

ASD-TDR-62-244

FOREWORD

Thomas W. Bailey, 1/Lt. USAF performed the work and prepared the report under subtask 736003A "Radiation Physics," Task No. 736003 "High Energy Materials Phenomena," Project No. 7360 "The Chemistry and Physics of Materials." The work was performed for the Directorate of Materials and Processes, Deputy Commander/Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

The work, on which this report is based, was done between May 1961 and December 1961.

ABSTRACT

Electrostatic shielding was studied to determine if it should be considered for protecting manned space vehicles against solar cosmic rays. After this study, it was concluded that electrostatic shielding is feasible and that it has some advantages over other types of shields. However, considerable applied research will be necessary.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

FOR THE COMMANDER:

for R. J. Vossler
RICHARD J. VOSSLER, Capt., USAF
Chief, Radiation Branch
Physics Laboratory
Directorate of Materials and Processes

TABLE OF CONTENTS

	Page
INTRODUCTION	1
Space Radiation	1
Description	1
SHIELDING	2
General	2
Magnetic Shield	2
Electrostatic Shield	3
Design Concepts	3
Shield System	3
CONCLUSION	5
APPENDIX I. Charge Calculations for Three Electrostatic Shield Concepts	6
APPENDIX II. Mechanical Forces on Charged Shells	9
APPENDIX III. Power Requirements	11
LIST OF REFERENCES	12

LIST OF FIGURES

Figure		Page
1	Isolated Spherical Satellite	13
2	Concentric Spherical Shield	14
3	Coaxial Cylindrical Shield	15
4	Charge Required to Shield 10 Bev Protons	16
5	Mechanical Pressures on Charged Shells	17

INTRODUCTION

The purpose of this study is to examine the use of the electrostatic field to shield personnel against charged space radiation. It was undertaken after calculations showed that conventional shielding materials could put a severe weight penalty on any space craft which required protection against high-energy solar protons.

Space Radiation

Description:

There are three general categories of charged particle radiation occurring in space; galactic cosmic rays, solar cosmic rays, and Van Allen radiation. Galactic cosmic rays are 85-90% protons; the rest are alpha particles and heavier nuclei. Particle energies range from 6×10^8 ev up to 10^{17} ev with an average about 3.6×10^9 ev. Beyond the geomagnetic field these cosmic rays have an omnidirectional flux of about 2 particles per cm^2 per sec which does not vary with time more than a factor of 2 (refs. 1, 2, 3, and 4).

Van Allen radiation consists of protons and electrons trapped by the earth's magnetic field. Trapping takes place in two separate belts or zones which are centered about the geomagnetic equator. The inner zone contains both protons and electrons; integral fluxes are reported to be 2×10^4 protons per cm^2 per sec greater than 40 Mev and 2×10^{10} electrons per cm^2 per sec greater than 20 Kev. The maximum proton and electron energies are about 700 Mev and 800 Kev, respectively. Particle density in this zone appears to be constant in time. The outer zone contains only electrons except for brief periods of time after major solar activity when protons become temporarily trapped. The integral electron flux is about 10^{11} electrons per cm^2 per sec greater than 20 Kev with a maximum energy on the order of several Mev. The time variation of particles in this zone has not been determined, except that changes of several orders of magnitude can occur (refs. 2, 3, 4, and 5).

Of the three particulate space radiations solar cosmic rays are the least well defined. They occur sporadically but are very intense and highly energetic. Solar cosmic ray events are classified as one of two types; high energy events, so called because they can be detected at the earth's surface and low energy events which are detected only at high altitudes. Solar cosmic rays are almost exclusively protons. In the low energy events, protons have peak integral fluxes of $10^6/\text{cm}^2$ sec greater than 5 Mev; maximum particle energies are 500-1000 Mev. The high energy events have peak integral fluxes of $10^5/\text{cm}^2$ sec greater than 40 Mev; maximum particle energies are 10-100 Bev. The time history of these events varies widely. There is a sequence of happenings, however, which seems to be characteristic of all events. First, a major solar flare occurs (importance 2 or greater) with accompanying radio noise and X-rays. After an interval that ranges from 30 minutes to several hours, protons are detected over the earth's polar regions. The particle flux near the earth increases 5-10 hours to its maximum and then decays.

Manuscript released by author December 1961 for publication as an ASD Technical Documentary Report.

The frequency of these outbursts of solar cosmic rays depends on the type of event. High energy events have occurred about once every four years. Low energy events seem to depend more on the cyclical solar activity. For low energy events, four to five day predictions of high or low probability of occurrence can be made with some accuracy by observing solar activity and analyzing sun spots. Both types of outbursts are still random in nature, however (refs. 2, 3, 4, and 6).

Based on present knowledge, solar cosmic rays present the most severe radiation hazard to manned space flight. It is estimated that the total exposure dose for a low energy event without shielding can be several hundred rem. Solar cosmic rays apparently can be encountered anywhere in the solar system and can appear with only minutes of warning. An interplanetary flight could expect to encounter from 2 to 10 solar events per year. This high probability of encounter and appreciable dose make the solar cosmic rays one of the most real hazards of space flight.

SHIELDING

General

Because there is the distinct possibility of encountering solar cosmic rays during interplanetary flight, shielding is an important consideration in design of a manned space capsule. Conventional bulk material shielding is the logical first choice for study. Calculations for this type of shield show that adequate protection is provided only by a very heavy shield (refs. 2 and 4). For example, if the dose from a low energy event (upper proton energy approximately 500 Mev) is to be limited to 25 rem, then the total weight of a spherical carbon shield with 5 ft inside diameter would be several thousand pounds. This estimated dose is from primary solar cosmic rays; secondary particles, resulting from interactions in the material, will also produce additional dose.

Since there is a distinct possibility of several solar events during any given interplanetary flight (an average of 10 per year in 1957, 1958, and 1959), shields will have to be designed for a low exposure per event. In attempting to keep gross shield weight low the protected volume must be kept small. This may restrict capsule operations for several hours, perhaps at critical times in the flight.

Because solar cosmic rays are charged, they can be deflected by electric or magnetic fields. These fields have several advantages when used for protection: Theoretically they can deflect any charged particle within any given distance. They release no secondary radiation. They are well defined mathematically. Their interaction with charged particles is well understood. The shield itself has no weight. The shield system weight is the weight of the field producing and defining system.

There are disadvantages in using fields too. Obviously electrically neutral particles and photons are not affected by them. A relatively complex "dynamic" system is required to produce and define the field, introducing a reliability problem not present with "passive" shields. Finally the system requires power, a precious commodity on a space vehicle.

Magnetic Shield

Magnetic shields have been suggested and studied by several authors (refs. 7, 8, and 9). These discussions indicate that practical magnetic shields require superconducting coils. These requirements in turn imply a relatively advanced technology in the fields

ASD-TDR-62-244

of superconducting materials and cryogenics. Such a technology is not in the offing in spite of some recent spectacular advances in superconductivity (refs. 10 and 11).

Electrostatic Shields

We found electrostatic shields for protecting personnel against charged space radiation has not been given much consideration in the literature. This study is an attempt to examine its potential.

Design Concepts

The concept of electrostatic shielding is based on the force between charged bodies; like charges repel, unlike attract. Because this shield is for protons which carry a charge of $+1.602 \times 10^{-19}$ coulombs (+e), the simplest scheme is to charge the space capsule to +Q. Simple electrostatic repulsion occurs with the force increasing as $1/r^2$ as the proton approaches the vehicle. If Q is large enough, the proton will not have enough energy to reach the capsule. A calculation of the charge for protection against a high energy event is presented in Appendix I. This concept, although simple in theory, would be difficult to attain in practice; the problem is how to charge a body isolated in space. Various schemes have been proposed, such as charging small spheres and propelling the spheres away from the capsule, or using an electron gun. However, these schemes have the obvious difficulty that the negative charges cannot be prevented from returning.

The next concept considered was concentric shells. In this concept a potential is developed between the inner and the outer shell by transferring charges with an electrostatic generator. A calculation of the charge required for this concept is also shown in Appendix I. It is presented for two simple designs, concentric spheres and coaxial cylinders. This concept requires more charge than the isolated spheres, but it has the advantage of no electric field outside the outer shell. Thus only particles on a collision course with the space vehicle; that is, the outer shell will be affected. Because the concentric shell concept appears somewhat more practical, it was selected as the basis of the rest of the study.

Shield System

The electrostatic shield system can be broken down into three main components: shells and shell supports, electrostatic generator, and power supply. The shells need to be conducting, but since mechanical forces are not large (See Appendix II) they can be made of light weight materials. Metallized cloth or wire screen are materials that might be used. The main requirement on the inner shell is that it be of such a material and/or geometry that the electric field intensity at its surface is below the threshold for field emission. The outer shell should be as large as possible, considering engineering limitations. Since the voltage is fixed a large shell keeps the total charge and shield capacity small. A calculation of weight for a wire screen sphere shows that such a shell could weigh as little as a few hundred pounds.

The shell supports serve two functions. The first is to provide structural support for the shells themselves if needed. Any charged shell tends to expand; this inherent self supporting tendency may reduce or eliminate structural support requirement (See Appendix II). The second is to maintain the shells' position relative to each other. Concentric charged shells are in unstable equilibrium i.e., any small displacement results in a force tending to increase the displacement. Position requirement suggests using a light framework made of an insulating material.

The Van de Graaff type of electrostatic generator appears to be the best type for space shield application. Theoretically there is no limit to the amount of charge which can be transferred by the Van de Graaff machine. Practically, it has been limited by corona discharge, beam current, and surface leakage. The equilibrium potential is reached when the rate of charge introduction equals the rate of loss due to the various mechanisms. This type machine also provides system flexibility. It can develop any desired potential up to its design maximum. It can be turned on and off as desired. It can supply losses due to leakage or particle neutralization. The weight of present machines is many thousands of pounds. Much of this weight is from the high pressure gas tanks necessary to maintain a reasonable size. Use of the gas reduces corona and leakage. For space operation corona and surface leakage should be reduced considerably. Thus, the generator can take its simplest form and consequently its lightest weight.

The power requirements for the system depend on how the shield is to be operated. If the shield is to be erected and charged soon after starting the flight; then power requirements may be a few thousand watts. However, if the shield is not to be charged until a solar event is suspected then requirements may be as high as 200 kilowatts (See Appendix III). Even this type of shield operation could require considerably less power depending on the warning time, maximum energy to be shielded, permissible dose, initial charge, and shell capacity, that is, dimensions. Since the maximum proton intensity does not occur until several hours after the event is detected, a fast rate of charging may not be necessary and power requirement can be reduced accordingly.

The power source would probably be a nuclear reactor because it is an interplanetary mission. Anticipated specific weights of nuclear power plants are 20 lbs/kilowatt. This means power supply weight chargeable to the shield system could be up to 6000 lbs, depending on the power requirements. Although this type study cannot hope to provide more than a half-educated guess, it does seem possible that the total shield system weight could be on the order of 20,000 lbs for almost complete protection from a high energy solar event.

The electrostatic shield has several advantages over the magnetic shield. It can be designed for easy erection and storage. This feature will permit uninhibited observation and communication except during the danger period. It can be made large enough to protect any size space craft thus permitting uninterrupted operation of the vehicle during the danger period. Perhaps most important, much of the technology required to develop the electrostatic shield is already available. High voltage problems have been with us for many years and much effort has been expended to understand them.

Certain problems still have to be dealt with, however, to achieve the desired shield performance and potential capability, a light weight conducting material is needed for the shells. It needs to have a high threshold for field emission. It is desirable that the shell can be stored and erected easily.

The support structure must also be light weight. It must have sufficient structural strength to keep the shells in position. It must be insulating and capable of withstanding 5000 volts/mil. It is desirable that installation be simple so that the structure can be stored when not in use. All materials for shells and supporting structure must be capable of withstanding the space environment; that is, meteoroid impact, ultrahigh vacuum, heat, and radiation. For example, vacuum and heat may combine to erode exposed materials by sublimation.

ASD-TDR-62-244

The main criteria for the electrostatic generator is that it be capable of developing the desired voltage between spheres in the desired time. For a high energy event this is 10^{10} volts in approximately 30 minutes. This probably means new approaches to Van de Graaff design and new generator components, especially insulating belts which are a big problem in present machines. The generator may have to operate continuously or at least intermittently to compensate for loss of charge due to ionized particles actually striking the shells.

CONCLUSION

In conclusion, the following areas are suggested for further study to see if electrostatic shielding can be developed.

1. High voltage vacuum breakdown (10^{10} volts at 10^{-12} mm of Hg)
2. Electron field emission and methods of preventing it, for example, coatings to withstand 10^7 volts/meter
3. Insulation (breakdown greater than 5000 volts/mil)
4. Light weight electrostatic generator design
5. Conducting shell materials.

APPENDIX I

Charge Calculations for Three Electrostatic Shield Concepts

Case I: Isolated Spherical Satellite

This satellite is portrayed in Figure 1. This situation is the same as for the classical Rutherford scattering of alpha particles by heavy nuclei. It can be shown that for $b = 0$, a head-on collision, particle p will have its closest approach to the satellite (ref. 1). The force equation for this condition, a proton directed at the satellite center, is:

$$F = \frac{qQ}{4\pi\epsilon_0 r^2} = m \frac{d^2 r}{dt^2}$$

where ϵ_0 = permittivity of free space
 r = distance between p and the center

since $d^2 r / dt^2 = v \, dv / dr$

where v = speed of p at a distance r

then $v \, dv = \frac{qQ}{4\pi\epsilon_0 m} \, dr / r^2$

The solution for this equation is :

$$v^2 - v_0^2 = -\frac{qQ}{2\pi\epsilon_0 m} (1/r - 1/r_0)$$

where v_0 = initial speed of p
 r_0 = initial separation of p and S

since $1/2 \, m v_0^2$ = initial kinetic energy of p, KE_0
 and $1/2 \, m v^2$ = kinetic energy of p at r , KE

then $KE - KE_0 = \frac{qQ}{4\pi\epsilon_0} (1/r - 1/r_0)$

solving for Q,

$$Q = \frac{4\pi\epsilon_0}{q} \times \frac{KE_0 - KE}{1/r - 1/r_0}$$

Thus given any initial and final proton energy and any initial and final separations, the required satellite charge is determined. For the Case I electrostatic shield, the satellite charge, Q_I , will have to be just enough to deflect the highest energy solar proton at its radius, R_1 , thus $KE = 0$ at $r = R_1$. The protons will be coming from great distances, so $1/r - 1/r_0 = 1/R_1$. Therefore,

$$Q_I = \frac{4\pi\epsilon_0}{q} R_1 \cdot KE_0$$

Case II: Concentric Spherical Satellite

The concentric spherical satellite is shown in Figure 2. The solution is the same as Case I with condition that $R_1 \leq r \leq R_2$. There is no electrostatic force on p for $r > R_2$ thus $r_0 = R_2$. Satellite charge, Q_{II} , has to be just large enough to deflect the highest energy solar proton at $r = R_1$. Therefore,

$$Q_{III} = \frac{4\pi\epsilon_0}{q} \frac{KE_0}{1/R_1 - 1/R_2}$$

Case III: Coaxial Cylindrical Satellite

This is portrayed in Figure 3. The particle will have its closest approach to C_1 if it is traveling along a radial line from the satellite. The force equation for this case is:

$$F = Eq = m \frac{d^2r}{dt^2} \quad \text{where } E = \text{electric field acting on } p.$$

For coaxial cylinders (ref. 13),

$$E = Q/2\pi\epsilon_0 rL, \quad r_1 \leq r \leq r_2$$

$$= 0, \quad r_1 > r > r_2$$

Substituting $v \frac{dv}{dr}$ for $\frac{d^2r}{dt^2}$

$$\frac{Qq}{2\pi\epsilon_0 rL} = m v \frac{dv}{dr}$$

solving this for $v = v(r)$

$$v^2 - v_0^2 = \frac{Qq}{m\pi\epsilon_0 L} \ln r/r_0$$

$$\text{or } KE - KE_0 = \frac{Qq}{2\pi\epsilon_0 L} \ln r/r_0$$

$$\text{solving for } Q, \quad Q = \frac{2\pi\epsilon_0 L}{q} \frac{KE_0 - KE}{\ln r_0/r}$$

For this shield, the particle has kinetic energy KE_0 at $r_0 = r_2$ and the satellite charge, Q_{III} , has to be large enough to just deflect solar protons at $r = r_1$.

Thus

$$Q_{III} = \frac{2\pi\epsilon_0 L}{q} \frac{KE_0}{\ln(r_2/r_1)}$$

The following constants are used in calculating the required satellite charge for the three cases:

$$\epsilon_0 = 1/36 \pi \times 10^9 \text{ farads/meter}$$

$$q = 1.602 \times 10^{-19} \text{ coulombs}$$

$$KE_0 = 10 \text{ Bev} = 1.602 \times 10^{-8} \text{ joules}$$

KE_0 was chosen to be 10 Bev because this is the energy at which the high energy solar event flux is approximately equal to the galactic cosmic ray flux (ref. 6).

$$Q_I = 0.0111 R \text{ coulombs}$$

$$Q_{II} = 0.0111 / (1/R_1 - 1/R_2)$$

$$Q_{III} = 0.00555 L / \ln r_2 / r_1$$

Assume a manned satellite with crew capsule volume of 30 cubic meters. This capsule is similar to that assumed in References 2 and 4. This volume is attained in a sphere of 2 meters radius or a cylinder of 2 meters radius and 3 meters long. Then $R = R_1 = r_1 = 2$ meters and $L = 3$ meters.

Therefore

$$Q_I = 0.0222 \text{ coulombs}$$

$$Q_{II} = 0.0222 / (1/2 - 1/R_2)$$

$$Q_{III} = 0.01665 / \ln r_2 / 2$$

It is more convenient to plot the ratios of these charges to

$$Q_I \text{ thus } Q_{II}/Q_I = 1 / (1/2 - 1/R_2)$$

$$Q_{III}/Q_I = 0.75 / \ln r_2 / 2$$

The results of these calculations are shown in Figure 4.

APPENDIX II

Mechanical Forces on Charged Shells

The mechanical pressure at a dielectric-conductor boundary is given by

$$P = \rho_s^2 / 2 \epsilon \text{ where } P = \text{mechanical pressure, newton / m}^2$$

$$\rho_s = \text{surface charge density, coulombs / m}^2$$

$$\epsilon = \text{permittivity of the insulator, farads / m}$$

The force is directed normally toward the dielectric (ref. 13).

Case I:

$$\text{Since } \rho_s = Q_I / 4 \pi R^2$$

$$\text{Then } P = \frac{Q_I^2}{32 \pi^2 \epsilon_0 R^4}$$

$$= 1.103 \times 10^4 \text{ newtons / m}^2 = 1.6 \text{ lbs / in.}^2$$

Case II:

$$\rho_{s1} = Q_{II} / 4 \pi R_1^2 \qquad \rho_{s2} = Q_{II} / 4 \pi R_2^2$$

$$P_{s1} = \frac{Q_{II}^2}{32 \pi^2 \epsilon_0 R_1^4}$$

$$P_{s2} = \frac{Q_{II}^2}{32 \pi^2 \epsilon_0 R_2^4} = P_{s1} (R_1 / R_2)^4$$

Case III:

$$\rho_{c1} = Q_{III} / 2 \pi r_1 L \qquad \rho_{c2} = Q_{III} / 2 \pi r_2 L$$

$$P_{c1} = \frac{Q_{III}^2}{8 \pi^2 \epsilon_0 r_1^2 L^2} \qquad P_{c2} = \frac{Q_{III}^2}{8 \pi^2 \epsilon_0 r_2^2 L^2}$$

The normalized functions of P_s , P_{s1} , P_{s2} , P_{c1} , and P_{c2} , are plotted in Figure 5.

Required Thickness of Shell

The greatest pressure calculated is produced in Case II for inner and outer radii of 2 and 3 meters respectively. For a spherical shell of radius R and thickness ΔR

$$P_{ES} = \pi R^2 = P_{DS} \cdot 2 \pi R (\Delta R)$$

where

P_{ES} = electrostatic stress

P_{DS} = design stress

The highest stress comes on the inner shell, therefore calculate the thickness, ΔR , for it.

$$\Delta R = \frac{P_{ES} R_1}{2 P_{DS}} ; P_{ES} = 14.4 \text{ lbs/in.}^2 \quad R_1 = 78.74 \text{ in.}$$

If stainless steel is used, $P_{DS} = 25,000 \text{ lbs/in}^2$ and $\Delta R = 0.0226$ inches.

If aluminium is used, $P_{DS} = 10,000 \text{ lbs/in}^2$ and $\Delta R = 0.0567$ inches.

APPENDIX III

Power Requirement

Case I:

$$\text{Power, } P = dw/dt$$

In the case of charging concentric shells of a fixed geometry, the work done, W , is the same as the increase in electrostatic energy, ΔE , on a two body capacitor. $\Delta E = E_f - E_i$ where E_f and E_i are the final and initial electrostatic energies of the system. The electrostatic energy of the system is given by $E = 1/2 CV^2$ where C is the system capacitance and V is the system voltage. For the shield system the final voltage V_f is determined by the maximum energy particle to be shielded. Assuming that the shield is for 10 Bev protons and it is initially uncharged, that is, $V_f = 10^{10}$ volts and $V_i = 0$ then

$$E = 1/2 CV_f^2 - 1/2 CV_i^2 = 5 \times 10^{17} \text{ C}$$

The maximum ΔE will occur for maximum system capacitance.

Case II:

$$C = 4\pi\epsilon_0 / (1/R_1 - 1/R_2)$$

$$\text{For } R_1 = 2 \text{ m and } R_2 = 3 \text{ m}$$

$$C = 6.67 \times 10^{-10} \text{ farads}$$

$$\text{and } \Delta E = 3.33 \times 10^8 \text{ joules}$$

Case III:

$$C = 2\pi\epsilon_0 L / \ln r_2/r_1 \quad \text{At } r_1 = 2 \text{ m and } r_2 = 3 \text{ m}$$

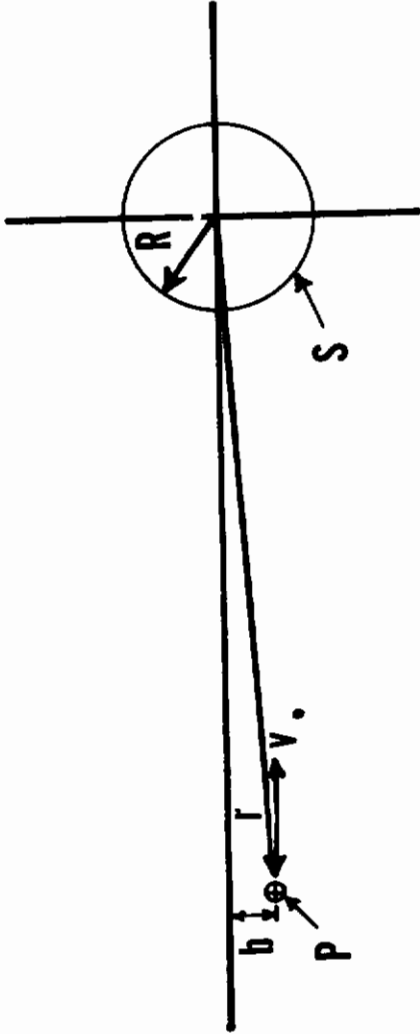
$$C = 4.41 \times 10^{-10} \text{ farads and } \Delta E = 2.20 \times 10^8 \text{ joules}$$

Assuming one half hour warning is available, let $P = \Delta E/\Delta t$

If $\Delta E = 3.33 \times 10^8$ joules and $\Delta t = 1800$ seconds, $P = 185,000$ watts.

LIST OF REFERENCES

1. Halliday, David, Introductory Nuclear Physics, 2nd ed, John Wiley & Son (1955)
2. Naugle, John E., "Space Radiation Levels" Nucleonics, Vol 19, No. 4, pp 89-91, April, 1961
3. "Space Environment Criteria for Aerospace Vehicles," USAF Specification Bulletin No. 523, Aeronautical Systems Division, Wright-Patterson AFB, Ohio
4. Keller, J. W., "A Study of Shielding Requirements for Manned Space Missions," Report FZK-128, Convair, Fort Worth, Texas, 10 October 1960
5. Van Allen, J. A., Journal of Geophysical Research Vol. 65, 1377 (1959)
6. Winkler, J. R., Report at Conference on Radiation Problems in Manned Space Flight; NASA TN D-588; December, 1960, pp 3-7, 72-93
7. Singer, S. F., "Some Consequences of a Theory of the Radiation Belt," Ninth Annual Congress of the IAF, Amsterdam, 26 August 1958
8. Dow, Norris F., "Structural Implications of the Ionizing Radiation in Space," Proceedings of the Manned Space Stations Symposium; Los Angeles, California, April 20-22, 1960
9. Levy, Richard H., "Radiation Shielding of Space Vehicles by Means of Superconducting Coils," AF Ballistic System Division TN 61-7, April, 1961
10. Kunzler, J. E., Beuhler, E., Hsu, F. S. L., and Wernick, L. F., "Superconductivity in Nb_3Sn at High Current Density in a Magnetic Field of 88 Kilogauss," Physical Review Letters, February 1, 1961, pp 89-91
11. Research on the Phenomena of Superconductivity in Metals and Alloys, Quarterly Progress Report 8, 1 September 1961, Contract AF 33(616)-6405, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio
12. Finger, Harold B., "The Case for Nuclear Energy" Nucleonics, Vol 19, No 4 p 62, April 1961
13. Attwood, Stephen S., Electric and Magnetic Fields, 3rd ed. John Wiley and Sons (1949)

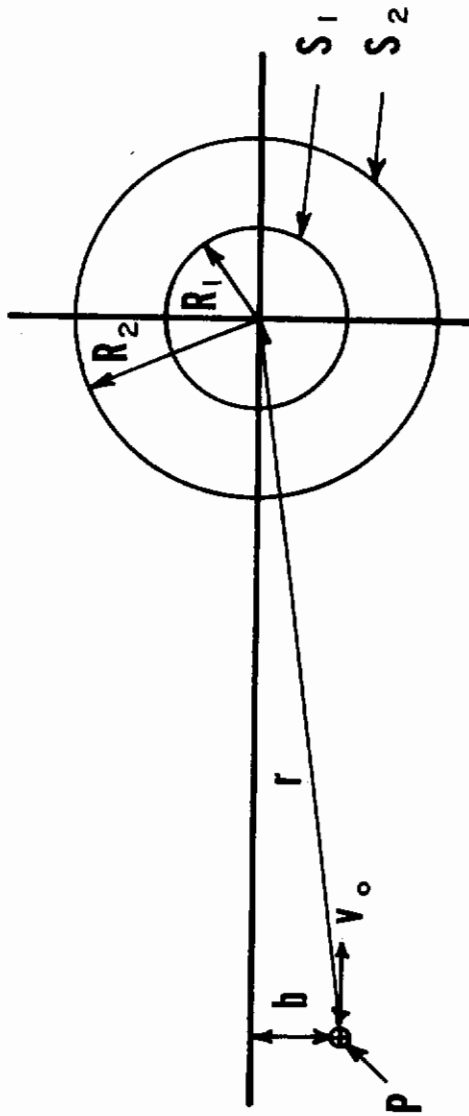


S: Spherical Shell; Surface Charge, +Q; Radius, R

p: Proton; Kinetic Energy, $\frac{1}{2}mv^2$; Charge, +q

b: Impact Parameter

Figure 1. Isolated Spherical Satellite

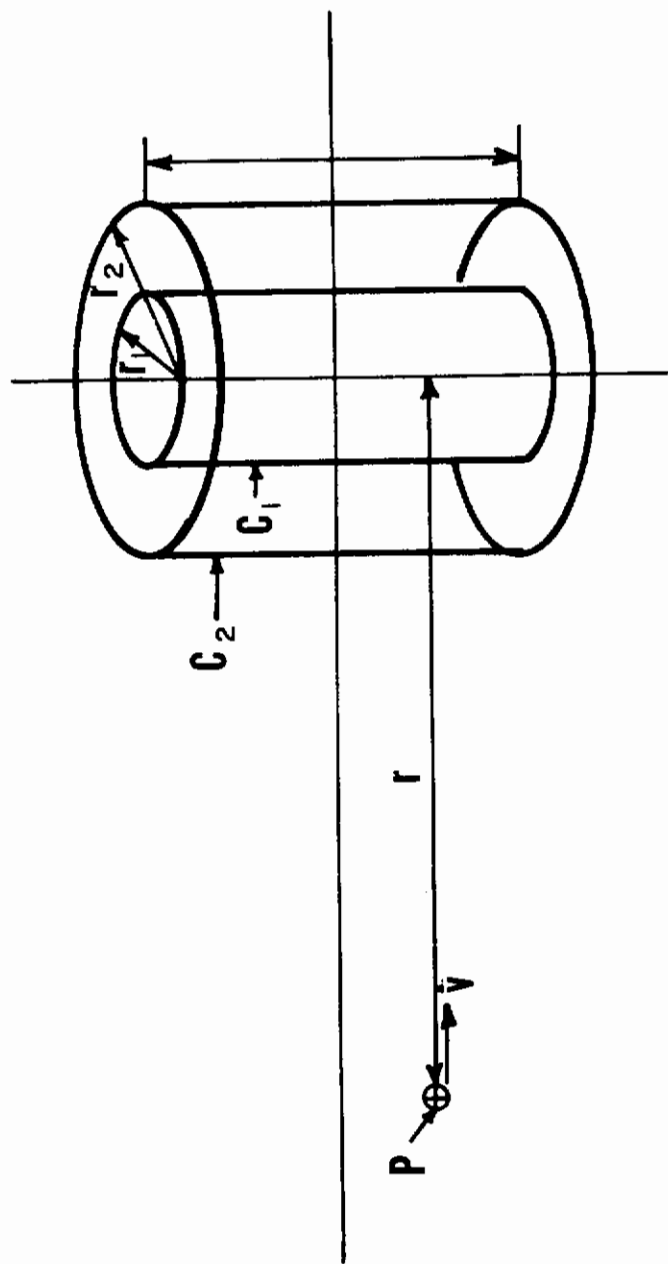


S_1, S_2 : Concentric Spheres; Radii, R_1 , And R_2 ;

Charge, $+Q$ And $-Q$, Respectively

p: Proton; Kinetic Energy, $KE = \frac{1}{2}mv^2$; Charge, $+q$

Figure 2. Concentric Spherical Shield



C_1 , C_2 : Coaxial Cylinders; Radius, r_1 , And r_2 ;

Charge, $+Q$ And $-Q$, Respectively

P : Incident Proton; Kinetic Energy, KE ; Charge, $+q$

Figure 3. Coaxial Cylindrical Shield

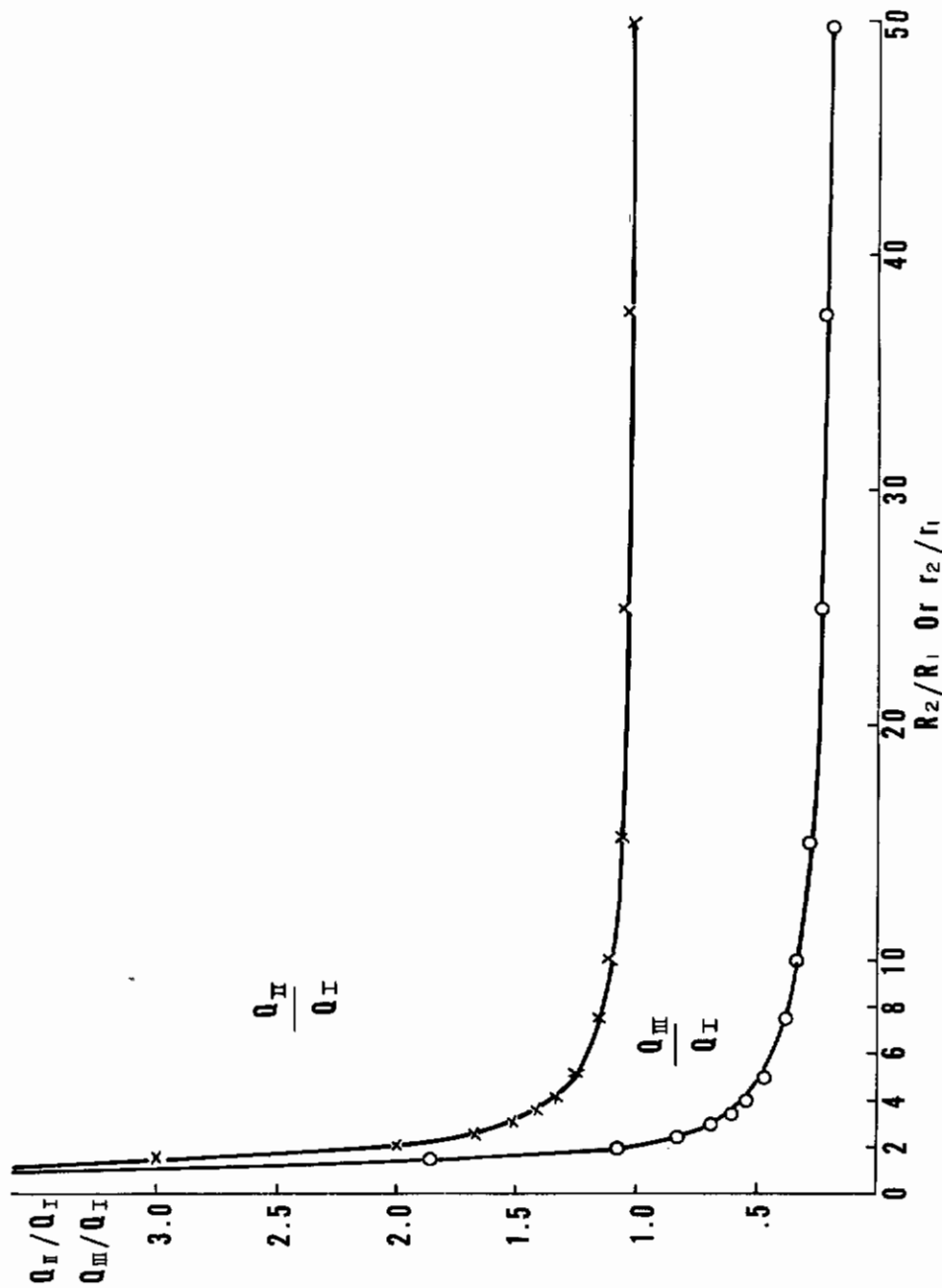


Figure 4. Charge Required to Shield 10 BeV Protons

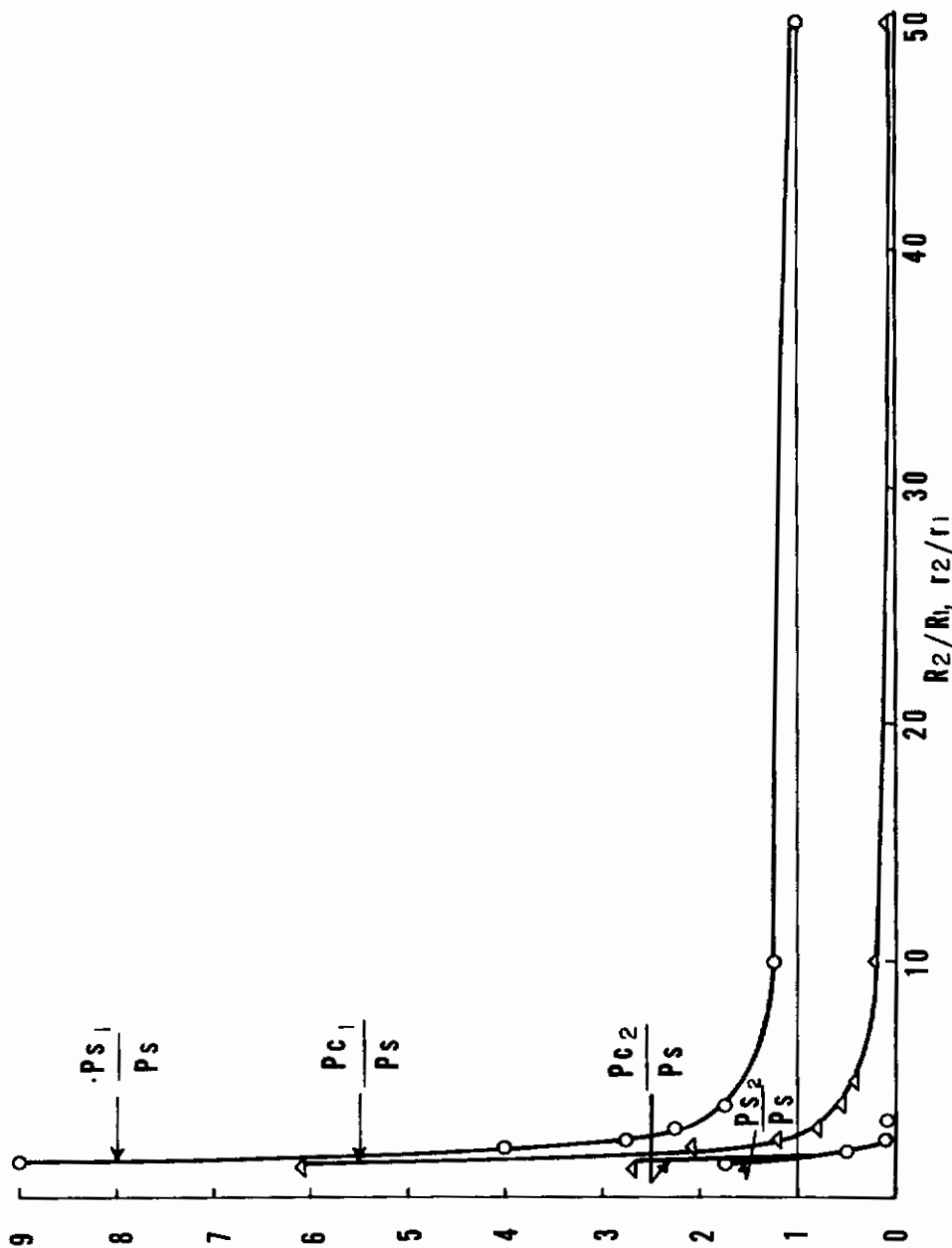


Figure 5. Mechanical Pressures on Charged Shells