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6. Secondary Emission Conductivity of High Purity Silica Fabric *

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Abstract

High purity silica fabrics have been proposed for use as a material to control the effects of electrostatic charging of satellites at synchronous altitudes. These materials have exhibited very quiet behavior when placed in simulated charging environments as opposed to other dielectrics used for passive thermal control which exhibit varying degrees of electrical arcing. Secondary emission conductivity is proposed as a mechanism for this superior behavior.

Design of experiments to measure this phenomena and data taken in GE research facilities on silica fabrics are discussed as they relate to electrostatic discharge (ESD) control on geosynchronous orbit spacecraft. Studies include the apparent change in resistivity of the material as a function of the electron beam energy, flux intensity, and the effect of varying electric fields impressed across the material under test.

1. INTRODUCTION

While the temperature of a satellite can be adjusted through the use of active and semiactive devices such as louvers and heat pipes, the thermal designer relies

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heavily on passive techniques. Here the amount of heat into a spacecraft by incident solar illumination and the amount radiated or reradiated at infrared wavelenghts is adjusted by selecting external materials and coatings with appropriate reflectances, absorptances, and emittances. Because this passive temperature control subsystem comprises the entire outer shell of a satellite, it must bear directly the brunt of the indigenous space environment. At geosynchronous altitudes this includes the electron plasma which can produce static charge buildup with the attendant problems of electrical arcing and discharging.

The most critical elements in a spacecraft passive temperature control subsystem are the white, high emittance coatings used not only to reflect a major portion of incident solar energy, but also to dissipate internally generated heat. Historically, white paints employing zinc or titanium oxides have been used. However, these have been shown to degrade rapidly by discoloration under solar ultraviolet illumination. The degradation is manifested by a decrease in the amount of incident solar energy that is reflected, which results in increased surface and subsequent equilibrium temperature because the energy which is not reflected is absorbed by the coating.

Solar reflecting coatings derived from fabrics produced from high purity silica (SiO_2) yarn such as those available under the J. P. Stevens Company's Astroquartz trademark have been shown to be extremely stable to the damaging radiation components of space.[1] The high radiation stability which is typical of high purity SiO_2 is derived from the fabric by merely removing the sizing or finish placed on the yarn to facilitate weaving by baking in air at temperatures in the 800 to 1000°C range. The solar reflectance of the processed fabric is in excess of 0.82 while its hemispherical emittance is 0.82 at 0°C. A total loss in reflectance of only 0.03 is experienced after long term exposure to solar ultraviolet radiation.

To obtain high solar reflecting, high emittance characteristics, only dielectric materials can be used. These of course will support static charge buildup at geosynchronous orbit. Electrically conducting materials in many instances exhibit high reflectances to solar energy, but without exception have low thermal emittances which violate the requirements for solar reflecting coating applications.

At the onset of this study it was planned to investigate modifications of the strictly dielectric characteristics of silica fabric by interweaving occasional conductive yarns, such as aluminum or stainless steel, within the material. These would provide paths for the drainage of static charge as it develops in geosynchronous orbit missions. Conductor spacings were to be close enough to effect reduction of large surface gradients.

Although the experimental plan called for fabrication of silica/metal yarn interweaves, baseline data collected initially for silica fabric itself showed that the fabric did not support charge buildup under electron beam bombardment at energies to at least 30 keV with associated current densities in excess of 30 nA/cm^2. This seemed to be anomalous in view of the high resistivity of silica which is in excess of 10^{17} ohm/m at ambient conditions. This study, then, was undertaken to explain the unusual behavior exhibited by silica fabric under bombardment by highly energetic electron beams designed to simulate conditions found at geosynchronous altitudes.

2. REVIEW OF THE SECONDARY EMISSION PROCESS

Behavior of silica fabrics in a simulated plasma charging environment indicated that the secondary electron emission (SEE) process would be the overriding consideration in the absence of photoelectric effect due to solar illumination. Solar illumination, of course, will not play an important role in neutralizing static charge buildup during that time a geosynchronous spacecraft is in umbra which has been shown to be the most probable time for anomalous events.[2] Knott[3] has also shown the importance of SEE in the equilibrium process for nonilluminated spacecraft.

Experimental data on the secondary emission of materials yield the characteristically shaped curve in Figure 1 which is common to most substances. This curve relates the secondary emission ratio (δ) to the energy of the bombarding primaries (E_P). For most metals and graphite, δ does not exceed 1; however, a slight oxide layer on a metal can produce a much higher value for δ.

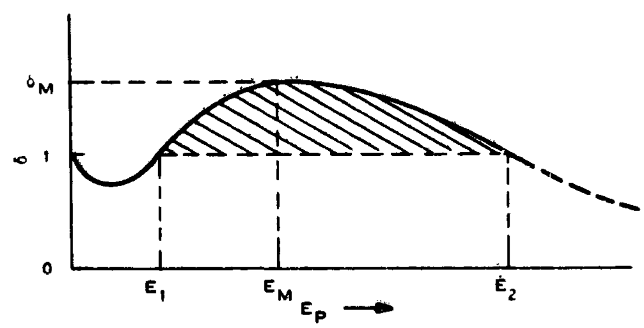


Figure 1. Characteristic Secondary Emission Curve for Most Materials

The primary features of interest in this characteristic are: E_1, the first crossover, E_2, the second crossover, E_M, the primary energy of maximum δ, δ_M, the maximum secondary emission ratio, and the cross-hatched area where the secondary emission ratio is greater than 1. A simplified explanation for the shape of the curve would be that the secondary emission ratio increases with increasing primary energy. However, these secondaries are generated along the path of the primary electron as it penetrates into the crystal lattice of the material and the secondaries must then diffuse to the surface where they can be emitted as a free secondary electron. Associated with this diffusion is a diffusion probability that is a decreasing function of path length. At the point E_M in the characteristic, $\delta(E_P)$ becomes dominated by the decreasing diffusion probability and, hence, passes through a maximum. This, of course, has been more rigorously treated by many authors. The Sternglass approximation discussed by Dekker[4] is most frequently cited. His approximation for this function is semi-empirical and considers electron shell structure of materials as related to atomic number. This approximation has been shown to correlate well with experimental data when corrected for backscattered electrons.

The major shortcoming of the Sternglass approximation is that it does not consider non-normal incidence primaries. Again, Dekker,[4] in interpreting efforts by Bruning, has shown that $\delta(E_P)$ is a strong function of the primary incidence angle with an approximate $1/\cos\theta$ dependence. This dependence has the effect of both increasing δ_M and shifting E_2 towards the higher energy primaries thus increasing the cross-hatched area shown in Figure 1. From this and consideration of the surface geometry in silica fabric, which has the following characteristic numbers for normal incidence primaries

δ_{max} = 2.1 to 2.9
E_{max} = 400 to 440 eV
E_1 = 30 to 50 eV
E_2 = 2.3 keV

it can be concluded that secondary emission conductivity can effectively reduce differential charging in the electron bombardment environment found at geosynchronous orbit.

3. SECONDARY EMISSION CONDUCTIVITY

Secondary Emission Conductivity (SEC) is a well known process used primarily in image processing vacuum tubes such as the SEC Vidicon TV camera tube. SEC targets used in these tubes are somewhat different than silica fabric; however, they have in common an inorganic dielectric matrix mixed with continuous voids of free space. Generally speaking, inorganic dielectrics have secondary emission ratios greater than 1. Silica, for example, runs from 2 to 3 for normal incidence primaries. This ratio can go much higher for non-normal and grazing incidence. As will be shown later, this increase in the peak secondary emission ratio (δ_M) and the shift of the second cross-over towards higher energy primaries for non-normal incidence primaries contributes to the enhancement of SEC in silica fabrics. Both of these shifts may be viewed as in increase in that area of the secondary emission curve which lies above the $\delta = 1$ line. Figure 2 illustrates the SEC process as related to a quartz fiber yarn fabric.

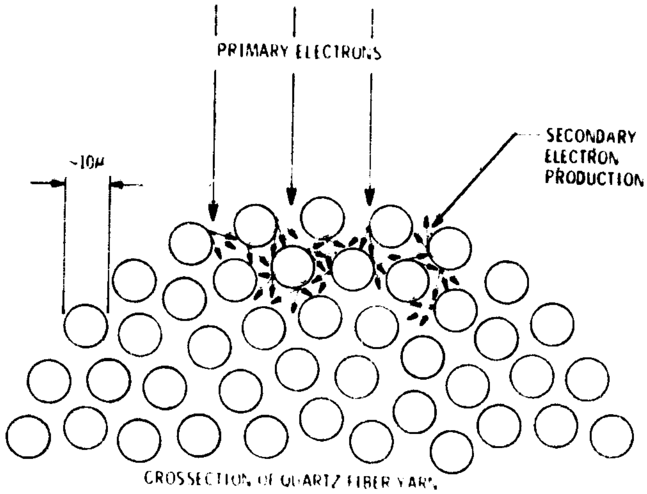


Figure 2. The SEC Process as Related to a Quartz Fiber Yarn Fabric

Because secondary electrons generated have energies less than 10 eV and therefore have a longer mean life time as compared to primaries given the same mean free path, the SEC process, (Figure 2), continues until free electrons exist in all the inter-fiber voids. This mean free path is, of course, a mechanical property of the dielectric matrix and is therefore the same for both secondaries and primaries.

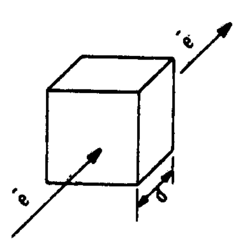
A typical silica fabric contains 10-μ diameter filaments. Approximately 250 filaments are contained in a yarn strand and 16 strands or more are used to produce a weaving yarn. There are nominally 60 weaving yarns per lineal inch of fabric so each contains almost a quarter of a million filaments. From this, it is evident that there is an extremely large surface to volume ratio associated with silica fabric which is an essential criteria for SEC effect. Secondary electron emission being primarily a surface effect is the contributing factor responsible for this surface to a volume ratio dependence.

Secondaries may then be thought of as a cloud of free charges within the dielectric matrix and in the presence of an electric field will migrate through the matrix in the direction of that field much in the same manner as charge carriers move through a conductor. If the field is caused by a differential charge residing on the dielectric, conductivity will continue until the differential charge is neutralized and the E field dissipated.

The SEC effect should not be confused with electron bombardment induced conductivity (EBIC), a somewhat related phenomena exhibited in dielectric solids, since the EBIC effect is not a surface process as is SEC. Both processes require electron bombardment and an external electric field to cause the generated secondaries to drift producing a conduction current through the material. In the EBIC process the internal secondaries drift in the conduction band of the solid, while in the SEC process secondaries are "emitted" and move under the influence of the field through the vacuum space in the pores of a low density dielectric.[5]

4. CHARGE DENSITY AMPLIFICATION

Several questions may arise from the discussion so far. What is the population density of the free electrons in the fabric? And since the fabric behaves like a conductor in a charge bombardment environment, will it attenuate the propagation of electromagnetic radiation? These questions are related since electromagnetic wave propagation is affected by the presence of a plasma medium. Subsequently it will be shown that the free electron density in the fabric is low enough to have negligible effect on wave propagation at communications frequencies. This will be a non-rigorous analysis of the free electron population/concentration within the fabric.



The three controlling factors of this phenomena are, as discussed in previous sections: the fixed mean free path independent of velocity; the low velocity of secondary electrons; and the high secondary emission ratio of the fused silica enhanced by non-normal incidence of the primary beam.

Consider a finite volume in space of cubic dimensions (d) subject to an electron flux. The average charge density (σ) inside this volume will be proportional to the time (t) that an electron is within its boundaries. Since

$$t = \frac{d}{V_e},$$

and since

$$\sigma \propto t,$$

the charge density is inversely proportional to the electron velocity. If an electron were to slow down from V_p to V_s, there would be a resultant increase in charge density ($\Delta\sigma$) which would be proportional to the velocity ratio

$$\Delta\sigma \simeq \frac{V_p}{V_s} .$$

The velocity of an electron is proportional to the square root of its energy and by convention the velocity of an electron is usually referred to by its energy, therefore

$$\Delta\sigma = \sqrt{\frac{E_p}{E_s}} .$$

The charge density can also be increased by increasing the electron flux which essentially occurs with the secondary emission process concurrently with a velocity reduction so in effect if there is secondary emission within this finite volume, the charge density increase is approximated by

$$\Delta\sigma \simeq \delta\sqrt{\frac{E_p}{E_s}}$$

where (δ) is the secondary emission ratio.

Considering a primary electron energy of 10 keV, the fact that secondary electrons are within the 10 eV order of magnitude and an approximate secondary emission ratio of 10 within the silica fabric,

$$\Delta\sigma \simeq 10\sqrt{\frac{10^4}{10}} \approx 320$$

it appears that the free charge density within the fabric will be approximately 320 times the charge density in the primary electron environment.

Traditional metal conductors which could be modeled as solid plasma have free charge concentrations many orders of magnitude greater than that estimated for the fabric. For the purpose of electromagnetic radiation shielding, therefore, the fabric will not behave as a conductor and further calculation using theories developed for wave propagation in plasma would show the charge concentration levels here to be of little consequence in attenuating electromagnetic radiation.

5. SECONDARY EMISSION CONDUCTIVITY IN SILICA FABRIC

Tests were performed to measure SEC for several silica fabrics. Results of these tests explain the superior behavior of this material when subjected to a plasma environment.

Silica fabrics were subjected to bombardment by an electron beam with a known electric field imposed across the cross-section of the fabric. This was accomplished by mounting a fabric sample on a conductive backplate. The sample was held in place by a wire screen (~90 percent transmission) in intimate contact with the fabric. A potential was placed between the screen and the backplate and the current flow monitored while varying the potential across the fabric. Resistance of the fabric was calculated from the V/I characteristics as a function of beam energy and density. Figure 3 shows this test configuration schematically.

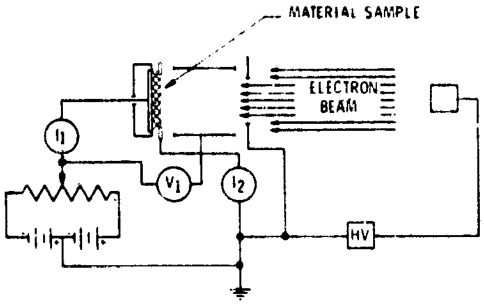


Figure 3. Schematic of Secondary Emission Conductivity Test

Voltage (V_1) was varied and the current (I_1) was measured. These were used to calculate the resistances of the silica fabrics which are shown in Figure 4 for J. P. Stevens Style 581 and Figure 5 for Style 570 Astroquartz Fabrics.* As shown in these figures both fabrics exhibit a constant resistance out to 50 to 75 V across the fabric with the Style 581 having the lower resistance of the two. The resistance, however, is much lower than the dc resistance of the fabric due to the presence of the bombarding beam. This resistance then decreases as the voltage across the fabric is increased until it reaches another plateau above 120 to 150 V. This plateau results from depletion of the free charge carriers within the cloth as the bombarding beam can no longer sustain the requirement for charge carriers in the fabric. This saturation results from the fact that the experiment is forcing a potential across the cloth; whereas, in an actual space environment, the potential will disappear as the charges are depleted. This is further evidenced by the lower resistance characteristics which develop as the current density of the beam is increased.

Though it was more difficult to measure and control the bombarding beam when its energy was reduced below 3 keV, it appears that lower energy bombardment would further enhance the conductivity of the fabric. This is substantiated by the fact that above the $\delta = 1$ line, the area under the secondary emission curve increases as integration is extended towards the lower energy primary electrons.

*Style 581 is an 11-mil thick fabric which weighs 8 oz/yd^2, while Style 570 is 27 mils thick with a weight of 19 oz/yd^2.

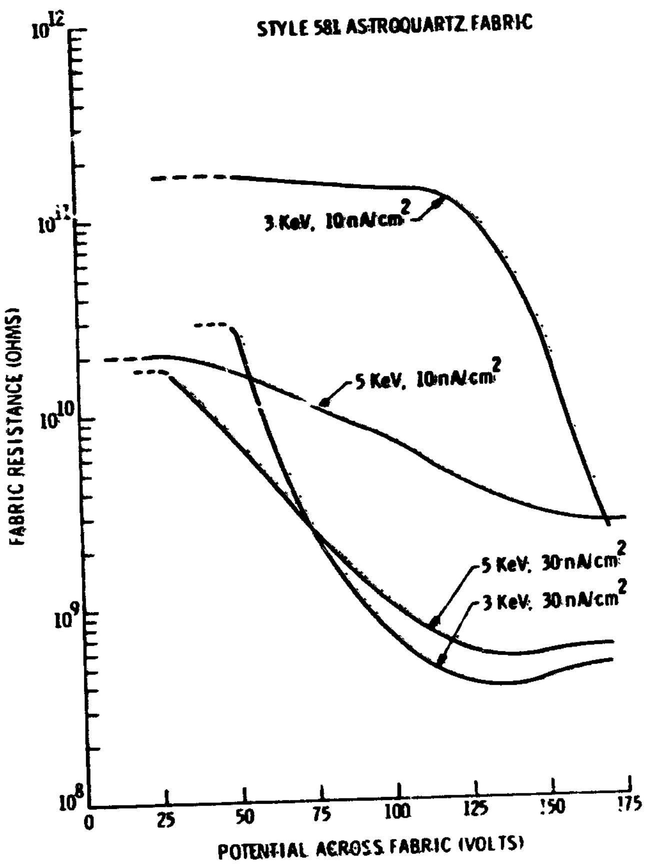


Figure 4. Resistivity of Style 581 Astroquartz Under Electron Bombardment

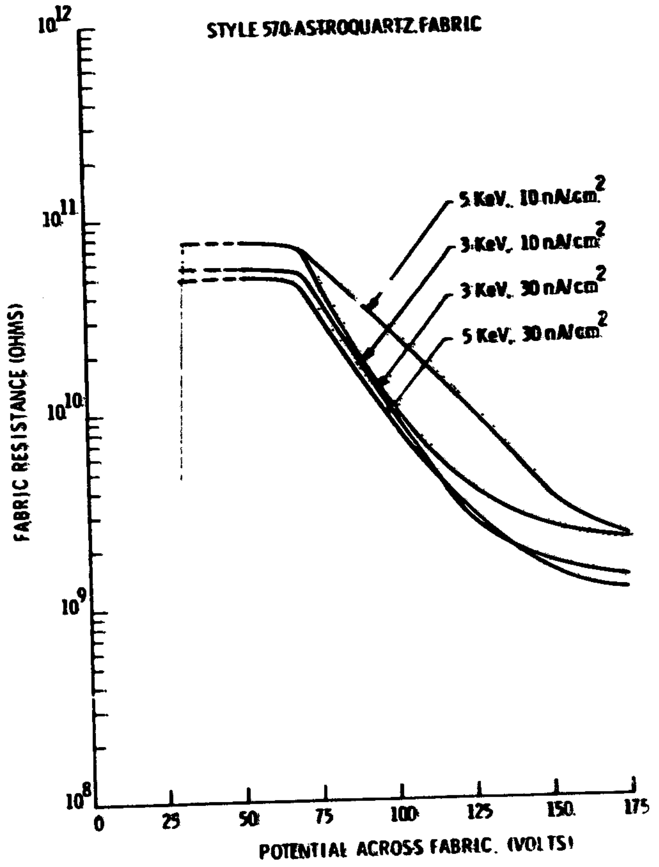


Figure 5. Resistivity of Style 570 Astroquartz Under Electron Bombardment

As the beam energy is increased above 5 keV, the resistance of the fabric tends to increase because the incident electrons generate secondaries deeper within the material where they are unavailable to act as charge carriers near the first surface (wire screen side). In this case the test tends to be pessimistic because at geosynchronous altitud .. there are always 3 to 5 keV electrons present to generate secondaries near the surface.

In reviewing the results of this experiment it would appear that in an actual environment, where this is a continuous distribution of electron energies, the fabric can be expected to support no more than a 200 V gradient. In fact from conversations with Walter Viehman[6] of NASA Goddard, measurements were conducted in his laboratory which indicated that a 100 V gradient would probably be the maximum encountered. This is in contrast to the kilovolt order static potentials measured at GE and NASA-LeRC in other experiments using monoenergetic electron beams with energies greater than 5 keV.

6. ELECTROSTATIC DISCHARGE INDUCED RADIO FREQUENCY INTERFERENCE

In considering the process by which deposited charge is redistributed within silica fabric, the possibility of micro-discharge was considered. These could conceivably produce electro-magnetic radiation causing radio frequency interference (RFI) to electronic subsystems. In an effort to study these effects an experiment was conducted to measure radiation in proximity to materials in an electron bombardment environment.

Material samples were placed in an evacuated Bell-jar mounted on a grounded metal plate. A Brad-Thompson Industries electron gun was employed as the electron beam source. A thin film of gold (200 Å) was deposited on the inside surface of the Bell-jar. This film is used to prevent a charge buildup on the inside glass surface and possible RFI from spurious discharges. This conductive film was so thin that it produced little attenuation of the electrostatic discharge (ESD) propagated field (3 dB loss at 100 kHz and 0.0 dB loss at 1 MHz). All tests were performed in a shielded room which effectively prevented externally produced fields from interfering with the measurements and of the ESD propagated fields. The setup is shown schematically in Figure 6.

Samples were bombarded by a high energy monoenergetic electron beam at a current density of 5 nA/cm^2 which is greater than that normally experienced during geomagnetic substorms. The beam voltage was varied from 5 to 25 kV. Field strength data were measured at 30 cm from the interference source and is expressed in units of dB relative to an arbitrary level. Calibrated, tuned antennas were used to measure the ESD produced fields. The spectral density at UHF, X- and S-band

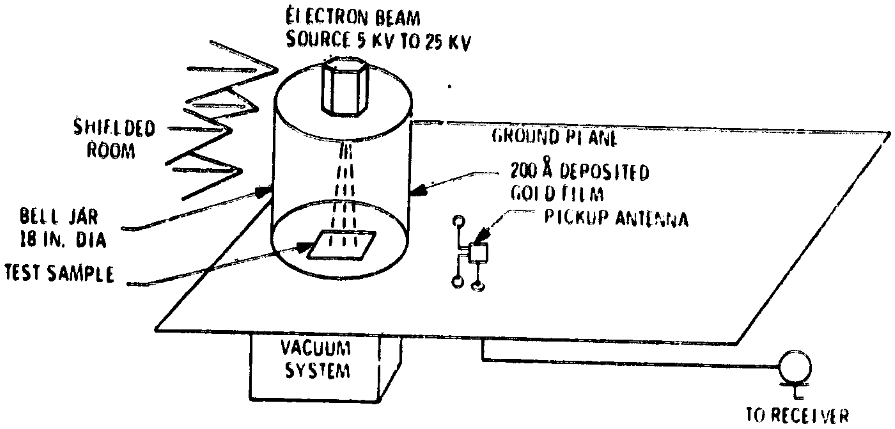


Figure 6. Experimental Test Set-up for ESD Induced RFI Spectrum Measurements

were of primary concern. The antennas were sufficiently directive to reduce the influence of the propagated fields produced by the electron gun source itself. This can be explained as follows. The potential difference between the electron gun and the samples changes simultaneously with the electrostatic discharge and the change in this potential difference produces a propagating field. A directive antenna effectively reduces this source of spurious fields. The results of the ESD induced RFI field measurements are shown in Figure 7.

The materials evaluated in this experiment were:

(1) A conventional multilayer insulation blanket consisting of 15 layers of 1/2 mil aluminized Mylar with an outer (top) layer of 2 mil thick single sided aluminized Kapton placed with the uncoated side facing out. All metallic film surfaces were connected to a common ground point with a ground strap.

(2) A multilayer insulation blanket identical to that described in (1) above but with an outer layer of J. P. Stevens, Style 503 Astroquartz fabric (8 mils thick - weighing 3.5 oz/yd^2) which had been baked at 800°C for two hours to remove sizing.

(3) A 6-in. aluminum disc with 2 × 2 cm glass covered silicon solar cells bonded to the disc with Eccobond 57C conductive adhesive. This solar array composite was grounded via a strap attached to the back of the aluminum plate.

(4) Optical Solar Reflector (OSR) tiles bonded to a 6-in. diameter aluminum plate with Eccobond 57C conductive adhesive. A ground strap was connected to the back face of the aluminum disc of this OSR composite.

(5) Two layers of J. P. Stevens, Style 581 Astroquartz Fabric (each 8 mils thick and weighing 8 oz/yd^2 per layer) baked at 600°C for three hours to remove sizing. Both layers were tied to a common ground point with a ground strap.

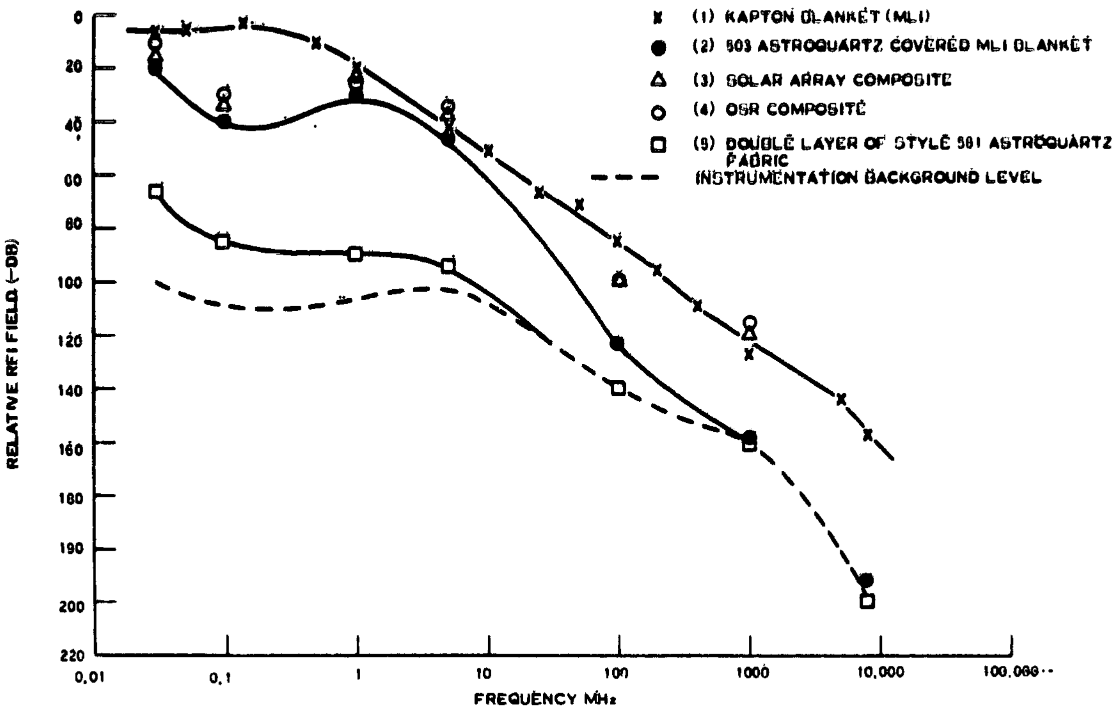


Figure 7. Electric Field Strength Spectral Distribution for Some Spacecraft Materials Under 15 kV - 5 nA/cm^2 Electron Bombardment

Results obtained from this series of ESD induced RFI tests, indicate that the multilayer insulation blanket with the Kapton outer covering, OSR plates, and solar cell arrays produce substantial RFI field strengths in the frequency range 100 to 10,000 MHz. Astroquartz 503 and 581 (especially) produced significantly little or no RFI field strengths in the 100 to 10,000 MHz frequency range. It should also be noted that about 1000 MHz where most spacecraft communication is done, the RFI generated by the silica fabric samples were within experiment noise.

7. CONCLUSIONS

Silica fabric exhibits rather unique behavior as a dielectric spacecraft thermal control coating. It has been shown that it will not sustain a differential charge in excess of 100 V while in a simulated electron plasma charging environment. This is contrary to the behavior of other dielectrics tested under similar conditions. Secondary emission conductivity has been established as the process responsible for this desirable characteristic. Essentially, the primary beam is transmitted through the material after reducing its velocity to under 100 eV, where it can be harmlessly conducted and uniformly distributed to the spacecraft structure. Through active means such as electron guns or plasma engines the structure potential can be controlled with respect to the plasma if mission requirements dictate.

As the bombardment intensity increases the resistivity of the material correspondingly decreases to maintain a fixed differential potential, thus the material acts as a passive control device in a changing environment employing a process much like dc conductivity. Other dielectrics redistribute charge by electrical arcing and hence can produce significant RFI which can disrupt a variety of spacecraft subsystems. Though the fabric behaves like a conductor during bombardment, the charge carrier density in the material is sufficiently low so that it does not interfere with propagation of electromagnetic radiation. This means the material can be used even over antennas and feed horns.

So far, testing of this material has been done with monoenergetic electron beams. In the actual environment, the charged, bombarding particles will be distributed over a broad range of energies from a few eV to possibly 50 keV; however, the major portion of the population will be below 10 keV. With the low energy component always present secondary emission will be greater and the fabric behavior can be expected to be much improved as compared to the results reported here. Monoenergetic bombardment is the most conservative test that can be done on materials which depend on high secondary emission for desirable behavior unless the bombarding energy is held within their most efficient emission range.

High purity silica fabrics should be considered as a prime candidate for thermal control application on geosynchronous satellites. The properties discussed here show what can be expected of the material, and with utilization design, its benefits can be maximized for each spacecraft application.

Acknowledgments

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