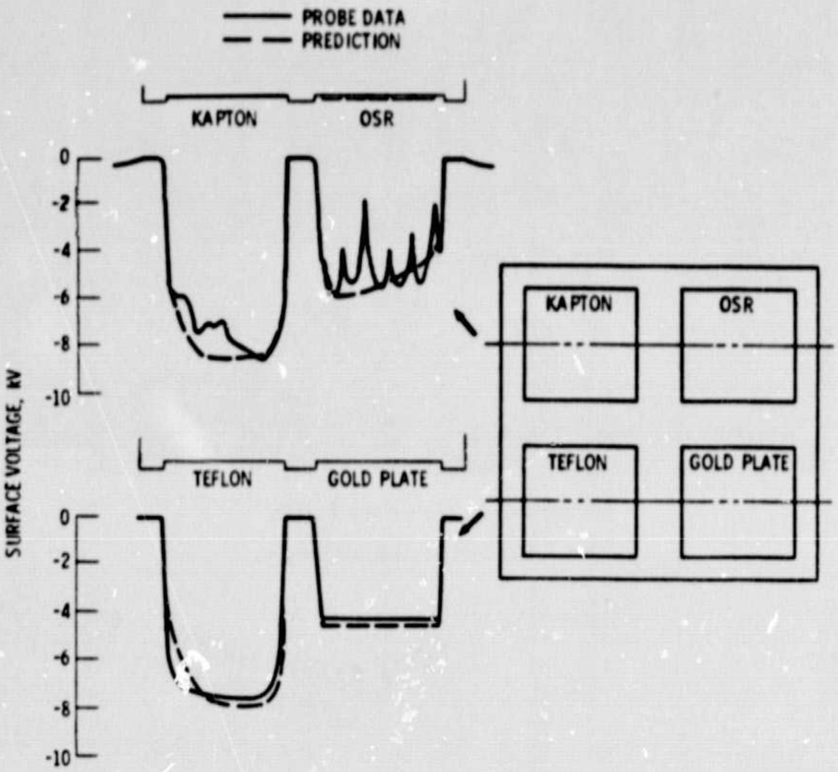


Figure 9. - Comparison of data to predictions multiple insulator sample, 10 keV beam.

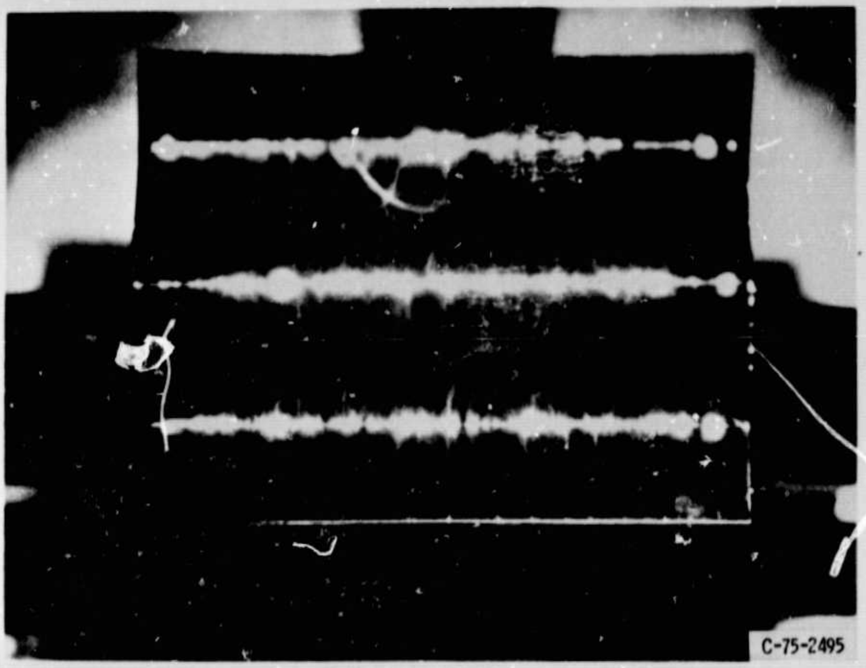
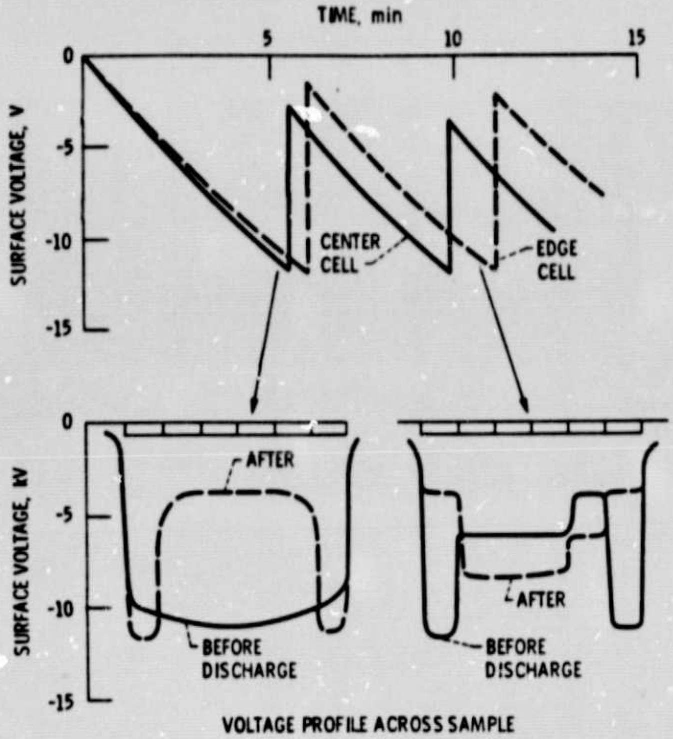
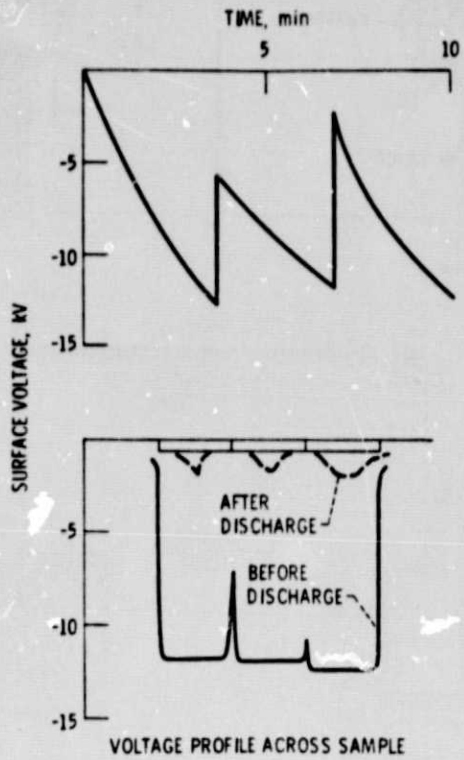


Figure 10. - Visible discharges in silvered Teflon sample.



(a) NASCAP SIMULATION.

Figure 11. - Single insulator sample discharge data silvered teflon, 20 kV beam.



(b) EXPERIMENTAL RESULTS.

Figure 11. - Concluded.

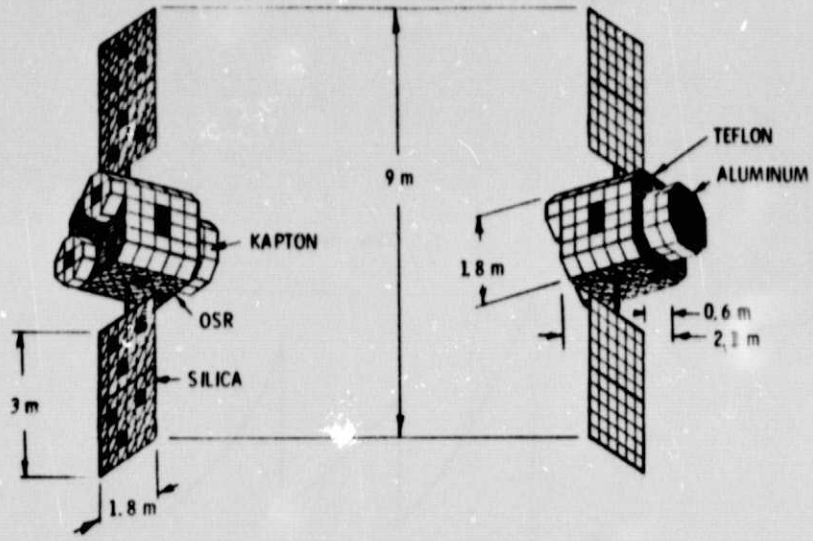


Figure 12. - NASCAP model typical geosynchronous communications satellite.

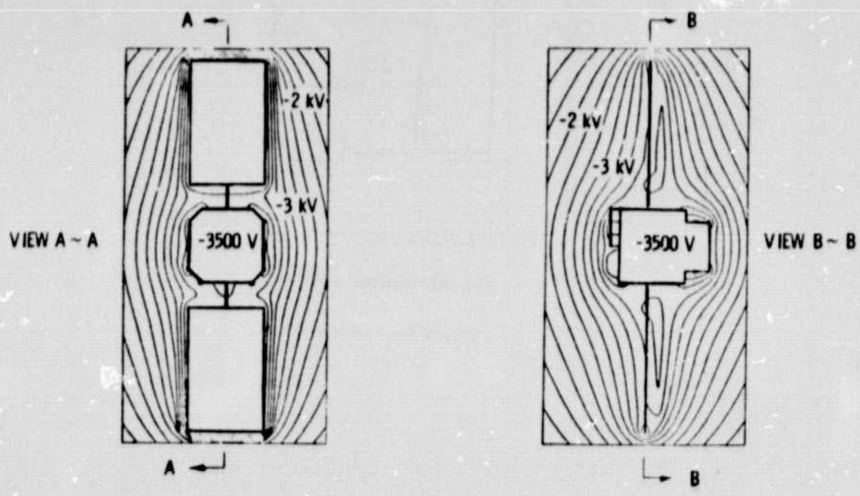


Figure 13. - Voltage contours around satellite in eclipse substorm electron temperature 5.6 keV. Contours in 200 V steps.

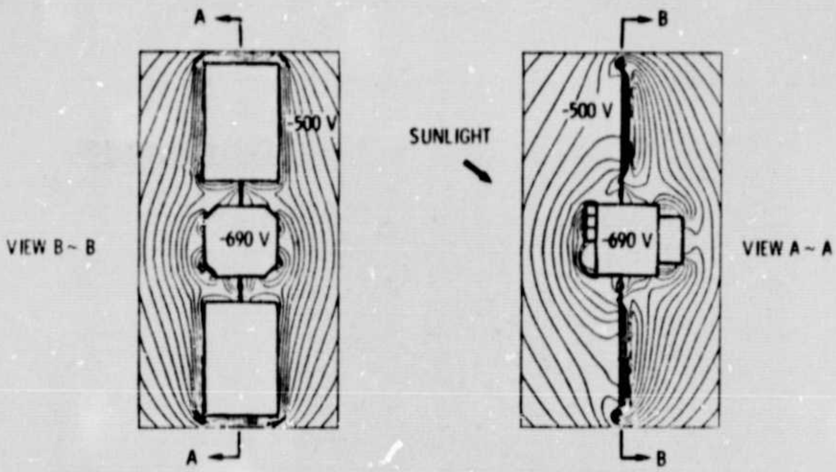


Figure 14. - Voltage contours around satellite in sunlight. Substorm electron temperature 5.6 keV. Contours in 50 V steps.

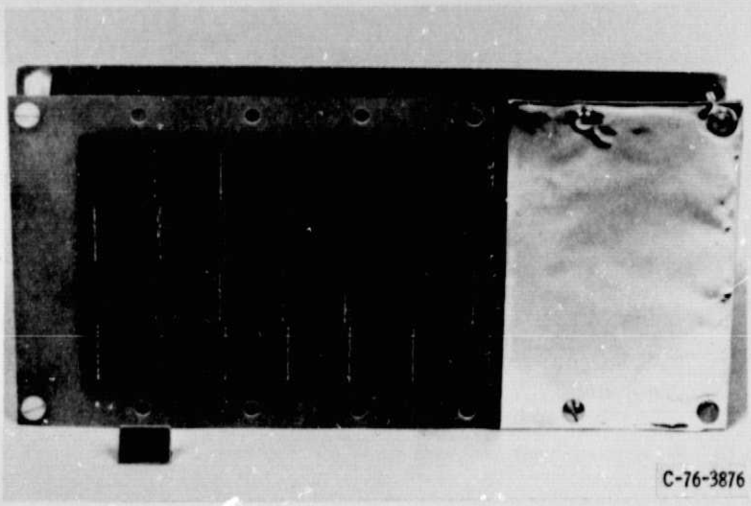


Figure 15. - Solar array segment

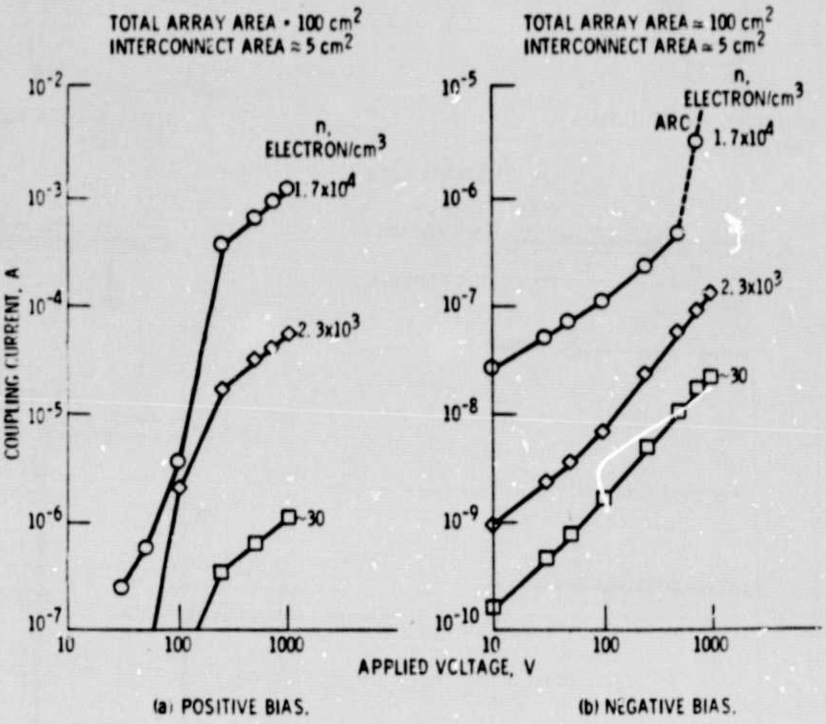


Figure 16. - Plasma coupling currents for 100 cm^2 solar array.

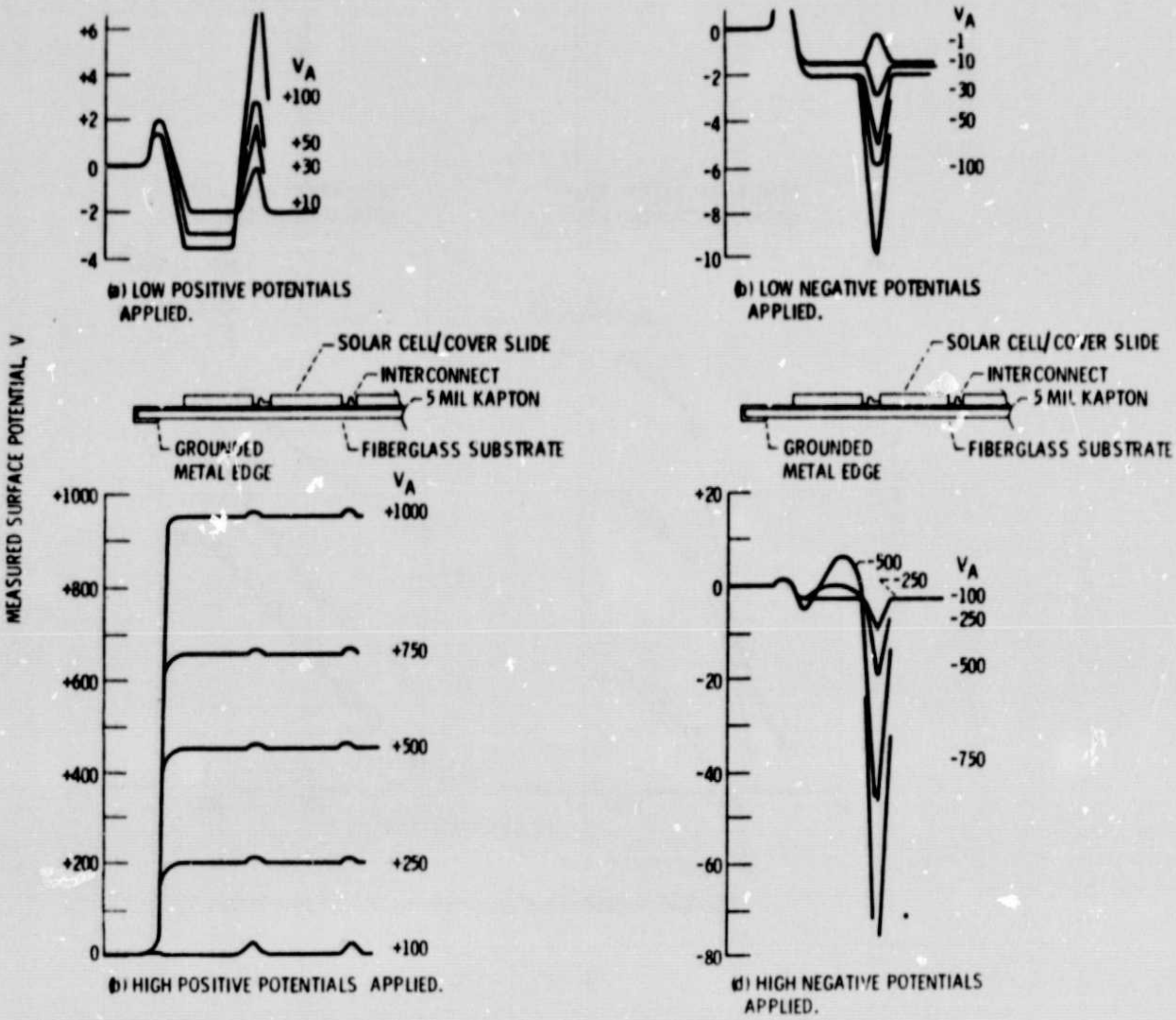


Figure 17. - Typical surface voltage profiles-solar array segment.

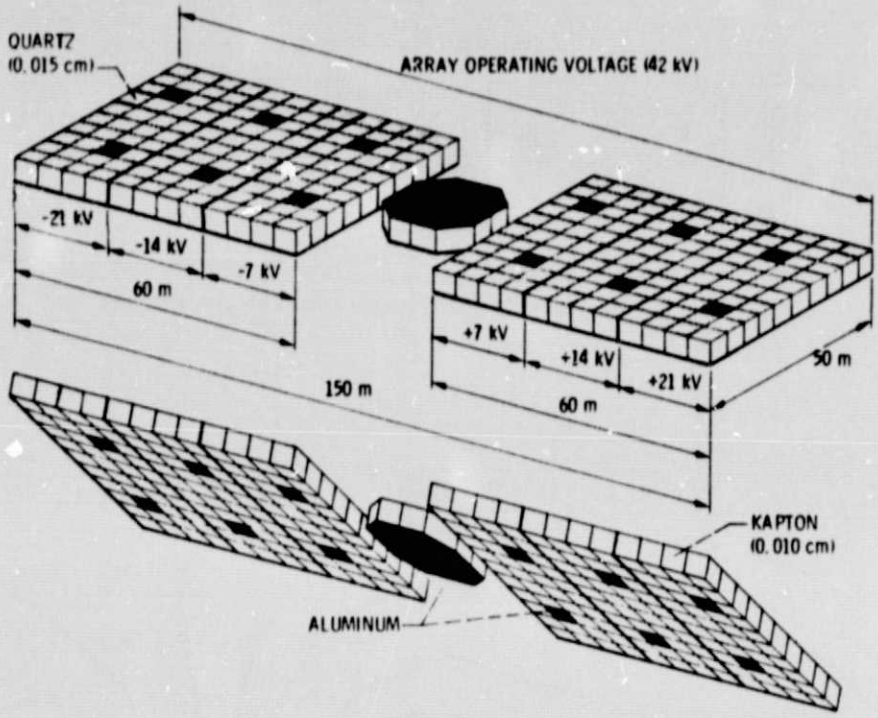


Figure 18. - NASCAP model space power system.

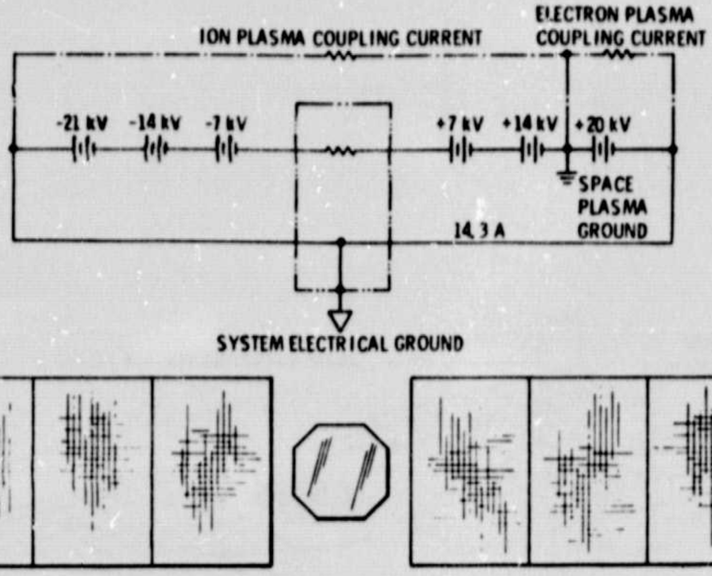


Figure 19. - Schematic diagram of high voltage power system ion plasma coupling current.

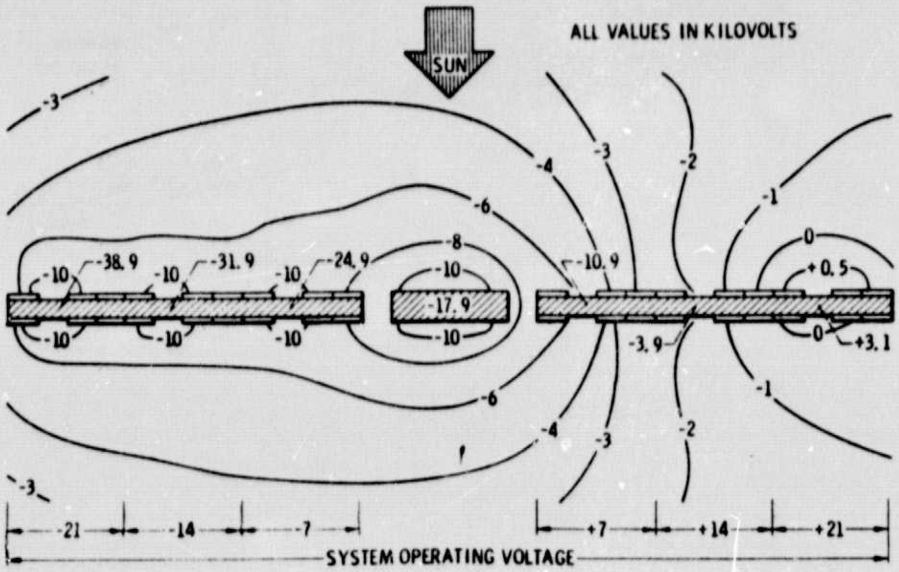


Figure 20. - Voltage distribution around space power system. (Relative to space plasma potential.)

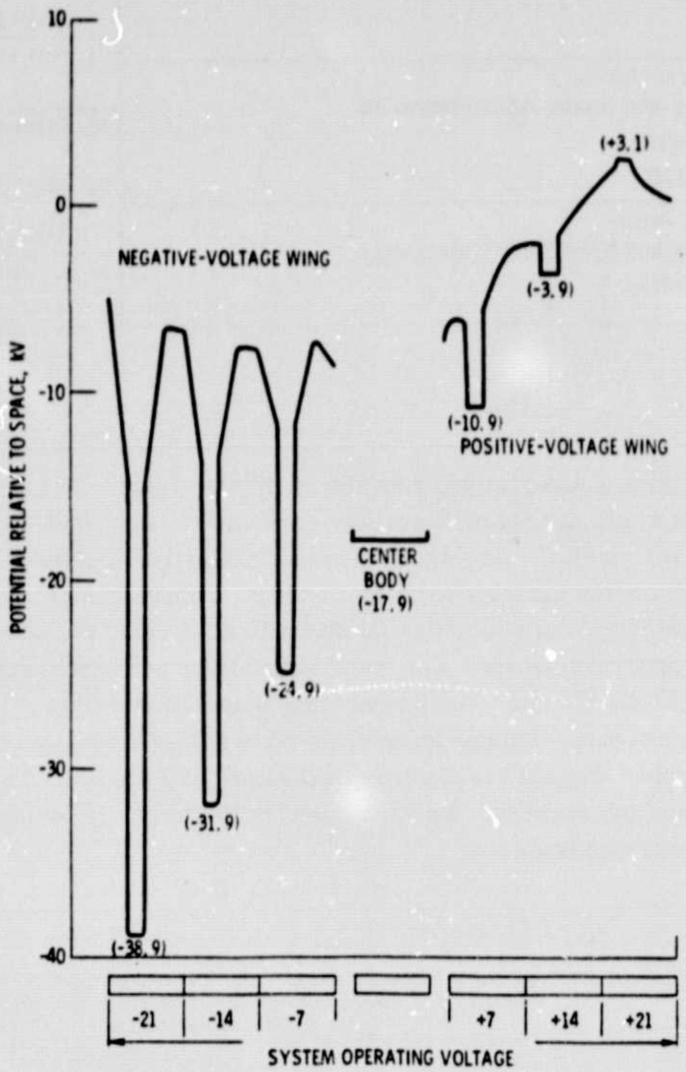


Figure 21. - Potential profile across sunlit surface. (Relative to space plasma potential.)

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15. Supplementary Notes

16. Abstract

There are two categories of interactions considered in this report. The first, spacecraft passive, refers to cases where the charged-particle environment acts on the spacecraft (e.g., spacecraft charging phenomena). The second, spacecraft active, refers to cases where a system on the spacecraft causes the interaction (e.g., high voltage space power systems). Both categories are studied in ground simulation facilities to understand the processes involved and to measure the pertinent parameters. Computer simulations are based on the NASA Charging Analyzer Program (NASCAP) code. Analytical models are developed in this code and verified against the experimental data. Extrapolation from the small test samples to space conditions are made with this code. Typical results from laboratory and computer simulations are presented for both types of interactions. Extrapolations from these simulations to performance in space environments are discussed.

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