Analysis of an Electrostatic Shield for Space Vehicles

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Results of a preliminary feasibility study of the effectiveness of an electrostatic shield against an isotropic flux of charge particles are presented and discussed Shield system efficiency for three different ranges of operating voltage and for various electrode sizes is examined Weight of the structure required to support loads induced by the electrostatic charge on the electrodes is estimated Shield effectiveness is defined as the fraction of the radiation removed for a given system weight; electrostatic shield performance is compared to that of a static shield composed of polyethylene Performance of the static shield is superior in removing primary radiation for all cases examined

I Introduction

THE discovery of the Van Allen radiation belts has prompted a considerable number of articles regarding the radiation hazards to manned space flights References 1 and 2, which reflect studies of the space radiation dose on man, have investigated the shielding required to protect the astronaut Personnel in the Nuclear Products Division of Lockheed-Georgia have conducted extensive studies and analyses of shields for space vehicles as are shown in Ref 3

There are two types of dynamic radiation shields which use a force field to deflect the radiation before it can penetrate the space-vehicle cabin These fields are magnetostatic and electrostatic This report gives the results of a preliminary feasibility study of one type of dynamic radiation shield which uses an electrostatic field to deflect the radiation before it can penetrate the space-vehicle cabin This shield is composed of two concentric spherical conductors where the shielded space is the volume enclosed by the inner sphere

In determining the effectiveness of a shield, it is necessary to establish some method of measuring performance Effectiveness of the shield system is expressed as the fraction of the radiation prevented from entering the inner sphere as a function of shield system weight This measure of effectiveness is similar to the method suggested in Ref 4

In this paper the characteristics of the inner Van Allen belt radiation are examined, the shield operation described, system weight estimated, and shield effectiveness compared to a static shield

II Charged Particle Radiation Characteristics

The two most important sources of penetrating radiation to be found in space are the protons in the inner Van Allen belt and the protons ejected by the sun during solar flares For this study, the radiation in the inner Van Allen belt is used for illustration The amount of physiological damage which would result from exposure to this radiation is a function of proton energy, proton flux, and exposure time Effect of exposure time on the radiation dose is not pertinent to this study because exposure time depends upon space-vehicle speed and trajectory through the radiation zone Vehicle speed and trajectory effect are discussed in Ref 5

The dependence of the radiation dose upon proton energy and flux is briefly examined in order to establish the nature of the hazard Proton flux, as a function of proton energy, is adequately characterized by the radiation spectrum shown in Fig 1 The data in the figure are taken from Ref 6

In the analysis of the electrostatic shield, it is advantageous to express the radiation spectrum in the form of a normalized cumulative flux distribution as a function of proton energy The cumulative distribution shows the fraction of the total flux with energy between zero and any value (E) as a function of proton energy The radiation spectrum transformed to the cumulative distribution function is shown in Fig 2 This cumulative distribution is convenient, since it can be used to indicate the fraction of the total flux which remains after the radiation passes through a given potential difference in an electric field

The next characteristic of the radiation to be examined is the relationship between dose rate and proton energy Figure 3 shows the flux-to-dose conversion factor for protons as a function of proton energy These data are taken from Ref 7 The most important characteristic of the radiation dose rate as a function of proton energy, in relation to this study, is the decrease in dose rate as the proton energy increases These data in Fig 3 show that, for a given proton flux, the particles that have energy below 100 Mev do far more physiological damage than particles with energy of several hundred million electron volts In the Van Allen belt where the radiation spectrum has a large low-energy component, the biological damage due to low-energy particles assumes major importance The nature of the spectral distribution and the high level of biological damage due to the low-energy particles makes it seem plausible that the most effective shield for space applications would remove only the low-energy protons

The large low-energy component of the proton radiation spectrum and the high radiation dose received from these low-energy protons have a compounding effect upon the radiation dose rate These two factors are combined into a single function shown in Fig 4 As in the case of the proton energy spectrum, it is advantageous to express the dose rate contributed by the portion of the spectrum between zero and any energy (E) as a fraction of the total dose rate

Figure 4 shows the cumulative normalized distribution of dose rate as a function of particle energy and indicates the fraction of the total dose rate which is contributed by all of the radiation below any given energy This type of distribution is also useful in determining the dose-rate reduction after the radiation has passed through a known potential difference in an electric field These data show that a large fraction of the total radiation dose rate is due to the particles with energy below 200 Mev If this low-energy component of the spectrum were removed, the radiation dose rate would be reduced to about 2% of its original value

Characteristics of charged particle radiation presented in the preceding paragraphs provide sufficient basic information to proceed with an examination of the feasibility of using an electric field as a shield for space vehicles penetrating the Van Allen belt

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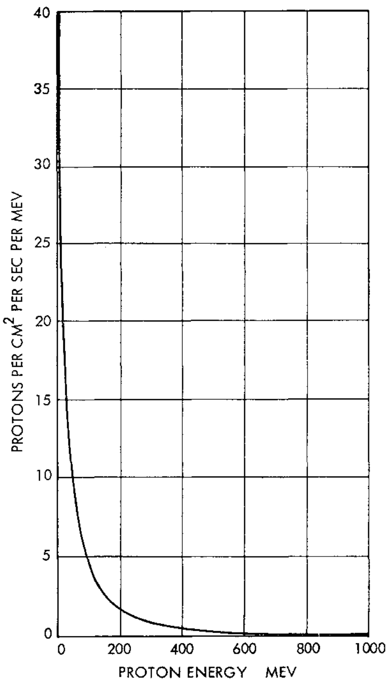

Fig 1 Inner Van Allen proton energy spectrum

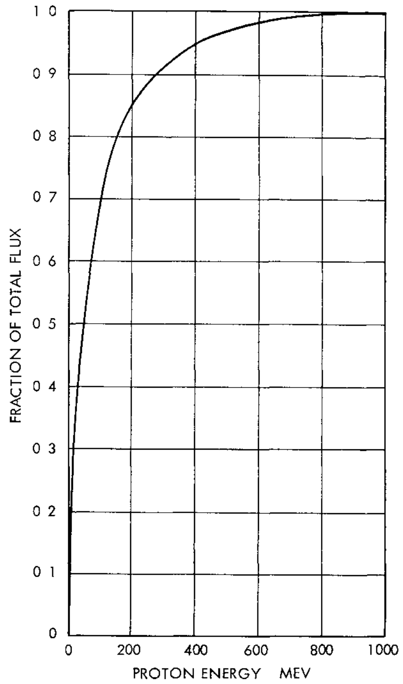

Fig 2 Cumulative proton flux distiibution

III The Electrostatic Shield

The electrostatic shield prevents a substantial portion of the incident proton flux from entering the shielded volume by deflecting or scattering the particle radiation Conventional shields against charged particle radiation reduce the intensity by stopping a portion of the flux before it can reach the shielded region In order to protect a space vehicle from protons by means of an electric field, the region to be shielded must be surrounded by a field with the electric intensity vector oriented outward The simplest field geometry suitable for a shield is the region surrounding an isolated charged sphere This configuration, however, has two undesirable characteristics, and there is apparently no feasible way to alter these properties First, in a practical sense, it is difficult to charge an isolated conductor to a high potential; and, second, an isolated charged conductor will accelerate free electrons to dangerously high energy levels

If the field were induced between two concentric hollow conducting spheres, the desired geometry would be obtained without the undesirable characteristics mentioned in the preceding paragraph First, it is less difficult to obtain a large potential difference between the electrodes of the shield by transferring charge than it would be to charge an isolated sphere to the same potential The isolated conductor would require a high-energy particle accelerator to dispose of the negative charge This accelerator would be more complicated than the proposed two-electrode shield

The second difficulty, accelerating electrons in the vicinity to high energy level, is eliminated by the outer electrode In this study, it is assumed that the outer shell or electrode will act as a static shield against electrons in the radiation environment A large fraction of the electrons in the inner Van Allen belt have energy levels below 0 5 Mev and can be removed by modest amounts of bulk shielding

The use of an isolated charged sphere as a shield against protons is discussed in Ref 8 As indicated in that paper, the electrons will be accelerated to high energy levels by the charged electrode A second charged electrode inside the proton shield was proposed to remove the electrons

The electrostatic field configuration selected for this analysis is the field between two concentric spherical conducting surfaces, since it is an effective arrangement for a shield against isotropic charged particle radiation The region within the inner electrode is the shielded volume

Another shield configuration that may be suitable for use with space vehicles consists of coaxial cylindrical electrodes with hemispherical end caps The electrode structure for the cylindrical field would be somewhat heavier than the electrode structure for the spherical field, but it may have an advantage in that it could utilize expended rocket tankage

Proton Motion in the Electrostatic Field

Charged particles that enter the region between the two electrodes will be either deflected away from the shielded volume or retarded by the electric field Whether a particle penetrating the outer surface penetrates the inner surface depends upon 1) the electrostatic potential between the two

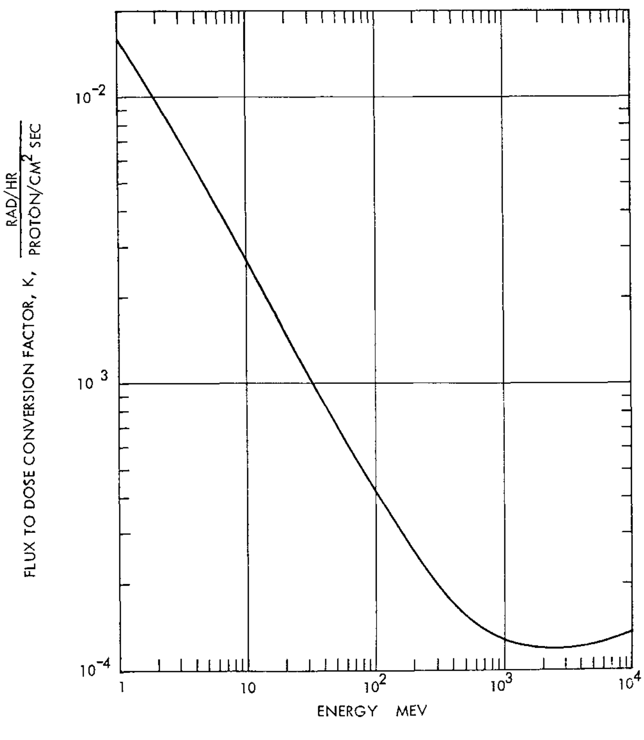

Fig 3 Flux-to-dose conversion factor for protons as a function of energy

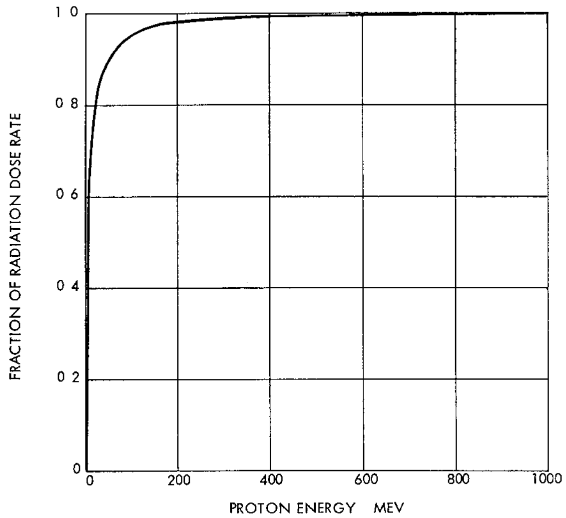

Fig 4 Cumulative dose-rate distribution

surfaces, 2) the angle between the particle's initial velocity vector and the normal to the surface, 3) the radii of the surfaces, and 4) the particle energy The expression for the fraction of the total flux incident on the outer surface which penetrates the inner surface or shielded volume will be developed in the following paragraphs

The path of the charged particle while it is between the spherical surfaces lies in the plane determined by its velocity vector when it penetrates the outer shell and the common center of the spheres, as shown in the cross-sectional view of the system in Fig 5 This type of trajectory is characteristic of motion under an inverse square force of repulsion By referring the particle motion to polar coordinates in the plane of the trajectory, the equations of motion are

$$m(\ddot{r} - r\dot{\theta}^2) = [r_2 r_1/(r_2 - r_1)](Ve/r^2) \quad (1)$$

$$m(2\dot{r}\dot{\theta} - r\ddot{\theta}) = 0 \quad (2)$$

where

m = mass of the particle
r, θ = polar coordinates of the particle position
V = potential difference between the electrodes
e = charge on the particle
r_1 = radius of the inner electrode
r_2 = radius of the outer sphere

The equation for the conservation of energy obtained from Eqs (1) and (2) by integration can be written as

$$E = E_i - U \quad (3)$$

where

E = kinetic energy of the particle while it is in the field
E_i = initial kinetic energy of the particle
U = potential energy of the particle while it is in the field

The kinetic energy of the particle at any point in the field can be expressed as

$$E = E_i(r_2/r)^2 \sin^2 a \quad (4)$$

where r_2 is the radius of the outer sphere, r is the radial position of the particle, and a is the particle angle of incidence The potential energy of the particle at any point in the field is

$$U = Ve[(r_2/r) - 1][(r_2/r_1) - 1]^{-1} \quad (5)$$

where V is the potential difference between the shield electrodes, and e is the electron charge

Equations (3–5) can be used to obtain the expression of the potential required to prevent penetration beyond r_1 by a particle with energy (E_m) and angle of incidence (a) on the outer sphere The expression is

$$V = (E_m/e)\{1 - [(r_2/r_1) \sin a]^2\} \quad (6)$$

Shield Efficiency

The fraction of the incident radiation prevented from penetrating the protected region is defined as shield efficiency and is derived by using Eq (6) and the radiation energy spectrum, assuming the flux isotropic For any given energy distribution, the fraction of particles that have energy in a given range between (E) and ($E + dE$) can be expressed as

$$dn/n = (1/n)f(E)dE \quad (7)$$

where $f(E)$ is the cumulative proton flux distribution shown in Fig 2 A particle with energy less than E_m cannot penetrate the inner surface, as shown by Eq (6)

The fraction of the total flux entering the outer sphere at an angle of incidence between (a) and ($a + da$) with energy less than E_m, the minimum energy required to penetrate the inner sphere, is given by

$$F_\phi = \frac{1}{n}\int_0^{E_m} f(E)dE \quad (8)$$

By integrating the right-hand member of Eq (8), the expression for the fraction of the total flux at the angle (a), with energy less than required to penetrate the inner sphere, is obtained This expression takes the form

$$F_\phi = (1/n)g(a) \quad (9)$$

By using the relationship between two concentric spherical surfaces and the isotropic particle flux shown in Fig 6, the expression for shield efficiency can be derived Now, of all the particles incident on the element of area (dA) on the outer surface, only these in the solid angle (w_0) can penetrate the inner surface

The fraction of the entire solid angle (w_0) which is contained in the solid angle (w) is

$$w/w_0 = (1 - \cos a)/(1 - \cos a_0) \quad (10)$$

This ratio is also equal to the fraction of the total flux passing through (w) if the flux is isotropic The expression for the differential element of solid angle is

$$dw = 2\pi \sin a da \quad (11)$$

and it can be used to express the portion of the flux passing through (dA) which is deflected so that it does not penetrate

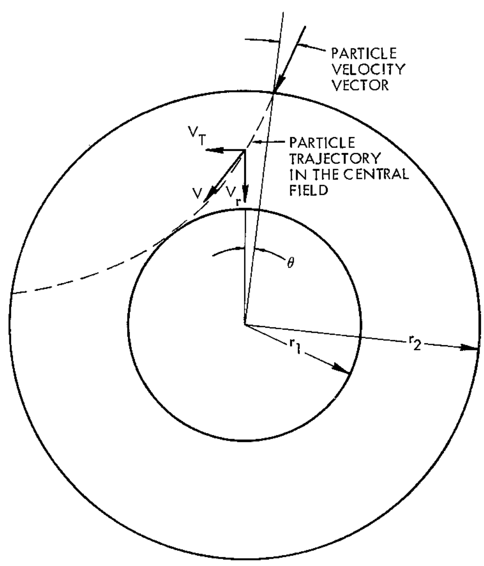

Fig 5 Particle trajectory in the electrostatic field

the inner sphere This expression is

$$S_E = \frac{1}{nw_0}\int_0^a g(a)\sin a da \qquad (12)$$

Equation (12) is the expression for shield efficiency Shield efficiency was computed by using Eqs (7–12) The data required for this computation include electrode dimensions, the potential difference between the electrodes, the proton spectrum in Fig 2, and the dose-rate function in Fig 4 Before these shield efficiency calculations can be made, values for potential difference between electrodes must be selected

Electrode Potential Difference

Electrostatic shield effectiveness depends, in part, upon the potential difference between the electrodes For this reason, the largest potential difference that can be supported by a given set of electrodes and the distance between them will be the shield voltage selected

In a study of this scope, it is necessary to make some assumptions based upon current technology when time and facilities do not permit deeper investigation Therefore, it has been assumed that the required potentials can be generated with a belt-type electrostatic generator In addition to generating high potentials, the problems of preventing discharge of the electrodes are similar to those encountered in electrostatic particle accelerators

The environment within the accelerating tube of electrostatic particle accelerators is similar to the conditions between the electrodes of the shield In both cases, charged particles are moving in a vacuum under the influence of an electric field produced by a large potential difference between electrodes Tube length and operating voltage of several electrostatic particle accelerators, shown in Ref 9, were used to estimate the potential difference that could be attained in the shield system The potential difference based upon Ref 9 is shown as curve A in Fig 7 In addition to these

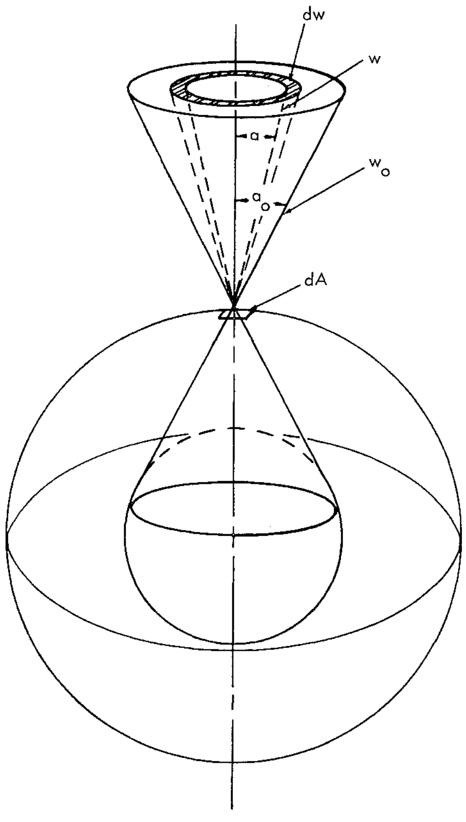

Fig 6 Flux incident on outer sphere which can impinge on inner sphere

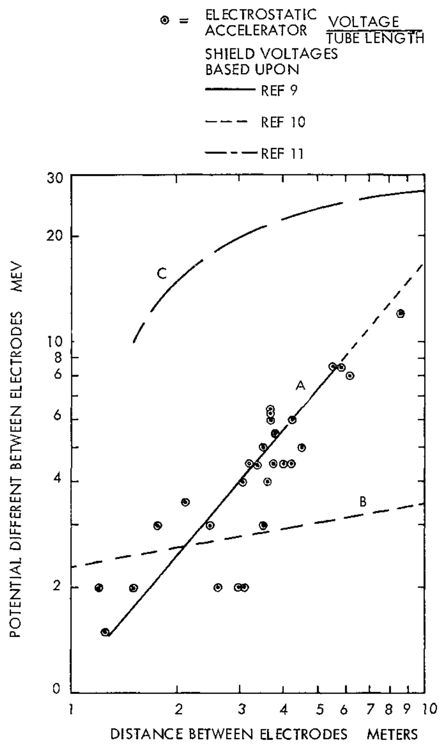

Fig 7 Voltage between electrodes as a function of electrode separation

potential drops, two other sets of shield voltages were estimated

Results of experiments on electric breakdown in vacuum, which are reported in Ref 10, were conducted using potential differences up to 1 7 × 10^6 v The potential difference based upon Ref 10 is shown as curve B in Fig 7 Shield potential differences have been estimated using these data

In an earlier analysis, the potential difference was given by

$$V = 3(r_1/r_2)(r_2 - r_1) \times 10^7 \text{ v} \qquad (13)$$

in order to keep the field gradient at the inner electrode below 3 × 10^5 v-cm^{-1} This voltage radii function was selected to keep the gradient below the vacuum spark level given in Ref 11 The potential difference based upon Ref 11 is shown as curve C in Fig 7 These values for shield potential are probably too large but are retained to illustrate effect of voltage on shield efficiency

Insulating properties of the shield elements and charge loss due to radiation or field emission determine the potential difference that can be maintained between the electrodes Thin plastic specimens can withstand potential gradients of 10^7 v/m Careful design, including the nonradial placing of the electrode separators and charging belt, may permit operation with potential differences in the range of 10^6–10^7 v over distances between electrodes of 1–10 m Calculations based upon data in Ref. 11 indicate that field emission will not be a serious problem Coating the electrodes can perhaps remove all danger of field emission

The question of discharge due to the secondary radiation produced by particle bombardment of the electrode surfaces was also investigated The products of the interaction consist primarily of neutrons, protons, and gamma rays Electrons would be produced only by secondary interactions and would have low energy and probably would not escape from the shield electrode Reference 12 shows that the mean free path of protons with energy from 2–500 Mev is in excess of 44 g-cm^{-2} for aluminum Thus, for a thin shield electrode, the probability of an interaction is estimated to be less than 1% The small chance of a proton interaction with thin shield electrodes and the nature of their secondaries indicate they will not cause disruptive discharges This conclusion is also supported by the fact that high-energy protons do not produce disruptive discharges in electrostatic accelerators

Results of Shield Efficiency Calculations

Shield efficiencies were computed by using a fixed inner electrode radius of 1 m for a range of outer electrode radii from 1 5 to 10 0 m The voltage drop, as a function of electrode radii shown in Fig 7, was used to make the calculations Results are shown in Fig 8 as the fraction of total proton flux incident on the shield which does not penetrate the protected region inside the inner electrode and the reduction of free space dose rate achieved by the system Shield efficiencies are based upon the primary radiation; secondary radiation was not considered in the analysis for the reasons discussed in the following paragraphs

Radiation that results from electron and proton bombardment of the electrodes is referred to here as secondary radiation Electron impact will produce x rays An example in Ref 13 shows that an omnidirectional flux of 10^8 electrons-cm^{-2}-sec^{-1} with energy of 0 5 Mev stopped in carbon will result in an estimated bremsstrahlung dose rate of 0 3 rad-hr^{-1} Since these x rays are a small fraction of the total unshielded dose rate, they have been neglected in this analysis

Proton bombardment of the electrode surface will release secondary particles As discussed earlier, there is a small chance of a proton interaction with thin shield electrodes; thus, secondary radiation due to protons is low and contributes very little to the total radiation

IV Forces on the Shield Electrodes

The two concentric conducting spherical surfaces of the electrostatic shield form a spherical condenser As a consequence of the energy stored in this system, a force is exerted upon each part of the shield The force on the inner shell places it in tension, and the force on the outer shell places it in compression If, instead of being concentric, the centers of the spheres are displaced slightly, there will be a force of attraction between the electrodes

The force per unit area on the electrodes in the concentric case is

$$p = \epsilon_0 E/2 \tag{14}$$

where ϵ_0 is the dielectric constant of free space and E is the electric intensity on the surface of the conductor Substituting the expression for E as a function of electrode radii and potential difference between electrodes in Eq (14) gives

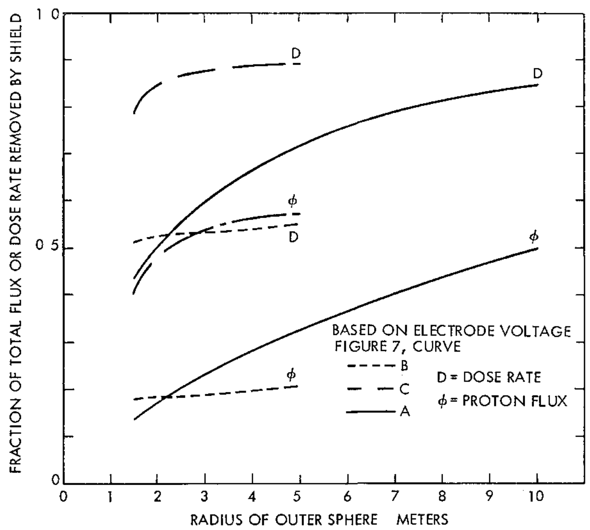

Fig 8 Shield efficiency

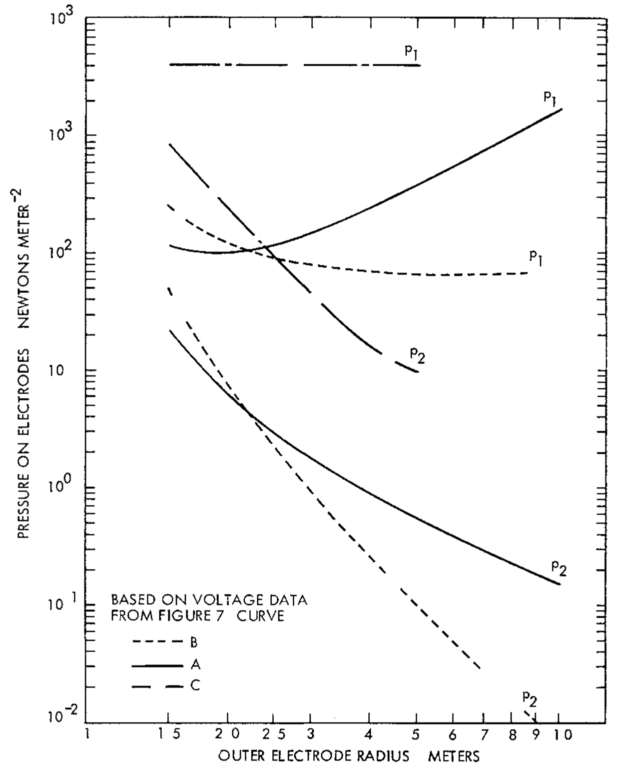

Fig 9 Pressure on shield electrodes induced by electrostatic charge

the expression for the pressure on the shield surfaces The resulting expressions of the pressure on the inner and outer surfaces are given by Eqs (15) and (16), respectively, as

$$p_1 = \epsilon_0/2[(r_2/r_1)V/(r_2 - r_1)]^2 \tag{15}$$

$$p_2 = \epsilon_0/2[(r_1/r_2)V/(r_2 - r_1)]^2 \tag{16}$$

where r_1 is the radius of the inner sphere, r_2 is the radius of the outer sphere, and V is the potential difference between the two spheres The pressure on the electrodes tends to decrease the space between the two spherical shells Figure 9 shows the pressure on shield electrodes as a function of outer shield radii Voltage as a function of electrode separation, shown in Fig 7, was used to compute the pressure

A concentric spherical condenser is unstable mechanically, and any small lack of coincidence between the centers will result in a force of attraction between the electrodes Expressions relating the force of attraction to sphere radii, displacement between centers, and voltage between the electrodes when one conducting sphere encloses another are derived in Ref 14 The expression for this force is

$$F = 2\pi\epsilon_0 V^2 r_1 r_2 \frac{\partial}{\partial s}\left\{\sinh\alpha \sum_{n=1}^{\infty} [r_2 \sinh n\alpha - r_1 \sinh(n-1)\alpha]^{-1}\right\} \tag{17}$$

where V is the voltage difference between the spheres, s is the distance between their centers, r_1 is the radius of the inner sphere, r_2 is the radius of the outer sphere, and α is defined by Eq (18) as follows:

$$\cosh\alpha = (r_1^2 + r_2^2 - s^2)/2r_1r_2 \tag{18}$$

The forces of attraction between the two spheres were computed when the separation between their centers was 0 05 $(r_2 - r_1)$ for the range of voltages shown in Fig 7 This factor, 0 05 $(r_2 - r_1)$, was assumed to be a reasonable misalignment tolerance encountered in assembling the system Equation (17) was evaluated by using the first 30 terms in the

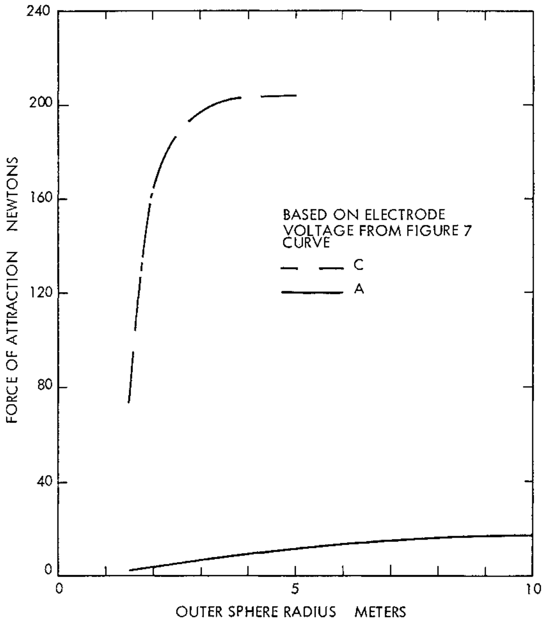

Fig 10 Attractive force between nonconcentric electrodes

series to insure adequate accuracy Figure 10 shows the force of attraction between the two spheres due to lack of concentricity The pressures on the electrodes and the force of attraction between them were used as design loads to estimate structural weight

V Shield System Weight

Shield system weight was estimated by using basic engineering methods, since a detailed structures and weight analysis is beyond the scope of this study Shield elements considered in estimating system weight are inner and outer spherical electrodes, support rings for the electrodes, spacers between the shield electrodes, and the power supply Each spherical electrode is attached to three rings along great circles of the spheres These rings intersect so that the diameters connecting the intersections meet in a common point and are orthogonal

The shield electrodes are kept in their correct relative position by a set of spacers made of insulating material These spacers are attached to the electrodes at the intersections of the electrode support rings As indicated by data in Fig 7, the dielectric strength required for these separators is probably within the capability of materials used in the tubes of electrostatic accelerators

The method used to estimate shield element weight is outlined in the following paragraphs The shield electrodes and support rings were assumed to be constructed of 6061 aluminum alloy The electrode separators were assumed to be polystyrene It is realized that, in a more detailed investigation, other materials would be investigated

The shell thickness required to support the electrostatic pressures p_1 and p_2 in a concentric system was computed using the following relations For the inner sphere, the allowable pressure in tension is

$$p_1 = 2\sigma t/r \tag{19}$$

where σ is the unit tensile stress, t is the thickness of the shell, and r is the radius of the inner sphere For the outer sphere, the allowable pressure in compression is

$$p_2 = 2E_y t^2/R^2[3(1 - v^2)]^{1/2} \tag{20}$$

where E_y is the modulus of elasticity, t is the thickness of the shell, v is Poisson's ratio, and r is the radius of the sphere

For thin shells in compression, the most common mode of failure is buckling In order to protect against structural failure by buckling, the value of the pressure used for design purposes is four times the value of p_2 obtained by Eq (16)

The cross sections of the support rings and separators are assumed to be square Both of these members were designed to support the entire force of attraction between the spheres because of the off-center condition The rings are assumed to be cantilever sections supported in the center with the load varying linearly from one-half the induced load at the center to zero at a distance of one sphere radius on either side of the support This estimate will give a conservative result, since the ring material required was doubled to account for the material necessary to transfer loads from the electrodes to the support rings

The separators were assumed to be axially loaded with simple end supports The critical mode of failure for these elements is compressive buckling In estimating the separator weight, the cross section required to prevent buckling was doubled as added insurance against compressive failure

Power supply weight was estimated by using the power-to-weight ratio of currently available turboelectric generating equipment The power-to-weight ratio used in this study is $5\ 5 \times 10^{-2}$ kw/kg By using the preceding data and the energy required to change the shield, the power supply weight was estimated The same power supply weight of 200 kg was used for all shield sizes, since this weight will be adequate for the largest shield in this study

VI Shield Effectiveness

The potential usefulness of any component of a manned space vehicle depends to a large extent upon its weight Effectiveness of the shielding system is expressed as the shield weight required to prevent a given fraction of the total radiation flux from penetrating the inner sphere, or as the shield weight required to reduce the unshielded dose rate by a given amount

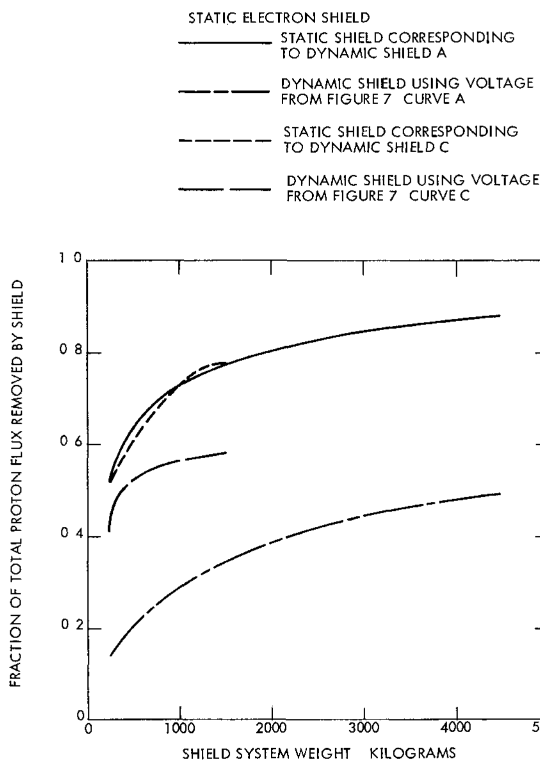

Fig 11 Comparison of static and dynamic shield effectiveness with passive electron shield

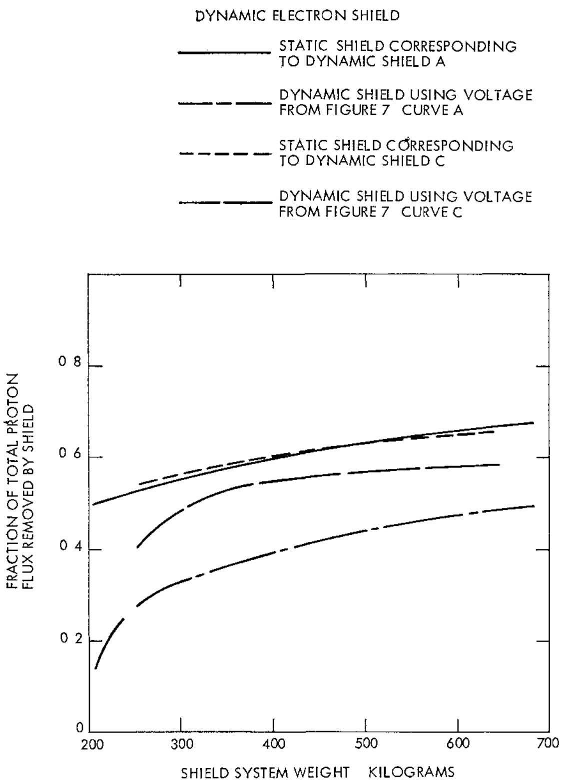

Fig 12 Compaiison of static and dynamic shield effectiveness with active electi on shield

Figure 11 shows the fraction of total proton flux removed as a funetion of shield weight for both the electrostatic shield and a shield composed of polyethylene The outer electrode thickness required to remove all electrons with energy below 0 65 Mev is greater than the electrode thickness necessary to support the induced loads The thicker electrode was used in computing the shield weight shown in Fig 11 The volume shielded is the same in both cases, a sphere with a radius of 1 m The polyethylene or static shield was designed with a thickness so that its weight was equal to that of the electrostatic shield over the range of electrode sizes It is shown that the electrostatic shield is not as effective as the polyethylene shield If the electrostatic shield weight can be reduced by good structural design, its performance can be improved

The interaction of the protons with the polyethylene in the static shield will produce secondary radiation that is not present in the electrostatic shield If this secondary radiation is intense enough to contribute significantly to the total radiation dose received by the astronaut, the effectiveness of the polyethylene shield will not be as high as shown in Fig 11 A comparison of the reduction in radiation dose rate, considering secondary radiation, as a function of shield weight for both types of shield is beyond the scope of this study

Weight estimates were made for a system that uses a dynamic shield against electrons The shield was located adjacent to the exterior of the outer electrode All electrons with energy up to 1 Mev can be removed by this shield Weight reduction is achieved by replacing the rather thick outer electron static shield element by a lighter electrode structure Figure 12 shows the fraction of total proton flux removed as a function of shield weight for both the electrostatic shield and a shield composed of polyethylene

This evaluation is based upon a preliminary analysis A more detailed study may show the electrostatic shield to have better weight-to-performance characteristics Other factors such as operational problems also should be considered in comparing the shields

VII Conclusions

In general, the electrostatic shield has a high capability against charged particle radiation that has a spectrum with a large low-energy component in the range from 0 to 100 Mev

The electrostatic shield is not as effective as the polyethylene shield against primary proton radiation However, a selection of a shield for a space vehicle should be based upon the radiation dose received by an astronaut in the shielded cabin

Based on the results of this study, a decrease in system weight for the electrostatic shield would be required to match its performance with that of the static shield against proton radiation

References

[1] Schaefer, H J , "Radiation danger in space," Astronautics **5**, 36–45 (July 1960)

[2] Dye, D L and Noyes, J C , Biological shielding for radiation belt particles,' J Astronaut Sci **VII**, 64–70 (Fall 1960)

[3] Allen, R I , Dessler, A J , Perkins, J F , and Price, H C , "Shielding problems in manned space vehicles, ' Lockheed-Georgia Co , Nuclear Products Div , NR-104 (July 1960)

[4] Dow, N F , Shen, S P , and Heyda, J F , "Evaluations of space vehicle shielding," Missiles and Space Div , General Electric Co , R62SD31 (April 1962)

[5] Schaefer, H J , "Radiation dosage in flight through the Van Allen belt," Aerospace Med **30**, 631–639 (September 1959)

[6] Perkins, J F , "Proton energy spectrum in the inner Van Allen belt," data from computer code used in Lockheed-Georgia Nuclear Products Div shielding studies, private communication (December 1960)

[7] Turci, J D "Flux to dose conversion for proton and electron radiation versus energy,' Lockheed-Georgia Co , interdepartmental communication from J D Turci, Dept 72 12, to F H Vogler, Dept 72-08 (July 19, 1960)

[8] Kash, S W and Trooper, R F , "Active shielding for manned spacecraft," Astronautics **7**, 68–75 (September 1962)

[9] Gorden, H S and Behman, G A , "Particle accelerators," *American Institute of Physics Handbook*, edited by D E Gray (McGraw-Hill Book Co , Inc , New York, 1963), 2nd ed , Chap 8i, pp 8 176–8 193

[10] Arnold, K W , Britton, R B , Zanon, S C , and Denholm, A S , "Electric breakdown between a sphere and a plane in vacuum,' Ion Physics Corp (July 1963)

[11] Dyke, W P and Dolan, W W , "Field emission," *Advances in Electronics and Electron Physics* edited by L Marton (Academic Press, Inc , New York, 1956), Vol VIII, pp 89–185

[12] Schofield, W M , Smith, E C , and Hill, C W , 'Shielding problems in manned space vehicles," Lockheed Georgia Co , Nuclear Products Div , ER 5957, pp 86–87 (1962)

[13] Allen, R I , Bly, F T , Dessler, A J , Douglass, C C , Perkins, J F , Price, H C , Schofield, W M , Smith, E C , and Tolan, J H (eds), ' Shielding problems in manned space vehicles, ' Lockheed-Georgia Co , Nuclear Products Div , NR-140, p 101 (September 1961)

[14] Smythe, W R , *Static and Dynamic Electricity* (McGraw-Hill Book Co , Inc , New York, 1950), 2nd ed , pp 118–121

[15] Nelms, A T , "Energy loss and range of electrons and positrons," National Bureau of Standards Circ 577 (1956)