High-Voltage Solar Array Technology

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A requirement for reliable, lightweight, multikilowatt, solar electric space power systems for electric propulsion spacecraft and high-power communication satellites has been established in numerous studies. Additional studies have shown that the High-Voltage Solar Arrays (HVSA) could be a competitive power system alternative to conventional power conditioning operated from low-voltage arrays. The objective of the present work is to develop a better understanding of the concepts and design criteria in the areas of HVSA power control systems and HVSA/space plasma interactions. In order to investigate the first area, a low-power HVSA breadboard has been fabricated and coupled with a computerized digital control system. It is shown that system control characteristics compare favorably with those achievable with conventional high-efficiency power conditioning. The interaction of a HVSA with the space plasma environment has been investigated in a large volume simulation facility. Quantitative results are presented for plasma power losses and electrical breakdown phenomenon which indicate that HVSA operation in the space plasma environment is understood in most of its aspects and involves only minor weight and size penalties.

I. Introduction

PREVIOUS high-voltage solar array (HVSA) studies conducted[1–7] under the sponsorship of NASA-LeRC have all come to similar conclusions with regard to the relative power system performance gains possible with the HVSA, the generalized techniques for implementation, the specific problem areas associated with device requirements, and the analytic evaluation of HVSA operation in the space environment. This paper considers forms most practical for ion propulsion and high-power communication satellite applications. Attention is focused on defining the concepts for total power systems in greater detail, on breadboard implementation and testing of critical subsystems associated with the total system approach, and on studies to increase the understanding of solar array/space plasma interactions so that the selection of array materials and physical designs can be based on a knowledge of the requirements and penalties involved.

II. Array Power Control System

Basic Concept

For the HVSA power systems of major interest multikilowatts of power will be involved. In general, the voltage and current requirements of any one load which is powered by such a system will be satisfied by configuring blocks of solar cells into series and/or parallel connections which form manageable subunits of the total array. From a consideration of numerous potential loads it appears that most blocks would typically have voltages, at maximum power output, in the range of 500 to 1500 v with an output current capability equivalent of from one to five (or more) solar cells in parallel. The specific design of the blocks will, of course, depend on the load specifications, the commonality in requirements among loads which may use the power during various phases of a mission, and the anticipated environmental factors which may lead to radiation degradation, solar illumination variations, and degradation and power loss due to interaction with the space plasma.

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A representative reconfiguration switching arrangement for meeting the power requirements for either the screen supply of an ion thruster or the electrode voltages for a high-power multicollector communication tube (TWT or klystron) is shown in Fig. 1. With the parallel-series switches open, solar cell power blocks $B_1 \ldots B_{10}$ are in parallel; when the switches are closed all blocks are in series. Closure of both shorting switches clamps the array output voltage regardless of the state of other switches. In addition, by proper selection of which shorting switch is closed the polarity of the array output with respect to a given reference point is established. Switches for connecting independent loads to the array power are also part of the reconfiguration subsystem.

In order to provide fine control and regulation, certain of the power blocks must be adjustable in their output with sufficient resolution to satisfy the most demanding regulation accuracy requirements. It appears that this can best be achieved by varying the I–V characteristics of given power blocks using control techniques which clamp or shunt solar cell groups within the blocks. With this technique the array output voltage is reduced by the difference between the cell group output voltage at the array operating current level and the clamped voltage. By using a number of these switches, each operating on a different cell group, and by selecting the cell group lengths according to a consistent coding scheme, it is possible to effect finely regulated control over a large portion of the array output voltage. Since each switch operates from a digital input (the switch is either fully on or fully off), the appropriate selection for the coding scheme will be some form of the binary code. Using this approach, the cell group lengths are binarily weighted and thus the effect of each

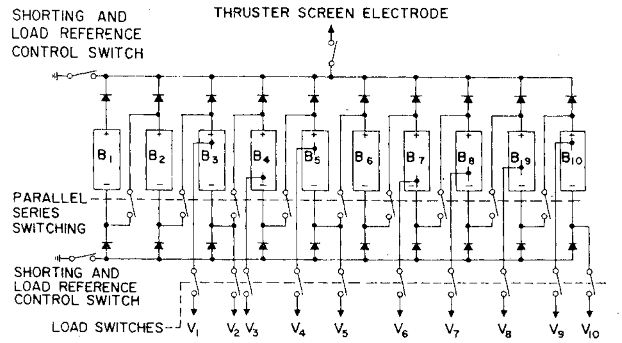

Fig. 1 Representative HVSA reconfiguration switching arrangement.

switch on the output voltage is related by a factor of two to that of its nearest neighbor.

The subdivision of array power into blocks, the configuring of these power blocks into series and/or parallel interconnected combinations, and the fine control of the output voltage (or current) with shunt switching internal to given blocks are the essential features usually associated with what is broadly referred to as the HVSA power system approach. The power block regulation and control circuitry, which represents a major subsystem of an HVSA, has been investigated in considerable detail using a small breadboard HVSA combined with a computerized control system.

HVSA Breadboard

A breadboard array consisting of a single controllable power block has been fabricated in order to demonstrate the specific control techniques outlined in the previous section. The HVSA is fabricated using 2112 series-connected, silicon N/P, 2 Ω-cm, 2 × 2 cm solar cells, each of which has a maximum power rating of approximately 45 mw. In addition, the breadboard contains small auxiliary array groups which provide isolated biases for the 12 array shunt switches as well as supplying power to the array-mounted control circuitry. Present illumination and cooling capabilities limit the available current to 35 ma at a voltage of about 900 v when the array is operating at maximum power.

The HVSA is tapped to provide 12 subgroups of various lengths. Lengths of subgroups are assigned according to a dual binary code, resulting in two sets of six binarily weighted subgroups. The minimum subgroup length is 10 cells, giving a theoretical maximum control resolution of one part in 200.

The array-mounted control circuitry is composed of four main sections: the array switches, the intermediate voltage isolation circuitry, the control electronics and the high-voltage isolation circuitry. Each of the 12 array switches is made up of a Darlington connected transistor pair. These transistors (2N5657's) are low-cost commercial grades and have been selected for their high collector-to-emitter breakdown voltage. A diode is connected across the output of each switch to provide a bypass path for array current in the event of failure within a subgroup.

Intermediate voltage isolation is provided for each switch by means of a Monsanto MCT-2 photocoupler. This is a four-terminal device composed of a light emitting diode (LED) and phototransistor. The photocoupler provides 2.5 kv isolation between input and output, but since the phototransistor base lead is not available, the response time of the device is limited to approximately 2 μsec. Intermediate voltage isolation allows flexibility in the allocation of the switches to various parts of the array.

Since each array switch is a digital element, the array output voltage may be determined by one 12-bit digital control word. It is the function of the array-mounted control electronics to accept this word from some external device, such as a digital computer, store it, and apply it to the array switches. In order to reduce the number of external control leads, the control word is transmitted in serial format. The control electronics is implemented with commercial grade transistor-transistor logic integrated circuitry.

In keeping with the concept that a full scale high-voltage array system would be composed of a number of blocks similar to this breadboard, each operating at a high potential with respect to the others, high-voltage isolation has been provided at the input to the control electronics. Isolation is implemented by the use of Monsanto MCT-25 photocouplers. These units are similar to the MCT-2's described above with the exception that they are designed to withstand 25 kv between input and output.

Control Loop Implementation

The output voltage of the breadboard previously described is a function of the load current, illumination, temperature and other factors, as well as the value of its digital input. However, by providing for feedback of the breadboard output the digital input may be used to stabilize array operation in the presence of variations in all parameters.

A control loop, shown in Fig. 2, has been implemented which includes the array breadboard, a digital computer, and the necessary interfaces. The computer operates on the scaled representation of the array output voltage according to a software control algorithm. Each iteration of the computer results in a new control input to the array. After a delay of approximately 700 μsec, during which the computer is available for other tasks, the results of the iteration are available for further evaluation and control..

To date, investigations of the regulation control loop have emphasized engineering testing of the implemented electronic hardware and operation in a closed-loop configuration with a Digital Equipment Corporation PDP-8/E computer using a very simple fixed control algorithm. This algorithm, although lacking in sophistication, appears adequate for the practical uses envisioned for the HVSA. The characteristics of the responses shown by this system compare favorably with conventional high efficiency power conditioning operating from a low voltage solar array bus.

III. Experiments in a Simulated Space Plasma Environment

Previous analytical studies have investigated the interaction of HVSA systems with the space enviornment, particularly the space plasma constituent.[4] In these studies, two areas were defined which may have a large impact on the feasibility and design of future HVSA power systems. These two areas are power loss due to the flow of plasma coupling currents, and electrical breakdown of insulating materials as

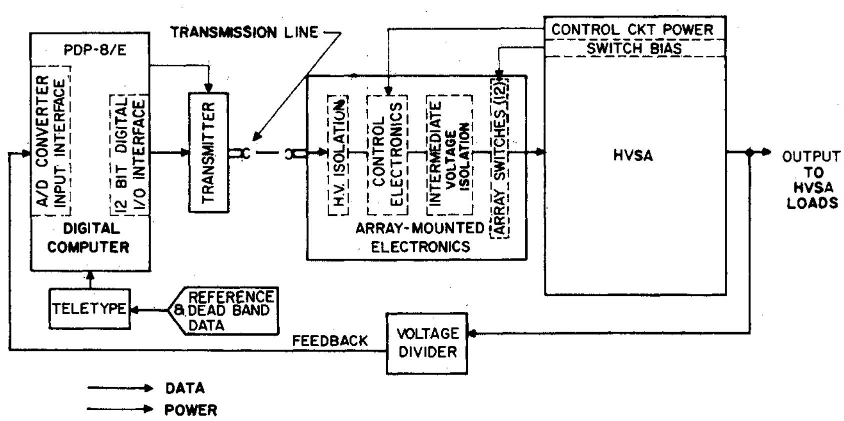

Fig. 2 Control loop block diagram.

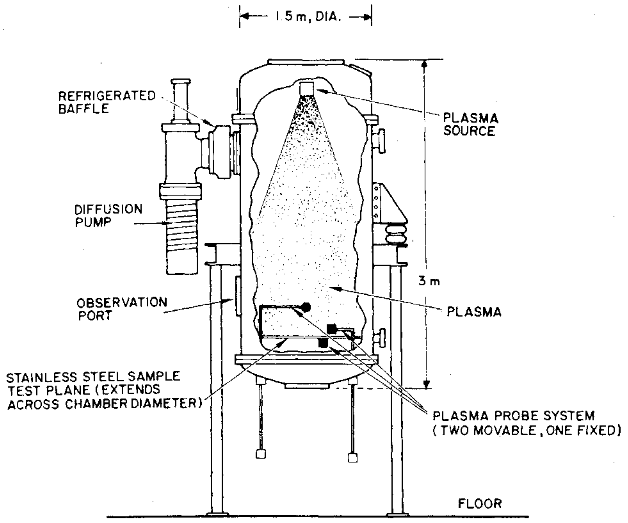

Fig. 3 Space plasma simulation facility.

a result of operation at high voltages in the presence of the surrounding plasma. The experimental program described below was undertaken in order to investigate these areas in a simulated space plasma through detailed studies of: 1) plasma coupling currents, 2) surface breakdown of insulators, 3) bulk breakdown of dielectrics, 4) electrical breakdown due to pinholes in insulating layers, and 5) current collection and electrical breakdown of solar array segments. The major objectives of the program are to: 1) develop an understanding of the relevant physical phenomenon, 2) evaluate HVSA designs, and 3) develop methods for reducing potentially degrading or damaging effects.

Experimental Apparatus

The experimental system, shown in Fig. 3, consists of a vacuum chamber, a plasma source, a plasma diagnostic probe system, and a sample test plane. The vacuum chamber is 1.5 m in diameter and 3 m long. A 24-cm-diam oil diffusion pump with a refrigerated chevron baffle provides an ambient pressure of less than 6×10^{-6} torr for plasma densities of less than 10^5 cm^{-3}, and less than 8×10^{-5} torr for larger plasma densities. A magnetic expansion nozzle plasma source similar to that discussed by Siekel et al.,[8] and recently developed into flight hardware by HRL,[9] is employed to simulate the space plasma environment. This source was chosen because of its well understood and reliable operating characteristics and because it can be controlled to supply a plasma which closely simulates that found in space over a large range of altitude (300 km to synchronous altitude). The plasma parameters were determined by means of two

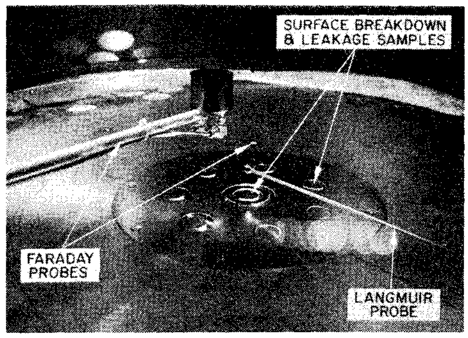

Fig. 4 Experiment to study surface breakdown and leakage in the HRL space plasma simulation facility. (Probes were moved aside during experimentation.)

Faraday probes and a 1-cm-diam spherical, guarded Langmuir probe (see Fig. 4). The Langmuir probe and one of the Faraday probes could be moved axially and across the chamber diameter; the other, which is identical, is attached to the test plane. An infrared lamp is located behind the test plane in order to heat specimens to temperatures representative of those encountered by an HVSA in space. Table I summarizes the parameters of the simulated space plasma for two altitudes and compares them with the values obtained in space. At the highest altitudes the simulation becomes increasingly questionable since the plasma sheath dimensions become comparable to the chamber dimensions. However, it is expected that the charged-particle current densities are of primary importance for the present experiments and these are maintained at values comparable to those existing in space.

Plasma Coupling Current Experiment

The objective of this experiment was to develop an understanding of current collection processes in a tenuous plasma. To accomplish this, the current collecting properties of a 5 cm^2 metal disc mounted on a large ground plane were investigated.

A great deal of theoretical work has been done to explain the characteristics of this geometry.[10] The results are summarized by the approximate relationship

$$I \cong Aj\{1 + \tfrac{3}{4}[e(V - V_{pl})/kT]\}f \qquad (1)$$

where I is the collector current, A is its area, j is the saturation current density of the attracted particle species, V is the collector voltage, V_{pl} is the plasma potential, and T is the temperature of the attracted species (for the present case kT for the ions is replaced by the average ion energy which is measured to be approximately 50 ev). The function f takes the presence of repelling potential barriers into account. For the present

Table I Plasma parameters and comparison with average values existing in space

	Ion saturation current density $j_i(A/\text{cm}^2)$	Average ion energy E_i (ev), or kT_i	Plasma density $n(\text{cm}^{-3})$	Electron saturation current density $j_e(A/\text{cm}^2)$	Average electron energy kT_e(ev)	Ambient pressure P, (torr)	Dominant ion species
Low-altitude (300 km) space plasma	3×10^{-7}	5	2×10^6	10^{-6}	0.03	$\sim 10^{-8}$	N+, O+
Low altitude (300 km) simulation	3×10^{-7}	50	6×10^5	2×10^{-6}	1.5	8×10^{-5}	N+
High-altitude (synchronous altitude) space plasma	10^{-11}	3	10^2	5×10^{-10}	3.0	$\ll 10^{-8}$	H+
Synchronous altitude simulation	10^{-11}	50	20	7×10^{-11}	1.5	5×10^{-6}	N+

experiments $f \approx 1$ since the plasma potential is measured to be within approximately kT_e/e of ground, and the applied potential $V \gg kT_e/e$. It must be noted that the size of the simulation facility forces the experiments to be performed in the orbital regime.[11] For a HVSA having large current collecting areas, the power losses depend strongly on the presence of space charge and particle orbiting will only be significant near the surface of the array.[3, 4]

The measured dependence of the collector current I on A, j and V was found to agree with Eq. (1) in most cases. For example, a change in the collection area by a factor of three led to the same change in the current. For collector potentials of plus and minus 200 v, the current varied linearly with electron and ion current densities (within 20% over two orders of magnitude variation in plasma density except at the lowest electron currents where potential barriers and wall interactions may become important). For positive collector voltages in the range 20–5000 v the collected current depended linearly on voltage and was within a factor of two of the expected result. For negative voltages in the range -50 to -200 v the measured current depended linearly on voltage and agreed within a factor of three with the expected values. In the range -1000 to -5000 v, the dependence on voltage was linear but the measured current exceeded the expected value by a factor of seven as a result of the generation of secondary electrons.

These results indicate that the current collection processes are generally well understood. Deviation from exact agreement between the experimental and theoretical results can be explained by density and voltage gradients in the plasma, and by the approximate nature of the theoretical relationships.

Surface Breakdown Experiments

The properties of electrical breakdown over a Kapton surface were investigated with the objective of determining the allowable spacings between solar cell blocks and busses. Since a HVSA will probably be operated at maximum voltages only at synchronous altitude, these tests were performed mostly at a plasma density $n \cong 30$ cm^{-3}.

The test configuration shown in Fig. 4 consists of an electrically biased, 2.5-cm-diam metal disk bonded to a 0.013 cm thick Kapton sheet and mounted concentric and coplanar with a slightly larger diameter hole in the grounded test plane. For some tests a metal ring was located between the disk and the ground plane in order to permit measurement of surface leakage currents. The electrodes were bonded to the Kapton either with a mixture of RTV 511 and RTV 577 or with an epoxy of the type used on FRUSA.[12] Electrical breakdown in these experiments, as in all others, was detected as a visible arc and/or a momentary increase in the probe currents due to the plasma burst resulting from an arc. An audio circuit sensitive to transient currents and meter observations were also used but only as indications of possible arcing.

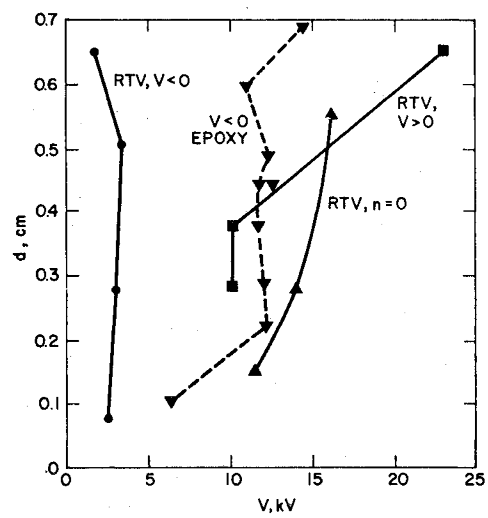

Fig. 5. Initial surface breakdown voltage as a function of electrode gap width d for electrodes bonded to Kapton with RTV 511-577 and with epoxy. The curve labeled $n = 0$ was obtained without plasma at an ambient pressure of 1×10^{-6} torr. All other data were obtained at a plasma density $n \cong 30$ cm^{-3}.

The measured dependences of surface breakdown voltage on electrode spacing are presented in Fig. 5. The maximum allowable stress without plasma, which varied between 75 v/mil and 200 v/mil, is consistent with the nominal maximum values characteristic of insulators in vacuum.[13] The results in a plasma environment are relatively close to the values obtained without plasma for positive voltages with samples employing RTV, and for negative voltages when epoxy was used. However, the results with RTV for negative polarities are different. The independence of breakdown voltage on spacing in this case may be explained by assuming the initiation of an arc to the plasma at the plasma-metal-dielectric junction.[14] Early in its formation such an arc would be directed to the nearby ground plane, thereby yielding the observed discharge over the insulator surface. This effect may also be important, to some degree, in the results given for epoxy. Finally, it was found that increasing the plasma density resulted in a decrease in the breakdown voltage.

These results indicate that, depending on the detailed dielectric configuration, an interelectrode spacing of about 1 cm should be applicable to a 16 kv HVSA operating at high altitudes. This agrees with expectations based on a previous analytical study.[4]

Bulk Breakdown Experiments

Experiments have been performed to measure the bulk breakdown strength of Kapton layers (0.0063 cm thick) during exposure to a low-density (10^3 cm^{-3}) plasma. In these experiments a 1-cm-diam metal disk was mounted and potted onto the back surface of the Kapton layer using a mixture of RTV 511 and 577 (0.0025 to 0.0075 cm thick). The assembly was then bonded to the test plane so that a 2 cm diam area of Kapton was exposed to the plasma.

The breakdown voltage for several samples was greater than or equal to 11 kv which agrees well with the manufacturer's data (without plasma) and with the results of others obtained at much larger plasma densities.[15] The results indicate that, as expected,[3, 4] the thickness of insulation employed in the construction of an HVSA can be selected on the basis of existing data obtained without plasma. It must be noted, however, that the simultaneous presence of high-energy radiation belt particles, plasma, and high voltage combined with long-term operation may affect this conclusion.

Pinhole Experiments

The effects caused by pinholes in insulating array surfaces can be considered one of the fundamental problems associated with a HVSA operating in the space environment. Other than fabrication and material imperfections in insulating materials, small holes will unavoidably exist as a result of micrometeoroid impacts. Previous investigations have demonstrated that such holes can lead to power losses and degradation due to electrical breakdown.[16, 17] The present experiments were performed with emphasis on high-altitude HVSA operation and were directed toward developing means of reducing the deleterious effects of pinholes particularly with respect to electrical breakdown.

Preliminary experiments were performed with single 0.025 cm diam holes drilled in 0.013-cm thick Kapton layers of large area (~ 500 cm^2). Collecting electrodes were bonded to the back surface of the Kapton just as in the bulk breakdown studies. For a plasma density of 2×10^3 cm^{-3} the collected

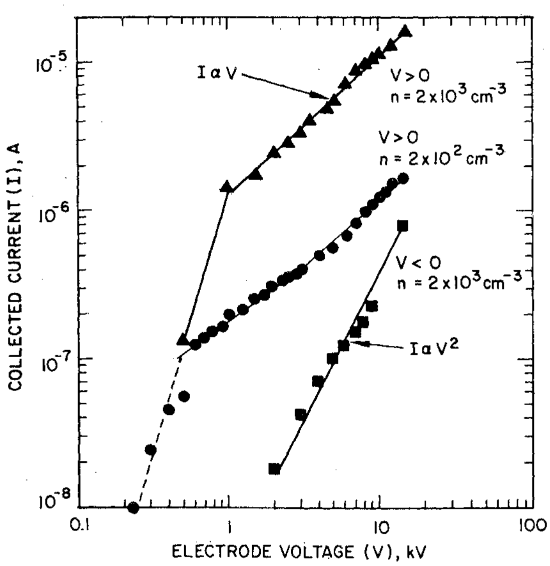

Fig. 6 Current-voltage characteristics of a pinhole in a 0.025 cm thick, 2 cm diam, Kapton test specimen.

currents exceeded by orders of magnitude those predicted by Eq. (1) and discharges were observed for voltages greater than +3 kv and −5 kv. At higher voltages arcs became destructive and, in some cases, a tenuous glow was observed to extend over the Kapton surface surrounding the hole. In addition, probe measurements for positive sample potentials indicated that the plasma sheath was much larger than would be expected for a small hole. One explanation for these observations is that the pinhole collects current primarily by conduction or migration of charges along the insulating surface, thereby increasing the effective current collection area. Discharges would then be expected to occur when the power density in the hole exceeded some maximum value which, for the present experiments, was roughly 1000 w/cm^2.

A second configuration was tested in which the Kapton surface was bounded by the metal test plane so that only a 2 cm diam portion of it was exposed to the plasma. Figure 6 shows the current-voltage characteristics for both voltage polarities and two plasma densities. It is seen that, for $V > 0$, the collected current rises very rapidly at low voltages and then appears to change abruptly to a linear dependence on the sample voltage. In addition, for voltages exceeding 1 kv, increasing the plasma density leads to a proportional increase in the collected current. The higher voltage portions of these characteristics are strongly reminiscent of current collection by a disk. However, calculations using Eq. (1) indicate an effective collecting area about 10^4 times larger than the area of the small pinhole or about equal to the area of the exposed insulating surface. This may be explained as follows: as the voltage is increased from zero, the voltage gradients in and near the hole become very large. As a result, particles originating from the plasma migrate along the insulator surface and are collected. With increasing voltage, the radius over which the collection process occurs increases and the current varies rapidly with voltage. When this radius becomes equal to the insulator radius the difficulty of removing electrons from the metallic boundary plane causes the effective collection area to stabilize; this occurs at the knee of the curves in Fig. 6. It is not yet clear how to explain the characteristics obtained for negative voltages; however, comparison of these results with those obtained with the large area specimens supports the above hypothesis for both polarities. In all cases, at high voltages, the current collected by the 2 cm diam samples was much less (at least a factor of four) than collected by large area samples. In addition, the voltage at which discharging or arcing was observed was much greater for the 2 cm diam specimens; a voltage of +15 kv was sustained by the samples at a plasma density of 2×10^3, without any observed arcing, and for negative voltages, arcing was first encountered at −11 kv.

These results indicate a possible new approach to preventing pinhole arcs. In this method an unbiased conducting grid would be placed, for example, on the fully insulated back surface of the HVSA. The grid conductors could be arbitrarily small but the open area would be determined for a given minimum altitude, so that all the current collected by it could be collected by a nominally sized pinhole without exceeding a power density of a few hundred w/cm^2.

A final set of experiments was designed to investigate the effectiveness of the depressed plasma collector for reducing pinhole currents.[3,4] In this approach a biased collector is placed near to the insulator surface with the objective of collecting, or repelling, particles which would otherwise reach the pinhole. The basic experimental configuration was identical with that used in the previous tests; however, a 1 cm wide metal electrode extended to the edge of the insulating surface. It was found that biasing of this electrode to voltages greater than about ±50 v led to at least a factor of three reduction in the collected current, thus giving preliminary verification of this approach.

HVSA Segment Experiments

The major objective of these experiments is to establish the electrical breakdown or arcing characteristics of possible HVSA front-side design configurations, particularly those with uninsulated solar cell interconnects, since these are considered most applicable to the HVSA.[3,4]

The uninsulated specimens consisted of nine, 2 × 2 cm, 0.020 to 0.030 cm thick, silicon solar cells. These were mounted on a Kapton or fiberglass-Kapton substrate and covered with 0.015-cm thick microsheet coverslides. Bonding was accomplished employing RTV 655. Only the front surfaces of the specimens, which were approximately 90% insulated, were exposed to the plasma.

Measurements of the plasma coupling current-voltage characteristics in the voltage range 0 to ±200 v and over a range of plasma densities indicates that the collection approximately (within a factor of two) satisfies Eq. (1) as expected. At voltages above ±200 v, the collected current increases rapidly as if surface leakage were becoming important.

Electrical breakdown data were obtained for plasma density levels corresponding to a typical mission which would involve orbit raising by means of electric propulsion (≤2 kv) at low altitudes and operation of a high-power, high-voltage (16 kv) communication tube at synchronous altitudes. For low-positive voltages at a plasma density of 10^6 cm^{-3}, no arcing was observed; however, a tenous blue glow formed around the sample at the highest voltages. In this case the sample current was sufficiently large (1 to 2 ma) to cause appreciable heating and locally high gas pressures. Such high currents would not be collected by a large area HVSA since the plasma sheath area would be much smaller in relation to the array area. At low-plasma densities ($n \approx 10^2$ cm^{-3}) no repetitive arcing was observed, even at +15 kv. A few random arcs did occur during a one hour test at +15 kv; however, their magnitude and number decreased with time. This indicates that some conditioning was taking place. For negative voltages the onset of arcing for samples prepared with a minimum amount of adhesive was −6 kv (with excess adhesive the arcing voltage decreased). Several samples were operated at −15 kv for 1 hr. The arcs, which occurred mainly on the periphery of the solar cells, decreased in severity and frequency during this time. These results were independent of the ambient chamber pressure over the range 5×10^{-6} to 8×10^{-5} torr.

Several specimens were fully insulated by covering the exposed interconnects with about 0.020 cm of RTV 655. The current collected by these samples was 10 to 100 times less than collected by the uninsulated samples; however, it was about 1000 times greater than expected from known resistivities. The arcing voltage was generally lower (probably because of small voids or holes in the insulation) than obtained with the uninsulated specimens, and subsequent to arcing the current collected from the plasma became comparable to that measured for the uninsulated design.

IV. Conclusions

A low-power HVSA power system has been investigated which includes all the elements necessary for the realization of a high-power HVSA power system having a high degree of control and power distribution capability. Operation of this system has verified the efficacy of the proposed HVSA control scheme and has demonstrated that the system responses compare favorably with those of conventional high-efficiency power conditioning operating from a low-voltage solar array bus.

Investigations of HVSA current collection charactersitics and electrical breakdown phenomena in a large volume space plasma simulation facility have demonstrated that the involved phenomena are understood in most cases. It is generally concluded that interaction of an HVSA with the space plasma environment, particularly near synchronous altitude, should result in only minor penalities with respect to conventional low-voltage arrays. These penalties are mainly in the form of increased spacings (~ 1 cm) between busses or solar cell blocks which have greatly different potentials, and of a requirement that large continuous insulating surfaces (HVSA backside) be covered by a fine conductive grid in order to prevent electrical breakdown caused by micrometeroid punctures. For some HVSA designs it may be necessary to increase the thicknesses of insulating layers; however, the thickness need only be based on electrical breakdown data obtained without a plasma. Finally, electrical breakdown of negatively biased solar array segments at high voltages is not presently understood.

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