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DIELECTRICS AND SPACECRAFT CHARGING

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W.D. Edwards

(Space Technology and Applications Branch)

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DIELECTRICS AND SPACECRAFT CHARGING

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W.D. Edwards

ABSTRACT

The assumption is made that spacecraft charging effects may be alleviated by using conducting dielectrics for spacecraft construction.

The sources of charge within dielectrics are considered. The conductivity of dielectrics is discussed in terms of the charge carrier density n and the mobility μ. An examination is made of the ways in which n and μ might be increased in a manner suitable for satellite use. Methods of reducing the spacecraft potential with respect to the plasma are also considered.

Recommendations are made and the steps to be taken are suggested.

1. INTRODUCTION

A number of anomalous electronic events have been observed in satellites operating at geosynchronous altitude. The events are attributed to electromagnetic interference. This interference is induced into sensitive circuits as a result of discharges which occur when the spacecraft becomes charged with respect to the surrounding plasma or its parts become overcharged with respect to each other. Relative potentials of up to 20 kV can build up between dielectric and metal surfaces or between sunlit and shaded portions of a dielectric surface[1]. Most anomalous events have occurred during geomagnetic substorms in the local midnight-to-dawn sector for the satellite.

Most of the problems are thought to arise in the insulation of the spacecraft and the author was asked to investigate and report on coating or impregnating techniques by which dielectric materials could possibly be rendered immune to negative charge buildup when under the influence of an electron flux.

A considerable amount of literature, including surveys on spacecraft charging, has appeared [1,2]. The present discussion will be restricted to a consideration of the dielectrics and what might be done to alleviate the problem of spacecraft charging.

The assumption is generally made that the observed spacecraft charging anomalies are due to dielectric breakdowns and that the associated radiative and/or conducting electrical transients interfere with the spacecraft electrical circuits.

In general, the dielectrics (insulation) involved are not circuit elements and are used as much for their optical and thermal properties as for their electrical insulation value. A reduction by several orders of magnitude in the specific resistivity of the insulation, without significant change in the optical and thermal properties, is required.

The author sees the problem of spacecraft charging, which leads to electrical discharge, as one in which a solution is known, i.e., to have partially conducting dielectrics; the problem is how to achieve this. Related to this problem and very interesting scientifically, are the questions:

1) What is the environment and what are the exact processes leading to the observed phenomena in synchronous orbit?

2) How might the effects be simulated in the laboratory?

With limited manpower and monetary budgets the main thrust should be towards a solution of the problem with the scientific investigations[1,2] taking a secondary role.

Another associated problem is the charging of the whole spacecraft with respect to the surrounding plasma. Although electrical discharges to the plasma from the spacecraft have been postulated[3,4] it is not thought that this leads to the generation of significant spurious signals. However, it does complicate particle velocity and density measurements in the immediate neighbourhood of the spacecraft because of the disturbance of the reference potential.

On the assumption that the high resistivity of the dielectrics used is the main problem, this property will be considered in the following sections.

2. CHARGE STORAGE AND MOVEMENT IN INSULATORS

The literature on this topic is extensive; however, the understanding remains incomplete. Although the theory is considerably more complex than that for semiconductors, there has not been the same effort and incentive present as for studies on semiconductors. Many dielectric losses originally attributed to 'dipoles' are now interpreted in terms of charge movement.

2.1 CONDUCTION IN A DIELECTRIC

Conduction in a dielectric may occur because of the motion of ions or electrons. In the organic insulators of most interest, any conduction taking place is assumed to be the result of the motion of electrons. The specific conductivity σ can be expressed by

$$\sigma = ne\mu$$

where n is the mobile electron density per unit volume, e the electronic charge and μ the electron mobility. The ionic contribution is usually ignored. Both n and μ are extremely small in an insulator. The mobility $\mu \sim 10^{-10}$ cm^2/volt-sec and $n \sim 10^{11}$ electron/cc yields a resistivity $\rho \sim 10^{18}$ ohm-cm where $\rho = 1/\sigma$. To reduce the resistivity one has the choice of increasing n, μ or both of these factors.

2.1.1 The Charge Carrier Mobility μ

In a semiconductor the charge carrier mobility is usually dominated by lattice, neutral-impurity and charged-impurity scattering. In thin or highly dislocated samples, trapping of charge carriers may also occur. When this happens the effective mobility is considerably reduced. A trapped charge may be released thermally at some later time or may travel under the influence of the applied field and become trapped again before reaching the electrodes. The time spent in traps is sufficiently long that in samples with appreciable trap densities the mobility is entirely 'trap dominated'.

This thermally-assisted, trap-hopping mechanism is the picture thought to apply to insulators. The nature of the traps is essentially unknown but both the degree of crystallinity and the presence of phenyl and unsaturated groups in polymers may contribute to carrier trapping[5]. It is generally assumed[6] that in between trapping events the electrons move in a conduction band such as is pictured for semiconductors. By injecting electrons directly into the conduction band, carrier mobilities ~ 100 cm^2/volt-sec have been measured in dielectrics. Mobilities found in microcrystalline semiconductors (~1 cm^2/volt-sec) are also orders of magnitude higher than those normally found for insulators and the degree of crystallinity alone is therefore not thought to be the major factor. The forbidden bandwidths involved (several eV) are much greater than those for semiconductors and it appears likely that the intercrystallite (intermolecular) boundaries may be the site of very deep traps and scattering effects. The formation of a halogen-polymer complex at the site of unsaturated bonds has been suggested[7] to explain the observed increase in carrier mobility when polyethylene is doped with iodine.

Trap-controlled mobilities $\sim 10^{-6}$ cm^2/volt-sec have been observed and apparently decayed to $\sim 10^{-10}$ cm^2/volt-sec with duration of the experiment. The mechanisms are unclear at the present time. Enormous increases in mobility should be possible but the attainment thereof depends upon both theoretical and practical advances.

2.1.2 The Charge Carrier Density n

The low values of $n \sim 10^{11}$/cc are quite commensurate with the picture of an insulator as a wide band-gap material. The resistivity of a dielectric may be reduced by increasing n in any of a number of ways.

a) Light - photoconductivity

Light incident upon a dielectric can increase the conductivity by ejecting trapped carriers or by directly exciting electrons into the conduction band ($E_g \sim$ 3 eV). Spacecraft are illuminated non-uniformly by the sun and the relative photoconductivity of the dielectrics on board is a significant factor in determining the extent of the differential spacecraft charging. The illumination of vulnerable dielectrics is one method of increasing their conductivity and is a possible approach to the spacecraft charging problem if used with dielectrics having relatively large carrier mobilities. (see Appendix A)

b) Injection from Metal Contacts

If a conduction/valence band-gap theory is considered to apply to insulators, the possibility exists that carriers can be injected into the conduction band from any metallic contacts (or significant inhomogeneity) present. In principle, the metal can be chosen so as to reduce the barrier height and maximize the effect. However, because of the incomplete state of the conduction/valence band theory as applied to insulators, this would be a hit-and-miss approach and not very satisfactory. Additionally, the presence of a metal film on a dielectric that is thick enough to be effective will significantly change the very properties for which the dielectric was chosen.

c) Heat - Thermal Conductivity

Heating a dielectric increases the number of mobile charge carriers by exciting more electrons across the band-gap and by increasing the rate of ejection of carriers from traps.

This effect of heat in increasing the dielectric conductivity is probably another significant factor in determining the extent of differential spacecraft charging between non-uniformly illuminated components[2].

The application of heat to problem dielectrics would be one way of relieving charge buildup, although it is not really practical in the case of satellites.

2.2 THE PRESENCE OF CHARGE IN DIELECTRICS

Electrical charge may be present in the bulk, or on the surface, of an insulator. The charge may be present as a result of any one of a number of processes.

2.2.1 Static Charges due to Friction

Static charges arising as a result of friction were historically the first manifestations of electric charge to be investigated. Their elimination is still a problem of prime concern, e.g., in hospital operating rooms, grain elevators and on domestic carpets.

The method of elimination, i.e., to make the insulation conducting is, to some extent, straightforward although the implementation is often considerably more difficult.

2.2.2 Static Charges due to Phase Changes

Phase changes or reordering of the material structure may result in the separation of charge at phase or grain boundaries.

2.2.3 Static Charges due to Piezoelectric and Pyroelectric Effects

Piezoelectric and pyroelectric effects in polar materials can give rise to surface or volume charge effects. They are not likely to be a problem on spacecraft and will not be considered further.

2.2.4 Charge Produced by External Radiation

The interaction of external radiation with dielectrics can result in the production of large electric fields within the dielectric and is of most concern in this report. In a radiation environment even small fields arising from the polarization of plastics with time could become important for low-power plastic-encapsulated circuits.

2.2.4.1 Photoelectric effects

When visible or X-radiation is absorbed in a dielectric, electron-hole pairs are generated[8].

If the absorption takes place near a material/vacuum interface an electron may be ejected from the solid into the vacuum - the photoemissive effect. This leaves the dielectric/conductor with a positive charge which may build up to approximately 100 volts in low-plasma density regions[1,9].

If the absorption takes place in the bulk of a dielectric, a conductance/valence band model is usually used in an attempt to explain the effects observed. The electrons have a limited mobility and become localized in traps lying in the forbidden band.

Separation of charge may thus occur and a semi-permanent polarization or electret results[8]. Under continuous irradiation the production and movement of charge into traps and the continuous low level ejection from traps can give rise to a steady state conduction. On cessation of excitation the induced conduction current slowly decays to zero. The decay current is of the form[10]:

$$I = I_o\, t^{-n}$$

This is a form of absorption current and is of more than academic interest. Following 'discharge' of high voltage capacitor stacks, lethal potentials may appear due to movement of the absorbed charge. Another manifestation of the release mechanism for absorbed charge has recently been described[11]. Plastic film capacitors with dielectric materials such as Mylar have been observed to generate small voltage spikes in the range of 10-300 microvolts. The transients appear at time intervals of a fraction of a second to years and are more frequent when the dielectric temperature is changed. Because the voltage levels are small and are below the noise immunity level of logic circuits, this last effect will not be considered further.

2.2.4.2 Corpuscular radiation

Irradiation of dielectrics by electrons and protons can create electric fields sufficient to cause breakdown if no mechanism for discharge is present.

When a dielectric is bombarded by relatively low-energy electrons a negative space charge is built up near the dielectric surface. When energetic electrons penetrate a material, secondary electrons are produced. Near the surface the secondary electrons may be ejected leaving the surface region with a net positive charge. The primary electrons usually end their path much deeper in the bulk of the material and here create an excess of electrons. For polymer films of ~ 1 gm/cc density the electron range is 0.25 μ at 2 keV to 25 μ at 30 kev[12]. If the dielectric conductivity is too small an electric field can build up until the breakdown strength is exceeded and a discharge takes place.

Extremely small charge decay rates have been observed. For example at room temperature and low humidity the charge decay rate on Teflon foils charged with 5 → 30 keV beams was ~ 2% per year[13].

2.3 DISCHARGE MECHANISMS

2.3.1 Disruptive Discharge Mechanisms

Charge may be accumulated in a dielectric by some of the mechanisms discussed above until the voltage gradient produced exceeds the breakdown strength of the medium and a discharge occurs. The discharge may occur through the dielectric or through the surrounding medium, e.g., air.

The intensity of the discharge depends upon the stored energy immediately available and this, in turn, depends upon the physical structure involved and the breakdown path taken. The discharge may take one or more paths depending on the form of the 'capacitor'.

2.3.1.1 Metal-to-metal discharge

The discharge observed from a capacitor and those experienced in an electrical distribution system are typical of this type of discharge. The electrical energy stored is all available within the timeframe (< microsecond) of the discharge and as a result the discharge is intense and may be destructive. The discharge path may be through an air or vacuum gap, along an insulating surface or through any dielectric separating the metal conductors. The discharge through the dielectric of a capacitor and through the bulk of metallized Kapton, for example, is of this type.

2.3.1.2 Metal-to-charged-surface discharge

Depending upon the configuration, the discharge may again be through the bulk of the dielectric carrying the charge, through an air gap or over the dielectric surface. Examples are the discharge of static electricity to a metal ground plane and the discharge of the charge on the non-metallized side of Kapton to the metallized, grounded side. Because of the distributed nature of the surface charge the actual discharge is not likely to be as intense and destructive as in the metal-to-metal case. For an idealized case Rosen[1] calculated that the current in the metal-to-metal discharge was ~10^5 greater than the case of metal-to-dielectric surface discharge.

2.3.1.3 Surface-to-surface (bulk-to-bulk) discharge

Since charge has a sphere of influence, surface-to-surface breakdown is really a special case of bulk-to-bulk breakdown. The rate of charge build-up, the material conductivity and the breakdown strength are the major factors contributing to the intensity of the discharge. For example, the high intensity of the lightening stroke arising as a result of the high rate of charge accumulation and high medium conductivity is to be compared with, first, the more modest spark obtained as a result of frictional effects on dry plastics such as carpets where the charging rate and conductivity are low and, finally, with the absence of spark in the last instance for the case of moderate conductivity (i.e., damp insulation). With the special case of thunderstorms excepted, the intensity of any discharge taking place will be less than that for either of the two previous cases, because of the distributed nature of the charges involved.

The mechanism of discharge is not understood. A picture based upon the normal bulk conductivity provides unreasonable values. For example, consider a dielectric surface which is highly charged with respect to metallic backing. If the carrier mobility on the dielectric surface is assumed to be ~10^{-10} cm^2/volt-sec and the surface field ~10^2 V/cm, then the carrier velocity is ~10^{-8} cms/sec. An 'arc' discharge takes place in << 10^{-3} sec which suggests that the distance involved around the arc discharge path is extremely small ($10^{-8} \times < 10^{-3}$ or $< 10^{-11}$ cm). The experimental observation that such discharges occur means that other mechanisms are operative. The most likely is that the discharge is a multiple sequence event. Under electron bombardment for example, the potential of the insulating face of a metallized dielectric, Figure 1, increases until bulk electrical breakdown occurs between two points such as 'a' and 'b', Figure 1. This may be at the site of a structural defect, void, etc., where the breakdown strength is lower than anywhere else. Establishment of the arc creates a low resistance path from 'a' to 'b' with the result that the potential of 'a' drops sharply and a high voltage gradient appears between 'a' and 'c' for example, see Figure 1. A surface/air (or surface/vacuum in space) breakdown is now involved in which the breakdown strength is much less than the bulk value. The discharge paths step rapidly out from the original stroke 'a' to 'b' and may give rise to discharge patterns which look rather like leafless trees. The process is terminated when the cumulative potential-drops reduce the voltage gradient below that required for breakdown or the supply of charge is insufficient to maintain the original arc.

An alternative mechanism is that for which the original arc occurs and is then supplied by charges which exist in some form of surface channel created by themselves. In this manner also a considerable area may contribute to the discharge at one point.

2.3.2 Passive Discharge Mechanisms

To avoid intermittent, radiative and perhaps destructive discharges the space-charge buildup must be limited so that the critical breakdown

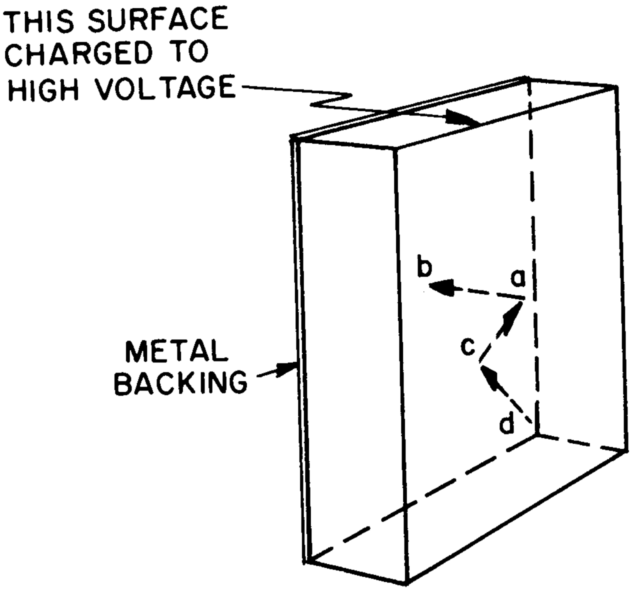

Figure 1. Figure to illustrate sequential nature of discharge. a, c and d are on the top surface, b is on the lower surface — the metal backing.

strength is not exceeded. This may be achieved by either limiting the inflow of radiation of all types or by providing sufficiently conductive 'discharge' paths so that troublesome space-charge buildup never occurs.

The limitation of the incoming radiation is not a practical solution in the case of a satellite. The parts believed affected are on the satellite surfaces and not the screened parts in the body of the spacecraft. Affected dielectrics must therefore be sufficiently conductive to prevent potential buildup. The provision of voltage limiters is not a good solution because the cheapest and most effective would be breakdown gaps of some type which would provide a noisy electrical environment which one wishes to avoid.

Studies of dielectrics have not received the same support as those of semiconductors and the present theoretical picture is far from satisfactory. The practical interest has been to obtain the maximum electrical breakdown strength with minimum dielectric loss. The bulk resistivity of some of the materials of interest, e.g., Kapton and Teflon is extremely high and there is no obvious way to reduce the resistivity in a controlled manner to levels $\sim 10^9$ ohm-cm.

It should be mentioned here that the antistatic used on plastic materials such as nylon carpets in order to prevent static charge buildup is a surface additive. It is believed that some humidity is necessary in order for the additive to be effective. This approach would obviously be of little use as a solution to the spacecraft charging problem.

Stevens has reported[3] that pinholes put into Kapton reduce the effective resistance between the two surfaces. The mechanism is unclear at present. The most likely explanation is that the insulating surface facing the plasma is charging up and modifying the field lines so that there is an increase of current to the exposed metal electrode beneath the hole. Also possible, but less likely, is the occurrence of microscopic discharges along the pinhole surface and/or a partially conducting layer formed as a result of stress and perhaps contamination around the pinhole. Further work is required to ascertain whether the apparent decrease in effective resistance is beneficial from a spacecraft charging point of view.

3. APPLICATION TO SATELLITES

A spacecraft at synchronous altitude is immersed in plasma of varying density and effective temperature. Each part of the spacecraft surface comes into electrical equilibrium with the plasma so that the net current to this surface is zero. At equilibrium, the surface sections have a potential with respect to the ambient plasma. A potential difference may also arise between adjacent parts of the spacecraft surface particularly where there is a difference in illumination of the surfaces. Other contributing factors are surface form and composition and non-isotropic flux distributions.

These effects give rise to two main spacecraft charging problems. One is the potential difference established between the spacecraft and the surrounding plasma which complicates the measurement of the plasma energy and density in the vicinity of the spacecraft. The second most serious problem is the appearance of considerable potentials between adjacent satellite components which may lead to destructive electrical breakdown or radiation of excessive noise signals that interfere with normal satellite operation.

3.1 POTENTIAL DIFFERENCES WITHIN THE SATELLITE

The potential buildup on a satellite and between satellite components is a function of the incoming particle and light radiation, the photoelectric and secondary emission and, of most importance, the geometry and resistivity of the satellite structure.

As discussed, potentially the most damaging discharges are between adjacent metal surfaces. These can be avoided by connecting all metal surfaces to a common satellite ground. Discharges between metal and dielectric surfaces or those occurring within a dielectric are not prevented in this manner.

The long term solution to the problem of potential buildup between parts of a satellite is to use dielectrics having a resistivity $\sim 10^{10}$ ohm-cm instead of the usual 10^{18} ohm-cm. Because voltage buildup is the prime concern a greater resistivity could be tolerated when the dielectric is in thin film form (see Appendix B).

It is likely that much theoretical and experimental work must be done before this can be achieved. For the immediate future, the best approach is to apply some type of conducting surface to the perceived capacitive elements.

3.1.1 Surface Conductivity Modification

Modification of the surface conductivity is not entirely satisfactory for a number of reasons.

(a) Conductive layers obtained by plasma treatment are only a few molecular layers thick. This conductivity is not expected to prove sufficiently stable in the plasma of synchronous orbit because the electron energies in the plasma used to create the layer are of the same order as those present in geosynchronous orbit during substorm activity. Thick, applied conductive layers would appear to be the most satisfactory short-term solution.

(b) When applying layers of conducting paint or metallization, the properties for which the dielectrics were chosen may be compromised, e.g., changes in emissivity, thermal conduction, and transparency may occur. The conducting layer properties would have to be assessed with respect to total satellite needs, including any requirement for enhanced secondary emission to reduce total satellite potential with respect to the surrounding plasma.

(c) Contamination of, and by, low resistivity surfaces - The components and adhesives chosen for spacecraft use have a low outgassing rate and low VCM (volatile, condensible material) loss. Contamination of critical optical surfaces, for example, by condensation of these VCM components is therefore reduced to a minimum. The VCM material could conceivably also cover low resistivity surfaces with a high resistivity layer. However, the layer thicknesses expected[4] are < 10 Å and would have little effect on the buildup of potential between component parts but would have a major effect on photoemissive effects. A breakdown strength of 10^7 V/cm means 1.0V across the 10 Å layer before breakdown, always assuming that one can consider breakdown across such a thin layer.

The contamination of other spacecraft components by the VCM products of any added conductive layer is also a possibility and coatings with low outgassing and VCM should be chosen.

(d) Energetic particles can penetrate insulation to a depth of several microns[12]. The trapped electrons will attract ions from the plasma to the surface of the dielectric and considerable fields can be built up, ultimately leading to breakdown[15]. Unless the conductive surface layer is thick enough to stop such energetic particles, the conducting layer will have little effect on this method of potential buildup. According to Meulenberg[15] layers several microns thick should be sufficient.

(e) The modification of the composition of solar cell cover-slips at the time of manufacture to render them slightly conducting is probably within the state-of-the-art. However, the conductivity would be mainly ionic and longer term instability could be expected. If a coating is necessary on this sunlit surface, a transparent coating of tin-doped indium oxide[16,17] may be the most reasonable approach.

3.1.2 Dielectric Bulk Conductivity Modification

3.1.2.1 Passive method

A reduction in the bulk resistivity from ~10^{18} ohm-cm to ~10^{10} ohm-cm of the dielectrics used on the outer surfaces of spacecraft is the best long-term solution to the problem of intra-spacecraft discharges. Ideally this should be achieved without significantly changing the other properties such as thermal conductivity and emissivity. New materials or modifications of presently used materials will be necessary. Apparently earlier forms of Kapton had a lower resistivity than that of present-day material. Whether this was due to a doping of the Kapton by impurities or due to a structural change is not known. As such materials are not readily available, research, development and test programs are necessary.

The effective reduction in resistivity of Kapton films containing pinholes has already been noted. This is not a method of reducing bulk resistivity and will not be discussed further.

3.1.2.2 Active methods of reducing dielectric resistivity

The dielectric resistivity may be reduced by either heating or illuminating the dielectric.

Heating the dielectric is probably unrealistic as far as spacecraft-surface materials are concerned. Incorporation of radioactive sources to provide a measure of conductivity is also dismissed as impractical.

Illumination of the dielectrics when in eclipse is a remote possibility but improved information about, and control of, the charge carrier mobility within the dielectric is needed (see Appendix A).

3.2 POTENTIAL DIFFERENCE WITH RESPECT TO THE SURROUNDING PLASMA

In the dark and during a plasma substorm an insulating surface may charge up to -20 kV with respect to the surrounding plasma. There is some question as to whether the surface can discharge by arcing to the plasma[4]. It is not thought to be as serious a problem as intra-spacecraft discharge. However, it is desirable to leak off the accumulated charge in a continuous, non-disruptive manner. To accomplish this it is necessary to promote electron emission from the charged surface.

3.2.1 Passive Discharge Mechanisms

3.2.1.1 Field emission

Field emission from microscopic points on a deliberately roughened surface is attractive since it is a self-adjusting system. Moore[19] states that there is evidence to show that discharges occur from points where the microscopic field is only ~ 100V/cm. If viable, this method of spacecraft potential control is very attractive because it is passive and also automatic in that it directly depends upon the presence of a potential difference and the discharge rate increases as the field strength increases. The concentration of charge at such asperities may give rise to ablation of the asperities and it may be necessary to devise a method of self-renewal. Research effort should definitely be directed to this approach.

3.2.1.2 Field emission and the surface barrier

Closely related to field emission from asperities is the enhancement of field emission by lowering of the surface barrier to electron emission. The principles are understood but the practice is something of an art. The use of surfaces including cesium is an accepted approach but not one that could be used aboard a spacecraft. Lowering of the barrier height is definitely a surface effect involving the outside molcular layers. Any effect achieved would be extremely vulnerable to contamination, both pre-launch and post-launch, and for this reason this approach is not recommended.

3.2.1.3 Secondary emission

The use of dielectrics or surface coatings with a significant secondary emission coefficient is also a reasonable approach[18] in that the mechanism is a bulk mechanism and operates in the eclipse phase. However, the control achieved is secondary in that it is not necessary to have a potential difference present before secondary emission takes place. The secondary emission coefficient is chosen from calculations based upon an assumed plasma energy and density distribution. The material chosen must also be compatible with other major spacecraft requirements with respect to thermal emissivity, thermal conductivity, etc.

3.2.1.4 Photoelectric emission

Photoelectric emission counteracts the buildup of negative charge and maintains sunlit portions of the spacecraft within a few volts of plasma potential.

Photoemissive control has the same disadvantages as secondary emission with the additional major disadvantages that it is not operative when needed, i.e., for spacecraft surfaces that are shaded or eclipsed. The extent of the photoconductivity of Kapton is in doubt. Kofoid[20] found strong photoconductivity, whereas Shkarofsky and Tam[4] observed no difference between dark or light conditions.

3.2.2 Active Control of the Spacecraft Potential

The potential of the spacecraft with respect to the surrounding plasma has not been considered in detail as it was feld that this does not play a big part in the generation of 'anomalous' events. The maintenance of the spacecraft potential close to that of the plasma is desirable when making plasma density and energy measurements.

3.2.2.1 Use of an electron gun

Some potential control may be achieved[21] by artificially ejecting electrons from a simple electron gun. However, whilst the spacecraft potential may now be close to that of the plasma the effect of the electron gun on the plasma becomes a problem. To allow for active control of the situation onboard spacecraft, charging monitors would be necessary.

3.2.2.2 Optical possibilities

The biggest voltage differentials are predicted between sunlit and shaded spacecraft dielectrics. The relatively unknown photoconductivity of Kapton or Teflon may be such that some transfer of the sunlight to the shaded components may be sufficient. This could be achieved either by artificial illumination, a mirrored system or an optical fibre system. These are 'far out' suggestions which cannot be tied down until the photoconductivity of the insulation used is better known.

3.3 PREVENTATIVE MEASURES AGAINST RF RADIATION FROM DISCHARGES

The most intense and potentially most destructive discharges are metal-to-metal discharges. These may be avoided by connecting all metallic surfaces to the satellite ground. It should be noted here that the metallization of dielectric surfaces in an attempt to reduce spacecraft charging may actually worsen the situation unless the metallized layers are carefully grounded to a common point.

Most circuits within the spacecraft will be effectively shielded from radiation by the chassis or the spacecraft framework. Power supplies should be filtered to reduce conductor-borne noise and sensitive circuits hardened to withstand the arc discharge environment. A recent paper by Rosen[1] elaborates upon this approach. Direct current isolated elements of microstrip lines may be exposed and could conceivably accumulate a d.c. potential. It would not be difficult to provide a high-resistivity leakage path to prevent such charge buildup and which would not materially affect the line properties.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The direct and most permanent solution to spacecraft charge buildup is to use conducting dielectrics for all the exposed structural and electrical features of the spacecraft. These conducting dielectrics should be bonded to the common ground of the spacecraft. Resistivities of the order of 10^9 ohm-cm instead of the usual 10^{14} -10^{18} ohm-cm should be sufficient. This change in resistivity should not affect the other properties for which the materials were chosen, e.g., emissivity, thermal conductivity. However, because of the incomplete state of knowledge with respect to dielectric theory this approach is not readily applicable.

An alternative and presently practical approach is to create some surface conductivity on all structural dielectrics (potential capacitors) by metal deposition, plasma radiation, etc.. The conducting layers created would all be connected to the satellite 'ground'. Discharges within dielectrics would not be prevented but because of their 'distributed source' nature and the fact that the consequent radiation is screened, they would not be a significant problem.

All circuits should be protected against excessive electromagnetic radiation spikes and, as a precautionary measure, sensitive circuits should be shielded to minimize RF pickup from plasmas, arc and stray RF signals.

4.2 RECOMMENDATIONS

(a) The main aim is to obtain dielectrics of bulk resistivity ~10^9 ohm-cm. Substantiation of this target resistivity of ~10^9 ohm-cm should be obtained by carrying out appropriate spacecraft charging simulation experiments. To carry these out, dielectrics not normally considered for spacecraft use because of undesirable properties but having suitable resistivity may have to be used, e.g., PVK (polyvinyl carbazol).

(b) Theoretical and practical studies of ways to modify the bulk resistivity of dielectrics used on spacecraft are needed. It should be noted that processing to give lowered surface resistivity is really a special case of bulk resistivity modification. The capability of tailoring bulk resistivity to order in the 10^9 ohm-cm range has not yet been developed. One might be able by means of doping to increase 'n' but an increase in mobility, μ, is equally desirable. The electron mobility within a long chain molecule is reasonable; it is the scattering or trapping at grain and large molecule interfaces that reduces the microscopic, bulk mobility to very low values. A possible solution to the problem is the addition of dopants which segregate to the molecular and grain interfaces or attach to the unsaturated molecular groups. This should result in a reduction of the trap depths and extent of scattering and a consequent increase in the carrier mobility. However, it should be noted that the simple addition of 3% carbon to polyethylene had essentially no effect upon the electrical conductivity, whereas the color was changed[22].

A contract to a university should be given to explore this approach; this would be relatively long term. In-house or industrial effort should also be brought to bear to explore the practical approach, working in close liaison with the university group. There are many applications for partially conducting dielectrics, particularly for the prevention of damaging discharges arising from static electricity.

(c) Stabilization of spacecraft potential by the provision of multiple asperities on the outer surfaces is very attractive and should be investigated. An in-house program or an industrial contract would be most suitable.

(d) There is controversy over the extent of photoconductivity in the dielectrics of interest, e.g., Kapton. Specimens should be obtained and the photoconductivity as a function of light intensity and wavelength determined. This study is suitable for a university contract.

(e) Of more short-term or immediate interest there should be action to:

(i) Obtain the dielectrics of interest in bulk and in coated form and establish values of their initial bulk and surface conductivities. If a significant range were found, the source of relatively high conductivity material should be specified for use in future spacecraft use.

(ii) Check the resistivity stability of the bulk and coated specimens in a simulated space environment. The specimens may be coated to improve surface conductivity and/or to improve secondary electron emission. The main effort should concern item (b) as this is the main problem perceived.

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APPENDIX A

The conductivity of a dielectric may be increased by increasing the number of charge carriers or by increasing the carrier mobility. The number of charge carriers may be increased by appropriate illumination - the photoconductive effect.

It is of interest to present some approximate calculations to obtain a feel for the size of the effect.

At synchronous spacecraft altitude the sun irradiates the spacecraft with approximately 1.35 kW/sq. metre. The energy is distributed over a range of wavelengths and peaks at ~ 0.5 microns. Photons at this wavelength have an energy ~ 2.3 eV. The light intensity at synchronous altitude is

$$1.35 \text{ kW/m}^2 = 1.35 \times 10^3 \times 10^{-4} \text{ watts/cm}^2 \text{ or Joules/sec/cm}^2,$$

$$= \frac{1.35 \times 10^6}{1.6 \times 10^{-12}} \text{ eV/sec/cm}^2$$

or

$$\frac{1.35 \times 10^6}{1.6 \times 10^{-12} \times 2.3} \text{ photons/sec/cm}^2$$

$$= 3.6 \times 10^{17} \text{ photons/sec/cm}^2.$$

If the exact nature of the absorption is ignored and a 1% efficiency is assumed for carrier generation per cc then the electron/hole pairs created per cc/sec = 3.6×10^{15}.

Considering the electron alone as mobile, an electron mobility of 10^{-10} cm^2/voltsec then,

if $$\sigma = \frac{1}{\rho} = n\ e\ \mu$$

where n is the charge carrier density, e the electronic charge and μ the mobility.

Substituting

$$\sigma = 3.6 \times 10^{15} \times 1.6 \times 10^{-19} \times 10^{-10}$$

or

$$\rho = 1.7 \times 10^{13} \text{ ohm-cm}.$$

The calculation suggests that sunlight may reduce the dielectric resistivity from ~10^{18} ohm-cm to an effective value ~10^{13} ohm-cm. The experimental evidence suggests that the presence of sunlight is sufficient to significantly reduce spacecraft charging effects, i.e., that dielectric resistivities of ~10^{13} ohm-cm may be acceptable. However, the mobility figure of 10^{-10} cm^2/voltsec used is very tentative and the mobility is also very temperature- and field-dependent.

Consider the possibility of artificially illuminating key surfaces during an eclipse. At a distance of 1 metre a 100 watt bulb would irradiate a surface with

$$\frac{100 \times 0.1}{4\pi \times 100^2} \text{ watts/cm}^2 = 8 \times 10^{-5} \text{ watt/cm}^2$$

or about $\dfrac{1.35 \times 10^{-1}}{8 \times 10^{-5}} = 1.7 \times 10^4$ times less than the sun value quoted above.

or $\equiv 2.1 \times 10^{13}$ incident photons/sec/cm^2 and

$\sim 2 \times 10^{11}$ electron hole pairs/sec/cc/produced.

A dielectric resistivity of 10^{18} ohm-cm and a carrier mobility of 10^{-10}cm^2/voltsec indicates a carrier concentration of 6×10^{10}/cc. It is thus seen that the number of carriers induced by a 100-watt lamp is comparable with the number normally present. This may account for the conflicting experimental evidence about the photoconductivity of Kapton[4,23]. However, it should be noted that, at best, the calculations are only of decade accuracy because of considerable experimental difficulty and the unknown value of, μ, the mobility.

APPENDIX B

For the purpose of spacecraft charging considerations, the variation in bulk dielectric breakdown strength with sample thickness can be ignored. Surface/air, surface/vacuum interface breakdown will also be essentially independent of dielectric thickness. The voltage buildup on the surface rather than the field through the dielectric is the likely crucial point. Consider a maximum desirable voltage of 10 and an incoming electron current of 10^{-9} A/cm^2. Then for a 1 cm thick dielectric the maximum acceptable value of ρ is 10^{10} ohm-cm and for a 10 μ film ρ_{max} is $10/10^{-9}$. $1/10^{-3} = 10^{13}$ ohm-cm.

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8. ABSTRACT: The assumption is made that spacecraft charging effects may be alleviated by using conducting dielectrics for spacecraft construction.

The sources of charge within dielectrics are considered. The conductivity of dielectrics is discussed in terms of the charge carrier density μ. An examination is made of the ways in which η and μ might be increased in a manner suitable for satellite use. Methods of reducing the spacecraft potential with respect to the plasma are also considered.

Recommendations are made and the steps to be taken are suggested.

9. CITATION:

SOMMAIRE À L'INTENTION DE LA DIRECTION

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TITRE:	Les diélectriques et la production de charges électrostatiques dans les engins spatiaux
AUTEUR(S):	W.D. Edwards
DATE:	Avril 1978

On a attribué un grand nombre de défauts électroniques de fonctionnement des sous-systèmes des engins spatiaux à des effets de charge électrostatique qui s'y produisent. On croit que les activités orageuses secondaires géomagnétiques causent d'importantes différences de potentiel, accompagnées de décharges d'arc, dans les éléments diélectriques du satellite. Des défaillances catastrophiques se sont produits; il est donc primordial de mettre en oeuvre de meilleures lignes directrices régissant la conception afin d'éviter que ce problème se pose à l'avenir.

Des études des défauts de fonctionnement qui ont été enregistrés à ce jour et de leurs causes probables ont été publiées. Le présent rapport est basé sur l'hypothèse selon laquelle l'accumulation de charges électrostatiques au niveau des diélectriques constitue le principal problème. On y examine la conductivité des diélectriques en fonction de la densité n et de la mobilité μ des porteurs de charge. On se penche également sur les façons d'augmenter n et μ d'une manière qui corresponde à l'utilisation des satellites. Des méthodes de réduction de la différence de potentiel entre les engins spatiaux et le plasma sont également étudiées dans le présent document.

Le rapport énonce des lignes directrices quant à l'orientation que les travaux en cours au CRC et les projets qu'il est prévu de confier aux universités devraient prendre. La principale conclusion du rapport insiste sur la recherche de moyens de réduire la résistivité des diélectriques des engins spatiaux (jusqu'à $\sim 10^9$ ohm/cm). Si ces recherches s'avèrent fructueuses, on pourra en appliquer les résultats à de nombreuses utilisations commerciales dans d'autres domaines.

English on Reverse

EXECUTIVE SUMMARY

DOCUMENT NO: CRC Report No. 1317

TITLE: Dielectrics and Spacecraft Charging

AUTHOR(S): W.D. Edwards

DATE: April 1978

A large number of electronic malfunctions in spacecraft subsystems have been attributed to spacecraft charging effects. Large potential differences and accompanying arc discharges are thought to occur in satellite dielectric structures as a result of geomagnetic substorm activity. Catastrophic failures have occurred and there is a pressing need for better design guidelines in order that the problem is avoided in the future.

Reviews of the malfunctions to date and their likely interpretation have appeared in the literature. In this report it is assumed that dielectric charging is the main problem. The conductivity of dielectrics is discussed in terms of the charge carrier density n and the mobility μ. An examination is made of the ways in which n and μ might be increased in a manner suitable for satellite use. Methods of reducing the spacecraft potential with respect to the plasma are also considered.

The report provides guidelines for the direction in which current CRC and proposed university projects should proceed. The main conclusion is that ways of slightly reducing the resistivity of spacecraft dielectrics (to $\sim 10^9$ ohm-cm) should be sought. If successful there are considerable commercial applications in other fields.

Français au verso

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