CHARGING OF GEOSYNCHRONOUS SPACECRAFT BY VARIABLE INTENSITY SUBSTORM ENVIRONMENTS

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ABSTRACT

An analytical study has been undertaken using engineering level computer codes to determine the charging characteristics of a spin-stabilized spacecraft subjected to variable intensity substorms. Both surface charging and buried charge effects are considered. The primary objective of this study is to determine the length of time that spacecraft surfaces would remain charged under variable environmental conditions. The study shows that, once started, surface charging can continue if the substorm level remains above 5KeV and the surfaces are not in sunlight. Buried charge effects follow the substorm intensity variations. In both cases, the most likely source for discharges are the sun/shade interfaces.

INTRODUCTION

Surfaces on geosynchronous spacecraft are charged by encounters with geomagnetic substorm environments [1]. This charging has resulted in discharge generated transients that have disrupted spacecraft electronic systems and have caused mission failures [2]. The Spacecraft Charging at the High Altitudes (SCATHA) satellite was launched in 1979 to evaluate these interactions between spacecraft surfaces and the substorm environments [3]. The results of the experiments on SCATHA has indicated that surface charging occurs only between 20:00 and 10:00 hours satellite local time [4] where 12:00 hours local time occurs when the satellite is between the earth and the sun. However, system upsets seem to occur at any time in orbit- even those on SCATHA [5,6]. With the modern tendencies of designing larger, more autonomous spacecraft, functional upsets can not be tolerated. Hence, it is important to understand the charging behavior of spacecraft surfaces in this environment in order to be able to design systems to be immune to these upsets with the minimum cost impact.

The standard analytical tool to predict surface charging of spacecraft is called NASCAP (NASA Charging Analyzer Program) [7], an outgrowth of the AF/NASA Spacecraft Charging Investigation [8]. The recommended approach to evaluate the surface charging characteristics is to model the spacecraft using the NASCAP code and then subject it to either a constant or a series of different constant substorm environments [9]. The idea is to impose an environmental condition that will generate the worst-case electrical stress in the surface dielectrics. The use of these constant environment results in voltage predictions that are more severe than those experienced in the actual space environment [10]. There are no standard codes to be used to

evaluate buried charge effects although this effect is, at least, as important as surface charging. For the purposes of this paper, surface charging is defined as that condition that arises when charge is deposited on or just under the surface. This is the limitation imposed by NASCAP and hence, limits the substorm electron energies to less than 20 KeV. Buried charge or bulk charging occurs when a charge distribution is imposed within the dielectric by energetic particles (electron energies up to the MeV range).

The NASCAP code can use a variable intensity substorm environment. There have been at least two cases studied using the SCATHA data [11,12]. The first study considered the charging profile for an eclipse charging case. Here it was found that, for the measured environmental inputs, the code would predict the measured spacecraft potential. The difficulty was that the code had to compute at least three steps for each substorm environment change and soon reached the storage limitation of the code. When larger time steps were imposed, the code predictions started deviating from the measured values. The second study used a broader time stepping approach and found that, while it didn't predict all of the variations in structure potential, it did generate a reasonable match. However, this approach also required considerable computer time.

The computer time is just one aspect of the cost necessary to conduct analyses; they are time-consuming to set up as well as complete the evaluation. Based on this cost impact, hardware project personnel, generally, do not feel that spacecraft charging analyses produce results commensurate with the expenses involved in conducting them. If the only change that can come from the study is to change the surface coatings, then this would impact the thermal design. The thermal designers can demonstrate that mission failures will occur if an exterior change results in excessive interior component temperatures while the charging analysist can only say that the change could reduce the probability of a discharge that may affect a system. The change will not be made. The tendency, therefore is to develop engineering level codes that can provide reasonable predictive capability while minimizing the cost impact. By conducting these simpler analyses, trends can be found that allows the development of guidelines that can aid future spacecraft designs.

In this paper, an investigation of a spin-stabilized spacecraft is conducted, using engineering level analytical tools, to evaluate its behavior in a variable intensity substorm. Spin-stabilized spacecraft experience a series of system upsets that occur centered around local dawn and dusk rather than concentrated in the more traditional midnight to dawn quadrant [3]. The speculation is that charging of the earth facing, despun antenna or deposition into an ungrounded substrate was the cause of the discharges that caused the anomalies. A variable intensity substorm is used to limit the structure voltages more to the values observed in space than those that would result for the standard analytical approach.

ANALYTICAL MODELS

For the surface charging analysis, the criteria under which all engineering models must be judged is the NASCAP code. For this study, the data from a NASCAP evaluation of a spin-stabilized spacecraft [13] was used. The spacecraft considered was a cylindrical spacecraft with a despun, earth-facing antenna and a extended solar array. The NASCAP model employed a few hundred cells to describe the spacecraft exteriors shown in figure 1. The engineering code used a modified version of the TRW Spacecraft Charging Technique (TSCAT) [14] and allowed the spacecraft to be described with 33 plates. The modification to TSCAT changed the code from a steady-state predictor of charging levels of several dielectrics connected to the same substrate to a transient charging predictor of up to 100 surfaces incorporating the three dimensional "barrier" effect. The reduction in detail is permissible since the NASCAP results for surfaces of the same material in the same environment have the same values. The antenna back surface is modelled as four triangular plates so that sunlight angle effects could be evaluated. This is done to simulate the fact that the antenna is a bowl shaped surface and, at shallow angles of incidence, the surfaces can be self-shaded.

The TSCAT model did not include the interior cavity of the extended solar array, but otherwise treated the spacecraft similar to NASCAP. Unfortunately, not all of the material properties for the surfaces used in the NASCAP analysis were available - the standard properties found in the NASCAP code were not always used.

The buried charge studies were conducted using the Deep-Dieletric Charging Analytical Technique (DCAT) [15]. This code has been checked against ground test results and other published analytical predictions.

The surface charging environmental models were derived from the NASA Guidelines Document [9]. The comparison to the NASCAP results used a "severe" environment while the variable environment study used a combination of three different environments. The buried charge study used the maximum flux of energetic particles reported [16].

Surface Charging Comparisons

The comparisons to NASCAP were made under both local midnight (sunlight on the earth-facing side of the antenna) and local dawn (sunlight on the edge of the antenna). In both models, spinning was simulated by inputting 1/3 solar intensity onto to the cylindrical solar arrays. The substorm was encountered at time zero and the the intensity was held constant for the duration of the runs.

The comparison of the structure voltages are shown in figure 2. As can be seen, the comparison is generally within 10% for both cases over the substorm encounter time of about 900 seconds. The local midnight comparison starts out in excellent agreement but deviates after 600 seconds when the NASCAP predictions start to stabilize. The TSCAT predictions also tend to stabilize but not at the same rate. The local dawn predictions show an initial deviation that comes back

together at about 600 seconds. This difference between the runs is due to the lack of modeling of the cavity (additional grounded area missing) and uncertainty of the properties of the antenna screen material.

The comparison of the surface differential voltages (the difference between the surface voltage and the structure voltage) is shown in figure 3 for local midnight. Similar results were found for the local dawn runs. The agreement for the Optical Solar Reflectors (OSR) and Kapton are excellent. The comparison between the the Teflon data indicates that the resistivity value used in the TSCAT run should have been increased slightly to improve the agreement. At the end of the run, the difference is on the order of 10%. The largest discrepancy was found in the initial charging of the paint. Here, differences of up to 25% were found. At the conclusion to the run, the agreement did become much better.

The engineering code does seem to incorporate all of the capability to be useful to conduct system behavior studies. The NASCAP runs took hours on a mainframe computer to complete while the TSCAT runs took about 10 minutes on a PC. This is a reasonable trade between code precision and time.

SURFACE CHARGING IN VARIABLE ENVIRONMENTS

In this section of the report, the surface charging behavior of a spin-stabilized spacecraft in a two hour period from 05:30 to 07:30 hours, spacecraft local time charges in response to a variable intensity substorm (see figure 4). The substorm encounter starts at 05:30 hours with an intensity level of 0.60 corresponding to a substorm that could occur about 40% of the time in orbit according to the NASA Guidelines [9]. After a short interval the substorm intensity increased to 0.9 (corresponding to a frequency of occurrence of 10%), then drops back down to the 0.6 level for a considerable period. The substorm level increases to the 0.6 level and reduces again just before 06:30 hours. The substorm intensity increases to duplicate the initial characteristics at about 6000 seconds into the simulation. This substorm characteristic is an arbitrary selection and is not meant to duplicate a specific substorm. The 0.6 and 0.9 intensity levels correspond to the "moderate" and "severe" levels in the NASA Guidelines document.

There is a constant sunlight input to the spinning solar array on the cylindrical sides of the spacecraft at 0.33 solar intensity (to provide the average sunlight to the spinning array). This assumes that the spacecraft spin rate is faster than the tens of minutes required to charge the dielectrics. Sunlight incident to the earth facing antenna is stepped every 30 minutes (corresponding to a 7.5 degree angle change). This provides and adequate simulation of the sunlight effect.

The spacecraft structure profile is shown in figure 5 along with the substorm characteristics. The structure charging reaches only to -850 volts which is more in keeping with the actual space data on charging of spin-stabilized spacecraft.

Structure charging becomes more negative as the substorm intensity increases. In the mild substorm corresponding to the 0.2 intensity (electron temperature of 2.2 KeV), decharging of the structure depends upon the sunlight incident upon the antenna back surface. This can be seen by comparing the initial behavior in the 0.2 substorm (about 1000 to 3000 seconds in the storm) to that from about 3500 to 5000 seconds. Initially, there is a period in which the structure charging did not change and then at about 06:00 hours, when one panel of the antenna back received the first shallow incident sunlight, the structure started to decharge. In the second cycle, the sunlight on the panel became stronger and the structure decharged faster. This is also apparent in the 0.6 intensity substorms: the sunlight incident upon the antenna changes the charging rates.

The antenna surface differential voltages (relative to the structure potential) are shown in figure 6. The sunshade surfaces (those that face earth) are all the same potential. The back of the antenna (Kapton surfaces) are divided into two groups: one is that surface exposed to sunlight at 05:30 and the other group is the three remaining panels that have sunlight incident upon them at 07:30. The sunshade material has a quasi-conductive surface to provide surface leakage since grounding would prevent the antenna operations. The back is modelled as a Kapton thermal blanket in which the metal sides are grounded.

For the first 600 seconds, the difference between the charging levels are too small to show on the curve. Then a small difference, due to the different grounding appears. The 7.5 degree sunlight incident upon the sunshade material does not affect the surface charging of this material. After 06:00 hour, the sunlight on the Kapton back does affect the surface voltage of the one panel in sunlight and allows a progressively stronger differential to exist between that panel and the surrounding Kapton blankets as well as the sunshade material. When the rest of the Kapton blankets are exposed to sunlight at 07:30 hours in the "moderate" substorm environment, the difference on the back side disappears while the difference between the back and sunshade material persists. This voltage difference between the front and back surfaces reaches 4 KV and can occur some time after a peak intensity of the substorm. Such differential voltages could result in discharges. This has been shown in a simulated discharge test of an antenna thermal blanket (see figure 7). Note that the discharges originate at the edges and imperfections in the blanket. The same could occur in space.

The charging of spacecraft surfaces is strongly dependent on sun/shadow effects and prior charging history. Since the dielectrics are good insulators, the decharging time without sunlight can be long resulting in unexpected differential voltages. These differential voltages can trigger discharges between sunlit and dark areas of the antenna blanket as well as between the blanket and the sunscreen or the structure. Such discharges are not considered in the NASA Design Guidelines at the present time. This study indicates that the guidelines should be expanded.

For those interested in the economics of charging analysis, the previous study required about 60 data points. The time required for the run, once the technique was established, is on the order of 30 minutes using an IBM AT personnel computer.

BULK CHARGING IN VARIABLE ENVIRONMENTS

Bulk charging effects in the antenna thermal blanket were evaluated using the Deep-Dielectric Analytical Technique (DCAT) code. This code is essentially a one dimensional computer program and hence, in common with other similar codes, assumes an infinite dielectric surface rather than specific spacecraft geometries. The charging response to a changing substorm environment for Kapton in the dark is shown in figure 8. Here, a very severe environment corresponds to the maximum high energy environment published in the literature [16]. The severe and moderate are then scaled versions of this high level. As can seen, Kapton approaches equilibrium values in the very severe environment after about 150 seconds. In the severe environment, the Kapton surface becomes more negative but still approaches equilibrium after about 300 seconds longer. In the moderate environment, the surface decharges. The charge density and internal electric fields for these conditions are shown in figure 9. In the very severe environment, the charge is distributed throughout the dielectric - the particles penetrate through the material - producing the relatively low surface potential. In the severe environment, a charge centroid develops about 0.001 cm within the surface producing the more negative surface voltage. The moderate environment also causes a charge centroid but at a lower level. The electric fields within the dielectric are not large enough to cause concern for discharges.

If the Kapton surface is charged while in the shadow and then is exposed to sunlight, there is a change in the boundary conditions which can trigger discharges. In sunlight, it is assumed that the dielectric surface would be held close to the structure potential by photoemission. This changes the charge distribution and internal electric fields as shown in figure 10. If the value of the electric field exceeds a breakdown threshold, then a discharge will occur resulting in the dissipation of the difference in the charge density distributions shown.

Finally, there is a question of possible penetration of the thermal blanket and deposition of charge within the substrate material. Here, there are two consequences: one, the substrate is conductive and tied to the structure and two, the substrate is a dielectric. If the substrate is conductive and grounded, then the result will be as shown previously. If the substrate is floating, then another charging process occurs. Now, the dielectric is essentially isolated from ground and is weakly capacitively coupled to the structure It will charge fast as shown in figure 11. Here, the code predicts that the surface potential for a 5 mil Kapton layer on a 10 mil fiberglass substrate will charge to about -10 KV at equilibrium. The internal voltage distribution through this combination is shown in figure 12. The code requires that the bottom of the substrate be grounded, so the computation would be more appropriate to a case where

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the substrate were thin. This result indicates that the substrate could be charged to about 9 KV. If the substrate is attached to the structure at an edge, then this differential voltage could exist across the joint and give rise to discharges. One explanation for the spin-stabilized spacecraft anomalies is that energetic charged particles penetrated the thermal blankets charging the poorly grounded graphite epoxy substrate underneath. This resulted in discharges which caused the anomalies. While this is could occur, based on the analysis conducted here, it is hard to correlate the occurrences in the local dawn and dusk periods. This penetration effect could occur anytime that there are sufficient energetic particles.

The modeling of the multilayer thermal blanket [illegible] not precise. In reality, the outer layers of the multilayers are grounded [illegible] numerical techniques [illegible] are more complicated [illegible] agree with the trends shown here [illegible] trends.

[illegible]

A study of the [illegible] variable intensity, environment [illegible] to evaluate possible charging and discharging mechanisms. Both surface and bulk dielectric charging [illegible]

Surface charging effects are eliminated by ambient sunlight. The charging characteristics change due to shallow incidence of sunlight and to discover the possible sites of discharges. Detailed studies with variable environmental conditions are required. This study has shown that it is possible to have discharges after the peak of the substorm intensities due to the long decharging time constants of spacecraft surface dielectrics. This negates the recommended design approach of using a constant intensity substorm environment to obtain the maximum electrical stress in dielectrics. Such an approach results in overpredicting spacecraft potentials (and probably overcompensating for charging effects) as well as possibly missing potential discharge sites. Furthermore, the use of a variable intensity substorm has shown that, once started, dark dielectrics remain charged for long periods of time and that discharges can be triggered in the low intensity substorm periods when charged surfaces are exposed to shallow angle incident sunlight. The discharges that can occur here vary from charge loss to space, to breakdown between dielectrics or to the structure. There can be more processes than originally given in the NASA Guidelines.

Buried charge effects have not received the consideration that they deserve since they probable cause more discharges than the surface phenomena. In this study, an engineering code has been used to evaluate the charging of the antenna coatings. It has been found that sun/shade effects here are probable source of discharges. This occurs when a surface is charged in the dark and then moves into sunlight. The rapid change in conditions forces a redistribution in the internal charge distribution and could trigger discharges. There is a

possibility that energetic electrons could penetrate to substrates. These materials could be charged if they are not adequately grounded and possibly discharge across joints.

The results of this study indicate that the prevalent view that discharges are primarily charge losses to space should be reexamined. The cases illustrated here indicate that there is a strong possibility that discharges between surfaces as well as in internal structures exists. These concepts should be factored into design criteria. The NASA Design Guidelines, developed about 10 years ago, should be reviewed and upgraded.

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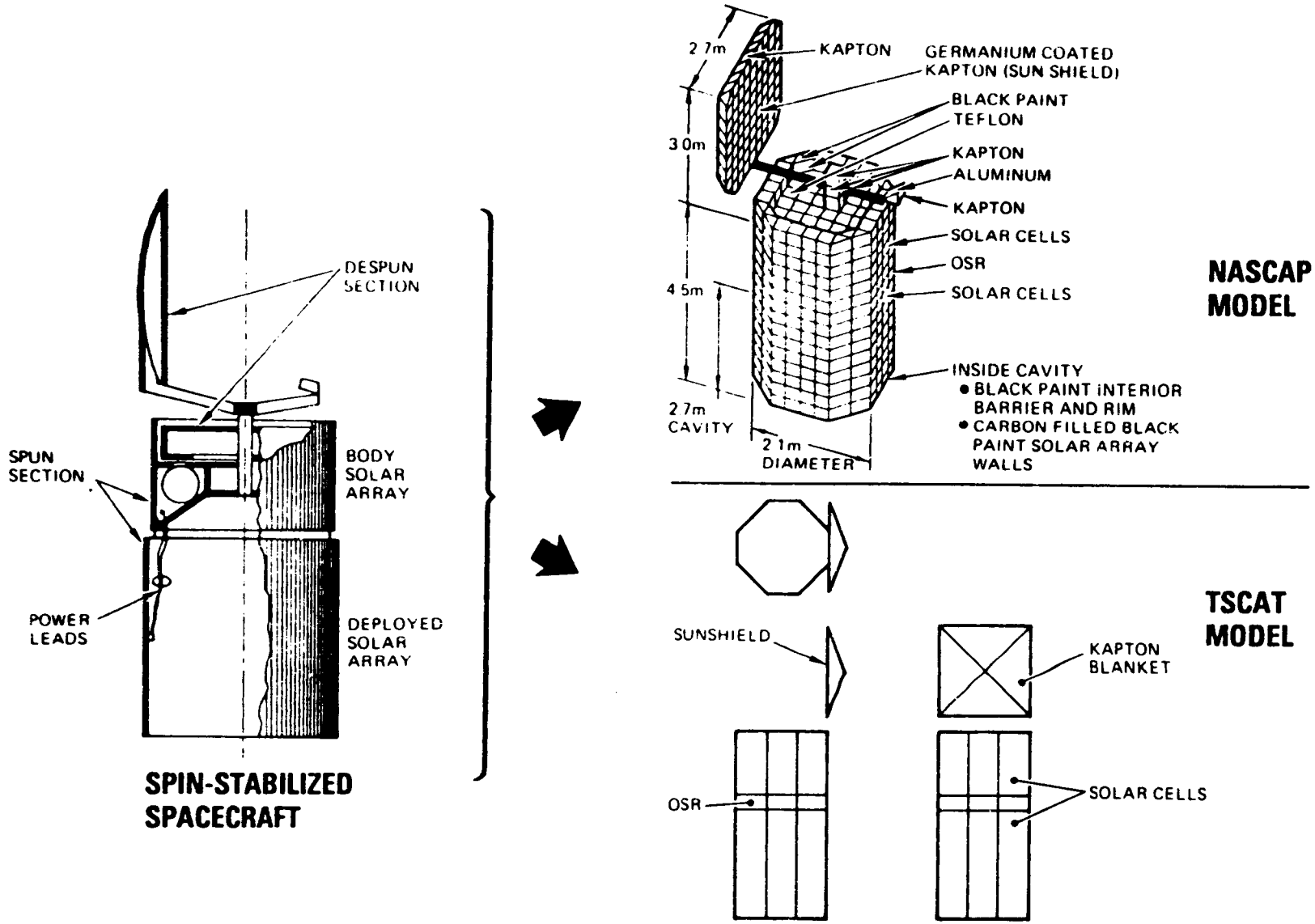

Figure 1. Spin Stabilized Spacecraft Models

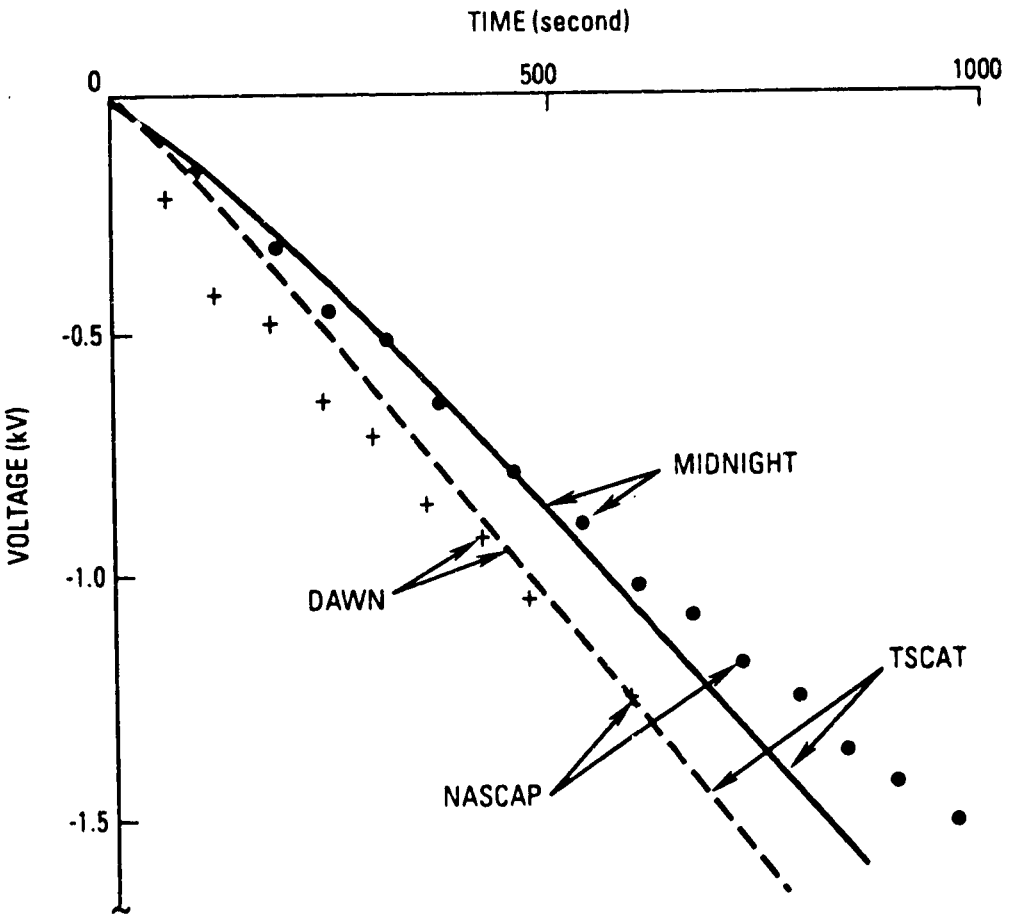

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Figure 2. Spin Stabilized Spacecraft Structure Potentials

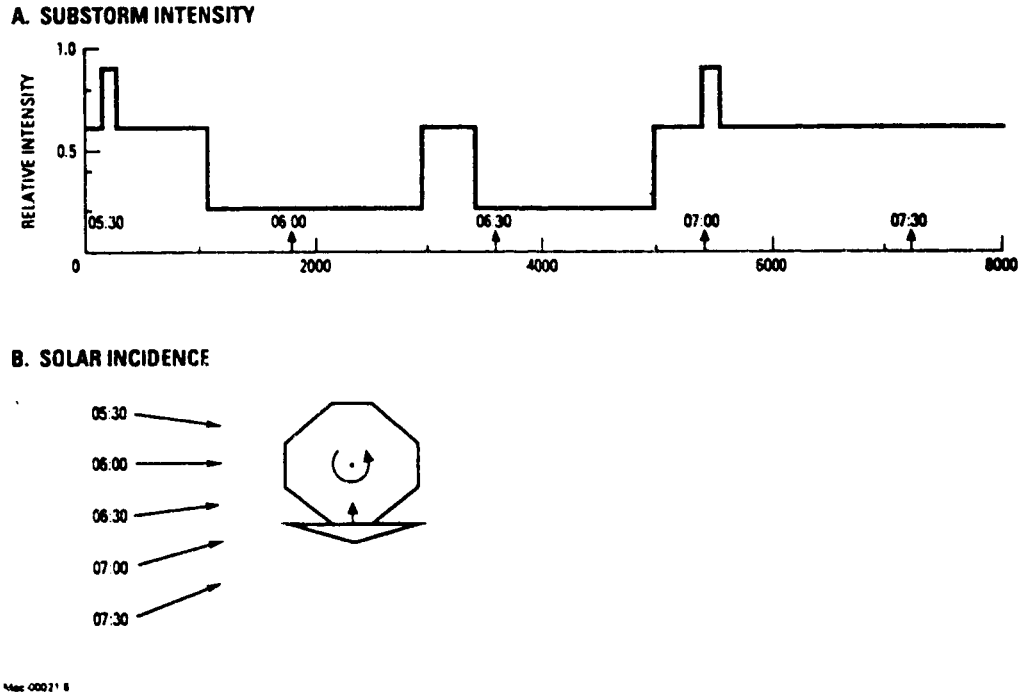

Figure 4. Environment Conditions

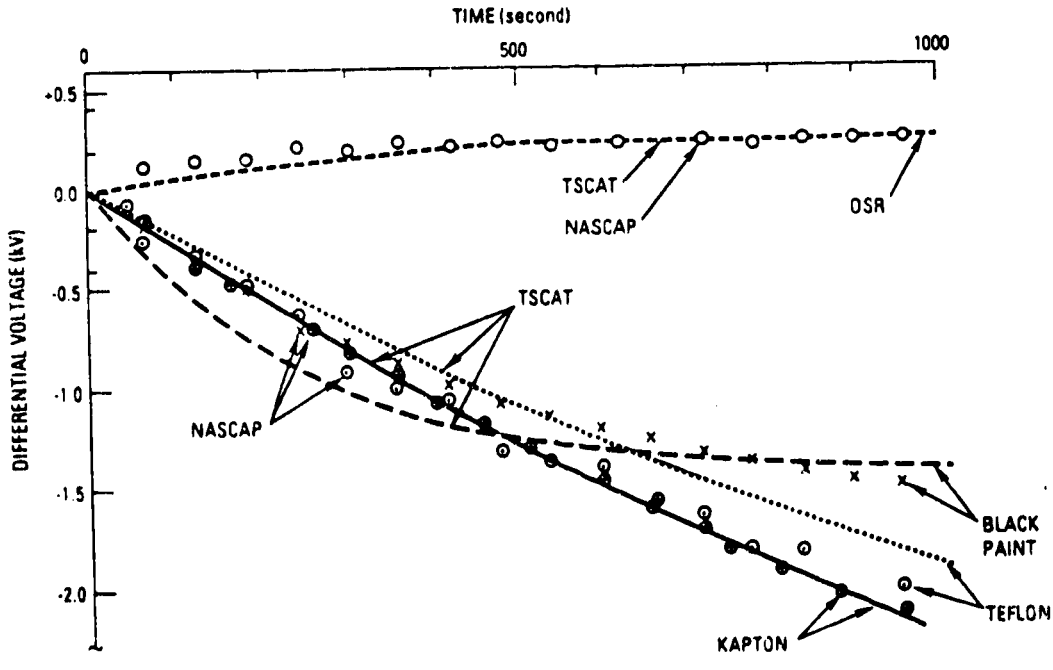

Figure 3. Spin Stabilized Spacecraft Dielectric Differential Voltages (Severe Substorm – Midnight Simulation)

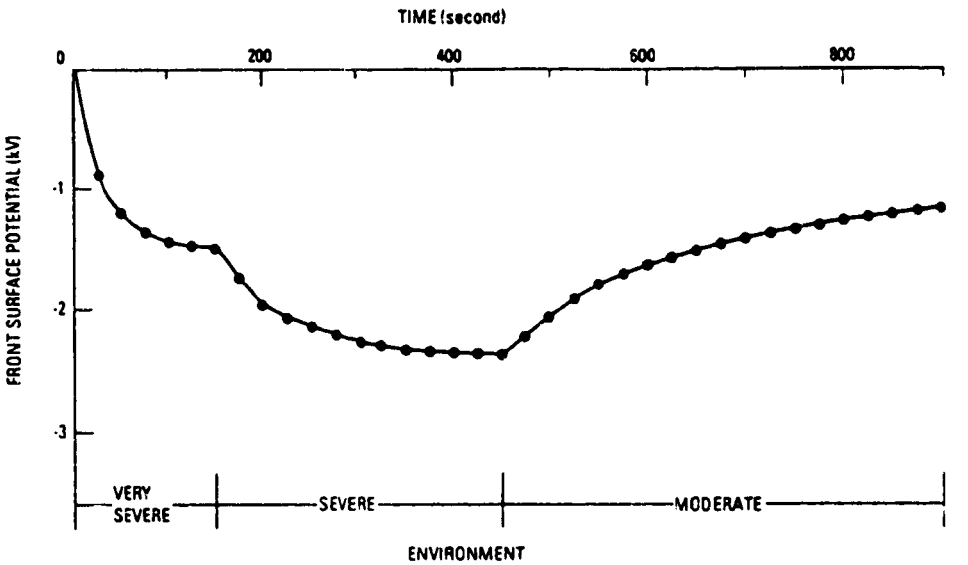

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Figure 8. Predicted Front Surface Potential Due to Buried Charge (Dark 3 mil Kapton in Variable Intensity Storms)

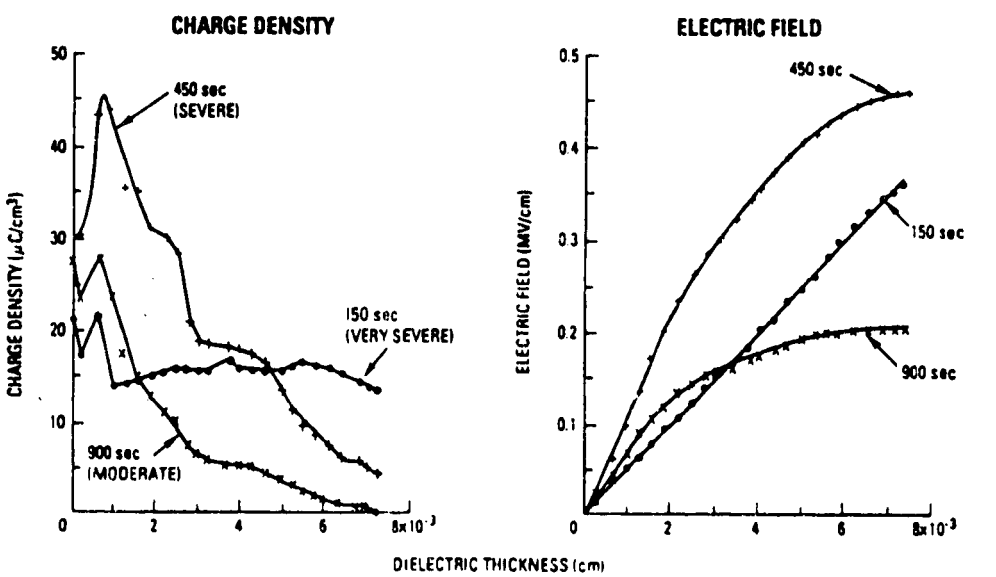

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Figure 9. Predicted Internal Distributions in 3 mil Kapton (Variable Storm Intensity)

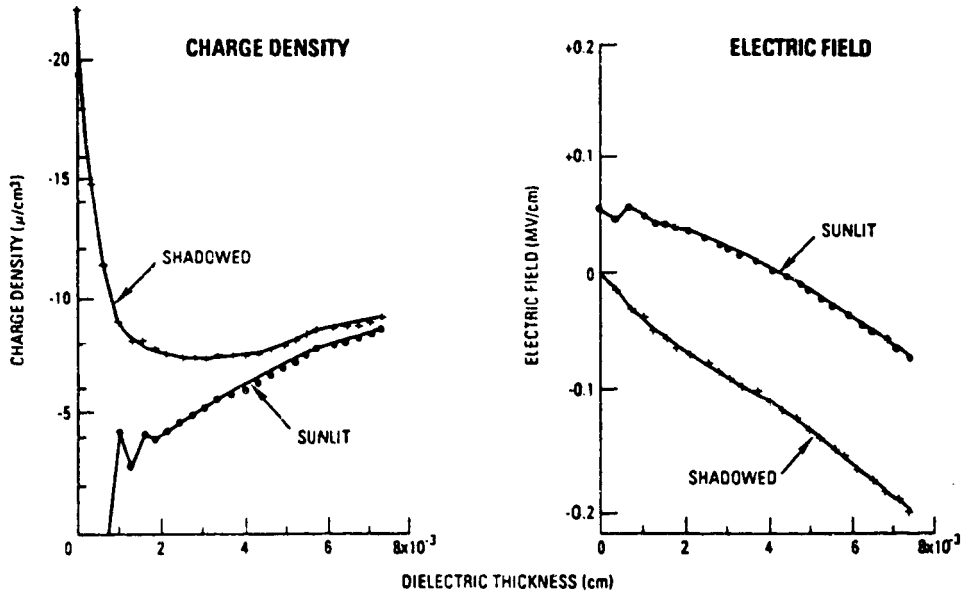

Figure 10. Predicted Change in Internal Distributions Due to Shadowing (Very Severe Environment – 10 Seconds After Shadow)

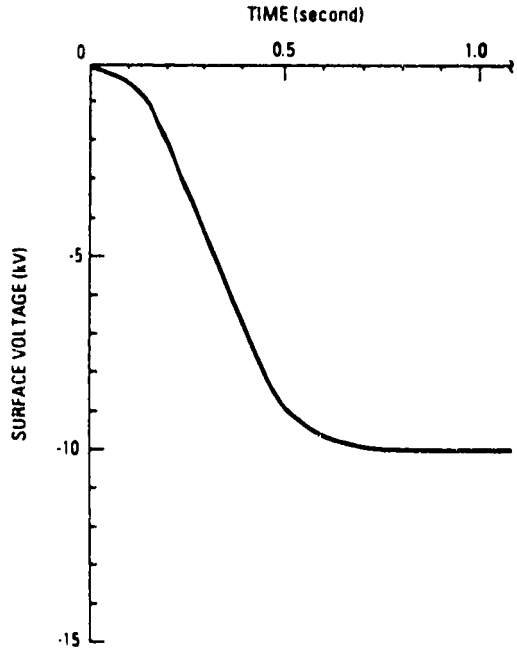

Figure 11. Front Surface Voltage in Thermal Blanket Covered Substrate (Very Severe Environment)

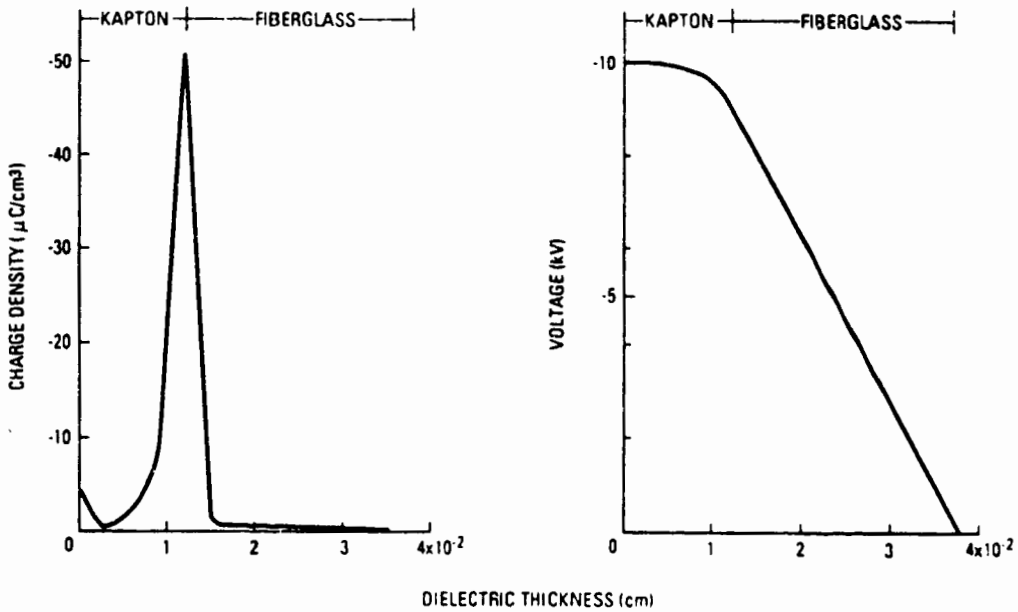

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Figure 12. Charge Density & Voltage Distribution in Thermal Blanket Covered Substrate (One Second in Very Severe Environment)