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**THE PHYSICS OF GRIDDED AND CONDUCTIVE COATED  
DIELECTRICS FOR SPACECRAFT**

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**ABSTRACT**

Theoretical aspects of electrostatic control and design of gridded and conductive film bonded polymers, for spacecraft Thermo-optical control blankets are considered. Brief commentaries relative to the salient features of the primarily developed facility for and characterization of said polymers is also considered.

**INTRODUCTION**

Absence of electrically conducting grid or transparent semi-conducting coating on typical spacecraft dielectrics (e.g., polymers such as Teflon and Kapton, which are utilized for the outermost dielectric of Thermo-optical control blankets, etc.), limits the electron irradiated dielectric's rate of relieving charge (e.g., by secondary electron emission, photo-electron emission, surface and volume leakage currents and charge spreading) before ultimately step-wise transition to electric and thermal breakdown occur, or as soon as the charging rate exceeds the charge dissipation rate so that the resulting normal and tangential electric potentials attain the electric breakdown potential or total voltage in the medium.

Charge leakage mechanisms of solid dielectrics are enhanced by induced conductivities, due to electron bombardment (EBC), spreading potential (tangential electric field of charge layer) and normal electric field. In the case of highly porous or fiber cloth and even compact dielectrics, all comprising micropores, charge leakage mechanisms also include, in the first two cases, field enhanced internal secondary electron emission, (provided the corresponding yield is greater than unity at low electron energy), leading to self-sustained micropore electron emission under certain conditions (aside from impact ionization) [1]. In the case of compact dielectrics, electron avalanche in the micropores and Malter emission from their apertures and/or electron avalanche in the conduction band by impact ionization occur. At  $30\text{nA/cm}^2/\text{sec.}$ , charging rate, the magnitude of the residing charge and said charge dissipation mechanisms of the dielectric must be such that electric breakdown threshold voltage is not attained.

For transparent semi-conducting coating on said typical dielectrics, this means substantially less than  $10^{12} \Omega \text{ cm}$  or more specifically the order of  $10^9 \Omega \text{ cm}$  and preferably less resistivity is required. The coating thickness (resistance) and volume resistivity must satisfy the required discharge current capacity, without undue heating, and still satisfy tolerable requirements of the spacecraft Thermo-optical control blanket, etc.

For electrical conducting grids on said typical dielectrics, the pitch must be such that not only must the residing charge be properly subdivided, to limit the charge accumulation and hence energy of a possible electric or thermal breakdown discharge, but more preferably the grid pitch should be so related to the propagation velocity of the electron avalanche, originating at the center of a window pane of the grid, such that step-wise transition to electric or thermal breakdown is aborted. The cross-section of the filaments of the grid must be adequate to avoid electric breakdown and satisfy the conduction current capacity of the grid, without undue heating, and limit optical screening by the grid so as still satisfy the requirements of the spacecraft's Thermo-optical control blanket, etc.

Degradative electron irradiation etching reveals various micron size structures attributed to processing and molecular orientation of the polymer film (e.g., etched parallel stretch lines occur in one-way stretched polymer films, while lamellate brick-wall, not grid, structures occur in two-way stretched polymer film). The etched regions are characterized by treeing discharges. Said etching increases the surface energy of the polymer by breaking bonds at the surface layer (i.e., of a few microns depth). The degree of increased surface energy, by said means, is not comparable with that afforded by alternate gaseous (e.g., oxygen) discharge (e.g.,  $61^\circ \pm 7^\circ$  to  $31^\circ \pm 4^\circ$  contact angle), which functions by displacing atoms of one kind by those of another to a significant degree (e.g., an atom of one kind per several atoms of another) at the surface layer. The intensity of said etching increases with exposure time to the electron irradiation, since the dependence of moles of absorbed molecules takes time to diffuse into the polymer. Apparently large (micron-size) regular structure, composed of long period spatially ordered volumes (500-1000 Å.D) of highly ordered molecular groups with rheological mobility, representing distribution of strain due to fabrication stresses, is built into anisotropically stretched polymer film. Correlation of physical properties (e.g., % elongation tenacity, tear, modulus etc.) with said structural size of brick pattern is apparently indicated, especially in the size range of 1 to 100u.

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## REDUCED CHARGE CHARACTERISTICS OF DIELECTRICS & SEMI-CONDUCTORS

A threshold criterion for charge storage and leakage as a function of the resistivity of a dielectric may be defined. Surface resistivity is usually a dominant factor, and it may be modified as the situation may warrant. The residual charge on the surface of a dielectric may be limited, aside from secondary electron and photoelectric emissions, by electric [3] or thermal [3] discharges in ambient residual gas, due to normal outgassing, especially from electron and/or ion bombardment heating, and/or by ionization irradiation and in vacuum by microthermionic and field emissions, spreading potential [4] and total voltage [5].

Reduced charge,  $\sigma/\epsilon'$ , defined by the ratio of charge density,  $\sigma$ , to (real) dielectric constant,  $\epsilon'$ , becomes invariant, at and in excess of a specific resistivity,  $\rho$ . However, in the event that the resistivity is such that said reduced charge is markedly reduced, the charging is also reduced, due to leakage. The threshold criterion of charge storage and charge leakage asserts itself at and below about  $\rho = 10^{12} \Omega\text{cm}$ . It is a step function of reduced charge,  $\sigma/\epsilon'$ , versus resistivity,  $\rho$ , [6]. The resulting resistivity demarcation, between dielectrics and semi-conductors, may serve as a threshold criterion for significant charge leakage or charge storage. Exceptions do occur, the most conspicuous of which is vinyl polymer of methyl-methacrylate (i.e., Perspex or Plexiglass or Lucite), having a resistivity  $\rho = 10^{15} \Omega\text{cm}$ , but which nevertheless affords relatively negligible charging! Residual charge on the dielectric of resistivity  $\rho \gg 10^{12} \Omega\text{cm}$ , is independent of the dielectric resistivity whenever, normally, limited in ambient residual gas electric discharges, as previously mentioned.

The field just outside a localized charge on the surface of an dielectric tends to zero as the dielectric constant,  $\epsilon'$ , approaches infinity, in contrast to that of a metal's  $4\pi\sigma$ , since the charge distribution, for a dielectric is impossible for a metal. In the case of a semi-conductor, if the residual lifetime of a charge is short relative to the relaxation time for redistribution of charge, then the semi-conductor will act like an insulator; otherwise, if the residual lifetime is sufficiently long, for a stable configuration of charge formation, then that semi-conductor will act as a metal, provided that the size of the material is not comparable with the thickness of the surface skin or layer within which the charge is accommodated. In other words, the cardinal parameter which characterizes an insulator is the time or relaxation time-constant, for charge transfer,  $\tau = \epsilon'/\sigma_c$  sec., where  $\epsilon$  denotes the permittivity of the dielectric (i.e.,  $\epsilon = \epsilon'\epsilon_0$ , F/m, where  $\epsilon'$  denotes the real dielectric constant or real permittivity or simply dielectric constant and  $\epsilon_0 = 8.85 \times 10^{-12}$ , F/m denotes the permittivity of space) and  $\sigma_c$  denotes the electric conductivity, mho/m. The effect of the (real) dielectric

constant,  $\epsilon'$ , of a dielectric in reducing the electric field,  $E$ , just outside the charged surface with charge density,  $\sigma$ , is illustrated by the relation,  $E = 2\pi\sigma[2/(1 + \epsilon')]$ .

Whenever the magnitude of the localized charge densities become such that the normal component of electric field to the surface becomes sufficient to evoke field emission (i.e.,  $10^6$  to  $10^7$  V/cm), then at the edges of the charged area, the electric field parallel to the surface, becomes of comparable magnitude. Such tangential electric fields create enhanced dielectric surface conductivity, thus permitting the charge to rapidly spread over much larger areas, so as to promote stability against electric or thermal discharge, before stray ion incidence; i.e., the spreading of the surface charge leaves an overall surface density smaller than that required for electric or thermal discharge, before stray ion incidence. The spreading of the surface charge leaves an overall surface density smaller than that required for electric or thermal discharge, by a factor denoted by the ratio of the original charged area, prior to said electric field induced conductivity, to the final spreading charged area attained.

The decay of surface charge on dielectrics is determined by the electron (or hole) conduction in the dielectrics. The degree of retention of surface charge on dielectric surface is a function of its carrier mobilities, such that decreasing the temperature means decreasing the carrier mobilities and hence increasing ability of charge retention. Hence, low temperatures means extremely low carrier mobility and hence high resistivity of dielectrics [6]. Furthermore, the heating of most organic, in contrast to inorganic, polymer dielectrics, even in vacuum, may cause surface oxidation and hence significant change of its properties (e.g., surface resistivity, electric strength, etc.).

Surface charges reside in various energy levels, some of which render charge mobility, while others do not. Unavailability of an occupation level induces the charge to create its own level by descending into its self-generated potential well, due to its own image in the dielectric surface. A charged dielectric, in principle, ceases to be a dielectric insulator. When electrons enter a dielectric, its electron traps become charged such that their resulting potential energy barriers stop further electrons from entering the conduction band, thus accounting for the high resistivity of dielectric insulators. Absence of freely or loosely bound mobile electrons in dielectrics is also attributed to their transparency.

## CONSIDERATIONS PERTINENT TO CHARGE CONTROL WITH CONDUCTIVE COATING AND GRID BONDED POLYMERS

The quiet time ambient environment is characterized by essentially low density (e.g.,  $\sim 1/\text{cm}^3$ ), low temperature (e.g.,  $\sim 10^4\text{K}$ ) hydrogen plasma. During geomagnetic substorms, the said spacecraft environment plasma at synchronous altitude depends substantially on local and universal time variations, during the midnight to dawn sector. The low energy plasma component decreases by 1 to 2 orders of magnitude and a hot plasma (e.g.,  $T_e \sim 10 \text{ keV}$ ,  $T_p \sim 2-6 T_e$  of ambient density of  $1/\text{cm}^3$ ) surrounds the spacecraft, with rapid time varying parameters. Although a portion of the trapped hot (e.g.,  $> 1 \text{ MeV}$ ) environment electrons occur at synchronous altitudes, these irradiations (e.g.,  $\sim 10^6 \text{ electrons/cm}^2/\text{sec}$  - omnidirectional) apparently do not contribute significantly to the spacecraft charging problem.

Since, during severe charging events, the incident ion or proton current may be a significant portion of the incident electron current (e.g.,  $\sim 10\%$  [ 7 ]), the proton induced secondary current,  $I_{ps}$ , is therefore significant and ought not be ignored, since the proton (exterior) scattering electron emission yield,  $\delta_{ps}(E) > \delta_s(E)$ , between 10 to 20 keV, at which incident electron and proton irradiations are maxima. During quiet synchronous altitude sunlit environment, the secondary electron current,  $I_{see} \ll I_{pe}$ . However, during severe charging events (substorms)  $I_{see} \approx I_{pe}$ , due to the primary electron irradiation current rising by about two orders of magnitude.

Whenever the spacecraft is in the said (hot) plasma environment, its potential is a function of whether its photoemissive yield (i.e., in sunlight) is significant. If so, the said potential is substantially controlled by the  $I_{pe}$  and  $I_{pE}$  relationship and thus significantly reduced, though of significant residual (negative) magnitude [ 7 ] (e.g., hectovolts). Without the (hot) plasma environment,  $I_{pE}$  dominates, if the photoemission yield is significant, and the resulting potential accrues from  $I_{pE} \sim 0$ . Without sunlight or with insignificant photoemission yield, the spacecraft charges negatively until its potential (e.g.,  $> -10 \text{ kV}$ ) significantly reduces  $I_{pe}$ . This potential should be distinguished from that of the sticking potential,  $V_s$ , of the dielectric surface, subjected to electron (and ion or proton) irradiation from the plasma. At about 1 keV, the secondary electron emission yield,  $\delta_{see}$ , and the stopping power,  $dE/dx$ , are comparable, i.e.,  $\delta_{see} \sim dE/dx$  and  $dE/dx \sim \ln E/E$ . So,  $\delta_{see}$  is put in the approximate energy-independent form [ 8 ]:  $\delta_{see}/dE/dx$ , which typically vary between  $\sim 0.015$  to  $\sim 0.025 \text{ l/MeV-cm}^2/\text{g}$ .

The coupling of insulated surfaces, in close proximity to the external environment is via the net charge on these surfaces rather than the differential charge. An inhomogeneous potential distribution surrounds the spacecraft, due to differential

charging. This follows from the fact that the spacecraft surfaces comprise a variety of materials with various electrical characteristics. Hence; dominant local current variations prevail and the various components of the spacecraft accumulate charge at various rates causing large voltages. Such differentially charged components in close proximity establish large electric fields and can lead to electric breakdown, externally and internally, whether in darkness or in sunlit shadows on the spacecraft. Such electrostatic discharge phenomena besides causing EMI, also degrades the spacecraft dielectrics, by tracking, causing carbonization of polymers and so altering their thermo-optical properties and so disturbing the thermal balance of the spacecraft. Even in sunlight, the dielectrics of the spacecraft beyond the terminator can accumulate large [ 7 ] negative potentials, provided that the charging time is small relative to the rotation period of the spacecraft.

Besides the differential charged components, as causes of electric discharges, there are the internal dielectric causes, for while charge deposition in dielectrics charges them, energy deposition causes ionization, inducing either: (1) transient conductivity (e.g., bombardment induced conductivity (BIC), which is electronic (EBC) and/or ionic; or (2) dielectric deterioration, due to the Thomas effect [ 9 ], for significant secondary electron emission and/or photoemission coefficients, with electron and/or ion or proton and/or photon irradiation of the dielectric. The transient conductivity relaxes the otherwise charge accumulation, due to irradiation of the dielectrics.

Electron penetration depth in polymers may be derived from analytical approximations or from tables [10]. In any event, this is of the order of 1/10 mil in typical polymers of spacecraft's thermo-optical control blankets (e.g., Kapton) at about 10 kV energy, in contrast to mils thickness of these dielectrics. In contrast, proton penetration may be derived by integration of the stopping power, which data are available [11]. For the said energy, the proton penetration is less than that for the electron.

Dielectric degradation of typical organic, in contrast to inorganic, polymers, utilized for the spacecraft's thermo-optical control blankets, are due essentially to:

1. Charge particle (e.g., electron, proton, etc.) and electromagnetic irradiation etching and aging; and
2. Electrostatic vacuum and residual gaseous discharge phenomena.

The former (i.e. #1) has already been commented upon in this text's INTRODUCTION. The latter, to be commented upon, causes carbonization and blackening of the organic polymer's surfaces, which disturbs the spacecraft's thermo-optical control.

TRANSPARENT SEMICONDUCTING COATING BONDED TO SOLID (OUTERMOST SHEET) DIELECTRIC, OF SPACECRAFT THERMO-OPTICAL CONTROL BLANKETS, ETC.

To mitigate the high resistivity ( $\gg 10^{12} \Omega\text{cm}$ ) of typical solid sheet dielectrics (e.g., Kapton, Teflon), utilized for the outermost sheet of spacecraft thermo-optical control blankets, etc., transparent semiconducting coating may be bonded to the surface of such dielectrics, thus affording:

1. Complete coverage of sufficiently low resistivity ( $\ll 10^9 \Omega\text{cm}$ ) and sufficiently high current capacity coating, bonded to said high resistivity dielectric, in order to dissipate to grounding terminals, the residing charge, due to the incident electron irradiation, even in the event that the secondary electron and/or photo-electric yields of the said coating are negligible.
2. Negligible optical screening or shielding, due to absence of opaque metallic grid, described elsewhere in this text.

Specifically binary anion - deficient oxides (e.g.,  $\text{In}_2\text{O}_3$ ,  $\text{SnO}_2$ ) are optically required, for transparent semiconductor coatings on high resistivity dielectric polymer substrates, for charge control, since their bond gap ( $\sim 3.5 \text{ eV}$ ) yields transparent (visible spectrum) coatings, for the outermost dielectric of spacecraft thermo-optic control blankets. The degree of doping controls the transparency beyond the absorption edge of the high transparent region, which decreases with decreasing resistivity of the semiconductor coating.

However, said semiconductors are chemically relatively unstable (i.e., readily oxidized (or reduced) since the free energies of oxide formation for  $\text{SnO}_2$  and  $\text{In}_2\text{O}_3$  at  $500^\circ\text{K}$  are  $-114$  and  $-123 \text{ kcal/mole}$ , respectively [12]. Furthermore, the host oxides are very hygroscopic (e.g.,  $\text{In}_2\text{O}_3$  decomposes partially into  $\text{In}(\text{OH})_3$  at  $<150^\circ\text{C}$ , which in turn decomposes to  $\text{InOOH}$  at  $200^\circ\text{C}$ , all of higher resistivities than the simple oxide. In the presence of moisture, single phase  $\text{In}_2\text{O}_3$  prevails at  $375^\circ\text{C}$  only [13]. Also  $\text{SnO}_2$  forms readily hydrates of  $\text{SnO}$  and  $\text{SnO}_2$  [14], all at higher resistivities than the simple oxide, of which the most stable is  $\text{SnO}_2 \cdot \text{H}_2\text{O}$  [15] of higher resistivity than the simple oxide. Relative to temperature stability, Sn doped  $\text{In}_2\text{O}_3$  coating by e.g., chemical vapor deposition [16,17] or vacuum evaporation [16,17] (as indicated for plastic or polymer substrates on account of temperature considerations) is satisfactory, as is the hardness, which is a function of the  $\text{SnO}_2$  content. The composition of the transparent binary oxides (e.g.,  $\text{SnO}_2:\text{In}_2\text{O}_3$ ), for relatively low temperature deposition required on a polymer (e.g., Kapton, Teflon) substrate, results in a relatively amorphous

structure, which is not at all as critical in every chemical respect, including the effect of the substrate on which the coatings are deposited, even though the said polymer substrates provide more pollution of copious mobile ions, than even glasses, which otherwise would diffuse into the transparent semiconductor binary oxides and inadvertently interstitially and/or substitutionally dope them at the normally much higher deposition temperature. Whether a dopant is effective normally as a source of charge carriers in a structured binary transparent semiconductor, depends upon whether its ionic size is sufficiently small, for a substitutional site, regardless of whether compound formation or solid solution prevails. Dopants are selected empirically since equilibrium phase diagrams for many binary anion-deficient oxides are not available [18]. Even in the ideal case, mixing equations for complex permittivities are much more difficult to solve in the equilibrium state, let alone for the nonequilibrium (reaction) state. Even in the equilibrium state, the results are already so complex that only qualitative properties accrue and these are of questionable practical merit even qualitatively, let alone as a quantitative guide, although some generalities do accrue [19,20]. Hence, resort to empirical mixing techniques prevail [6,21]. Nonstoichiometric  $\text{In}_2\text{O}_3$  and  $\text{SnO}_2$  semiconductors, due to oxygen vacancies, are relatively unstable without doping for donor or acceptor states. In the case of  $\text{In}_2\text{O}_3$ , the Sn atom dopant is utilized, which displaces the In atoms in the lattice to yield free electrons to the conduction band, on account of their greater valence. The optimum doping is much lower for higher deposition temperature (of the substrate) than for lower deposition temperature, though other factors of the deposition kinetics, determine the ratio of active to inactive dopant sites, created oxygen vacancies; etc. The optimum doping for sputtered oxides (and for reactive sputtering of In-Sn alloy) is about 20 mole % Sn in the binary oxide,  $\text{SnO}_2:\text{In}_2\text{O}_3$ , transparent semiconductor. The optimum doping for chemical vapor deposition is less than that, for the former deposition processes [16].

The surface resistivity of 20 mole %  $\text{SnO}_2:\text{In}_2\text{O}_3$  coatings [21] (e.g., 1000 Å thick) vary typically between  $>2$  and  $>10 \text{ K}\Omega/\square$ , for  $<10$  to  $>30$  mole %  $\text{SnO}_2:\text{In}_2\text{O}_3$ . The corresponding volume resistivity varies between  $600 \mu\Omega\text{cm}$ , to  $>3500 \mu\Omega\text{cm}$ , as deposited, for  $\sim 1000$  Å to  $>2000$  Å coating thickness. For thicker coating, the surface resistivity decreases radically, approaching an asymptote e.g., of the order of  $<50 \Omega/\square$  as deposited [21] at and beyond 2000 Å thickness. The radical variation of surface and bulk resistivity with said coating thicknesses from  $\sim 1000$  Å to  $> 2000$  Å is practically inconsequential, with respect to charging control considerations and even Joule heating considerations, since these resistivities are so much lower than the derived maximum of  $<10^9 \Omega\text{cm}$ , as discussed elsewhere in this text. Consequences of an electrical double layer, implied by Coehn's law [22] at the boundary, between said transparent semiconducting coating bonded to said typical polymers, has not been considered



in this text, neither has it been referred to in the literature.

For any semiconductor, if the residual lifetime of charge is short relative to the relaxation time for redistribution of charge, then the semiconductor will act like an insulator; otherwise, if the residual lifetime is sufficiently long, for a stable configuration of charge formation, then that semiconductor will act as a metal, provided that the size of the material is not comparable with the thickness of the surface layer within which the charge is accommodated. In other words, the cardinal parameter which characterizes an insulator is the time constant or relaxation time constant,  $\tau = \epsilon/\sigma_{cc}$  sec, for charge transfer, where  $\epsilon$  denotes the permittivity of the dielectric (i.e.,  $\epsilon = \epsilon' \epsilon_0$ , F/m, where  $\epsilon'$  denotes the real dielectric constant or real permittivity or simply dielectric constant,  $\epsilon_0 = 8.85 \times 10^{-12}$  F/m, denotes the permittivity of space, and  $\sigma$  denotes the electric conductivity, mho/m. The initial requirement to satisfy the resistivity of a dielectric for charge control is based on determining the ratio of reduced charge,  $\sigma/\epsilon \dot{m}$ , for the candidate dielectrics [23]. Reduced charge storage for candidate dielectrics denotes the initiation of charge leakage, whenever this ratio exceeds unity.

Since said polymer dielectrics exceed the threshold of  $10^{12}$   $\Omega\text{cm}$ , by a significant margin, charge storage on the surface will be limited by electric discharge in any residual gas, (e.g., during spacecraft outgassing by induced ionization from incident radiation) or by enhanced surface conduction by electron irradiation (EBC), or by spreading potential (i.e., tangential electric field at the edge of a charge path), which may approach in magnitude that of the normal electric field of the residing charge to abort step-wise transition to electric and/or thermal breakdown.

Therefore, resistivities of polymer substrates (e.g., Kapton, Teflon) have to be shunted to the degree that the exit charge (rates) and the charge leakage (rates) equate to the incident charge (rate), without encountering electric or thermal breakdown,  $V_c$ , as represented by the following equality:

$$I_{pe} + I_{pp} + I_{re} = -(I_{pE} + I_{see} + I_{ps} + I_{sl} + I_{vl})$$

where  $I_{pe}$  denotes the primary electron current, due to the plasma environment of the spacecraft;

$I_{pp}$  denotes the primary ion or proton current, due to the plasma environment of the spacecraft;

$I_{pE}$  denotes the exterior photoelectron current;

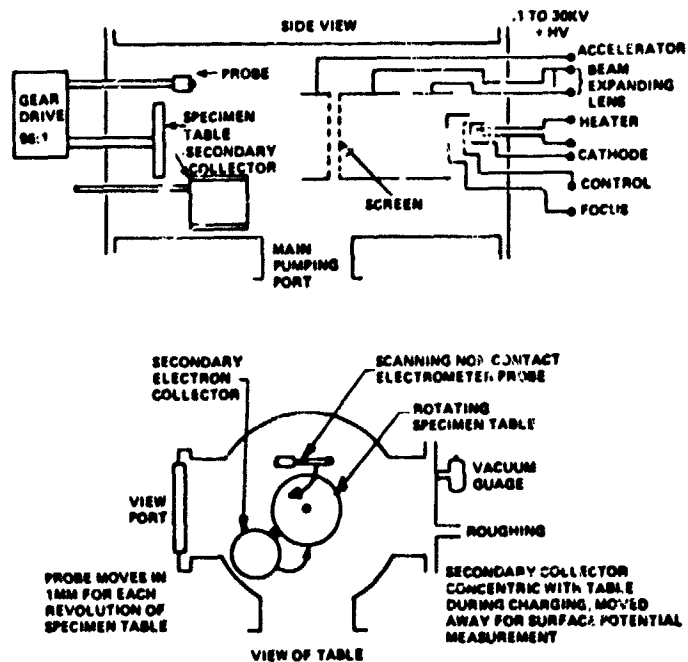
$I_{re}$  denotes the redistributed electron current or incident electron backscatter current;

- $I_{see}$  denotes the secondary electron emission current;
- $I_{ps}$  denotes the proton exterior scattering electron current (i.e., due to  $I_{pp}$ );
- $I_{sl}$  denotes the surface dielectric leakage current;
- $I_{vl}$  denotes the volume dielectric leakage current.

From the foregoing considerations, the foregoing equality may be satisfied without encountering step-wise transition to electric and thermal breakdown, due to differential charged surface components as well as within the polymers themselves, subject to environmental life test.

Pertinent data relative to the experimental aspect of transparent semiconductor coatings bonded to typical polymer substrates designed for spacecraft thermo-optical control blankets, etc., was presented elsewhere [24]

The foregoing current equality may be simulated in the laboratory to the degree warranted. For reasons to be briefly commented upon in the last section of this text, the said simulation is limited to currents,  $I_{ps}$ ,  $I_{re}$ ,  $I_{see}$ ,  $I_{sl}$ ,  $I_{vl}$ . Hence, an electron flood beam bombards said target polymer specimen in a vacuum chamber, as illustrated.



**METALLIC GRID BONDED TO SOLID (OUTERMOST SHEET) DIELECTRIC  
OF SPACECRAFT THERMO-OPTICAL CONTROL BLANKETS**

To mitigate to a substantial degree the deleterious effects of the high resistivity ( $> 10^{12} \Omega \text{cm}$ ) typical solid sheet dielectrics (e.g. Kapton, Teflon) which are utilized for the outer layer of spacecraft thermo-optical control blankets, an electrically conductive grid may be bonded to the outermost surface of such dielectrics so as to:

1. Subdivide the dielectric surface into proper and identical pane area. Thereby, the residing charge, due to electron irradiation, and hence associated potential energy available for step-wise transition to electric and/or thermal breakdown, along the surface (i.e., tracking) and/or through the dielectric, is limited so as to minimize or avoid failure of the dielectric.
2. Ensure that the pitch of the grid is so related to the propagation velocity of an electron avalanche, originating on a pane so that step-wise transition to electric and/or thermal breakdown along and/or through the dielectric is aborted. The cross-section of the filaments of the grid must be of adequate current capacity to avoid undue heating, as well as maintain structural integrity of the grid and afford sufficient total pane area for required thermo-optical control. Bonding of an electrically conducting grid, onto the typical outermost sheet polymer (e.g., Kapton, Teflon) of spacecraft thermal control blankets, requires consideration of:
  1. Induced conductivities accruing from simulated electron irradiation (i.e., 0 to ~30 keV energy and ~30 nA/cm<sup>2</sup>, flux) experienced by spacecraft, at synchronous orbit or altitude, from the enveloping plasma during the midnight to dawn sectors' geomagnetic substorm environment comprise:
    - 1.1 Bombardment induced conductivity (BIC).
      - 1.1.1 Electron bombardment induced conductivity (EBC).
    - 1.2 Photo-induced conductivity (PC), only during sunset periods.
    - 1.3 Normal electric field induced conductivity - the Rasch-Hinrichsen Relation.

1. Cont'd
  - 1.4 Malter avalanche interstice conductivity (MAC)
  - 1.5 Spreading potential induced conductivity.
2. Dielectric deterioration, due to the:
  - 2.1 Internal (surface layer) deterioration, due to the Thomas Effect [ 9 ], for significant secondary electron emission and/or photoemission yields on electron and/or proton and/or photon irradiation of said polymers.
  - 2.2 External surface dielectric deterioration, due to tracking phenomena
  - 2.3 Volume dielectric deterioration, due to:
    - 2.3.1 Treeing, coring, etc. in contaminated polymers, due to discharges in microscopic voids, cracks, filers, pits, etc., resulting in carbonization thereof.
    - 2.3.2 Ultra-violet and/or soft x-rays and charged particle bombardment erosion and chemical processes and products (e.g. ozone, nitric acid) of residual ionized gases.

Evaluation of the various cited induced conductivities, with respect to the said polymers, indicates that the spreading potential is of predominant influence in determining the grid geometry, for the adverse conditions of negligible secondary electron (and/or photoelectric) yield(s), as well as localized circular surface or spot charge on the dielectric, which may have a metal substrate.

The normal and tangential components of the electrostatic potential, due to said spot charge on the dielectric may be derived from classical considerations, [25] using series expansions by the method of images. Results of the necessary numerical integrations for this case of the potential (Green) function for the circular spot charge on the dielectric, on a metal substrate, are available [26]. The essential features of the results of said numerical integrations are:

1. The tangential component of the electric field,  $E_{1t}$ , (i.e., corresponding to the spreading potential referred to previously), at the edge of the spot charge can become substantial. In fact, it can become

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not only of substantial absolute magnitude but comparable to that of the perpendicular component, which is maximum over the center of the spot charge and nearly negligible at the edge of the spot.

2. The electrostatic field is more concentrated near the center of the spot charge and spreads out toward the edge and beyond.
3. Outside the charge spot, where the electrostatic field returns to the backplate, the field is much less, for the charge spot.
4. The negative electrostatic field outside the charge spot is nearly negligible.
5. The electrostatic fields are relatively independent of the dielectric thickness, sufficiently removed from the edge of the charge spot. Near the edge of the charge spot the electrostatic field intensity increases, as the dielectric thickness decreases. For equal charge densities, the electrostatic field near the edge is nearly independent of dielectric thickness, for equal charge density difference; and the electrostatic field, far from the edge of the spot charge, is nearly independent of dielectric thickness, for equal voltage.

The cardinal consideration relates to the tangential electrostatic field,  $E_{||}$ , to the dielectric at the edge of the spot charge. That is, at the rim of the spot charge, the parallel electric field component, comparable in magnitude to that of the normal electrostatic field component,  $E_{\perp}$ , not only enhances the surface conductivity [27, 28] of the dielectric, but permits the charge spot to spread out rapidly (e.g., ten times its original spot diameter) and thereby tends to restore stability against otherwise electric discharge, before arrival of any stray ion. Thereby, a dielectric surface may be charged completely, to grounding terminations, if any, or eventually lead to electric and/or thermal breakdown, for continued charging by incident electron irradiation. Whenever, the dielectric surface is limited by electric discharge, well after the induced surface conduction has equalized the charge distribution, that which is left is an overall surface charge density, less than that for corona breakdown, by a factor determined by the ratio of charging area to total area. A local charge spot or area on a dielectric is more stable than a larger area with the same surface density. Surface charge, with many qualifications, may be limited to the order of 3 keV/

cm<sup>2</sup> by electric discharge in a residual gas, however, attenuated. For a minute (e.g., <math>\overline{\text{mm}^2}</math>) spot charge on a dielectric, the limit of the area of the electric field for cumulative ionization, which may occur, increases the electric breakdown, so that higher charge densities will be stable. Still higher charge densities will be supported for brief periods, until a stray ion initiates an electric discharge, limited only by field emission, due to the normal electric field of such higher charge densities when charge spreading ensues. For the maximum normal component of the electric field of 30 kV, a comparable tangential electric field engenders a charge spot rim expansion at a radial tangential velocity  $v = 5.93 \times 10^5 (E_{11})^{1/2} = 3.25 \times 10^6$  m/s. The distance covered,  $S_d = vt$ , where

$$t = (1/5.93 \times 10^5) \int_{y=0}^{y=s} dy (E_{y0} + yF)^{1/2} \text{ and } F = E_{11}/s, \text{ V/cm,}$$

is equated to the step-wise transition to electric breakdown,  $t_{\text{SWTB}}$ , threshold of between  $10^{-8}$  to  $>10^{-9}$  sec. Hence, the radial distance,  $S_d$ , transversed by the rim of the spot charge amounts to 0.325 cm. Hence, the pitch,  $p = S_d 2^{1/2}/2$ , of a square net or array varies between  $\sim 3/32'' + \sim 1''$ , respectively, in vacuum,  $<10^{-3}$ T, and  $\sim 1''$  at  $pd = 4$ T, mm residual air (spacecraft outgassing). The governing criteria, for the grid filament geometry and cross section are the critical or electric breakdown field or potential or voltage at the grid filaments and the grid or mesh currents to the grounding terminations. Application of the Kilpatrick [29] (empirical) criterion, for vacuum breakdown; the Peek [30] (empirical) criterion and Felsenthal-Proud [31] criterion, for gaseous breakdown; and the Parr-Scarbrick [32] tracking criterion are considered elsewhere, [33] for the electrically conductive grid bonded to said typical polymers.

The determined grid parameters bonded to said typical polymers with or without metallic substrate are summarized in the accompanying table:

| $t_{\text{SWTB}}$       | $S_d$    | $p$      |
|-------------------------|----------|----------|
| $10^{-9}$ sec (min.)    | 0.325 cm | 0.229 cm |
| $10^{-8}$ sec (nominal) | 3.25 cm  | 2.28 cm  |

| Parameter      | Vacuum ( $<10^{-3}$ T.)       | Residual Air ( $pd=4$ Tmm) |
|----------------|-------------------------------|----------------------------|
| Lattice Pitch  | 3/32" to 1"                   | to 1"                      |
| Filament Size  | >2 to <10 mils D.             | 12.6 mils D.               |
| Dielectric Tk. | >2.5 to <15 <sup>+</sup> mils | 1 to <3.5 mils             |

These results denote order of magnitude anticipated.

The foregoing considerations assume that:

1. The bonding, between the electrically conducting grid and the dielectric is continuous; and that the
2. The grid filaments are continuous (no gaps) and are free of asperity;

Otherwise, the inception of surface discharges may ensue at the gaps and asperities. This prospect is particularly serious in sufficient ambient residual gas  $\gg 10^{-3}$ T. (e.g., due to outgassing). Furthermore, require absence of

3. scratches, pits, inclusions (e.g., gas filled voids, fibers, and impurities), on the surface and in the dielectrics (polymers), as they are sources of treeing, coring, tracking, and internal discharges, leading to dielectric deterioration and failure. In the case of voids, for example, some speculative parameters may be illustrated:

| Applied electric stress | Permitted air* NTP filled spherical cavities | Permitted discharge magnitude | Probability of potentially dangerous tubular cavities |
|-------------------------|--|-------------------------------|---|
| 2 kV/mm.                | < 1 mm.                                      | ~ 30pC                        | negligible  |
| 4 kV/mm.                | < 0.1 mm.                                    | < 0.05 pC                     | low   |
| >4 kV/mm.               | < 0.1 mm.                                    | < 0.05 pC                     | high  |

\* For lower pressure, discharges occur sooner.

The experimental results of the foregoing grid bonded polymers, for electrostatic discharge contro', are presented elsewhere [34].

There is another parameter which may affect the pitch of the lattice or grid pitch, if it is not small relative to the electron Debye length  $(\lambda_D)_e = (kT_e/4 n_e e^2)^{1/2} = 6.9 (T_e/n_e)^{1/2}$  cm. Where ions and electrons are not in thermal equilibrium, the ion Debye length  $(\lambda_D)_i$  is slightly different than  $(\lambda_D)_e$ :

|                     |     |     |     |     |
|---------------------|-----|-----|-----|-----|
| Height, Km.         | 100 | 150 | 200 | 400 |
| $(\lambda_D)_e$ cm. | 0.3 | 0.4 | 0.5 | 0.4 |
| $(\lambda_D)_i$ cm. | 0.3 | 0.3 | 0.4 | 0.3 |

Where  $k$ ,  $T_e$ ,  $n_e$ ,  $e$  denote the Boltzmann's constant, electron temperature, electron concentration and electron charge, respectively.

## BRIEF COMMENTARIES RELATIVE TO THE FACILITY FOR AND CHARACTERIZATION OF POLYMERS

The electron irradiated polymer specimen's characterization includes: I. Its VOLTAGE-CURRENT CHARACTERISTICS, comprising dependent variables, (1) surface and volume charging-discharging currents, (2) D.C. (and pulsed) secondary electron emission (SEE) current(s), and (3) the uniform or average primary electron beam current and if desired the former dependent variables (i.e., 1 and 2) normalized with respect to the latter (i.e., 3), as a function of independent variable, primary electron beam energy or voltage. The SEE collector and backplate potentials, specimen temperature and ambient gas pressure are parameters, with negligible photoelectron current and primary electron beam interception currents or the latter dependent-variable-corrected; II. ELECTROSTATIC DISCHARGE (ESD) PHENOMENOLOGY; and the III. ELECTROSTATIC POTENTIAL OR CHARGE DISTRIBUTION over the electron irradiated specimen's surface. These characterizations are determinable with the aid of the SS-ESD Facility, which essentially comprises a vacuum chamber with flood gun and specimen diagnostic instrumentation and power supplies. The vacuum chamber size is sufficient with large access ports for mounting, dismantling and adjusting spacecraft materials for characterization with electron beam irradiation. A component of the vacuum chamber is the electron flood gun, providing electron irradiation simulation of the space vehicle environment.

Said SS-ESD facility presently does not provide ion or proton irradiation. Although, Knott, et al. [35] have shown that proton irradiation does not significantly affect spacecraft charging periods, about 10% [7] of the incident electron current is attributed to protons. The latter's generated secondary current cannot be ignored. The reason for this assertion is simply because its yield is greater than that for the electrons in the vicinity of 10-20 KEV DC, where the incident electron and photon fluxes are maximum. The resulting difference in yield, enables the photon generated secondary current to be comparable to the electron generated secondary current.

The design of the said flood gun includes an electrostatic, three-element cylindrical lens with a parallel plane grid accelerator section, to assure uniform beam expansion and required electron energy at the spacecraft material in the restricted space of the chamber. Furthermore, control grids may be modulated to simulate the required electron energy and current density and distribution and provide pulsed secondary electron emission yield measurement capability. A wide range of adjustment in electron flux density and energy of the beam is available (e.g., 0 to 30 KVC and 30n A/cm<sup>2</sup> at the spacecraft material on the diagnostic table referred to).

The design of the specimen diagnostic table yields versatility, for the measurement of various electrical properties of spacecraft materials. It consists of an electrically isolated rotatable table for securing spacecraft materials up to about five inches in



diameter. The charging currents flowing along the surface and/or through the specimen may be monitored. A non-contact surface potential probe may be mounted on a movable arm, which is connected through a gear box to the rotating table. The gear ratio is such that for every rotation of the table the probe arm is advanced in millimeter steps, allowing the probe to track the surface of the sample, similar to that of a tone arm which tracks a record on a phonograph. This motion is driven by a DC reversible electric motor, which may be coupled to a resistance commutator for driving one axis of an X-Y recorder. A Monroe model 144 "Isoprobe" electrostatic voltmeter requires their #1009 probe. This is a feed-back electrostatic probe, which has high resolution and is relatively independent of probe-to-surface distance within its operating range. The required electronics incorporates a phase-lock loop amplifier, for the reduction of spurious pick-up and noise. During the electron irradiation, of the sample under test, said probe may be swung completely out of the way so no part of it will shadow the sample, during electron beam irradiation.

A secondary electron emission collector (cylinder) is also part of the diagnostic table assembly. This may be swung in place around the sample during the charging phase. It is used to monitor electrons leaving the surface of the sample. By pulsing the flood gun's electron beam, secondary electron emission yield measurement capability of dielectrics is provided.

Other salient features of the SS-EDS facility include a large viewing port for photographing samples during electron beam irradiation and for observation of electrostatic effects.

The applications of the author's foregoing designed and primarily developed SS-ESD facility, for characterizations of spacecraft materials was presented elsewhere [24], [33], [37]

#### APOLOGY

Allotted space and time precluded incorporation of the following two of the originally submitted abstract topics, i.e.; 1. Theory of polymer electron irradiation effects and aging, aside from the brief comments made elsewhere [24]; and 2. Theory of D.C. voltage-exponential current threshold characteristic conduction, transversely and longitudinally, between close and loose packed dielectric cylinders (e.g., silica fiber fabric, for which experimental transverse (exponential) electrical resistance data already exists [1,2]).

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