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ELECTRON BREMSSTRAHLUNG SHIELDING AT SYNCHRONOUS ALTITUDE BY ELECTRON TRAPPING IN DIELECTRICS

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16. ABSTRACT

A theoretical study is made of synchronous altitude electron bremsstrahlung shielding by electron trapping in a layer of dielectric material on the outer surface of a spacecraft. Traps in the insulating material retain bombarding electrons and thereby produce an internal spacecharge field of large magnitude. The electric field repels or slows additional electrons. This acts to reduce bremsstrahlung production, lower the photon energy, and enhance photon absorption. The breakdown phenomenon causes the shielding effect of the trapped electrons to be cyclic. Qualitative calculations indicate that a 40 percent decrease in mass results when a thin layer of polyethylene instead of lead is used in reducing bremsstrahlung in an aluminum wall to the same level. Suggestions are given to modify existing Monte Carlo codes for this particular application.

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SUMMARY

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INTRODUCTION

Space stations and laboratories located at synchronous altitude will be subjected to energetic electrons with energies ranging past 1.5 MeV. Although the electron dose rate inside a space vehicle with 2 g/cm^2 aluminum walls will be negligible, the bremsstrahlung from electron-aluminum interaction is reported by Burrell, et al. [1] to be about 0.3 rad/day. Thus bremsstrahlung is a hazard to astronauts stationed aboard the space vehicle for an extended period of time. Damage to film and possibly to some equipment may occur also. Protons in this region are not energetic enough to penetrate the wall, and since their bremsstrahlung is negligible, they are not important from a shielding viewpoint.

The synchronous orbital region occurs at 6.6 earth radii from the earth's center. Here the gas pressure is of the order of 10^{-9} $dyne/cm^2$, or 10^{-12} torr, and the H^+ gas density is about 10^2 cm^{-3}. Values of the trapped electron fluxes are shown in Table 1 [2].

TABLE 1. TRAPPED ELECTRON FLUXES IN THE EQUATORIAL PLANE AT SYNCHRONOUS ALTITUDE

$n(E > 40\ \text{keV})$: $3(10^7)$ to $2(10^8)$ $cm^{-2}\ sec^{-1}$
$n(E > 230\ \text{keV})$: $2(10^6)$ $cm^{-2}\ sec^{-1}$
$n(E > 1.6\ \text{MeV})$: $3(10^5)$ $cm^{-2}\ sec^{-1}$

A time average electron integral flux for the synchronous orbit is [1]:

$$n(>E) = 5.2\ (10^7)\ \exp\ (-5E)\ cm^{-2}\ sec^{-1} \quad . \tag{1}$$

Bremsstrahlung dose rate for an average electron spectrum at synchronous orbit varies from 0.6 rad/day for no shield to 0.2 rad/day for 3 g/cm^2 aluminum [1]. In other words, an aluminum shield has relatively little effect against bremsstrahlung for moderate thicknesses. This is not surprising, since bremsstrahlung production occurs near the entrance plane of the shield, and since the absorption coefficient is relatively low for aluminum even though the radiation spectrum is peaked toward lower energies. Hence, there is a large weight penalty with the increase in aluminum wall thickness necessary to reduce the radiation to safe levels. A high Z material, such as lead, attenuates bremsstrahlung much more effectively, and a thin layer would suffice to adequately absorb the radiation. The greater density of lead, however, still results in a large amount of excess mass.

Electrons can be prevented from striking a spacecraft by surrounding it with a magnetic field. Much has been done on the shielding of very energetic particles by this method, and at first it might appear that weak fields would be sufficient to repel the less energetic electrons of the outer magnetosphere. Levy [3] points out, however, that at least 10^5 amperes are required to produce fields which repel electrons of several MeV. Such a system would increase considerably the complexity and mass of the spacecraft.

Charge buildup because of excess electrons may develop on the outer metallic surface, and the resulting electric field would repel additional negative particles. Since synchronous altitude is near the vacuum-geomagnetic interface, the magnetic field provides a mechanism which can lead to charge separation [4]. This phenomenon is explained by the differences in gyration radii of the electrons and their ions which for the same kinetic energy and field have a ratio equal to the square root of the masses. The gyration radius of an electron is about 1/40th of the proton radius for nonrelativistic conditions. Electrons are thus closely coupled to the B-lines, while solar wind protons orbit farther into the magnetosphere. If this excess electron population exists, it probably is slight in view of the reported electron density of 10^2 electrons/cm^3 [2]. Because of the lack of empirical data on charge excess in this region, any analysis based on present understanding would be too speculative.

Charge buildup from electron bombardment does occur in dielectrics, and large electric fields are produced inside the material. The objective of this investigation is to examine the feasibility of utilizing this phenomenon in an electron bremsstrahlung shield.

ELECTRON TRAPPING

Dielectrics are characterized by a forbidden energy zone of several eV between the valence and conduction bands. Atomic impurities, dislocations, or other imperfections in the crystal produce levels in the forbidden band which can capture an electron or hole. The number of these traps normally existing in materials is large; in fact, Kittel [5] states that it is difficult to grow crystals with trap concentrations less than 10^{14} cm^{-3}. Not all insulators have crystalline form. Organic polymers (particularly pertinent to this discussion) consist of molecular chains rather than lattice arrays. Their insulation properties are explained by an absence of a conduction mechanism under ordinary conditions. However, disruptions in the molecular bond structure can result in the formation of electron traps which are effective in retaining these particles. Fowler [6] reports electron trap densities greater than (10^{17}) cm^{-3} in polyethylene terephtholate. Some of these traps are induced by radiation, and trapping of incident electrons results in charge buildup which remains for extended periods of time [7, 8]. The charge buildup produces large electric fields with repulsive potentials which can exceed the accelerating potential of the impinging electrons. In addition to collision losses, the space charge field is responsible for energy losses of the incoming electrons which increase while breakdown is approached [9]. As breakdown conditions are reached, the space charge layer recedes toward the incident surface of the material. A model has been developed by Gross and Nablo which describes the principal features of the process. The space-charge field E_o is considered constant for a given range R of the electrons and is written as:

$$E_o = -U_o\left(R^{-1} - R_m{}^{-1}\right) \quad , \tag{2}$$

where eU_o is the energy of incidence and R_m is the maximum electron range. Electron charge in coulombs is designated by e. Energy loss per unit length due to the space-charge field is $-eE_o$. Maximum range occurs with no electric field:

$$R_m = U_o(e/a) \quad , \tag{3}$$

where a represents the ionization and excitation collision losses per unit length. Let x be the depth in the material and D its thickness. Space-charge density is:

$$\rho(x) = \epsilon U_o D/x^2(D - x) \quad , \tag{4}$$

where ϵ is the dielectric constant. Intensity of the incident electron beam is designated by n electrons cm^{-2} sec^{-1}, and total charge per unit area is:

$$net = \epsilon U_o \left[\frac{R_m - R}{R_m R} + D^{-1} \ln \frac{R_m(D - R)}{R(D - R_m)} \right] . \tag{5}$$

Total power loss per unit area of the electrons as they penetrate into the dielectric material is:

$$dW/dt = naR + neU_o \; (1 - R/R_m) \tag{6}$$

Since the first term is collision loss, the second accounts for energy loss due to the electric field. Electron energy lost per unit area to the electric field is:

$$\phi = \int_o^t neU_o \; (1 - R/R_m) \; dt \tag{7}$$

An expression for R as a function of time t can be obtained from equation (5). Gross and Nablo [10] give an equation only for the limiting case of $R_m/D \to 0$. For space applications, this restriction is not practical; therefore, a more general statement is required. Refer to Appendix I for details in deriving this expression for R:

$$R \approx (1/2)\,[-\alpha + (\alpha^2 + 4D^2/3)^{1/2}] \quad , \tag{8}$$

where

$$\alpha = (\text{net } D^2/3\,\epsilon\, U_o) + D^2/(3R_m) - R_m \tag{9}$$

Space charge within the dielectric continues to accumulate until breakdown occurs. At this point the charge quickly escapes to the surface, and the process begins again, as long as there is electron bombardment. Breakdown field strengths for different materials can be found in the literature [6,7,9,10, 11]. According to the model of Gross and Nablo [10], electric field as a function of position in the material is:

$$E = E_o + \epsilon^{-1} \int_R^x \rho(x)\, dx \tag{10}$$

where space-charge density is given by equation (4). Equation (8) must be used for the lower limit.

Trapped electrons are retained in the dielectric material for considerable periods of time. Decay of a volume charge distribution q is described classically [8] by:

$$q = q_o \exp(-t/\tau) \quad , \tag{11}$$

where

$$\tau = \rho_r \epsilon$$

Resistivity ρ_r shows a temperature dependence of this form:

$$\rho_r = \rho_o \exp(w/kT) \tag{12}$$

Activation energies w for a few materials are listed in Reference 8; k is Boltzmann's constant. The same paper cites an experiment which indicates that no charge is lost over a 30-day period when the temperature is -78.5° C. At room temperature the resistivity decreases by 3 to 5 orders of magnitude, and the decay times are much smaller. Nevertheless, minutes, hours, and, in some cases, days are the units of measure for trapped charge decay at room temperatures [12].

SPACE SHIELDING APPLICATION

Trapping of electrons as discussed in the preceding section can be used to reduce bremsstrahlung in the spacecraft wall from synchronous altitude electrons. By covering the exterior surface with a dielectric layer just thicker than the maximum range of the most energetic electrons, the resultant charge buildup will produce repulsive fields which will stop or at least slow additional electrons. Although bremsstrahlung covers a continuous spectrum up to the electron's energy, it peaks toward the lower end. Thus bremsstrahlung intensity from electrons of reduced energy is much less than the energy difference would indicate; in fact, total bremsstrahlung production is roughly proportional to ZE^2 [13, 14, 15]. Leighton [14] quotes the following empirical formula to describe this observation for moderate and lower energies:

$$\frac{dW}{d\nu} = C[Z(\nu_m - \nu) + 0.0025\, Z^2]. \tag{13}$$

Photon energy is W; ν is frequency such that $h\nu_m$ corresponds to the electron kinetic energy; and C is a constant of the order of 10^{-3} MeV^{-1} for aluminum [15]. Graphically, equation (13) is represented by the linear curve of Figure 1. X-ray absorption coefficients in the lower energy range generally increase as energy is reduced, and sometimes the change is pronounced. Thus not only is bremsstrahlung production decreased by the field of the trapped electrons, but attenuation of the emitted rays is greatly enhanced.

Lackner, et al. [9] report that a retarding electric field of 6.3 MeV/cm exists within Lucite prior to breakdown caused by bombardment of 1.5-MeV electrons. When this field is produced, 0.95 MeV of the electron's energy is stored in the electric field and only 0.55 MeV is attributed to collision losses.

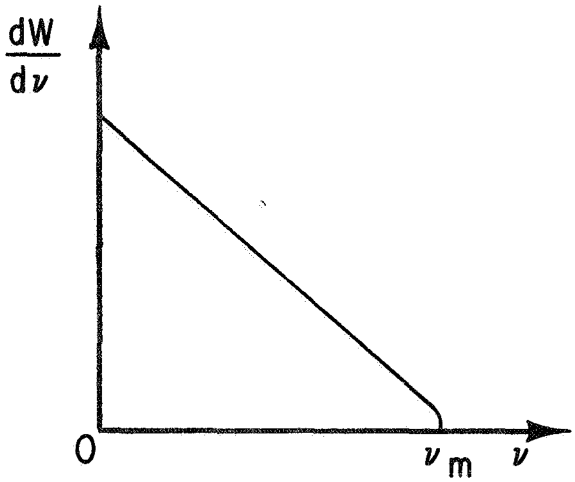

Figure 1. Spectral distribution approximation of bremsstrahlung for thick targets from electrons of moderate and lower energies.

A fluorescing spot marks the electron penetration into the Lucite, and photographs show the depth decreasing from a maximum of 0.5 cm to 0.15 cm as breakdown is reached. If a thin layer of this material about 0.6 cm thick were placed on the outside of a spacecraft, the bremsstrahlung dose rate inside the vehicle would be reduced by the action of electron trapping. It is true that the shielding effect will be cyclic, since breakdown occurs after a period of time determined by the electron flux. But the charge buildup begins immediately thereafter, so the integrated dosage will be less with the plastic coating. For Lucite, 5 C/cm^2 are required to initiate breakdown [9]. This corresponds to about 10^{13} electrons/cm^2. At synchronous altitude the electron fluxes range up to 10^8 electrons cm^{-2} sec^{-1}; therefore, a little more than 1 day is required to trap enough charge for breakdown.

Retention of the trapped space-charge within the dielectric is little affected by positive particles on the surface. It is only when the trapped charges finally escape to the surface that neutralization takes place. A feature unique to space applications is the isolation of the vehicle, in contrast to earth-bound experiments for which excess charge eventually leaks to ground. After breakdown, the trapped electrons surge mostly to the outer surface, and there they may combine with positive particles of the surrounding space. Rate of neutralization could be slow enough to allow a negative surface charge density to accumulate which would aid the shielding effect.

Plastics have been considered before as shielding material, but the specific utilization of electron trapping and field repulsion has not been reported. Magnuson and McReynolds [13] show a plot of dose per electron from bremsstrahlung behind 1/4-inch (0.64 cm) aluminum laminated with 1/4-inch polyethylene as a function of emission angle. After multiplying the synchronous electron flux by the dose per electron, and making adjustments for conditions of the two sets of data, dose rate for the laminar combination is 10 to 100 times less than that reported by Burrell, et al. [1] for a pure aluminum shield 1/2-inch thick. This is a qualitative analysis, but it could also be conservative since the laminar shield was wrapped with 0.030-inch aluminum foil to prevent charge buildup in the polyethylene. The foil probably is responsible for extra photons which add to the measured dose. Dose rate for the laminated shield is not integrated over all emission angles, but this omission is counteracted by the fact that for low energies ($E<m_o c^2$), the bremsstrahlung intensity tends to peak in the direction perpendicular to the electron's motion [14,16]. As the electron energy increases, the intensity maxima are shifted to the forward direction. Segre [16] states that for high electron energies ($E>m_o c^2$), the average angle of emission is independent of the quantum's energy and is given by:

$$\Theta = m_o c^2/E \tag{14}$$

Since bremsstrahlung production occurs near the incident surface, the effective thickness of the remaining part of the shield is increased by the directionality of the emitted photons. These arguments suggest that the probability of bremsstrahlung transmission through a thick target increases for electron energies greater than 0.511 MeV. Neglect of angular dependence on the emerging bremsstrahlung may not cause a larger error because most of the synchronous altitude electrons have energies less than this figure. A complete analysis must include the effects of the electron incident angle, but for this case electron flux is used as an intensity to insure a conservative calculation.

Consider two shield configurations. Both have 2 g/cm^2 aluminum as the base; but one is covered on the outside with polyethylene, and the other has a layer of lead on the inside. Outside and inside refer to the direction of incident electrons. In view of earlier discussions, the dielectric thickness is not critical beyond the maximum electron range. Let the plastic thickness be 0.6 cm. The lead must be of such a thickness that the bremsstrahlung emerging from the aluminum will be attenuated by a factor of 50. With this adjustment, the two shields are considered to be equivalent. As Figure 1 indicates, bremsstrahlung will have maximum intensity at small frequencies, but it is not correct to assume that the radiation emerging from the aluminum will be of the lowest frequencies [15]. These photons will be readily absorbed by the aluminum; i.e., the mass absorption coefficient in aluminum of 12 keV X-rays is 14 $cm^2\ g^{-1}$, while the same coefficient at 0.1 MeV is 0.164 $cm^2\ g^{-1}$ [14]. Appendix B provides the details for calculating an average energy weighted with lead attenuating coefficients. Values for the fraction of transmitted photons are obtained from a Monte Carlo code for 1 MeV electrons in 2 g/cm^2 aluminum [17]. Only the largest fractions are included, which means that the calculation is favored slightly toward lower energies. The weighted average energy of 0.109 MeV corresponds to a mass attenuation coefficient of 4.2 g/cm^2 in lead. For this coefficient the required lead thickness is 0.082 cm, and the resultant lead mass is 0.93 g/cm^2. Polyethylene has a spread of densities varying from 0.912 to 0.965 g/cm^3. Using the larger figure the required plastic mass is 0.58 g/cm^2, which represents a saving in mass of almost 40 percent. Again, this is probably a conservative estimate. No attempt has been made to optimize the dielectric mass, and the average energy of the emerging bremsstrahlung may be low.

A problem that must be considered in dealing with plastic materials exposed to solar thermal radiation is the possibility of exceeding maximum continuous service temperature. Most plastics of interest are limited to temperatures between 60°C and 120°C. A thin coating of highly reflecting material or a thin covering may be sufficient to protect the plastic. If temperatures are still excessive, slow rotation of the spacecraft could provide the necessary cooling.

NUMERICAL ANALYSIS

Monte Carlo techniques are especially suitable for analyzing bremsstrahlung production and transport in materials. Several programs describe the process. One code, named BETA [18], even includes the trapping effect in Lucite, and a plot of potential buildup versus depth from this reference is very informative. BETA could be adapted to the particular problem under consideration in the following manner.

1. Change from cylindrical to one-dimensional slab geometry.

2. Choose a thickness of Lucite from optimization studies or directly from the aforementioned plot. The choice of 0.6 cm used in this paper is compatible with the computer results.

3. From the literature, find breakdown field strengths for different dielectrics and use these values to specify cutoff ranges for charge buildup. Equations (10) and (8) provide the necessary relations. Synchronous altitude electron fluxes will have to be applied here, and by their application periods between breakdown can be found.

4. Use these electron fluxes to calculate bremsstrahlung production in and transport through the dielectric slab, subject to the cyclic nature of step (3).

5. Calculate dose rate, also periodic, through various thicknesses of aluminum caused by bremsstrahlung in the dielectric layer.

6. Integrate dose rate over at least one period to determine aggregate dose.

7. Make parametric studies with different materials and thicknesses to find maximum shielding with minimum mass.

8. Consider the effects of increase in trap densities caused by radiation and crystal damage.

9. Examine the possibility of surface charge buildup as electrons are released during breakdown. If the neutralization rate with atmospheric positive ions is less than the charge release rate, surface charge buildup can take place.

Berger and Seltzer's code [17] also computes bremsstrahlung production and photon transport in materials. It could be expanded to include the effects of trapped charges. Energy loss per unit area due to the repulsive electric field is described by equation (7). Time dependence exists via R in the form of equation (8). Actually, the variable α in equation (8), as given by equation (9), may be simplified after the electron flux if applied. Table 1 or equation (1) could be used for this purpose. An "if" statement is needed to incorporate cutoff caused by breakdown as outlined in step (3) above. With these added details, bremsstrahlung production in and transport through, say, 0.6-cm thick plastics (or water) can be calculated. The emerging bremsstrahlung should then be directed through aluminum of various thicknesses, and the dose rate on the other side calculated. This code is designed on a per electron basis for a given incident energy, which means that application of synchronous altitude electron flux may best be made in flux-energy blocks.

CONCLUSIONS

According to the theory of the second section, a thin layer of dielectric material should act as an effective shield against electron bremsstrahlung. The physical effects of trapped electrons are to repel or slow additional electrons, decrease the production of bremsstrahlung, and reduce the photon energy, which leads to greater absorption. This is true not only at synchronous altitude but wherever there is an electron flux. The examples in the application section must be considered only from a qualitative viewpoint. The results are important mainly as illustrations of the details involved in such a system. They do imply that the dielectric shield should be relatively light and inexpensive, while not interfering with any of the spacecraft functions.

Numerical analyses of the trapped electron shield concept should be made, and if the results are favorable, an experimental optimization plan should be formulated to determine maximum shielding for minimum mass. In addition to finding the material which meets these basic requirements, other properties should be considered. Maximum continuous service temperature is an important limitation which must be investigated. There is a range of temperatures between 60°C and 120°C associated with different plastic materials from which the most desirable material should be chosen. A coating of reflecting material should act to reduce the effects of excessive solar temperatures. Influence of different radiations over a prolonged period of time should be considered. This influence may not be too critical; in fact, it could be favorable since production of electron traps is caused by irregularities in the lattice structure. An interesting study would be that of breakdown and the cyclic nature of the shield. The breakdown phenomenon is not completely understood, and meaningful experiments in this area would be beneficial from the shielding and scientific aspect. Continued experiments in space with the isolation peculiar to that environment would be of special interest.

APPENDIX A

DERIVATION OF AN EXPRESSION FOR RANGE

Equation (5) can be written as

$$\left(\frac{net}{\epsilon U_o} + \frac{1}{R_m}\right) D - \frac{D}{R} = \ln \frac{R_m (D - R)}{R(D - R_m)} \tag{A.1}$$

Consider the logarithmic term,

$$\ln \frac{R_m (D - R)}{R(D - R_m)} = \ln \left(\frac{R_m}{D - R_m}\right) + \ln \left(\frac{D - R}{R}\right) \tag{A.2}$$

The two logarithmic terms are approximated as follows:

$$\ln R_m/(D - R_m) = \ln (R_m/D) - \ln (1 - R_m/D)$$

$$\approx 3 (R_m/D) - 3/2 \quad , \tag{A.3}$$

and

$$\ln (D - R)/R = -\ln (R/D) + \ln (1 - R/D)$$

$$\approx -3 (R/D) + 3/2 \tag{A.4}$$

Equation (A.1) becomes

$$R^2 + \alpha R - D^2/3 \approx D \quad , \tag{A.5}$$

where

$$\alpha \equiv (\text{net } D^2/3 \ \epsilon \ U_o) \ + \ D^2/(3R_m) - R_m \quad ; \tag{A.6}$$

therefore,

$$R \approx (1/2)[-\alpha + (\alpha^2 + 4D^2/3)^{1/2}] \tag{A.7}$$

APPENDIX B

AVERAGE ENERGY OF TRANSMITTED PHOTONS FROM 1 MEV ELECTRONS THROUGH 2 G/CM^2 ALUMINUM WEIGHTED WITH LEAD ATTENUATION COEFFICIENTS

W_i Photon Energy (MeV)	N_i Fraction Transmitted	τ_i μ/ρ (cm^2/g) Pb at Lower Energy	$n_i \tau_i$	$W_i n_i \tau_i$
0.55 - 0.50	0.006	0.145	0.001	0.000
0.45 - 0.40	0.011	0.208	0.002	0.001
0.35 - 0.30	0.018	0.356	0.006	0.002
0.25 - 0.20	0.038	0.896	0.034	0.007
0.15 - 0.10	0.107	5.29	0.565	0.056
			0.608	0.066

$$\langle W \rangle = \frac{\sum_i W_i n_i \tau_i}{\sum_i n_i \tau_i} = 0.109$$

The fraction data are taken from Reference 17.

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APPROVAL

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By D. L. Hollis

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