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The Role of Potential Barrier Formation in Spacecraft Charging

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THE ROLE OF POTENTIAL BARRIER FORMATION IN SPACECRAFT CHARGING

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ABSTRACT

The role of potential barrier formation in spacecraft charging at geosynchronous orbit is discussed. The evidence for, and understanding of, spacecraft charging at geosynchronous orbit and its hazards to spacecraft operation in the early 1970's are summarized. Theoretical and experimental advances which have changed the basic understanding of the role of barrier formation in charging phenomenology are described. Potential barriers are found to play a fundamental role in the dynamics of spacecraft charging. The consequences for structural and differential charging, and for discharging, are described.

I. INTRODUCTION

In 1976, the U.S. Air Force and NASA established an interdependency program known as the Spacecraft Charging Technology Investigation (Ref. 1). This program was initiated in response to a new hazard to spacecraft operation. A growing body of evidence suggested that the anomalous behavior (largely logic upsets) of a number of geosynchronous spacecraft was being caused by arc discharges. These discharges were caused by electrostatic charging of spacecraft surfaces by naturally occurring hot plasmas. This hazard to spacecraft operation was not discovered until the 1970's--more than a decade after the space program began. There are two key reasons. First, the presence of plasmas hot enough to cause charging of spacecraft surfaces to negative kilovolt potentials was not demonstrated until it was revealed by data from the ATS-5 spacecraft, (Refs. 2-4) launched into geosynchronous orbit in 1969. Second, it was not until the early 1970's that geosynchronous spacecraft began to exhibit anomalous behavior. These spacecraft, developed in the late 1960's, were the first of a new generation of satellites whose designs incorporated computer-level logic in electronics subsystems. This sensitive logic was more susceptible to upset by noise bursts than its predecessors (e.g., latching relays) had been.

The evidence linking electrostatic charging of spacecraft by naturallyoccurring hot plasmas to anomalous switching behavior was indirect. Data from the University of California at San Diego (UCSD) Auroral Particles Experiment on ATS-5 and ATS-6 (launched in 1974) indicated (Refs. 3,4) that the appearance of hot plasma clouds was associated with geomagnetic activity. It also indicated that a spacecraft encounter with such hot plasma was most probable in the midnight-to-dawn local time quadrant. During such encounters the spacecraft structures were observed to charge to negative kilovolt potentials (Refs. 4-6) in eclipse, and to less negative potentials (Refs. 4,5,7) in sunlight. None of the spacecraft which exhibited anomalous behavior had instruments capable of identifying the plasma environment or the structure potentials. However, it was found that the anomalies occurred preferentially in the midnight-to-dawn local time quadrant (Refs. 8,9) and were correlated with geomagnetic activity (Refs. 8,10). Furthermore, laboratory studies indicated that spacecraft surface materials exposed to kilovolt electron beams exhibited energetic arc discharges (Refs. 8,11-13).

This evidence, in conjunction with simple models of the charging mechanisms, (Refs. 4,8,14) was sufficient to stimulate the establishment of research programs in both the USA and Europe. These programs were designed to obtain a detailed understanding of the phenomena, and to provide means of eliminating their deleterious effects on both satellite performance and scientific measurements. Two interrelated programs were established in the USA. One was an Air Force flight measurement program known as SCATHA (Refs. 9,15) (Spacecraft Charging at High Altitudes) whose purpose was to develop and operate a neargeosynchronous orbiting satellite which was instrumented to obtain data on all aspects of the charging phenomena. The SCATHA satellite was to be capable of determining the environment and the charge state of its structure and some insulating surfaces, and of detecting discharges. It was also equipped with active potential control devices and detectors to evaluate surface contamination. Data from this satellite was to provide verification and improvement of design tools and criteria being developed under the second program, a broad research and technology program established as a joint AF-NASA investigation. This program, the Spacecraft Charging Technology Investigation, (Ref. 1) has the ultimate objective of providing design criteria and test methods to ensure control of spacecraft charging effects. The program utilizes both ground test and space flight data in conjunction with model development and verification.

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The various investigations of spacecraft charging have led to theoretical and experimental advances which have produced basic changes in understanding of the dominant charging and discharging mechanisms. This paper focuses on the concept of potential barrier formation which is critical to the understanding of spacecraft charging phenomenology. The potential barriers in question are due to the presence of differentially charged surfaces rather than to space charges. Their presence under spacecraft charging conditions was anticipated (Ref. 16), but realization of their fundamental importance is more recent.

II. EARLY SPACECRAFT CHARGING MODEL

The conceptual model of spacecraft charging phenomenology in the early 1970's was essentially that proposed by investigators such as Fredericks and Scarf (Ref. 8). In this treatment, potential barriers played no important role. It had been known for years that a spacecraft immersed in an ambient plasma will come into equilibrium with the plasma by acquiring surface charges such that the net current to each surface (or surface element, for insulators) is zero (Ref. 17). The net current is just the algebraic sum of currents due to environmental fluxes, secondary and backscattered electrons, and photoelectrons emitted from sunlit surfaces (Refs. 4,17). In his early papers, DeForest (Refs. 4,5) distinguished between "total" spacecraft charging and "differential" charging. The former referred to charging of the spacecraft structure and will herein be referred to as "structural" charging. Differential charging referred to the development of different potentials on various spacecraft surfaces. At first these were regarded as essentially independent processes. ATS-5 and ATS-6 were observed to charge to large negative potentials (-10 kV) in eclipse (Refs. 4-6) and to less negative potentials (a few hundred volts, typically) in daylight (Refs. 4,5,7) during encounters with substorm plasmas. This suggested that shaded insulating surfaces could become charged to large negative potentials while sunlit surfaces were held at much smaller negative potentials by photoemission, (Refs. 1,8) i.e., that severe differential charging (order of 10 kV potential differences) could occur. This situation is illustrated schematically in Fig. 1. Such differential charging would result in large electric fields in thin insulating surface materials, or between different spacecraft surfaces. Such large fields present hazards to spacecraft because they compromise scientific measurements and can cause arc discharges. Energy from discharges coupled into spacecraft structures or wiring could then disrupt sensitive logic and result in anomalous spacecraft behavior.

Laboratory experiments, both those applying voltages in air, (Ref. 8) and those in which typical spacecraft surface materials were irradiated with monoenergetic 10-20 keV electron beams (Refs. 11-13) indicated that such materials did exhibit arc discharges. The discharges were energetic and appeared to remove charge from large areas of dielectric surfaces (Refs. 13,18,19). This was of particular concern because the material samples tested were generally much smaller in area than typical thermal blanket or solar array cover slides used on spacecraft. In addition, the discharges caused material damage, raising the possibility of long-term degradation of thermal control surfaces which could adversely affect mission life.

III. THE ROLE OF POTENTIAL BARRIERS

Potential barrier formation did not figure prominently in the spacecraft charging scenario just described. The formation of such barriers around differentially charged spacecraft was suggested by Fahleson (Ref. 16) in 1972. The existence of such barriers was inferred from ATS-6 data by 1976 (Refs. 22,23). However, the fundamental role played by these barriers in spacecraft charging response was not realized until later.

Fahleson (Ref. 16) concluded that the sunlit and shaded sides of a spacecraft cannot charge independently to equilibrium because plasma Debye lengths are large in the region of the magnetosphere near geosynchronous orbit, and because emitted photoelectrons and secondary electrons are low in energy. Even in eclipse, materials with different secondary electron emission characteristics will influence one another's charging. This is because the negatively charged shaded (or low yield, in the eclipse case) materials will cause the formation of potential barriers which will prevent the escape of low energy photo and secondary electrons. This results in all spacecraft surfaces acquiring negative potentials. Recent work (Refs. 20,21) has shown that structural and differential charging are frequently intimately connected. Indeed, the sequence of differential charging and potential barrier formation followed by structural charging plays a fundamental role in the charging response of spacecraft with insulating surfaces. For present purposes, this sequence of events will be referred to as "barrier dominated" charging.

When multidimensional charging simulation codes became available, Fahleson's conclusions were confirmed computationally (Refs. 24-26). Simulations of charging response using the NASA Charging Analyzer Program (NASCAP) (Refs. 27,28) indicated that the charging response of combined metal-insulator systems was strongly influenced by potential barrier formation (Refs. 20,29). Time dependent simulations also provide the clue to identification of barrier-dominated charging processes. Differential charging is generally a relatively slow process. It is the result of different net currents to various spacecraft surfaces charging the effective capacitor between a spacecraft's surfaces and its structure. By contrast structural charging on eclipse entry or exit charges the effective capacitor formed by the spacecraft as a whole and the plasma at infinity, and occurs quite rapidly. This observation had been made by DeForest (Refs. 4,5) who found that absolute charging of the ATS-5 structure occurred very quickly ($\lesssim$1 min.), while differential charging features persisted for tens of minutes. Because potential barrier formation is a consequence of differential charging, barrier-dominated charging occurs slowly (tens of minutes, typically) lagging the changes in the environment which cause it. Thus it can be distinguished from charging in which the structure potential follows environment changes by its temporal characteristics (Ref. 21).

Reexamination of data from ATS-5 and ATS-6 in light of the potential barrier formation concept reveals a number of important facts. First, it explains why the thermionic electron emitter on ATS-5 was unable to maintain the spacecraft structure near space potential in eclipse (Refs. 30-32). Differential charging and consequent potential barrier formation were preventing electrons emitted by the hot-wire filament from escaping. This interpretation was consistent with laboratory results showing that emission from the filament could be suppressed by differential charging of nearby surfaces (Ref. 33).

A second conclusion from the ATS data was that all daylight charging events were dominated by differential charging and consequent barrier formation. In contrast to eclipse charging response, which occurrs on a timescale of less than a minute, daylight charging requires tens of minutes, and is accompanied by evidence of differential charging (Refs. 20,21). This is illustrated by the data from the UCSD Auroral Particles Detectors on ATS-6 shown in Figs. 2 and 3. Fig. 2 shows data from day 91 of 1975 (April 1, 1975), when an injection of hot plasma occurred while the spacecraft was in eclipse. Particle data for this event are shown in spectrogram format (Ref. 36) in Fig. 2(a). This is an energy versus time plot for electrons (top) and ions (bottom) with count rate of particles arriving at the detector indicated by intensity, per the grey scale to the right of the plot. In general, low count rates result in dark areas, and high rates in bright ones. On day 91 of 1975, ATS-6 entered eclipse at 0549 UT (universal time). This is reflected in the particle data by the reduction in count rate of low energy electrons at that time, a common feature in the ATS-6 data (Ref. 37). The injection event occurred at about 0625, and the spacecraft responded by charging quickly to about -2000V, as indicated by the change in the ion spectrum. The bright band of ions represents low energy ions accelerated through the spacecraft's potential. The time history of the structure potential during this event is shown on a linear scale in Fig. 2(b). The spacecraft potential changed from near zero to about -2000V within one minute.

In contrast to eclipse charging, daylight charging events are notably slow, as is illustrated by the data of Fig. 3 for day 203 of 1974 (July 22, 1974). Fig. 3 (a) shows the data in spectrogram format. An injection occurred at 0740 UT. The boundary of the bright band of low energy electrons, indicating the height of the potential barrier (Refs. 21-23,38), increases in energy, and the spacecraft potential goes negative to about -400V. The structural charging, however, is not rapid. The -400V potential is not reached until 0840, although the electron "temperature" is relatively high and roughly constant during the charge up period (Ref. 21). Figs. 3(b) and (c) show the barrier height and structure potential during this event. Fig. 3(b) shows that the barrier height increased to about 50V before structural charging began; the barrier height rises to about 100-150V and is maintained at that level during most of the event. The structure potential becomes negative relatively slowly, reaching -400V after some 30 to 40 minutes of charging. The fall of the structure potential in the 0900-1000 period follows the cooling of the environment (Refs. 21,39).

Thus, in eclipse, rapid structural charging occurs in response to an injection. By contrast, in sunlight barrier formation and growth precede structural charging, and thus the charging rate is slow. Reviews of the ATS-5 and ATS-6 data have indicated that for these two craft daylight charging events were always associated with differential charging and barrier formation (Refs. 20,21), and were therefore barrier dominated charging events.

The potential barrier formation model also provides an explanation for the observation that ATS-6 charged to much larger potentials in sunlight than did ATS-5, (Refs. 4,5,7,20 21) while in eclipse the two spacecraft exhibited comparable charging response (Refs. 20,21,33-35). The main reason for this lay in the ease with which potential barriers could form and suppress photoemission from sunlit surfaces. A rapidly spinning spacecraft like ATS-5 (76 rpm) can only develop differential charges on completely shaded surfaces (e.g., ends or cavities) because the time required for substantial differential charging is long compared to the spin period. A three-axis stabilized craft such as ATS-6 has a larger proportion of its surface continuously shaded and therefore able to develop differential charges. Thus one expects three-axis stabilized spacecraft to develop potential barriers more easily than spinners. Their structures will charge more quickly in a given environment and reach larger negative potentials in a given time.

A NASCAP study of spacecraft configuration effects on charging response (Ref. 20) found that spinning spacecraft were predicted to charge much more slowly than three-axis stabilized ones (Fig. 4). It also predicted that compact spacecraft should charge more slowly than extended ones (Fig. 5). As can be seen from Fig. 4, the three-axis stabilized object's structure begins to charge sooner than that of the spinning object. After 30 minutes of simulated charging, the structure potential in the three-axis case is about three times that in the spinning case. The behavior of the shaded insulation in the two cases is notable. During the initial charging phase (before structural charging begins), dark insulation in the two cases charges at the same rate. The dark insulation on the spinner develops a larger differential potential before structural charging begins, and maintains this larger differential potential. At any given time in the simulation after the structural charging in the three-axis case begins, the spinner has a somewhat larger differential potential, even though its structure potential is less. Also, at any given value of structure potential, the differential charging on the spinner is dramatically larger. Thus the structure potential of a spacecraft is not, of itself, a good indicator of the amount of differential charging. The differential potential for a given structure potential is strongly dependent on spacecraft configuration, and, in particular, upon the amount of differential charging of shaded insulation required to cause formation of photoelectron-suppressing barriers. A small patch of shaded insulation on an otherwise conducting spacecraft could develop very large differential potentials before any structural charging would be observed.

Equipotential contours around three-axis stabilized and spinning objects after 11 minutes of charging are shown in Figs. 6 and 7, respectively. In these figures, ϕ_S is the structure potential, ϕ_{DI} is the potential of dark insulating cells, and ϕ_{SI} is the potential of a sunlit insulating surface cell near the metal belly band. The potential of sunlit insulating cells on these objects varies somewhat with position on the objects because of local variations in the barrier fields (all surface cells in these simulations had the same secondary and the photoyield properties). In general, the sunlit cells were somewhat more positive than the structure. The values of ϕ_{SI} given in Figs. 6 and 7 indicate the potentials of the most positive surface cells.

Structural charging response to eclipse entry and exit, and to plasma injections during eclipse is rapid (≲1 min.) and tracks the changes in environment. In general, this charging response occurs so quickly that differential potentials, if any, are maintained during the transient (Refs. 4,5,31,40). However over longer times (tens of minutes), differential potentials develop in eclipse and can dominate the long-term eclipse charging response (Refs. 21,40). Differential potentials and consequent barrier formation in eclipse result from the presence of spacecraft surface materials having different secondary electron yields. In this case, it is secondary rather than photoelectrons which are trapped by the barriers. Simulations of daylight and long-term eclipse charging response have indicated (Refs. 20,40-42) that differential potentials can develop in which the dielectric is more positive than its underlying substrate.

Formation of potential barriers also serves to prevent the development of the dielectric-negative differential potentials of 10 to 20 kilovolts which were originally envisioned. Instead, differential potentials are typically expected to be (Ref. 43) -2 to -5 kV. An exception to this rule occurs if a surface is weakly capacitatively coupled to the structure and/or physically small. The weak coupling permits rapid differential charging, and if the surface is small, its charging will not cause barrier formation (except in unusual cases). An example of such a surface is the tip of a dielectric boom, or a small piece of insulation on a dominantly conductive spacecraft.

Many of the features of barrier-dominated charging can be seen by considering the charging response of a model spacecraft such as shown in Fig. 8 (from Ref. 40). This figure depicts a NASCAP model of a three-axis stabilized spacecraft with a central body and extended solar arrays. In addition to various thermal control materials and antennae, the model includes a weakly capacitative coupled probe with an aluminum tip. Fig. 9 shows the predicted charging response of the model satellite exposed to an isotropic single Maxwellian environment having $kT_e = 8.0$ keV, $kT_i = 21.0$ keV, $n_e = 2.1$ cm^{-3}, $n_i = 0.7$ cm^{-3} in sunlight and eclipse. In the simulation, the model was subjected to the hot plasma environment for 12 minutes (720 sec) in sunlight. The sun was then "turned off" to simulate eclipse entry and the response followed for 12 minutes more.

Note that structure (ground) charging does not commence immediately, but only after some differential charging of shaded insulation has occurred. The solar array cover slides gradually become positive with respect to the interconnects (held at 25V above structure in sunlight, grounded to structure in eclipse). Upon eclipse entry the potential of the entire spacecraft drops rapidly while differential potentials are maintained. Then differential charging resumes. Note that the solar array coverslips become several hundred volts positive with respect to the interconnects. With the exception of the weakly coupled probe, the dielectrics which are negative with respect to the structure have several kilovolt differential potentials. The probe has a differential potential about twice as large as those of the body mounted dielectrics.

Realization of the dominant role of potential barriers in spacecraft charging response, and of the consequences for the magnitudes and polarities of probable differential potentials has forced a revision of expected discharge mechanisms (Ref. 41). The spectacular "big bang" discharges which swept charge from large areas of dielectric surfaces require larger differential potentials than are now expected to occur (Refs. 41-46). Yet space data indicates that discharges do occur (Refs. 47-49) and anomalies persist. Several discharge mechanisms have been proposed which do not require large differential potentials. These include discharges due to internal charge distributions in materials, (Refs. 19,50) and field emission from metals near dielectrics more positive than they (Ref. 51). Discharges with low surface voltages have been observed experimentally in tests using multiple and distributed energy beams (Refs. 52,53). It has been observed experimentally that spacecraft models in test facilities exhibit discharges more frequently under exposure to electron beams when they are electrically floating than when they are grounded, even if the "grounding" is through a large resistance (Refs. 54,55) (>10^6 ohms). The mechanism for such discharges is not presently understood. However, they evidently release negative charge from the model spacecraft to the environment, as is evidenced by sudden changes in the floating model structure potential (Ref. 55).

While the discharges observed under low differential potential conditions are much less energetic than the "big bangs" observed earlier, and appear to be localized, they do eject negative charge. If negative charge emitted by an arc discharge escapes from a spacecraft, the spacecraft must respond by changing its potential. Because discharges are rapid, the entire spacecraft will change potential. If the discharge is localized, the distribution of potentials on the spacecraft should be essentially unaffected. Thus a rapid return to the pre-discharge potential would be expected when the discharge extinguishes. Such a response to discharges should be observable on orbit with instrumentation capable of following spacecraft potential changes on a timescale of 10's to 100's of nanoseconds. This type of response has been observed in ground tests of a satellite model, (Ref. 55) and proposed as a model for spacecraft discharge response (Ref. 40).

The dominance of charging response by barrier formation also has important implications for active spacecraft potential control. Because of it, devices which emit unneutralized charged particle beams (e.g., electrons) are not suitable for active control applications unless all spacecraft surfaces are conducting (Ref. 31). Activation of such a device will result in a rapid change in spacecraft potential. However, differential charging of insulating surfaces will then occur, causing barrier formation. Emission of low energy particles will be suppressed, as occurred in the ATS-5 active control tests (Refs. 30-34). High energy emitted particles may escape, but their emission could result in the buildup of very large differential potentials. This is likely to present a more serious hazard than natural charging. On the other hand, devices which emit neutral plasmas or neutralized beams (i.e., ion engines) have been found to maintain spacecraft potential near plasma ground, (Refs. 30-33) and to suppress differential charging (Refs. 32,38, 56).

IV. SPACECRAFT CHARGING WITH POTENTIAL BARRIERS

The present view of spacecraft charging response in the presence of hot substorm plasmas is that it occurs in a sequence of steps. In sunlight the sequence can be described as differential charging of shaded surfaces leading to general barrier-dominated charging. In eclipse there are two possible sequences. If the substorm plasma is hot enough to charge all surface materials negative, the sequence is total charging, followed by the differential charging of surfaces having different secondary emission yields which leads to barrier--dominated charging. If the plasma is hot enough to charge some surfaces (low yield surfaces) but not others (high yield surfaces), the sequence is the same as for sunlight charging, i.e., differential charging of low yield surfaces leading to barrier-dominated charging of the whole spacecraft. If the spacecraft's surfaces are all conducting (and electrically connected), only total charging can occur. Because photoelectron current densities are generally much larger than plasma current densities, a sunlit conducting spacecraft is generally not expected to charge substantially. In eclipse, a conducting spacecraft, if it charges, will do so rapidly.

When the spacecraft potential is tracking environment changes, it does so rapidly, on timescales of a minute or less, because the capacitor (consisting of the spacecraft as a whole and the neutral plasma at "infinity") being charged is relatively small. The timescales for differential and therefore barrier-dominated charging depend on the capacitances between various spacecraft surfaces. These capacitances are generally much larger than that of the spacecraft to infinity, and consequently the timescales for barrier-dominated charging are much longer. Typically, barrier-dominated charging requires tens of minutes. This type of charging is also configuration dependent. The amount of differential charging required to form the barrier depends upon the relative areas and locations of the surfaces whose charging is causing barrier formation and those whose photoelectron or secondary electron emission is to be suppressed by the barrier. The required barrier height also depends upon the energy and density of emitted particles to be suppressed.

Because differential charging generally leads to barrier-dominated charging, differential potentials of large area insulating surfaces are generally limited to a few kilovolts negative. Differential potentials with insulating surfaces 0.5-2 kV positive are also expected. Larger negative differential potentials and strong electric fields can develop around small area surfaces which are isolated and/or weakly capacitatively coupled, such as the tip of the dielectric boom discussed earlier. Dielectric booms can, however, cause barrier-dominated charging if they are a prominent feature of the spacecraft's geometry. This was found to be the case in simulations of the charging response of the SCATHA spacecraft (Ref. 57) with its large booms.

The differential potentials developed in barrier-dominated charging are not generally large enough to cause energetic discharges which clear charge from large areas of insulation. A multitude of lower energy, localized discharges is seen as far more probable than a large discharge. This idea is consistent with the observation that spacecraft anomalies are generally attributable to upsets in sensitive computer level logic and with flight data from discharge occurrence monitors. A profusion of "big bangs" could be expected to have more dramatic results than low level logic upsets. Very energetic discharges are expected to be very rare.

Improved understanding of the charging process provides a basis for improved design of geosynchronous spacecraft. In addition to such measures as careful grounding, shielding and filtering of critical circuits which reduce chances of logic upsets, it is now possible to select materials and geometries which minimize the probability of arc discharges. Because barrier-dominated charging depends upon both geometry and material properties, and most spacecraft are geometrically complex and have a variety of surface materials, a sophisticated analysis is required. While each particular design is unique, some general recommendations can be made based on previous NASCAP studies (e.g., refs. 20, 40, 41, 57). Dielectric booms and cavities with insulating surfaces should be avoided. Electric field configurations near despun portions of spinning spacecraft should be examined closely. The most conductive materials available should be employed. Differential charging in eclipse can be reduced by choosing materials having similar secondary yield characteristics. If active potential control is desired for a satellite with insulating surfaces, a device which emits a neutral plasma or a neutralized beam should be employed. If a spacecraft is to be designed with all conducting surfaces, special attention should be paid to ensuring that no small areas are overlooked.

The only way to eliminate surface charging completely is to ensure that all spacecraft surfaces are conducting and grounded together, and to employ active potential control. Even this cannot guarantee that discharges will not occur if the surfaces are made conductive by application of thin conductive coatings to high resistivity insulation. It has been suggested (Ref. 58) that in this case, charge buildup in the underlying insulation due to higher energy (hundreds of keV) radiation which can penetrate the conductive coating may result in discharges.

Data from SCATHA, in addition to providing much valuable information about the natural environment, have confirmed the importance of barrier-dominated charging, and provided improved understanding of both this mechanism and its implications for active spacecraft potential control.

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Despite the acquired understanding of barrier-dominated charging and its consequences for realizable differential potentials across insulation, the precise nature of the discharges remains to be determined. They are certainly not, in general, the very energetic arcs, clearing charge from large areas of insulation, that were originally proposed. Analytical and experimental efforts to understand and characterize discharges, and to provide useful engineering descriptions of the discharges and their coupling into systems, continue.

V. CONCLUSIONS

A profound change in understanding of the way in which spacecraft charge in geosynchronous substorm environments has occurred. It has been realized that structural and differential charging are not independent, but are intimately connected. The sudden dramatic shifts in structure potential observed at eclipse entry and exit, and in response to injections of hot plasma during eclipse do not indicate the magnitude of differential charging. All daylight charging and some long-term eclipse charging is of the type described here as barrier-dominated. Shaded or low yield surfaces charge negatively. This results in the formation of vacuum potential barriers which suppress emission of photoelectrons and secondary electrons, which causes the whole spacecraft to charge negatively. This process, which is configuration and material dependent, generally limits the magnitude of insulator-negative differential charging to values substantially lower than had originally been supposed, and allows the possibility of insulator-positive differential charging. This change in understanding of probable charging levels and polarities has forced a revision of proposed discharge mechanisms and characteristics. Discharges are now believed to be less energetic and more localized than had been supposed. The realization that the spacecraft must change its potential if electrons are emitted in a discharge has also suggested a quenching mechanism, i.e., when the structure is driven positive, electron emission will cease. Efforts to understand the precise nature of charging-induced discharges, and to determine the best way of characterizing them in engineering terms are still underway.

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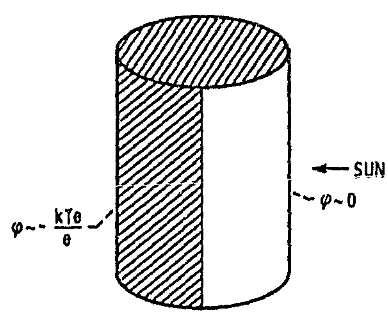
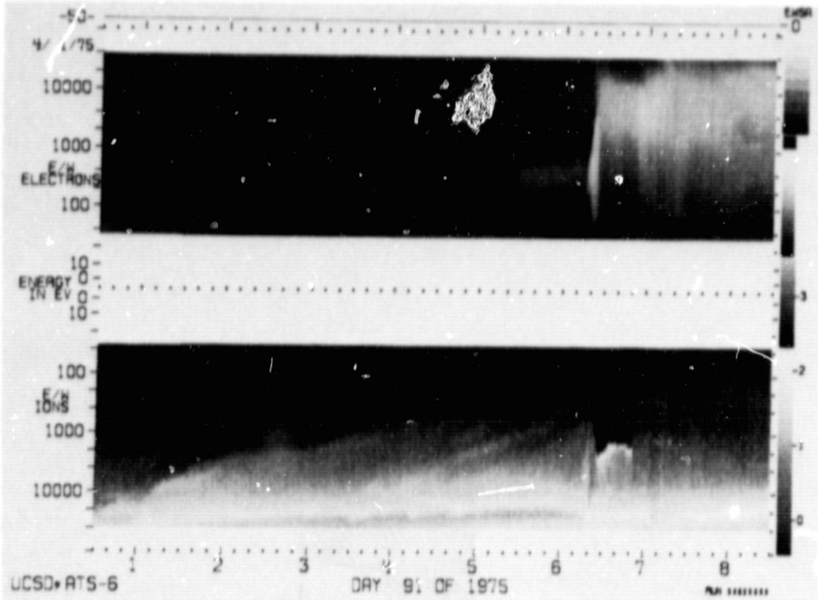
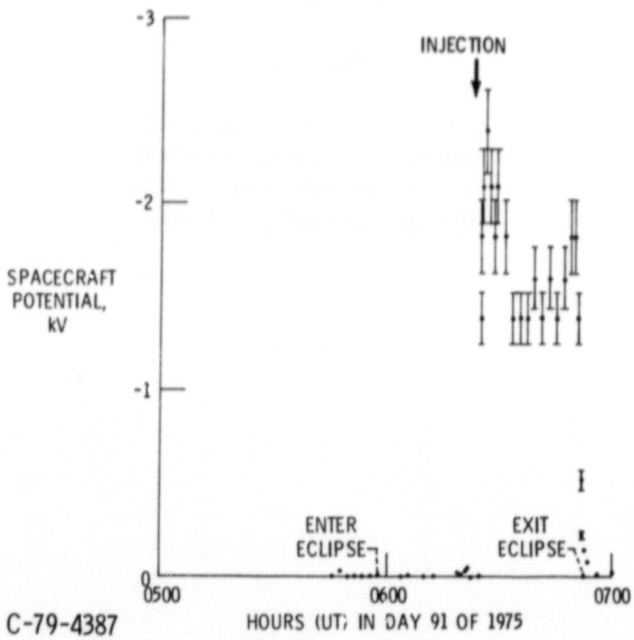


Figure 1. - Conceptual model of spacecraft charging assuming that shaded and sunlit surfaces charge independently (3-axis stabilized).



(a) ATS-6 spectrogram, day 91 of 1975: injection during eclipse.



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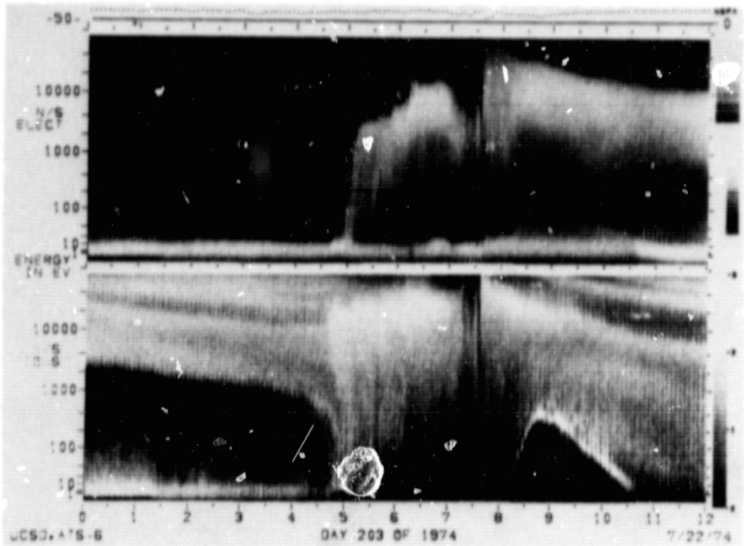
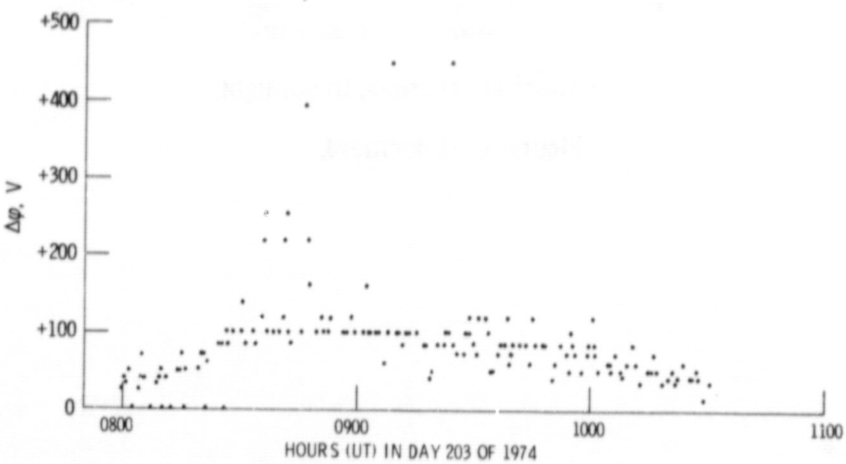
(b) ATS-6 potential: response to injection during eclipse.

Figure 2.



(a) ATS-6 spectrogram: daylight charging.



(b) ATS-6 potential barrier.

Figure 3.

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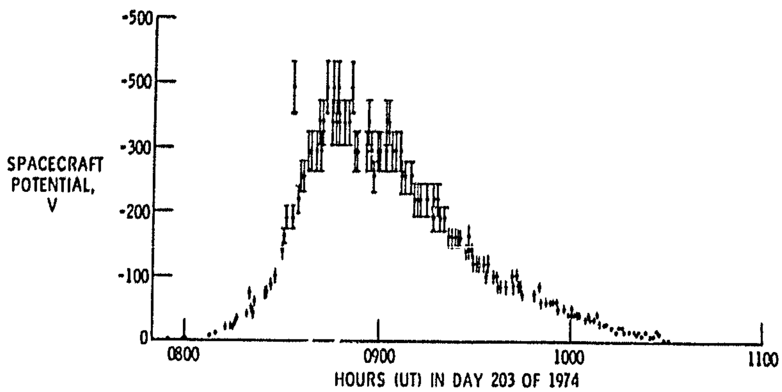


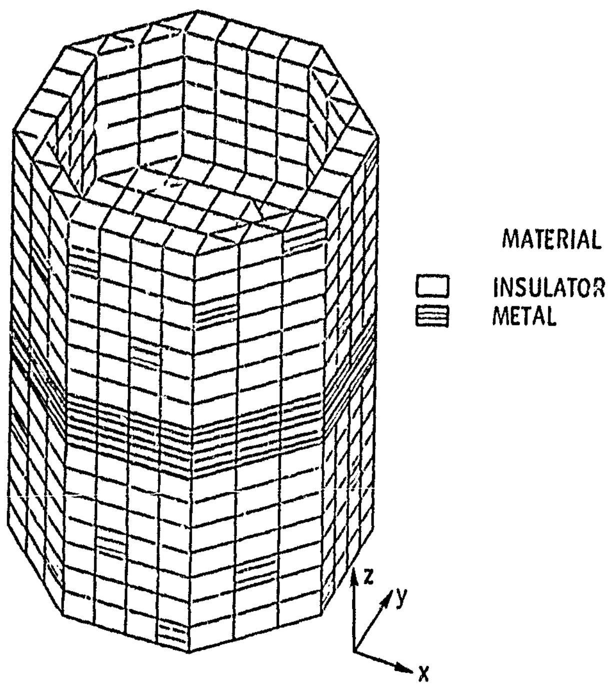
(c) ATS-6 potential: charging in sunlight.

Figure 3. - Concluded.

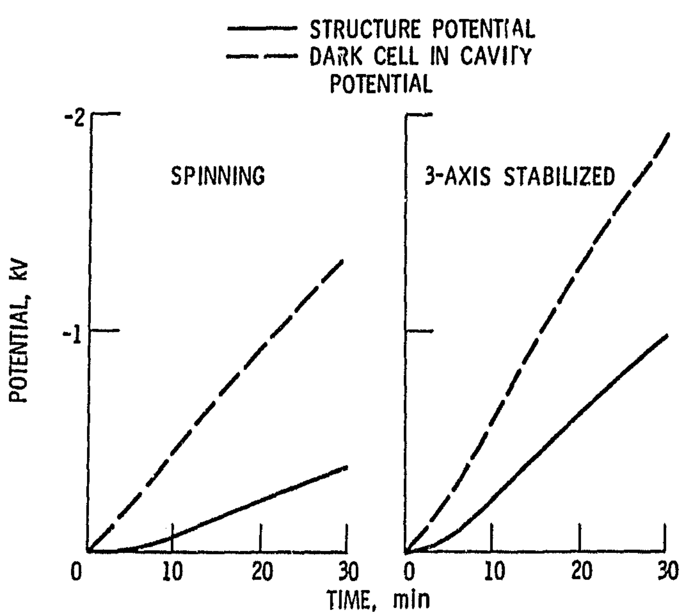
DESCRIPTION

GEOMETRY: OCTAGON WITH END CAVITIES, RAISED OCTAGONS IN CAVITIES, 2 CELL BELLY BAND, SCATTERED METAL PATCHES

STABILIZATION: SPINNING AROUND Z AXIS; 3-AXIS STABILIZED

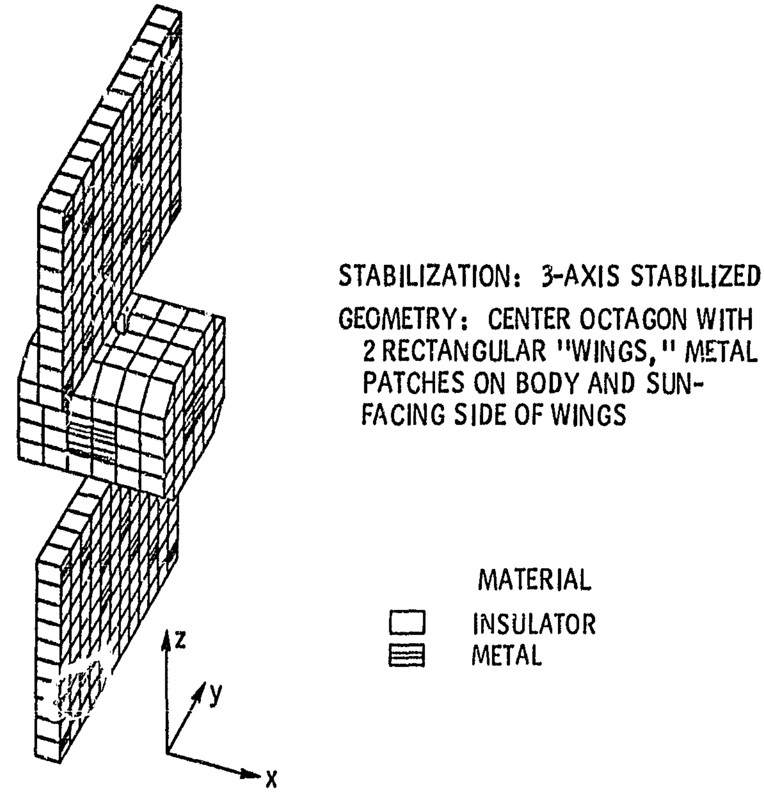


(a) Compact object (ATS-5 model object).

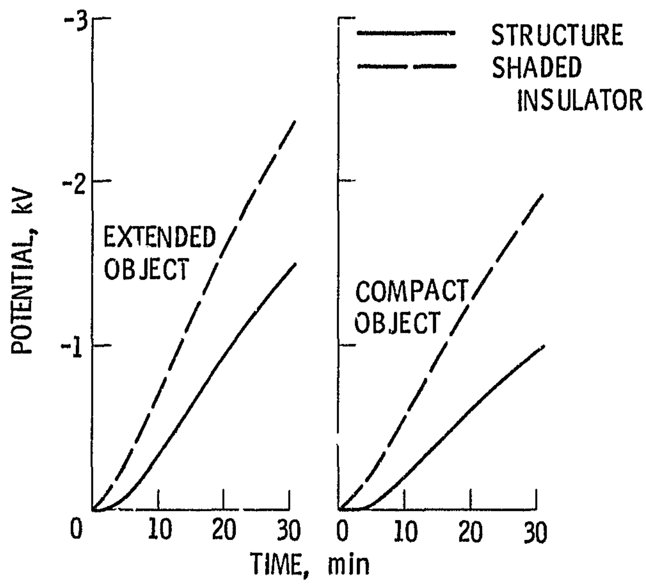


(b) Effect of stabilization type on charging response.

Figure 4. - NACSAP object and predictions of charging response.



(a) Extended object.



(b) Comparison of charging responses.

Figure 5. - NASCAP extended object and effect of geometry.

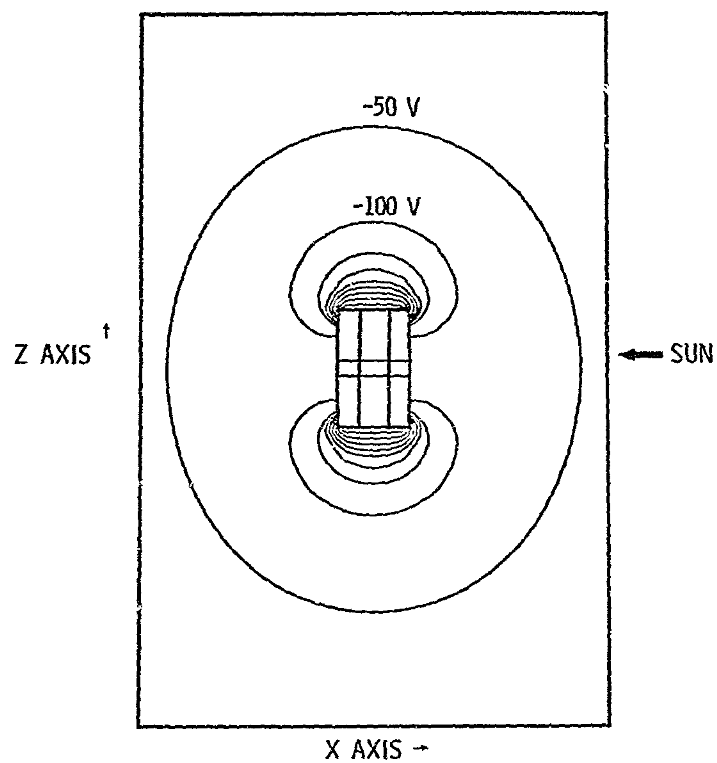


Figure 6. - Potential contours after 11 min of charging. Spinning: φ_S = -80 V; φ_{DI} = -490 V; φ_{SI} = -65 V.

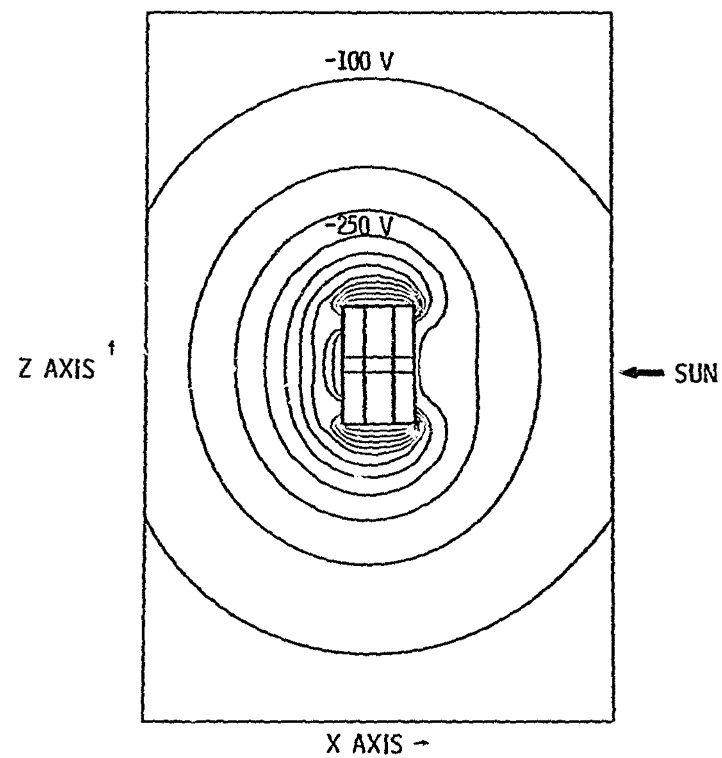


Figure 7. - Potential contours after 11 min of charging. Three-axis-stabilized: φ_S = -260 V; φ_{DI} = -660 V; φ_{SI} = -200 V.

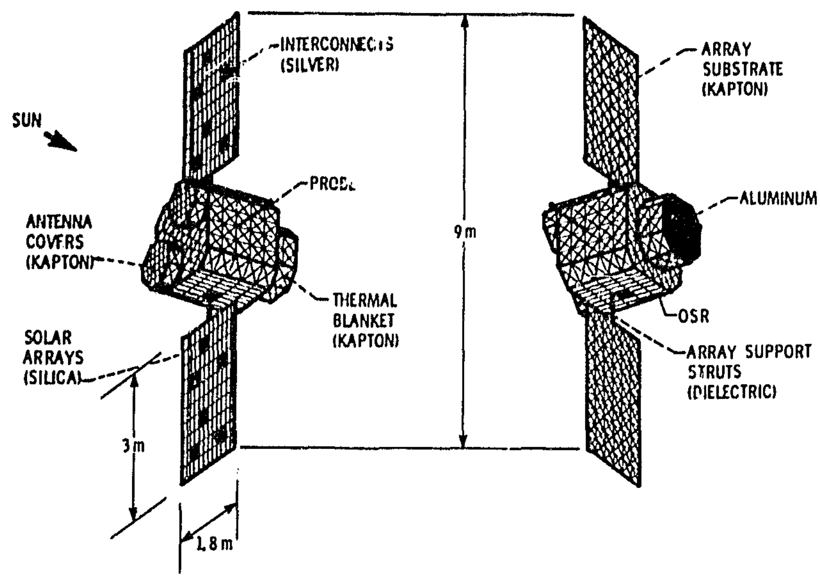


Figure 8. - Design guideline model of three-axis-stabilized geosynchronous satellite. (From ref. 40.)

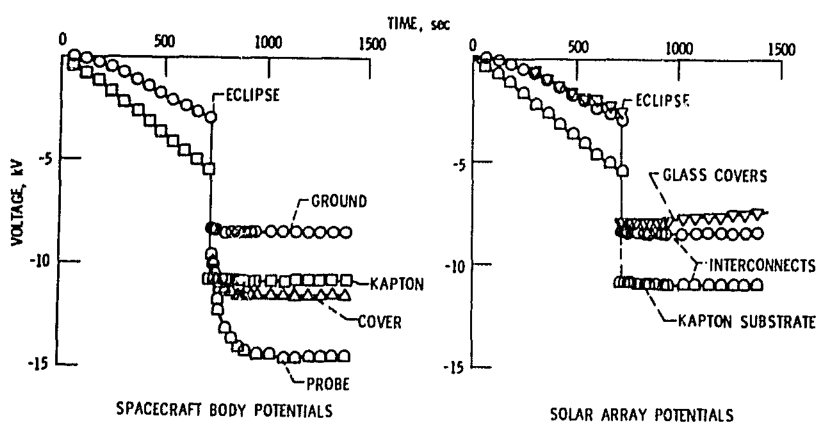


Figure 9. - Preliminary satellite design study - surface charging history. (From ref. 40.)