Feasibility of High Voltage Solar Arrays

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A detailed feasibility study of high-voltage solar arrays (HVSA), capable of 15 kw at 2 to 16 kv, has been performed. The major areas considered are 1) plasma power losses, 2) dielectric stresses, and 3) questions relating to high-voltage design, fabrication, and testing. It is concluded that the space plasma losses should be small except in the ionosphere where they may reach 20 to 30% of the array output power for array potentials of 2000 v. The dielectric strength of conventional coverglass and substrate materials should be adequate to withstand the anticipated voltage gradients; however, the presence of the space plasma may have an effect. Laboratory and space experiments are recommended for an assessment of the interaction between high-voltage surfaces and a tenuous plasma. Providing that dielectric materials maintain their integrity, HVSA designs need only differ slightly from those of conventional low voltage arrays for most missions.

Introduction

SUN powered spacecraft which incorporate ion thrusters and microwave power tubes presently require complex power conditioning units to transform the low-array output voltage to high-device voltages. The power distribution could be simplified substantially and the over-all electrical efficiency increased if the array itself could be made to generate high voltages. In principle, a change from low to high voltage can be considered a straightforward task. By placing large numbers of cells in series and few in parallel instead of the reverse as on conventional arrays, outputs of several kv can readily be achieved with kilowatt size panels. However, the presence of high voltages leads to a number of insulation problems, some of which are common to high-voltage gear in general, while others are unique to operation in space. This paper describes the results of a feasibility study for arrays capable of delivering 15 kw at 2–16 kv in which predominantly problems of the latter type were investigated.

The following aspects of the interaction of the array with its space environment were regarded as being of particular importance: 1) power losses due to collection of space plasma particles, 2) power losses due to interaction with ion thrust beams, 3) dielectric breakdown and damage to solar cells as a result of environmental charge accumulation on insulator surfaces, and 4) sputter and radiation damage to solar cells due to impact of energetic particles. In addition to these environment induced problems, attention was given to the design, fabrication and testing of high-voltage solar arrays.

Array Current Losses

Basic Considerations

A HVSA in space can be compared with an electrostatic probe in a laboratory plasma. A major interest in studying the probe properties of a HVSA is to determine the current losses associated with the array-plasma interaction. In general, probe characteristics depend on the geometry of the probe body and on the energy and density of the surrounding plasma particles. In the case of a solar array in space, additional complications arise from 1) the presence of the Earth's magnetic field, 2) motions of the array against the space plasma (primarily in the ionosphere), 3) potential structures on the array, 4) differences between floating and ion beam biased operation, and 5) trapping and reflection of attracted particles. At first, these complicating factors will be ignored and the situation of a unipotential array in an isotropic plasma at rest will be discussed.

The width of a plasma sheath depends significantly upon plasma density. At high densities the sheath is thin, and at low densities it is thick. Analytic determination of the I–V characteristics for probes which are as irregularly shaped as an array is possible only in the extremes where the plasma sheath is either small or large in comparison with the array dimensions. In the former case, the sheath can be considered a one-dimensional layer; in the latter case, it is very nearly spherical.

The ionospheric plasma density is sufficiently high (normally about 10^6 particles/cm^3) to permit a one-dimensional approach. In this case, the current collected by an uninsulated array is equal to the area of the array times the random current density of the particle species attracted to the array and is independent of the array voltage. It is obvious that this is true only within limits. As the voltage is increased to very high levels, the sheath width becomes so large that the assumption of a one-dimensional array breaks down. Current collection then begins to increase with voltage.

With increasing distances from the Earth, the plasma density decreases rapidly and at about 4 Earth radii it falls below 10^3 particles/cm^3. Beyond this distance and in the voltage range of interest, the sheath can be considered large and the losses can be determined using a more complicated spherical model. In this case, the collection of particles is determined by either space charge effects or, at very low-plasma densities, by the conservation of angular momentum and energy.[1] Calculations indicate that, to distances on the order of 8 Earth radii, space charge is the dominant factor and the collection of current can be expressed as[2,3]

$$I = 4\pi[(1.08/\pi)(e/m)^{1/2}]^{4/7}\,(aV)^{6/7}\,j_r^{3/7} \qquad (1)$$

where e is the electron charge, m is the electron mass, V is the array potential, a is the effective array radius, and j_r is the random current density of the attracted specie. For distances beyond 8 R (Earth radii) the collection current can be determined from the following expression, first derived by Langmuir[4]:

$$I = 4\pi a^2(1 + eV/kT)j_r \qquad (2)$$

where T is the temperature of the attracted species.

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In the intermediate space regions, sheath widths and leakage currents may be obtained by interpolation. The reliability of this procedure was checked with an independent computational procedure involving self-consistent electrolytic tank simulation techniques. This latter method was used to solve several selected cases and it yielded good agreement with the interpolated values.

Array Shape

Under conditions where the sheath width is small compared with the over-all array dimensions, the plasma losses can be expected to depend only on the array surface area and not on its shape. The situation is more complicated with large sheaths. Thus far, in Eq. (1), the array was assumed to be a sphere of radius a. The question arises, what radius must be used to yield a current collection rate equal to that of an arbitrarily shaped array. For an approximate answer, the array is approximated by a flat circular disk.[5] The current collection of a disk of radius r_d is then found to be equal to that of a sphere of radius $a = 0.63\ r_d$ for large sheath widths. For a 15 kw array with a 3×10^6 cm^2 surface area, the equivalent sphere radius a is approximately 7×10^2 cm. This value is used in the loss current estimates given below.

Geomagnetic Field

The geomagnetic field can be expected to influence array current collection rates when the orbital diameters of attracted particles are comparable to or smaller than the width of the plasma sheath. While ion orbits are generally larger than the anticipated array sheath widths, the cyclotron orbits of the electrons can be comparable to or smaller than the sheath widths. Accordingly, at low and medium altitudes the electron collection rates will depend on the orientation of the array with respect to the geomagnetic field. In some orientations they are reduced, in others they remain unaffected. However, because an orbiting array passes through all orientations with respect to the geomagnetic field during each orbit, the unaffected collection current must be considered as a realistic upper limit.

Spacecraft Motions

A low-altitude satellite moves through the ionosphere with an orbital velocity of about 7×10^5 cm/sec. It moves past ions and electrons with thermal velocities on the order of 10^5 cm/sec and 2×10^7 cm/sec, respectively. Because the satellite velocity is considerably greater than the average ion velocity, the region behind the satellite is rarefied. What happens in front depends upon the potential of the satellite (array). A positively charged array generates a detached "bow shock" for which the ion density at the center point in front is increased by a factor 2. A negatively charged array collects all ions through which it sweeps, and because the reflected electrons move much faster than the array, a normal sheath boundary is formed. Recent satellite experiments in which measurements yielded current collection ratios between front and rear as high as 100 : 1 have confirmed this picture.[6]

Because of the shape of high-voltage solar arrays, the current collection rates in low orbit should depend upon the orientation with respect to the direction of motion. A positive array which moves broadside through the ionosphere can be expected to collect only about half as much current as if it were at rest; while a negative array collects approximately ten times more current due to the high rate at which ions are swept up by the array. Both positive and negative arrays moving through the ionosphere with their narrow profile can be expected to collect approximately the same current as an array at rest.

Potential Structures on the Array

High voltage solar arrays incorporate large numbers of series-connected solar cells as a result of which the surface potential varies significantly from location to location. In fact, depending upon cell layout, a large number of different surface potential distributions can be created. The question arises whether some of these distributions are more conducive to low-plasma leakage than others. The answer is complicated by the fact that even individual cells do not constitute equipotential surfaces. Insulating cell coverslides, comprising about 95% of the surface area, adopt a potential very near to that of the space plasma. Only the exposed interconnecting tabs with about 5% of the surface area are at high voltage.

To deal with such a complex potential distribution, we resort to a method which assumes a periodic potential distribution and uses Fourier analysis to determine the electric field distribution adjacent to the surface.[7] The basic conclusion is that the near-field structure associated with such a "checkerboard" potential distribution affects particles only over distances on the order of the e-folding length of the periodic potential which is equal to $d/2\pi$ for quadratic checkers of width d. At larger distances from the surface, charge motions are determined by the average value of the surface potential. For the case of solar cells where 95% of the surface is at zero potential (with respect to space) and where 5% is at a high potential V, the average value of the surface potential becomes 0.05 V. The potential distribution away from such a surface is shown in Fig. 1.

According to this picture, particles are attracted to a checkerboard array by fields which are much smaller than those associated with a unipotential array. In the case of large sheath widths where the collection rate depends upon voltage, Eq. (1) yields much reduced plasma currents. In the case of small sheath widths, where the collection rates are independent of voltage, such a potential pattern will not help to reduce the plasma currents. This conclusion is subject to a more detailed examination of particle trajectories in the neighborhood of the array surface where the near fields affect the trajectories.

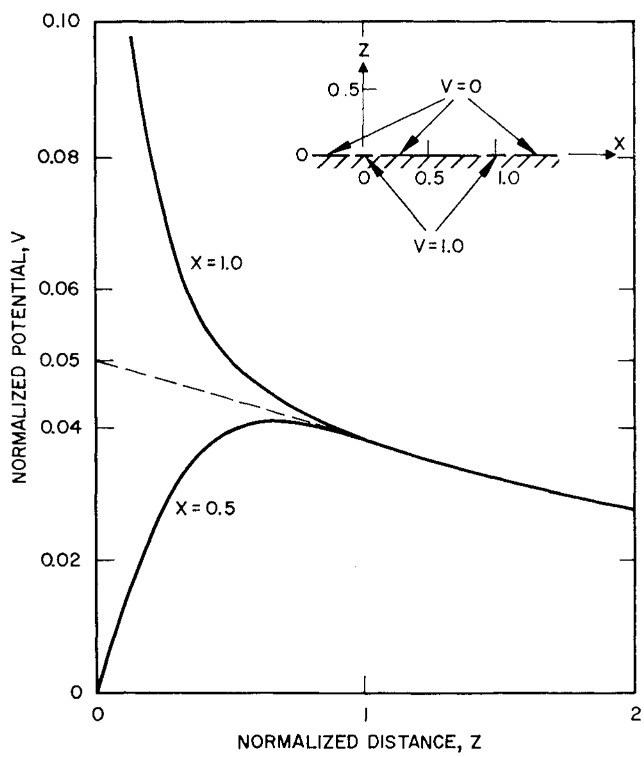

Fig. 1 Potential associated with a surface having a periodically varying potential distribution (5% at potential 1, 95% at potential 0).

Indeed, it is conceivable that a portion of the attracted particles is reflected back locally by insulating surface elements and returns to the plasma.

The above description applies to any panel using conventional cells with coverslides and open tabs. The large-scale array potential distribution can be expected to further reduce the current collection in cases of large sheath widths. However, the current collection rates for large sheath widths are tolerably small in most cases. Therefore, the arrangement of cells and cell blocks is not critical.

Floating and Ion Beam Biased Arrays

In order to derive collection rates for the various situations of interest, still another factor must be considered: A solar array may either float (electrically) with respect to the environmental plasma or be maintained artificially at a biased potential. An array floats when its output is used internally to power the spacecraft electronics. An array becomes biased when an electric propulsion system is activated.

A high-voltage array operating without a source of electrical bias will act as a floating probe and adopt an equilibrium state in which the total current to and from the array becomes zero. Ignoring photoelectric and secondary currents, equilibrium is achieved when ion currents to the more negative array portions equal the electron currents to the more positive portions. In space, the random ion currents are much smaller than the random electron currents. Therefore, when the sheath thickness is small, the array will tend to float predominantly negative with respect to space. When the sheath width is very large, the average potential of the array is important. In this case the array will have only a slightly negative (several kT_e/e) average potential.

If a high-voltage array is used primarily to power ion thrusters, the exhausted ion beam establishes a voltage link between the space plasma and the array. The neutralized ion beam can be considered as a highly conductive plasma bridge that forces the potential of the electron-emitting neutralizer to stay within about 30 v of space potential. To eject ions at space potential requires that they be accelerated from an ion source which is at a high positive potential. Thus, most of the solar array output must be delivered to a terminal at high positive potential, and most of the array will, therefore, be at a positive potential with respect to space.

If the various factors discussed above are incorporated into the loss current relations, reasonably reliable plasma loss estimates can be made. The computed power losses for floating and positively biased arrays are shown in Figs. 2a and 2b. They pertain to a 15 kw array with 95% insulated surface area and include the effects of array velocity (important only for a floating array). It can be concluded that the plasma leakage losses of floating arrays with standard, slide-covered cells remain generally small even for potentials as high as 16 kv. For arrays operating at +2 kv (when ion thrusters are operated), the power losses amount to a maximum of 20% to 30% of the output power in low orbit. During part of each orbit when the array collects on one side only, the losses will be lower by as much as a factor of two. At higher voltages the power losses become larger and, in low orbit, eventually reach the full output power.

Thrust Beam Losses

During the operation of ion thrusters, additional power losses can be expected to occur as a result of charged particle currents flowing from the ion beam to the array. This is not intended to imply that the array intercepts portions of the ion beam, but rather that the difference in potential between beam and array causes space charge-limited flow between the two. The most significant losses are expected to occur during the operation of the main thrust beam. In this case, electrons are drawn from the beam to the array which has a positive potential. The resultant current will only be limited by space charge since typical ion beam neutralizers can supply almost unlimited numbers of electrons. This problem is too complex to be solved analytically. Therefore, a computer program for space charge-limited flow was utilized. The array was approximated by a circular disk at constant potential (representing either the full array potential in the case of a conducting array surface or a reduced "average" potential in the case of a 95% insulating surface). The ion beam was simulated by a circular cone of 15° aperture, and electron extraction was assumed to take place from the entire beam surface. Worst case computations were performed in which the plasma sheath was assumed to be infinitely thick. The calculated electron trajectories indicate that most of the electrons are collected near the outer array edge and not, as might intuitively be expected, on the array sections closest to

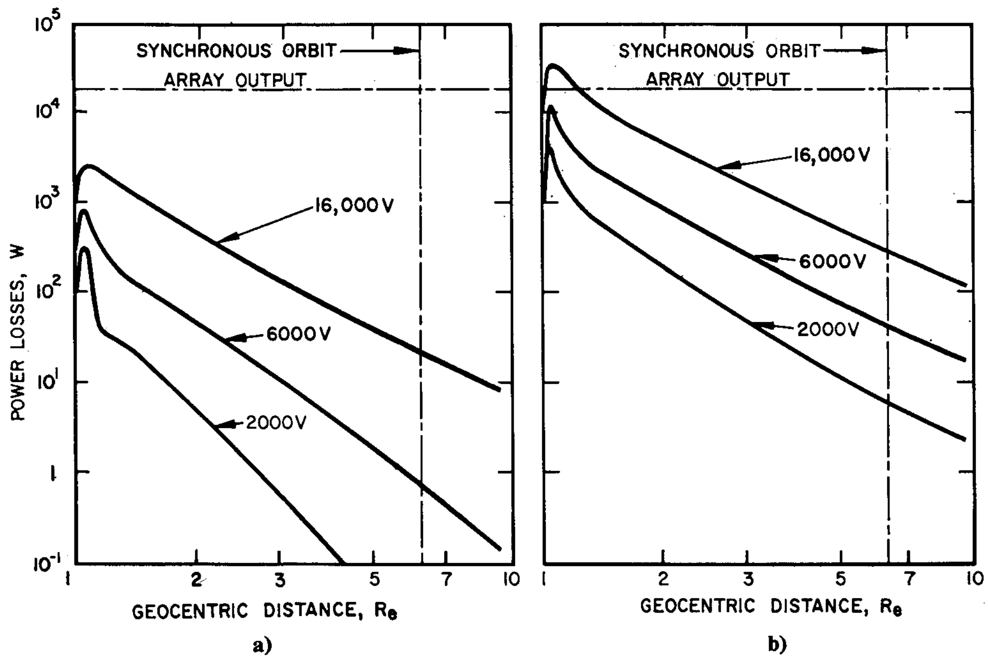

Fig. 2 Power losses of an array, with 95% insulated surface. a) floating array, b) positively biased array.

the ion beam. The power losses resulting from this electron flow pattern can be quite large if the array surface is conductive. The computations show that, for a 15 kw array which delivers its entire output to the ion beam, the losses, which increase with voltage, reach the level of the array power output at a voltage of about 4 kv. With 95% insulating surfaces, the losses remain much lower; at an array voltage of 10 kv they reach only about 10% of the power output.

Reduction of Leakage Current Losses

For missions in which high voltages (on the order of 16 kv) must be supplied at low orbit, the plasma losses with standard cells can be expected to be prohibitively large. Several methods are described below which promise to reduce these losses substantially.

It is evident that an array which is totally enclosed by an insulating layer should not suffer leakage losses. The question is whether inevitable cracks (due to mechanical stresses) and holes (due to micrometeoroid impacts) eventually will lead to pinhole arcs and thereby to gradually increasing losses. Indeed, the possibility of pinhole arcs on high-voltage solar arrays is suggested by laboratory experiments performed by Cole et al.[8] These investigators found that fully insulated solar panels immersed in a plasma of about 10^6 particles/cm^3 suffered from excessive leakage losses when the panel was maintained at a sufficiently high, positive potential (on the order of 1000 v). The losses were caused by large plasma currents passing to the array through tiny pinholes in the insulating coating. These results apply to rather special conditions and more experimentation is needed to determine the feasibility of using full insulation.

A second method is based on the likelihood that pinhole arcs are vapor arcs. The required vapor can be assumed to be generated by impact of accelerated electrons, converging from the plasma boundary to the front edge of the pinhole. This suggests that such an arc can arise only when a large number of plasma electrons are attracted to the pinhole. If neighboring electrodes of a sufficiently high voltage were to compete with the pinhole for electrons, the currents arriving at the pinhole might become too small to sustain the arc. If this hypothesis is correct, pinhole arcs may be prevented by the use of collecting electrodes, suitably distributed over the surface of the array. On arrays with exposed tabs, the tabs themselves should suppress pinhole arcs. In fact, solar panels tested by Sellen failed to show arcs when the tabs were exposed. With this in mind, a method for plasma loss reductions was conceived which also prevents pinhole arcs.

Consider an array on which the tabs are covered by an insulating layer and assume that a conductor ("collector") is attached to the outer surface of this layer. The potential of the collector is chosen just high enough to collect all electrons entering the plasma sheath. The array power losses are then determined by the collector voltage instead of the array voltage. Because several hundred volts should suffice to collect all arriving electrons, power savings of greater than a factor of 10 may be realized.

A third possible method to reduce plasma leakage losses is to surround the array with a biased screen. If, in conjunction with a positively biased array, the screen is biased negatively with respect to space potential, most plasma electrons are reflected before they can slip through the screen mesh. The ratio of reflected to attracted electrons depends upon geometrical factors and upon array and screen voltages. To some degree, it also depends upon trapping of particles in the space between screen and array. Except for this latter effect, the details of this approach have been worked out. Here, it is sufficient to state that a reduction of the losses by an order of magnitude may be achieved. A preliminary design exercise has indicated that suitable screens could be added to large array panels without much additional weight or complexity.

Surface Effects

A number of processes at the surfaces of a high-voltage solar array are of importance to the over-all array characteristics and must be assessed. The most important processes include surface charging of insulating layers which are exposed to the space plasma, sputtering, and propellant condensation.

Surface Charging of Insulators

When an insulating surface is exposed to a plasma, it will tend to accumulate electrical charge until the surface potential attains a value such that the current arriving at the surface equals the current leaving it. If the resulting surface potential differs greatly from the potential of the conductive substrate, the electric fields within the insulator may lead to electrical breakdown or deterioration of the material properties due to electrolytic processes.

The current arriving at an insulating surface is comprised of electrons and ions originating from the equilibrium space plasma, high-energy charged particles associated primarily with the radiation belts, secondary charged particles, and photoelectrons. All of the processes contributing to the total surface current density depend on altitude, spacecraft velocity, and insulator properties. From detailed considerations combining all of these factors, it has been concluded that a perfectly insulating surface will attain a potential which is very close to that of the plasma potential.

In order to determine the potential attained by an exposed insulating surface which is not perfectly insulated from the conducting substrate, the modes of current leakage between the surface and the substrate must be considered. The possible modes are 1) bulk conduction, 2) photoconductivity (not present in materials such as Kapton or fused silica), 3) bombardment-induced conductivity (BIC), and 4) exchange of charged particles between the insulating surface and nearby exposed conductors which connect to the substrate. For most insulating materials, the resistivity is so large (10^{17} Ω-cm) that bulk conduction is negligible. Bombardment-induced conductivity refers to the process in which energetic electrons or ions generate electron-hole pairs as they pass through an insulating layer and thereby increase the material conductivity. Many radiation belt particles have sufficient energy to produce this effect. However, a significantly increased conductivity occurs only at high altitudes and only during the short time periods when the energetic particle flux density is at its maximum level. Therefore, BIC does not provide a continuous mode of conduction. Finally, the motion of charged particles between an insulating surface and a nearby exposed conductor has been studied with the aid of a digital computer. The results indicate that only motion from the insulator to the exposed conductor can result in substantial changes in the surface potential (particles leaving the conductor all go into space when the insulator surface potential is only slightly different than the plasma potential). Consideration of the various processes by which particles can be emitted from the insulator surface indicates that only photoelectrons are important for this type of leakage mechanism and then only at high altitudes where the photoelectron current density becomes comparable to that associated with the plasma electrons. In any case, an alteration of the surface potential by this mode of current leakage is only possible for positive portions of the array.

It is concluded that no continuous leakage mode exists. Therefore, for the purposes of electrical breakdown considerations, the potential of the exposed surface of an insulating layer can be considered to be very near to that of the plasma, i.e., nearly the full substrate potential appears across all exposed insulating layers. The resultant electric fields within the insulation and along its surface may lead to electrical breakdown.

Based on existing data, present insulating materials such as Kapton and fused silica are expected to easily support the maximum array voltage of 16 kv. However, it is unknown whether exposure to the space environment reduces the electrical breakdown capability. Should this be the case, some means must be devised to reduce the electrical stress. Increased insulator thickness and, thereby, weight may not be desirable. Other possibilities include use of conductive films or of conductive insulators to effectively short the insulator surface to the substrate. It is expected that conductive films are a better choice, although future experimentation is required.

Sputtering

High external electric fields associated with a HVSA can result in the acceleration of space plasma ions onto the surfaces of the array. This may cause significant damage both due to erosion of the surface and deposition of sputtered material onto other surfaces. Calculations have been performed in which the sputtering of fused silica (a representative insulator) and several metals have been determined as a function of altitude. The results indicate that sputtering rates for fused silica and silver (an easily sputtered metal) have about the same value of 10^{-4} cm/year at the lowest altitudes where O^+ is the dominant sputtering ion. This sputtering rate is sufficient to completely erode the MgF_2 anti-reflection film used with coverslides in approximately three months. At higher altitudes, sputtering quickly becomes negligible due to the decreasing plasma density and average ion mass. Deposition of sputtered material on various array surfaces is inhibited by the fact that the array lies in a single plane. Material can only be deposited onto the array from the central spacecraft; however, if this portion of the spacecraft is maintained near plasma potential, incident ions will not be accelerated to sufficient velocities to cause sputtering. In general, it is expected that sputtering will not be a major problem except for missions involving extended operation at the lowest altitudes.

Propellant Condensation

Propellant condensation is not peculiar to the HVSA; however, the effects caused by condensation may be. These effects include reduction of the resistance to surface electrical breakdown, alternation of secondary and photoemission characteristics of surfaces and increased surface conductivity. The work of Reynolds and Richley indicates that significant condensation of mercury propellant (more than a monolayer) occurs for distances from the sun greater than 2 a.u.[9] For smaller distances, no major effects are expected.

Array Design

This section presents some basic considerations in the design of a HVSA which produces 15 kw (at 2–16 kv) in increments of 1 kv at 0.94 amp at the end of five years in synchronous orbit. The discussion presented in the previous sections suggests that a design similar to that of conventional low-voltage arrays is permissible for most missions except those involving operation at the highest voltages in the lowest regions of the ionosphere. The following considerations support this suggestion. Attention is given to array sizing and performance, material design, configuration, and reliability.

Array Sizing and Performance

The major factors in determining the over-all size of an array necessary to satisfy the end of life power requirements are the thermal characteristics, the degree of radiation degradation of solar cell performance, and the reliability. These factors are discussed for an array which utilizes 2 × 2 cm 10 ohm-cm silicon solar cells. With respect to thermal properties, a conventional array design utilizing a Kapton substrate and fused silica coverslides was analyzed for altitudes between low Earth orbit and synchronous altitude. At the lowest altitudes, a maximum array temperature of 85° C was obtained; at the highest altitudes, the maximum temperature was 60° C. The minimum temperature of the array at the end of a maximum duration eclipse was found to be −190° C.

Solar cell radiation damage which is common to both high and low-voltage arrays has been analyzed for a circular, orbit raising mission with the results illustrated in Fig. 3. It is important to note that both back and frontside radiation effects have been included; this is important for the thin flexible substrate considered here. The worst case degradation expected for 6 mil solar cells with 6 mil coverslides after five years in orbit is 59%. If the panel were raised directly to synchronous orbit, the degradation would be 30%. The greater degradation associated with orbit raising results from passage through the severe environment in the heart of the Van Allen belts. The degradation decreases as the solar cell and coverslide thickness increase. However, increased thickness leads to a larger array weight. A 6 mil solar cell with a 6 mil coverslide is considered a sound compromise in view of the fact that it yields the lowest array weight while providing sufficient dielectric strength (see below), equal back and frontside radiation protection, and sufficient thickness to render fabrication not unnecessarily difficult.

The reliability of a HVSA is dependent primarily on open circuit and short circuit solar cell failures. Short circuit failures can be minimized by use of a dielectric substrate and by the elimination of current-carrying busses on the array. Open circuit failures are much more severe for high-voltage arrays than for low-voltage arrays because few cells are in parallel. In fact, failures which result in fewer than a certain minimum number of cells in parallel cause the remaining cells in the same row to be back-biased by approximately 40 v. This results in severe power loss and may produce further damage due to localized heating. To prevent this problem, bypass diodes must be placed across each group of cells such that a failure within the group will not cause severe back-biasing. A computerized analysis has been performed to determine the configuration of these groups such that the array power output is reduced by less than one percent at the end of life. The failure rate used in the analysis is 3×10^{-8} hr or 1.3×10^{-3} for a five year mission. This number can be considered accurate only to within one order of magnitude due to a lack of adequate experience with flexible arrays in space. For 14 solar cells in parallel (this number can supply the full design current of 0.94 amp), it has

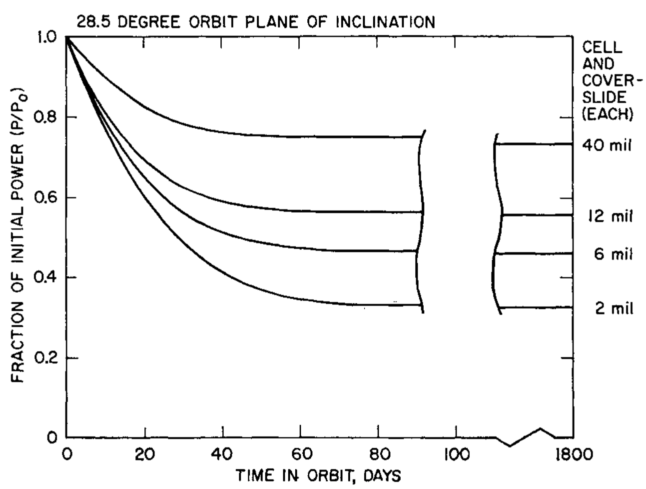

Fig. 3 Fraction of initial power as a function of the time in orbit. (−3σ).

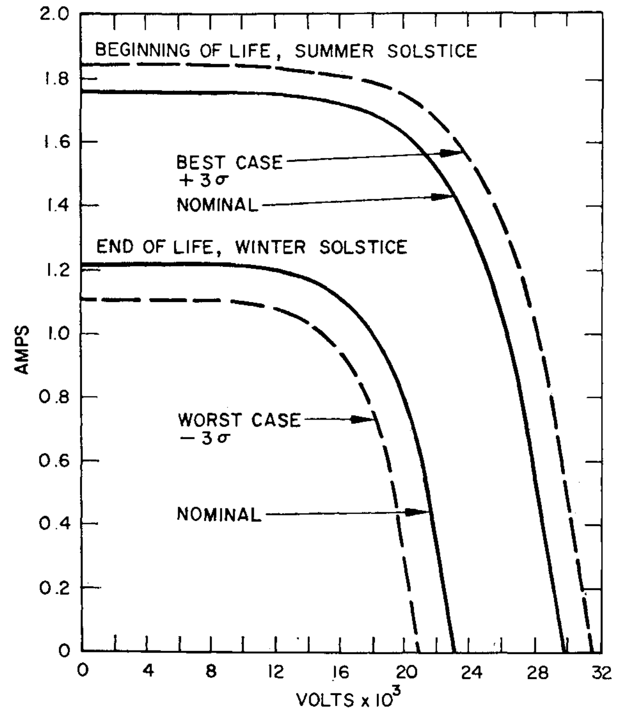

Fig. 4 High-voltage solar array electrical performance.

been found that less than 65 rows of solar cells in series per diode are required to satisfy the failure requirements. The present conceptual design will incorporate one diode for each block of cells consisting of 50 cells in series and 14 cells in parallel.

With the above considerations, it was determined that an array utilizing 985,600 solar cells would be necessary for an orbit raising mission. The predicted performance, illustrated in Fig. 4, includes the effects due to coverslide transmission loss and fabrication losses. The voltage generated by an array of this size during the short period after exit from eclipse can reach 50 kv at open circuit. To protect the array from this temporary over-voltage, one may isolate and short-circuit small voltage blocks during the warm-up period.

Material Design

The design of a HVSA is strongly dependent on the characteristics of materials, particularly with regard to electrical breakdown, outgassing, mechanical strength, and sensitivity to temperature and radiation. Detailed consideration of these factors has led to the following choice of materials for the various areas of application.

Kapton is considered a preferred substrate material because of its high-dielectric strength and high volume and surface resistivities. It also exhibits little temperature dependence over the array operating temperature range (−190° C to +85° C) and a generally superior radiation resistance. The major disadvantage of Kapton is that its absorptivity increases under ultraviolet radiation while its emissivity remains constant. This will result in increased array temperature. Mylar, Nomex (a calendered paper), and Teflon were also considered for this application but were rejected because of one or more inferior properties.

A methyl-phenyl silicone (RTV-655) was chosen as the cell-substrate adhesive because of the requirements for flexibility and operation over wide temperature excursions. Methyl-phenyls exhibit low transition temperatures and high elongation, which reduces stress within joints and the probability of separations. In addition, these materials show only a relatively slight dependence of volume resistivity on temperature. The dielectric strengths of methyl-phenyls are good, ranging from 1500 to 2500 v/mil. Methyl-phenyl, RTV-655, is chosen because it is a clear, transparent substance which permits backside inspection for voids and improved array thermal control through backside emission. Dimethyl silicones, RTV-602 or R63489, were chosen as the cell-coverslide adhesive based upon the successful use of this material for coverslide attachment. Its properties are also suitable for high-voltage design. The major limitation of other adhesives such as polyamine and polyamide epoxies is their rather severe temperature dependence. Both epoxies can be expected to exhibit a factor of 10^6 to 10^8 resistivity change over the operating temperature range.

A review of the dielectric and optical properties of fused silica resulted in its choice as the coverslide material. Possible problems resulting from the effects of surface electrical discharge on the optical properties of quartz are unknown; this area should be subjected to future study. It is expected that with a breakdown strength of 25 kv a 6-mil-thick quartz coverslide can easily withstand the expected electrical stresses associated with a HVSA.

Based upon the problems previously described for a HVSA, it may become necessary to add conductive or semiconductive coatings to the list of materials. These coatings would be used for both coverslides and substrate in order to dissipate surface charge. Furthermore, conductive or semiconductive adhesives may have to be employed for cell-substrate attachment in order to eliminate electrical stresses in the adhesive layers. Finally, metalization and photochemical etching techniques for producing conductive films or grids on the array and encapsulation methods to limit electrical stresses and reduce power losses may have to be analyzed in detail. The material preferred for use in encapsulation is RTV-655 (discussed previously). Consideration was also given to the parylenes which are a new class of coatings formed by a vapor phase polymerization under vacuum conditions. Unless it becomes desirable to coat the entire array, including coverslides (the transmission and degradation properties of the parylenes are expected to be poor), this material would be undesirable due to the extensive masking and film cutting required during fabrication.

Configuration and Fabrication

An array configuration has been chosen which consists of four flexible panels, each with dimensions of 15 × 85 ft. A flexible design is considered superior to the foldout design because: 1) it weighs less, 2) visual inspection is simpler, 3) no electrical jumpers are required (as between individual articulated sections), and 4) there is less susceptibility to Paschen breakdown since foam or honeycomb materials are not required. The choice of four panels results in easier handling and testing than would be possible with fewer but larger panels.

Various panel configurations are possible; however, the most desirable is one in which no busses are mounted on the array. This reduces the possibility of catastrophic electrical breakdown, increases reliability, reduces weight and simplifies fabrication. Each panel is divided into 88 sectors. The sector size (21 in. × 92 in.) is determined by the size of presently available pulsed xenon solar simulators; the sector is the largest unit that would be tested in this manner. Eight sectors are mechanically connected to form an array segment which is one sector long and has the same width as a panel. A segment is the smallest unit which can be replaced following complete fabrication. Any failures prior to launch can be rectified simply by replacing damaged segments. The spacings between active elements of the array are chosen (≅0.6 in.) so that the associated electrical stresses are less than one-tenth of the measured breakdown levels in vacuum. This assures a high degree of dielectric reliability. Two other factors are favorable in this choice: 1) testing at full voltage in air is

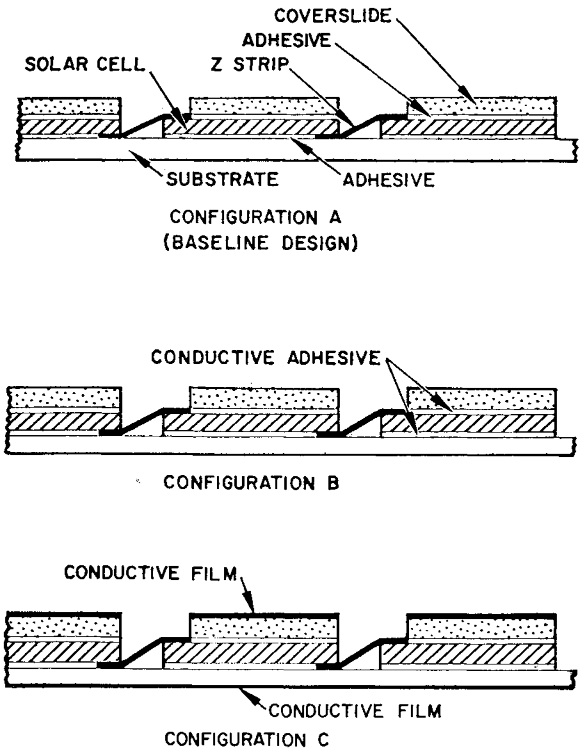

Fig. 5 Detailed dielectric configurations.

permissible and 2) the critical spacing of conductors in fabrication is minimized.

The detailed dielectric configuration is presented in Fig. 5. Configuration A forms the baseline design which is similar to that of conventional low voltage solar arrays. Configuration B employs a conductive adhesive, if found necessary, in order to eliminate electrical stresses across the adhesive. This avoids the danger of discharges at locations of interfacial separations between substrate and adhesive. Configuration C would be used if future experiments demonstrate the need to minimize electrical stresses across all dielectric layers. Here, the outer surfaces of the coverslides and the outer surface of the substrate are covered with conductive films. By connecting these films to the solar cells, the stress across the dielectric is eliminated.

It is expected that most fabrication procedures will conform to those used in conventional flexible array fabrication with emphasis on cleanliness, inspection (to isolate voids and separations), and safety. Safety during fabrication is enhanced by working with small units until final assembly where great care must be exercised. The use of ambient light filtering and pulsed electrical tests can decrease the dangers of HVSA fabrication significantly.

Summary and Conclusions

The results obtained may be summarized as follows. The computed power losses associated with plasma particles are acceptably low throughout space except in the ionosphere. Even there, arrays with standard solar cells (coverslides and open tabs) which are required to produce 2000 v can be operated with losses not exceeding 20 to 30% of their output power. For orbit raising missions, the spacecraft passes through the densest regions of the ionosphere in a matter of days and, for such short periods, losses of the described magnitude may be acceptable. Also, in the ionosphere arrays have not yet suffered any radiation degradation and can deliver their maximum power. For missions where high voltages must be provided over long periods at ionospheric altitudes, several alternative methods are discussed which can be used to lower plasma losses to acceptable levels.

An investigation of dielectric array surfaces has disclosed that all insulating surfaces adopt a potential very near that of the space plasma. This leads to the conclusion that large voltage gradients exist across most insulating layers. Electrical breakdown data collected for dielectric materials of interest suggest that comparatively small layer thicknesses (about 6 mils for quartz and 3 to 4 mils for Kapton) should suffice to withstand the maximum anticipated dielectric stresses. This is based on the assumption that all insulating layers are free of large voids, have clean surfaces, and that breakdown does not occur through micrometeroid pinholes. A further assumption is that the dielectric strength does not deteriorate in the presence of plasma and under energetic particle radiation. Both assumptions require verification through suitable experimentation.

Impact of fast particles also leads to surface erosion and deterioration of solar cell performance. From known sputtering rates for oxygen, nitrogen and hydrogen on quartz, one can conclude that, except in the ionosphere, the erosion rates should be much less than 10^4 atomic layers per year. This is sufficiently small so as not to adversely affect the optical quality of quartz coverslides for typical missions. Damage caused to solar cells by energetic radiation belt particles is considered to be much more serious. Radiation damage computations for an ion-thrusted, orbit raising maneuver predict a deterioration of 30 to 40% by the time the spacecraft reaches synchronous orbit, and that less than 50% of the original power output remains at the end of five years. These results apply equally well to low-voltage solar arrays.

Preliminary design studies have led to the conclusion that a HVSA can be built along rather conventional lines. The layout of cells can be chosen according to circuit needs and is little affected by environmental factors. Active elements at different potentials which border each other must be kept at a safe distance (about 0.6 in.). Because only few cells are connected in parallel, open circuit failures are more serious than for low-voltage arrays and bypass diodes must be incorporated. To facilitate manufacture and handling, and to minimize electrical shock hazards, a HVSA may be composed of smaller units. These "sectors," with output voltages not exceeding a few hundred volts, would be fabricated separately and interconnected with other sectors just prior to launch.

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